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LOAD ANALYSES OF SPACECRAFT AND PAYLOADS

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DOCUMENT HISTORY LOG

Status	Document Revision	Change Number	Approval Date	Description
Baseline			1996-06-21	Initial Release
Revision	**A**		2019-09-25	Significant changes were made to this NASA Technical Standard. It is recommended that it be reviewed in its entirety before implementation. Key changes were: Updates and additions to Definitions; moved requirements statements previously found in the scope section to the requirements section. Updated various sections within the document for clarification. Applicable documents were updated where necessary (i.e., new revisions or change of authors).

FOREWORD

This NASA Technical Standard is published by the National Aeronautics and Space Administration (NASA) to provide uniform engineering and technical requirements for processes, procedures, practices, and methods that have been endorsed as standard for NASA programs and projects, including requirements for selection, application, and design criteria of an item.

This NASA Technical Standard is approved for use by NASA Headquarters and NASA Centers and Facilities, and applicable technical requirements may be cited in contract, program, and other Agency documents. It may also apply to the Jet Propulsion Laboratory (a Federally Funded Research and Development Center (FFRDC)), other contractors, recipients of grants and cooperative agreements, and parties to other agreements only to the extent specified or referenced in applicable contracts, grants, or agreements.

This NASA Technical Standard was developed by the NASA Loads Standard Panel to minimize variations in methodologies, practices, and requirements for the conduct of load analyses among the NASA Centers. Such variations lead to misunderstandings and inefficiencies in the load analysis arena for large projects that generally involve more than one NASA Center.

This NASA Technical Standard describes the accepted practices and requirements for the conduct of load analyses for payloads and spacecraft structures. Load regimes are identified. Requirements are set for establishing forcing functions and mathematical models and for performing analyses and verification of models by tests. Major methods of analyses, practices, and processes are identified.

Requests for information should be submitted via "Feedback" at https://standards.nasa.gov. Requests for changes to this NASA Technical Standard should be submitted via MSFC Form 4657, Change Request for a NASA Engineering Standard.

Original signed by	09/25/2019
Ralph R. Roe, Jr. NASA Chief Engineer	Approval Date

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LOAD ANALYSES OF SPACECRAFT AND PAYLOADS

1. SCOPE

1.1 Purpose

This NASA Technical Standard defines the methodologies, practices, and requirements for the conduct of load analyses for payloads and spacecraft and describes accepted engineering practices for NASA programs and projects. This NASA Technical Standard also establishes general NASA requirements for the definition of loads to be used in the design and development of payloads and spacecraft. Guidelines are prescribed to establish consistent practices and facilitate integration at the program and project levels.

1.2 Applicability

This NASA Technical Standard applies only to spaceflight payload hardware. Launch vehicles (LV), payloads launched by sounding rockets, aircraft and balloons, and ground support equipment (GSE) are excluded.

This NASA Technical Standard is applicable principally to Classes A, B, and C payloads. Classification of NASA payloads is defined in NPR 8705.4, Risk Classification for NASA Payloads. For Class D or I-E payloads, this NASA Technical Standard is a guidance document. (The I-E payloads classification is defined in JPD 7120.9, Experimental Flight Hardware [Class I-E] Development Policy.) Class D and I-E payloads may utilize tailoring as stated in section 1.3 of this NASA Technical Standard.

This NASA Technical Standard is approved for use by NASA Headquarters and NASA Centers and Facilities, and applicable technical requirements may be cited in contract, program, and other Agency documents. It may also apply to the Jet Propulsion Laboratory (JPL) (a Federally Funded Research and Development Center [FFRDC]), other contractors, recipients of grants and cooperative agreements, and parties to other agreements only to the extent specified or referenced in applicable contracts, grants, or agreements.

Verifiable requirement statements are designated by the acronym LAR (Loads Analysis Requirement), numbered, and indicated by the word “shall”; this NASA Technical Standard contains 63 requirements. Explanatory or guidance text is indicated in italics beginning in section 4. Statements containing the verb “may” express permission or optional activities; formal verification is not required, and these statements are not subject to audits or inspection by NASA. Statements containing the verb “will” or “to be” indicate a declaration of fact, descriptive material, or an agreement on expected outcomes; formal verification is not required, although these statements remain subject to audits or inspection by NASA based upon the Program’s risk management assessments. To facilitate requirements selection and verification by NASA programs and projects, a Requirements Compliance Matrix is provided in Appendix A.

1.3 Tailoring

Document tailoring of the requirements in this NASA Technical Standard for application to a specific program or project as part of program or project requirements and obtain formal approval by the delegated Technical Authority in accordance with NPR 7120.5, NASA Space Flight Program and Project Management Requirements. NASA Technical Standard tailoring is addressed in NPR 7120.10, Technical Standards for NASA Programs and Projects.

2. APPLICABLE DOCUMENTS

2.1 General

The documents listed in this section contain provisions that constitute requirements of this NASA Technical Standard as cited in the text.

2.1.1 The latest issuances of cited documents apply unless specific versions are designated.

2.1.2 Non-use of a specifically designated version is approved by the delegated Technical Authority.

Applicable documents may be accessed at https://standards.nasa.gov or obtained directly from the Standards Developing Body or other document distributors. When not available from these sources, information for obtaining the document is provided.

2.2 Government Documents

NASA

NPR 7120.5	NASA Space Flight Program and Project Management Requirements
NPR 7120.10	Technical Standards for NASA Programs and Projects

2.3 Non-Government Documents

None

References are provided in Appendix C.

2.4 Order of Precedence

2.3.1 The requirements and standard practices established in this NASA Technical Standard do not supersede or waive existing requirements and standard practices found in other Agency documentation, or in applicable laws and regulations unless a specific exemption has been obtained by the Office of the NASA Chief Engineer.

2.3.2 Conflicts between this NASA Technical Standard and other requirements documents are resolved by the delegated Technical Authority.

3. ACRONYMS, ABBREVATIONS, SYMBOLS, AND DEFINITIONS

3.1 Acronyms, Abbreviations, and Symbols

$[\o_A]$	analytical modes
$[\o_T]$	test mode shape
$[M_A]$	analytical mass matrix
±	plus or minus
ATM	acceleration transformation matrix
BEA	boundary element analysis
CAD	computer-aided design
CDR	critical design review
CG	center of gravity
CLA	coupled loads analysis
c.m.	center of mass
DLA	Dynamic Loads Analysis
DOF	degree of freedom
DTM	displacement transformation matrix
FDLC	Final Design Loads Cycle
FEA	finite element analysis
FEM	finite element method
FFRDC	Federally Funded Research and Development Center
FLAC	Final Loads Analysis Cycle
FOS	factors of safety
g	acceleration of gravity
GSE	ground support equipment
GSE&I	general systems engineering and integration
HDBK	handbook
Hz	Hertz
IV&V	Independent verification and validation
JPL	Jet Propulsion Laboratory
kg	kilogram
KSC	Kennedy Space Center
LAR	Loads Analysis Requirement

LTM	loads transformation matrix
LV	launch vehicle
MAC	mass acceleration curve
MAF	Michoud Assembly Facility
mph	miles per hour
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NPR	NASA Procedural Requirements
OTM	output transformation matrix
PDLC	preliminary design loads cycle
PDR	preliminary design review
PLAC	Preliminary Loads Analysis Cycle
rad/sec^2	radians per second squared
rms	root mean square
RSS	root sum square
SEA	statistical energy analysis
SMC	Space and Missile Systems Center
STD	Standard
TA	Technical Authority
VLC	Verification Load Cycle

3.2 Definitions

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

Coupled Loads Analysis (CLA): Dynamic loads analysis with the LV and spacecraft or payload models coupled together.

Delegated Technical Authority (TA): The responsibility for structural dynamic limit loads and environments is delegated to (and served by) the technical team defined by the Program and/or Mission organization. It will be the responsibility of the delegated TA to demonstrate to the NASA TA that a proposed alternate requirement fully meets the intent of the requirements of this document. The NASA TA provides insight/oversight and serves an independent verification and validation (IV&V) role.

Design Loads: The product of the factor of safety and the limit load.

Dynamic Loads Analysis (DLA): An analysis intended to calculate the dynamic responses of a structural system when the spacecraft and launch vehicle are no longer coupled together.

Factors of Safety: See NASA-STD-5001, Structural Design and Test Factors of Safety for Spaceflight Hardware.

Forcing Function: The forces to which LV and spacecraft will be subjected in their operational environment. These forces are usually termed external loads as well.

Launch Vehicle: The vehicle used to transport a spacecraft or payload from Earth’s surface into space.

Life Cycle: The phases of a spacecraft or payload’s life, including assembly, testing, transportation, terrestrial operations, launch, ascent, space operations, extraterrestrial operations, re-entry, descent, landing, and recovery.

Limit Load: The maximum anticipated load experienced by a structure during a loading event, load regime, or mission. The factors of safety are not included in the limit load. (Refer to NASA-STD-5001.)

Load Factor: Usually prescribed in unit of g's and defined as the maximum of either the total interface force in each axis divided by the payload mass or the maximum total interface moment in each axis divided by the product of the payload mass and center of mass (c.m.) offset. The resulting load factor is commonly described as the c.m. load factor.

Payload: An integrated system that is carried into space on an LV for space operations. A spacecraft is a payload during the launch phase.

Primary Structure: The structure that is the principal load path for all subsystems, components, and other structures.

Spacecraft: 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.

Uncertainty: The inherent variation in the physical system; it is stochastic and irreducible without changes to the system or how it operates. A lack of knowledge of the quantities or processes identified with the system; it is subjective, is reducible, and comprises both model and parameter uncertainty.

Uncertainty Factor: Account for things that are not known in the analysis. A semi-quantitative (i.e., a quantitative magnitude based on past experience rather than data) adjustment, either additive or multiplicative or both, made to the results of an analysis to account for uncertainty. (Source: NASA-STD-7009, Standard for Models and Simulations)

Validation, Model: Addresses: "How does the model(s) behave or predict response with regard to actual physics in the real world?"

Verification, Model: Addresses the question of: "Is the mathematical model built correctly per the design intent (drawings)?"

4. REQUIREMENTS

This section defines overarching requirements applicable to conducting dynamic loads analyses for the development of payload and spacecraft loads. The requirements in this section are applicable to both payload and spacecraft analyses, unless noted otherwise. A thorough understanding of the operation and performance requirements is necessary to ensure complete definition of loads for a spacecraft or payload.

4.1 Load Analysis Cycles for Payloads and Spacecraft

4.1.1 [LAR 1] A minimum of three load analysis cycles **shall** be performed: Preliminary Design Load Cycle (PDLC), Final Design Load Cycle (FDLC), and Verification Load Cycle (VLC).

A loads analysis cycle provides the loads for a spacecraft or payload to support the design and verification process. Estimation of loads for payloads is an iterative process. Based on the resulting loads, structural sizing may need to be adjusted. The effect of design change due to loads or possible configuration changes can alter the static and dynamic properties of the structure, thereby changing the loads. Subsequent load cycles assess the changes in design, in launch vehicle and payload mathematical models, and in forcing functions.

See Appendix B.3 for an explanation of load cycles and additional information on the loads cycle process.

Plan the load cycle analysis process to provide maximum benefit to the overall program development plan and schedule.

4.1.2 [LAR 2] Coupled loads analyses (CLA) **shall** be performed on payloads that experience the liftoff and ascent load regimes and terrestrial landing to calculate loads, accelerations, and deflections for launch through payload separation.

See Appendix B.3 for an explanation of load analysis cycles and additional information on the loads analysis cycle process.

The LV organization will develop the dynamic loads and forcing functions for all the mission load regimes up to payload separation and verify that the payload dynamic characteristics comply with mission requirements.

4.1.3 [LAR 3] Loads analyses **shall** be performed on spacecraft that experience the mission load regimes beyond payload separation to calculate loads, accelerations, and deflections.

The spacecraft provider and/or mission organization will develop the dynamic loads and forcing functions for all the mission load regimes beyond payload separation and verify that the spacecraft dynamic characteristics comply with mission requirements. Mission load regimes beyond payload separation include on-orbit operations, space operations, extraterrestrial operations, etc. See Appendix B.2.2 for information on other load regimes.

4.1.4 [LAR 4] Each load analysis cycle **shall** use approved analysis methodologies, models (payload models, LV models, spacecraft models, etc.), analysis forcing functions, and planned mission trajectory that are representative of the design at the time of the loads analysis cycle.

4.1.5 [LAR 5] Limit loads **shall** be determined that will not be exceeded with 99.87/50 (99.87 percent probability at 50 percent confidence level).

This “3-sigma” probability of 0.9987 with 50-percent confidence is traditionally used for aerospace structure.

4.1.6 [LAR 6] Interface boundary conditions **shall** be consistent with the coupled configuration.

4.1.7 [LAR 7] Stress recovery directly from dynamic models for load analysis **shall** only be utilized for relatively simple load paths when the models have the fidelity necessary to accurately calculate stress.

Refer to Appendix B.4.2 for guidance.

4.1.8 [LAR 8] Random vibration loads analysis **shall** only be utilized for load predictions when the dynamic model has adequate fidelity in the frequency range of the analysis.

Refer to Appendix B.4.3 for guidance.

4.1.9 [LAR 9] For random vibration loads analysis, peak responses **shall** be used for the limit loads.

When payload developers are required to supply a dynamic model to the LV organization, specific model requirements are often implemented. See Section 4.4 for typical model requirements for payload dynamic models.

4.2 Load Regimes for Payloads and Spacecraft

4.2.1 [LAR 10] All critical load regimes to which the structure will be exposed **shall** be evaluated in the loads analyses.

[Rationale: Payloads and spacecraft have to be designed to maintain structural integrity and the required degree of functionality to ensure successful operation during all phases of the expected life cycle. Static and dynamic load environments to be encountered during assembly, testing, transportation, launch, ascent, space operations, extraterrestrial operations, descent, and landing have to be considered in flight structures and systems.]

Load regimes other than the liftoff and ascent regime are generally more benign, but all load regimes should be considered to help determine the critical load regimes for analysis.

Typical load regimes are described in Appendix B.2.

4.2.2 [LAR 11] If the structure has multiple configurations during its mission, the load regimes each configuration will experience **shall** be identified and each configuration evaluated in the loads analysis.

4.2.3 [LAR 12] Within each load regime, each source of loading **shall** be evaluated in the loads analysis.

For requirements to combine different load sources that can occur simultaneously, refer to section 4.8.

4.3 Payload and Spacecraft Preliminary Loads for Design

a. [LAR 13] To initiate the design process, a set of preliminary limit loads **shall** be developed and used for the sizing of primary structure, secondary structure, and components.

Estimation of loads for the payload is an iterative process. Loads for preliminary design are used for the initial sizing of the structure and should include conservatism to account for future models, forcing functions, and design changes.

b. [LAR 14] For spacecraft that can experience a variety of load regimes during operational phases, depending on the specific mission, the spacecraft providers **shall** develop envelopes that bound the accelerations for components for use in preliminary design.

4.3.1 Payload and Spacecraft Primary Structure Design

4.3.1.1 [LAR 15] Limit loads for preliminary sizing of primary structure **shall** be based on the design load databases, existing load analysis results for similar payloads, or flight data.

These load factors, usually prescribed in acceleration of gravity (g).

4.3.1.2 [LAR 16] Angular accelerations in radians per second squared (rad/sec^2) about the c.m. **shall** also be included, when appropriate.

A typical consideration would be the torsion of the vehicle.

4.3.2 Payload and Spacecraft Components Design

4.3.2.1 [LAR 17] Preliminary limit load factors for components **shall** be obtained from 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.

[Rationale: The development of a mass acceleration curve is to be based on previous experience with the LV and spacecraft, and, if possible, incorporate 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.]

These component load factors may be defined as a function of component weight, frequency range, structural support type, or other variables. The load factors should be based on available flight data, test data, analyses, and experience.

Load factors for payload components are typically higher than the payload load factors. Refer to Appendix B.5 for guidance.

For preliminary random load factors (prior to the design becoming more than a concept), methods include (1) use Mile's equation for a single degree-of-freedom system, and (2) use three times the composite g_{rms} *of the specified random vibration environments. See Appendix B.4.3, for additional information.*

4.3.2.2 [LAR 18] The component limit load factors **shall** include effects of quasi-steady, transient, and random loading and thus represent the total dynamic load environment for a flight event.

Other limit loads that contribute to structural strength analysis for components include pressure and temperature loads which are not developed by the loads analysis in this document. See information in Appendix B.4.1.

4.4 Development of a Payload and Spacecraft Mathematical Model for Loads Analysis

a. [LAR 19] To support CLA, a mathematical model of the payload **shall** be developed using finite element methods.

The original finite element model may be reduced in size using static or dynamic reduction methods. (See section 4.4.3 for more details.)

After the mathematical model is developed, it will then be coupled with the LV (or upper stages) to perform one or more cycles of analyses to update and refine the loads in the payload. The model may also be used to evaluate loads for mission scenarios, e.g., on-orbit, transportation, etc.

Random vibration model development requirements depend on the vibroacoustic analysis method and tools (and based on load regime and frequency of interest). See Appendix B.4.3 for information. The vibroacoustic delegated Technical Authority will determine modeling requirements for the methodologies and analysis tools identified by the payload/spacecraft.

b. [LAR 20] Spacecraft mathematical models **shall** be developed as needed to support load predictions for spacecraft post-separation and during operational phases, depending on the specific mission.

Depending on the load regime, spacecraft models may take the form of empirical models, rigid body models, kinematic models of mechanisms, finite element models, and boundary element models.

4.4.1 Form of Payload and Spacecraft Model

4.4.1.1 [LAR 21] The payload finite element model **shall** be developed to meet all pertinent interfaces identified by the LV for loads analysis.

[Rationale: Finite element models are based on mass, stiffness, damping, and geometry. The model may be a reduced version of a finite element model developed for stress analyses or may be a model developed specifically for load analysis.]

Regardless of the source, the modeling approach should be aimed at producing accurate dynamic model predictions (frequencies and mode shapes). For example, indeterminate (multi-point) LV/payload interfaces are needed to accurately capture the deformation of the interfaces and to make accurate post-flight comparisons to flight data.

4.4.1.2 [LAR 22] Interface boundary conditions **shall** be consistent with the coupled configuration.

Refer to Appendix B.4.1 for guidance.

4.4.1.3 [LAR 23] The boundary conditions for the model **shall** correspond to the attachment to the supporting structure.

4.4.2 Resolution and Fidelity of a Payload and Spacecraft Model

4.4.2.1 [LAR 24] The payload and spacecraft dynamic model **shall** have sufficient fidelity to capture the dynamic behavior of the payload and spacecraft in the defined analysis frequency range.

The LV organization will determine whether or not sufficient fidelity is captured by the delivered payload model, for the CLA. For the spacecraft model, the spacecraft developer and delegated Technical Authority will determine whether or not sufficient fidelity is captured.

For payloads, the frequency range for CLA is determined by the resolution and fidelity of the LV models and forcing functions. For spacecraft, the frequency range for the dynamic loads analysis is determined by the resolution and fidelity of the spacecraft models and forcing functions.

4.4.2.2 [LAR 25] Subsystem resonances and overall payload and spacecraft system modes **shall** be modeled up to a model upper bound frequency at least 1.5 times the cutoff frequency of the load analysis, assuming fixed boundary condition at its mounting interface.

The upper frequency bound is based on the energy content of the forcing functions and ability to generate accurate analysis models (e.g., typically 50 to 70 Hz for CLA).

Typically, the LV organization and the spacecraft provider would define a minimum upper bound frequency to the model providers.

4.4.3 Payload and Spacecraft Model Reduction

4.4.3.1 [LAR 26] If dynamic reduction is used, the finite element model **shall** be reduced to a cutoff frequency of at least 1.5 times the cutoff frequency of the load analysis (which is typically the cutoff frequency of the coupled launch vehicle/payload system or spacecraft system).

Typically, the LV organization and the spacecraft provider would define the cutoff frequency to the model providers.

4.4.3.2 [LAR 27] If static reduction is used, the dynamic characteristics of the reduced model **shall** preserve the characteristics of the original model up to the model upper bound frequency as defined by the delegated Technical Authority.

To obtain a loads model appropriate for coupling with a LV, the original finite element model may be reduced in size using static (Guyan Reduction method) or dynamic reduction (e.g., Craig-Bampton component mode synthesis method).

4.4.3.3 [LAR 28] For steady state portion of the analysis using models that are dynamically reduced, the effects of the reduced out modes above the frequency cutoff of the model on the steady state portion of the response **shall** be accounted for in the calculation of the limit loads.

Residual flexibility vectors is one of the options to use to account for the flexibility effects of the reduced out modes (See NASA-HDBK-7005, Dynamic Environmental Criteria, for additional information on steady state and residual vectors). Another option is to use the Mode Acceleration Method for data recovery for calculating any displacement-dependent responses.

4.4.4 Payload and Spacecraft Model Output

[LAR 29] Model output requests, an output transformation matrix (OTM) format, **shall** be documented and provided with grid and/or element identification information with a description of the type of response (e.g., peak acceleration).

The OTM is often used to describe output requests from CLA. The OTM includes loads transformation matrix (LTM), acceleration transformation matrix (ATM), and displacement transformation matrix (DTM).

4.5 Payload and Spacecraft Forcing Functions

4.5.1 [LAR 30] Non-deterministic forcing functions used in coupled loads analysis **shall** be 99.87/50 (99.87 percent probability at 50 percent confidence level) levels or greater.

4.5.2 [LAR 31] Forcing functions for events associated with the spacecraft **shall** be developed by the spacecraft provider and/or mission organization, as needed.

The LV organization will develop the CLA forcing functions for all the mission load regimes up to payload separation.

4.5.3 [LAR 32] For spacecraft forcing functions, analytical predictions, ground test data, and flight data **shall** be utilized to the maximum extent possible for the forcing function definition.

4.5.4 [LAR 33] For spacecraft forcing functions, the effects of variations and tolerances of parameters that govern the forcing functions **shall** be considered in the analysis methodology.

The goal is to provide families of forcing functions that yield load responses that will not be exceeded on 99.87 percent of flights with 50 percent confidence level. In addition, any flight experience for the same/similar configuration has to be enveloped. Acceptable approaches are statistical computation of results (this includes loads combination equations), or Monte Carlo selection of parameters with the statistical enclosure determined using order statistics. In both approaches, accurate knowledge of statistical variation of parameters is desired.

4.5.5 [LAR 34] For the Monte Carlo approach, an appropriate distribution **shall** be defined for each parameter so a value can be randomly selected.

4.6 Payload and Spacecraft Damping

4.6.1 [LAR 35] Damping used for dynamic loads analysis **shall** 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.

4.6.2 [LAR 36] In the absence of measured damping data, damping of one percent (1 percent) of critical **shall** be assumed for each mode for CLA.

4.6.3 [LAR 37] For random vibration load analysis, damping **shall** be specified per the delegated Technical Authority, in the absence of measured damping data.

4.7 Payload and Spacecraft Uncertainty Factors

4.7.1 [LAR 38] To reduce design impacts associated with load changes, uncertainty factors **shall** be approved for each loads analysis cycle by the delegated Technical Authority and applied to dynamic loads analysis results.

[Rationale: Coupled loads analysis has uncertainty associated with both the LV and spacecraft inputs to the CLA, which are typically accounted for by using uncertainty factors. From the LV perspective, the uncertainty is due primarily to using approximate forcing functions and unverified models in the CLA, especially for vehicles with no flight history.]

This uncertainty may be accounted for by incorporating a factor in the results of load cycles. This uncertainty factor is used to account for immaturity in models and design, forcing functions, and for changes in LV models and forcing functions. (See supplemental information in section B.6.)

Use of an uncertainty factor to account for model variations may be avoided by using sensitivity analysis. Systematic changes are made to potentially uncertain payload properties, and the resulting loads are computed. The design load is taken from the worst case analyzed or from a statistical combination of all cases. Since payload loads are strongly dependent on the frequencies of the payload modes, frequency sensitivity (or "tuning") analysis is a natural technique. By developing design loads that envelop a broad range of frequency shifts (for example, ±15 percent), the structural design is capable of handling the load increases that may occur as the design matures. This type of analysis has the advantage of increasing loads only for those items that are sensitive to frequency shifts.

For guidance on spacecraft uncertainty factors, see Appendix B.6.

4.7.2 [LAR 39] In subsequent load cycles, the uncertainty factor **shall** be gradually reduced as the structural design and load analysis prediction mature, requiring approval from the delegated Technical Authority for any uncertainty factor reduction.

See supplemental information in Appendix B.6.

CLA general practice calls for a minimum factor of 1.4 to 1.5 for the preliminary design load cycle and 1.2 to 1.25 for the final design load cycle to cover payload uncertainty. The payload uncertainty factor can be reduced to 1.1 for the verification load cycle after the structure is built and the model is verified based on the requirements specified in section 4.9. Additional factors may be used by the LV to address uncertainty associated with the maturity of LV models and forcing functions.

For static loads analysis, factor of safety (FOS) are to be applied to limit loads per NASA-STD-5001.

For random vibration loads analysis, the delegated Technical Authority should address application of input forcing functions that include uncertainty factors.

4.7.3 [LAR 40] If the model verification is determined to be inadequate by the delegated Technical Authority, an uncertainty factor higher than 1.1 **shall** be retained in the verification load analysis cycle.

4.8 Payload and Spacecraft Load Combination

4.8.1 [LAR 41] In cases where loads produced by different environments can occur simultaneously, these loads **shall** be combined statistically to define the limit load for each time/event period in load regime of interest.

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.

4.8.2 [LAR 42] Combinations of these loads occur at different times in flight and **shall** be examined for each flight event.

4.8.3 [LAR 43] Loads from each load regime contributor **shall** be combined by adding the means and root-sum-squaring the dispersed portions.

4.8.4 [LAR 44] The statistical distributions of each load regime contributor **shall** describe the peaks of the loads.

The dispersed portions are the differences between the means and the required statistical enclosure levels, typically 99.87 percent enclosure with 50 percent confidence level (99.87/50). For liftoff, the simultaneously occurring environments are described in Appendix B.2.1.

4.8.5 [LAR 45] The quasi-static, low frequency transient loads, and random vibration/acoustic limit loads **shall** be combined as approved by the delegated Technical Authority to determine the total load environment for liftoff.

For a component that weighs more than 500 kilograms (kg), the overall random vibration load may be assumed to be small relative to the low frequency transient load and therefore neglected. For components weighing less than 500 kg, the appropriate method of load combination will be 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 LV, but simultaneous occurrence of maximum low frequency transient and maximum random vibration load is improbable. Therefore, a root-sum-square (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.

4.8.6 [LAR 46] When an RSS approach to defining component loads is utilized, the maximum low frequency load factor and maximum random vibration load factor **shall** be root-sum-squared (RSS'd).

The RSS'd values are then applied in all axes simultaneously. When the load combination is directly applied to member loads, the maximum random vibration member forces and low frequency member forces are RSS'd.

4.8.7 [LAR 47] When a time-consistent/load regime-consistent approach to defining component loads is utilized, the low frequency transient load factor and random vibration load factor **shall** be combined in a time-consistent/load regime-consistent manner.

When the load combination is directly applied to member loads, the member loads due to low frequency and random vibration are combined in a time-consistent/load regime-consistent manner.

4.8.8 [LAR 48] Inertial forces in all three axes, including rotations if appropriate, **shall** be applied simultaneously, including sign combinations.

4.9 Verification of the Payload and Spacecraft Mathematical Model

4.9.1 Testing/Correlation

4.9.1.1 [LAR 49] Verification of the payload and spacecraft dynamic models by modal survey testing **shall** be performed to ensure the model is sufficiently accurate for load and deflection predictions.

Refer to NASA-STD-7002, Payload Test Requirements. Payload dynamic model verification may be accomplished by a combination of payload level and component level modal survey tests. A payload or component with a minimum frequency higher than the model upper bound frequency requirement defined by the LV organization can substitute sinusoidal sweep vibration testing to verify the frequency. In this case, mode shape correlation is not required. Additional guidance and references for modal survey testing can be found in NASA-HDBK-7005.

Verification of spacecraft dynamic models may require off-loading systems that simulate the free-free boundary conditions of the spacecraft.

Verification of static loads analysis models may be defined and performed as explained in NASA-STD-5001, section 4.1.2.

The delegated Technical Authority may incorporate additional test requirements for random vibration loads analysis models.

4.9.1.2 [LAR 50] The modal survey test **shall** measure all significant modes of sufficient accuracy below the model upper bound frequency and provide test data supporting the model correlation requirements of this section.

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 or deflection definition. All modes within the frequency range of the test should be identified and measured if at all practical.

4.9.1.3 [LAR 51] If the complexity of the system is such that a subset of modes can only be measured, then the subset **shall** include the first two primary bending modes, first axial, first torsion, and modes of appendages included in the test article.

Other modes should be measured such that the total number of modes provides sufficient constraints to the model correlation process so as to yield a test-verified model. This typically requires 20 or more modes.

4.9.1.4 [LAR 52] The modal survey test **shall** be performed as a fixed-base test.

A free-free test can be performed, if the size of the article precludes fixed-base testing.

4.9.1.5 [LAR 53] If alternate boundary conditions are utilized, additional testing and analysis **shall** be required to verify effects of the alternate configuration.

4.9.1.6 [LAR 54] The modal survey test **shall** include techniques approved by the delegated Technical Authority to identify nonlinearities.

Varying input excitation levels and reciprocity checks are commonly utilized for linearity assessment. Significant nonlinearities may require sinusoidal testing at multiple force levels. In *the case of nonlinearities that affect load predictions, the frequencies and mode shapes should be obtained from the highest practical excitation levels. The load model has to then be developed from the available data using best engineering judgment, and the effects of the resulting model uncertainty on the loads has to be incorporated.*

4.9.1.7 [LAR 55] Agreement between test and analysis natural frequencies (after model correlation) **shall** be within 5 percent for the target/significant modes.

The delegated Technical Authority can incorporate a modal effective mass (i.e., mass participation) requirement. The total modal effective mass for a direction is simply the sum of all contributions of all modes in that direction. For typical payload/spacecraft, these totals are often above 80 percent. For smaller, stiffer payload/spacecraft the totals can be significantly less or even zero if no modes are retained.

4.9.1.8 [LAR 56] Accurate mass representation of the test article **shall** be demonstrated with orthogonality checks using the analytical mass matrix $[M_A]$ and the test mode shapes $[\O_T]$. *The orthogonality matrix is computed as* $[\O_T]^T[M_A][\O_T]$*, where* $[M_A]$ *is the analytical mass matrix, and* $[\o_T]$ *are the test mode shapes.*

4.9.1.9 [LAR 57] The off-diagonal terms of the orthogonality matrix **shall** be less than 0.1 for significant modes based on the diagonal terms normalized to 1.0.

The delegated Technical Authority can incorporate additional requirements such as the modal effective mass value.

This check increases confidence in the mass matrix, but mass should be based on measurements.

4.9.1.10 [LAR 58] Mode shape comparisons **shall** be made via cross-orthogonality checks using the test modes $[\O_T]$, the analytical modes $[\O_A]$, and the analytical mass matrix $[M_A]$.

The cross-orthogonality matrix is computed as $[\O_T]^T[M_A][\o_A]$.

4.9.1.11 [LAR 59] The absolute value of the cross-orthogonality between corresponding test and analytical mode shapes **shall** be a minimum of 0.9 and all other terms of the matrix less than 0.1 for all significant modes.

The delegated Technical Authority can incorporate additional requirements such as the modal effective mass value.

4.9.1.12 [LAR 60] Qualitative comparisons between test modes and analytical modes using mode shape animation and/or deflection plots **shall** be performed.

4.9.1.13 [LAR 61] Modal damping **shall** be obtained for each mode measured.

4.9.1.14 [LAR 62] Failure to satisfy the criteria of [LAR 55] through [LAR 60] **shall** be accompanied by an assessment of the effects of model uncertainty on critical loads.

All modeling adjustments or changes made to achieve the above-stated criteria have to be consistent with the actual hardware and its drawings.

4.9.2 Quality Checks

The quality checks assess the mathematical model for suitability for analysis use over the frequency range of interest. A number of mathematical checks can be made to determine that all is well with the formulation of the model. Descriptions of quality checks can be found in NASA-HDBK-7005.

[LAR 63] For finite element models, the model quality checks listed below **shall** be performed:

a. <u>Free-Free Mode Check</u>: Demonstrate modal frequencies of the unconstrained system in applicable rigid-body modes with frequencies less than 1.0E–4 Hz.

b. <u>Mass Properties Check</u>:

(1) Compute the rigid body mass properties at the center of gravity (CG) for the modeled configuration.
(2) Compare output to those specified in the appropriate vehicle’s mass property report.

c. <u>Strain-Energy Check</u>: Subject the unconstrained model to an enforced unit, rigid body displacement for all six degrees of freedom (DOF) independently. Strain energies should be negligible or zero.

d. <u>Grid Point Singularities Check</u>: Explain all grid point singularities.

e. <u>Computer-aided Design (CAD)/Drawing Check</u>: Check the finite element model (FEM) against the CAD/drawing.

The LV organization may define additional quality checks based on the payload complexity. For reduced models, the LV organization should provide the quality check requirements to the payload.

APPENDIX A

REQUIREMENTS COMPLIANCE MATRIX

A.1 PURPOSE

Due to the complexity and uniqueness of space flight, it is unlikely that all of the requirements in a NASA technical standard will apply. The Requirements Compliance Matrix below contains this NASA Technical Standard's technical authority requirements and may be used by programs and projects to indicate requirements that are applicable or not applicable to help minimize costs. Enter "Yes" in the "Applicable" column if the requirement is applicable to the program or project or "No" if the requirement is not applicable to the program or project. The "Comments" column may be used to provide specific instructions on how to apply the requirement or to specify proposed tailoring.

NASA-STD-5002A				
Section	**Description**	**Requirement in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
4.1.1	Load Analysis Cycles for Payloads and Spacecraft	[LAR 1] A minimum of three load analysis cycles **shall** be performed: Preliminary Design Load Cycle (PDLC), Final Design Load Cycle (FDLC), and Verification Load Cycle (VLC).		
4.1.2	Load Analysis Cycles for Payloads and Spacecraft	[LAR 2] Coupled loads analyses (CLA) **shall** be performed on payloads that experience the liftoff and ascent load regimes and terrestrial landing to calculate loads, accelerations, and deflections for launch through payload separation.		
4.1.3	Load Analysis Cycles for Payloads and Spacecraft	[LAR 3] Loads analyses **shall** be performed on spacecraft that experience the mission load regimes beyond payload separation to calculate loads, accelerations, and deflections.		
4.1.4	Load Analysis Cycles for Payloads and Spacecraft	[LAR 4] Each load analysis cycle **shall** use approved analysis methodologies, models (payload models, LV models, spacecraft models, etc.), analysis forcing functions, and planned mission trajectory that are representative of the design at the time of the loads analysis cycle.		
4.1.5	Load Analysis Cycles for Payloads and Spacecraft	[LAR 5] Limit loads **shall** be determined that will not be exceeded with 99.87/50 (99.87 percent probability at 50 percent confidence level).		
4.1.6	Load Analysis Cycles for Payloads and Spacecraft	[LAR 6] Interface boundary conditions **shall** be consistent with the coupled configuration.		

4.1.7	Load Analysis Cycles for Payloads and Spacecraft	[LAR 7] Stress recovery directly from dynamic models for load analysis **shall** only be utilized for relatively simple load paths when the models have the fidelity necessary to accurately calculate stress.		
4.1.8	Load Analysis Cycles for Payloads and Spacecraft	[LAR 8] Random vibration loads analysis **shall** only be utilized for load predictions when the dynamic model has adequate fidelity in the frequency range of the analysis.		
4.1.9	Load Analysis Cycles for Payloads and Spacecraft	[LAR 9] For random vibration loads analysis, peak responses **shall** be used for the limit loads.		
4.2.1	Load Regimes for Payloads and Spacecraft	[LAR 10] All critical load regimes to which the structure will be exposed **shall** be evaluated in the loads analyses.		
4.2.2	Load Regimes for Payloads and Spacecraft	[LAR 11] If the structure has multiple configurations during its mission, the load regimes each configuration will experience **shall** be identified and each configuration evaluated in the loads analysis.		
4.2.3	Load Regimes for Payloads and Spacecraft	[LAR 12] Within each load regime, each source of loading **shall** be evaluated in the loads analysis.		
4.3a	Payload and Spacecraft Preliminary Loads for Design	[LAR 13] To initiate the design process, a set of preliminary limit loads **shall** be developed and used for the sizing of primary structure, secondary structure, and components.		
4.3b	Payload and Spacecraft Preliminary Loads for Design	[LAR 14] For spacecraft that can experience a variety of load regimes during operational phases, depending on the specific mission, the spacecraft providers **shall** develop envelopes that bound the accelerations for components for use in preliminary design.		
4.3.1.1	Payload and Spacecraft Primary Structure Design	[LAR 15] Limit loads for preliminary sizing of primary structure **shall** be based on the design load databases, existing load analysis results for similar payloads, or flight data.		
4.3.1.2	Payload and Spacecraft Primary Structure Design	[LAR 16] Angular accelerations in radians per second squared (rad/sec^2) about the c.m. **shall** also be included, when appropriate.		
4.3.2.1	Payload and Spacecraft Components Design	[LAR 17] Preliminary limit load factors for components **shall** be obtained from 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.		
4.3.2.2	Payload and Spacecraft Components Design	[LAR 18] The component limit load factors **shall** include effects of quasi-steady, transient, and random loading and thus represent the total dynamic load environment for a flight event.		
4.4a	Development of a Payload and Spacecraft Mathematical Model for Loads Analysis	[LAR 19] To support CLA, a mathematical model of the payload **shall** be developed using finite element methods.		

4.4b	Development of a Payload and Spacecraft Mathematical Model for Loads Analysis	[LAR 20] Spacecraft mathematical models **shall** be developed as needed to support load predictions for spacecraft post-separation and during operational phases, depending on the specific mission.		
4.4.1.1	Form of Payload and Spacecraft Model	[LAR 21] The payload finite element model **shall** be developed to meet all pertinent interfaces identified by the LV for loads analysis.		
4.4.1.2	Form of Payload and Spacecraft Model	[LAR 22] Interface boundary conditions **shall** be consistent with the coupled configuration.		
4.4.1.3	Form of Payload and Spacecraft Model	[LAR 23] The boundary conditions for the model **shall** correspond to the attachment to the supporting structure.		
4.4.2.1	Resolution and Fidelity of a Payload and Spacecraft Model	[LAR 24] The payload and spacecraft dynamic model **shall** have sufficient fidelity to capture the dynamic behavior of the payload and spacecraft in the defined analysis frequency range.		
4.4.2.2	Resolution and Fidelity of a Payload and Spacecraft Model	[LAR 25] Subsystem resonances and overall payload and spacecraft system modes **shall** be modeled up to a model upper bound frequency at least 1.5 times the cutoff frequency of the load analysis, assuming fixed boundary condition at its mounting interface.		
4.4.3.1	Payload and Spacecraft Model Reduction	[LAR 26] If dynamic reduction is used, the finite element model **shall** be reduced to a cutoff frequency of at least 1.5 times the cutoff frequency of the load analysis (which is typically the cutoff frequency of the coupled launch vehicle/payload system or spacecraft system).		
4.4.3.2	Payload and Spacecraft Model Reduction	[LAR 27] If static reduction is used, the dynamic characteristics of the reduced model **shall** preserve the characteristics of the original model up to the model upper bound frequency as defined by the delegated Technical Authority.		
4.4.3.3	Payload and Spacecraft Model Reduction	[LAR 28] For steady state portion of the analysis using models that are dynamically reduced, the effects of the reduced out modes above the frequency cutoff of the model on the steady state portion of the response **shall** be accounted for in the calculation of the limit loads.		
4.4.4	Payload and Spacecraft Model Output	[LAR 29] Model output requests, an output transformation matrix (OTM) format, **shall** be documented and provided with grid and/or element identification information with a description of the type of response (e.g., peak acceleration).		
4.5.1	Payload and Spacecraft Forcing Functions	[LAR 30] Non-deterministic forcing functions used in coupled loads analysis **shall** be 99.87/50 (99.87 percent probability at 50 percent confidence level) levels or greater.		
4.5.2	Payload and Spacecraft Forcing Functions	[LAR 31] Forcing functions for events associated with the spacecraft **shall** be developed by the spacecraft provider and/or mission organization, as needed.		
4.5.3	Payload and Spacecraft Forcing Functions	[LAR 32] For spacecraft forcing functions, analytical predictions, ground test data, and flight data **shall** be utilized to the maximum extent possible for the forcing function definition.		

4.5.4	Payload and Spacecraft Forcing Functions	[LAR 33] For spacecraft forcing functions, the effects of variations and tolerances of parameters that govern the forcing functions **shall** be considered in the analysis methodology.		
4.5.5	Payload and Spacecraft Forcing Functions	[LAR 34] For the Monte Carlo approach, an appropriate distribution **shall** be defined for each parameter so a value can be randomly selected.		
4.6.1	Payload and Spacecraft Damping	[LAR 35] Damping used for dynamic loads analysis **shall** 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.		
4.6.2	Payload and Spacecraft Damping	[LAR 36] In the absence of measured damping data, damping of one percent (1 percent) of critical **shall** be assumed for each mode for CLA.		
4.6.3	Payload and Spacecraft Damping	[LAR 37] For random vibration load analysis, damping **shall** be specified per the delegated Technical Authority, in the absence of measured damping data.		
4.7.1	Payload and Spacecraft Uncertainty Factors	[LAR 38] To reduce design impacts associated with load changes, uncertainty factors **shall** be approved for each loads analysis cycle by the delegated Technical Authority and applied to dynamic loads analysis results.		
4.7.2	Payload and Spacecraft Uncertainty Factors	[LAR 39] In subsequent load cycles, the uncertainty factor **shall** be gradually reduced as the structural design and load analysis prediction mature, requiring approval from the delegated Technical Authority for any uncertainty factor reduction.		
4.7.3	Payload and Spacecraft Uncertainty Factors	**[**LAR 40] If the model verification is determined to be inadequate by the delegated Technical Authority, an uncertainty factor higher than 1.1 **shall** be retained in the verification load analysis cycle.		
4.8.1	Payload and Spacecraft Load Combination	[LAR 41] In cases where loads produced by different environments can occur simultaneously, these loads **shall** be combined statistically to define the limit load for each time/event period in load regime of interest.		
4.8.2	Payload and Spacecraft Load Combination	[LAR 42] Combinations of these loads occur at different times in flight and **shall** be examined for each flight event.		
4.8.3	Payload and Spacecraft Load Combination	[LAR 43] Loads from each load regime contributor **shall** be combined by adding the means and root-sum-squaring the dispersed portions.		
4.8.4	Payload and Spacecraft Load Combination	[LAR 44] The statistical distributions of each load regime contributor **shall** describe the peaks of the loads.		
4.8.5	Payload and Spacecraft Load Combination	[LAR 45] The quasi-static, low frequency transient loads, and random vibration/acoustic limit loads **shall** be combined as approved by the delegated Technical Authority to determine the total load environment for liftoff.		
4.8.6	Payload and Spacecraft Load Combination	[LAR 46] When an RSS approach to defining component loads is utilized, the maximum low frequency load factor and maximum random vibration load factor **shall** be root-sum-squared (RSS'd).		

4.8.7	Payload and Spacecraft Load Combination	[LAR 47] When a time-consistent/load regime-consistent approach to defining component loads is utilized, the low frequency transient load factor and random vibration load factor **shall** be combined in a time-consistent/load regime-consistent manner.		
4.8.8	Payload and Spacecraft Load Combination	[LAR 48] Inertial forces in all three axes, including rotations if appropriate, **shall** be applied simultaneously, including sign combinations.		
4.9.1.1	Verification of the Payload and Spacecraft Mathematical Model - Testing/Correlation	[LAR 49] Verification of the payload and spacecraft dynamic models by modal survey testing **shall** be performed to ensure the model is sufficiently accurate for load and deflection predictions.		
4.9.1.2	Verification of the Payload and Spacecraft Mathematical Model - Testing/Correlation	[LAR 50] The modal survey test **shall** measure all significant modes of sufficient accuracy below the model upper bound frequency and provide test data supporting the model correlation requirements of this section.		
4.9.1.3	Verification of the Payload and Spacecraft Mathematical Model - Testing/Correlation	[LAR 51] If the complexity of the system is such that a subset of modes can only be measured, then the subset **shall** include the first two primary bending modes, first axial, first torsion, and modes of appendages included in the test article.		
4.9.1.4	Verification of the Payload and Spacecraft Mathematical Model - Testing/Correlation	[LAR 52] The modal survey test **shall** be performed as a fixed-base test.		
4.9.1.5	Verification of the Payload and Spacecraft Mathematical Model - Testing/Correlation	[LAR 53] If alternate boundary conditions are utilized, additional testing and analysis **shall** be required to verify effects of the alternate configuration.		
4.9.1.6	Verification of the Payload and Spacecraft Mathematical Model - Testing/Correlation	[LAR 54] The modal survey test **shall** include techniques approved by the delegated Technical Authority to identify nonlinearities.		
4.9.1.7	Verification of the Payload and Spacecraft Mathematical Model - Testing/Correlation	[LAR 55] Agreement between test and analysis natural frequencies (after model correlation) **shall** be within 5 percent for the target/significant modes.		
4.9.1.8	Verification of the Payload and Spacecraft Mathematical Model - Testing/Correlation	[LAR 56] Accurate mass representation of the test article **shall** be demonstrated with orthogonality checks using the analytical mass matrix $[M_A]$ and the test mode shapes $[ø_T]$.		

4.9.1.9	Verification of the Payload and Spacecraft Mathematical Model - Testing/Correlation	[LAR 57] The off-diagonal terms of the orthogonality matrix **shall** be less than 0.1 for significant modes based on the diagonal terms normalized to 1.0.		
4.9.1.10	Verification of the Payload and Spacecraft Mathematical Model - Testing/Correlation	[LAR 58] Mode shape comparisons **shall** be made via cross-orthogonality checks using the test modes $[ø_T]$, the analytical modes $[ø_A]$, and the analytical mass matrix $[M_A]$.		
4.9.1.11	Verification of the Payload and Spacecraft Mathematical Model - Testing/Correlation	[LAR 59] The absolute value of the cross-orthogonality between corresponding test and analytical mode shapes **shall** be a minimum of 0.9 and all other terms of the matrix less than 0.1 for all significant modes.		
4.9.1.12	Verification of the Payload and Spacecraft Mathematical Model - Testing/Correlation	[LAR 60] Qualitative comparisons between test modes and analytical modes using mode shape animation and/or deflection plots **shall** be performed.		
4.9.1.13	Verification of the Payload and Spacecraft Mathematical Model - Testing/Correlation	[LAR 61] Modal damping **shall** be obtained for each mode measured.		
4.9.1.14	Verification of the Payload and Spacecraft Mathematical Model - Testing/Correlation	[LAR 62] Failure to satisfy the criteria of [LAR 55] through [LAR 60] **shall** be accompanied by an assessment of the effects of model uncertainty on critical loads.		
4.9.2	Quality Checks	[LAR 63] For finite element models, the model quality checks listed below **shall** be performed: a. Free-Free Mode Check: Demonstrate modal frequencies of the unconstrained system in applicable rigid-body modes with frequencies less than 1.0E–4 Hz. b. Mass Properties Check: (1) Compute the rigid body mass properties at the center of gravity (CG) for the modeled configuration. (2) Compare output to those specified in the appropriate vehicle’s mass property report.		

		c. <u>Strain-Energy Check</u>: Subject the unconstrained model to an enforced unit, rigid body displacement for all six degrees of freedom (DOF) independently. Strain energies should be negligible or zero. d. <u>Grid Point Singularities Check</u>: Explain all grid point singularities. e. <u>Computer-aided Design (CAD)/Drawing Check</u>: Check the finite element model (FEM) against the CAD/drawing.		

APPENDIX B

ADDITIONAL GUIDANCE

B.1 PURPOSE

This Appendix provides additional guidance related to the requirements in this NASA Technical Standard.

B.2 TYPICAL LOAD REGIMES FOR PAYLOADS AND SPACECRAFT

Payloads and spacecraft can experience a variety of load regimes during their service life, depending on the specific mission.

B.2.1 Liftoff and Ascent Load Regime

The launch and ascent environments vary depending on the particular LV used. Load events may include engine ignition, launch pad release, liftoff, maximum dynamic pressure, transonic buffet, maximum acceleration, separations, engine shutdowns, thrust oscillations, and pogo.

The major induced environments during liftoff and ascent are typically produced by propulsion system operation. The LV thrust produces loads that are transmitted through the structure. The ignition transients of the propulsion system and launch pad release produce dynamic loading. The propulsion system also produces acoustic excitation that is amplified by reflections when still in proximity to the launch pad. Acoustic excitation is also produced by ascent aerodynamics. The magnitude of the transmitted energy at the LV/payload interface is dependent upon the particular LV.

Natural atmospheric winds and pressure as a function of altitude produces loads during the launch/ascent of all LV. The effect of venting on structural loading during ascent (and descent) may be significant. Winds can produce loading on the LV from prelaunch through atmospheric ascent. The loading is transmitted from the LV to the payload. Propulsion system thrust oscillations, as well as structural coupling with the control system, can also result in significant payload loading.

Three basic types of flight environments that generate dynamic loads on payload components are:

a. The low frequency dynamic response, typically from 0 to 70 Hz, of the LV/payload system to transient flight events.

b. The high frequency random vibration environment, which typically has significant energy in the frequency range from 20 Hz to 2000 Hz, transmitted from the LV to the payload at the LV/payload interfaces.

c. The high frequency acoustic pressure environment, typically 31 Hz to 10,000 Hz, inside the payload 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.

B.2.2 Other Load Regimes

For some operational regimes, the configuration of the payload or spacecraft may change as deployments and separations occur, and the susceptibility of the structure may be different.

a. Assembly. Assembly of components or integration of payloads can sometimes produce structural forces such as misalignment of parts and fasteners, shear pin connections, bolt torque, etc.

b. Terrestrial ground handling and transportation. The ground handling and transportation environments can be characterized with static, vibration, and shock inputs. These environments are generally limited, by design, to be less than launch and landing loads but should be assessed as part of the set of load requirements. Vibration loads for transport are classified by different modes of travel, including aircraft, rail, ships, or trucks. Because the hardware is available for inspection after transportation, statistical enclosure levels associated with ground handling and transportation loads analyses can be lower than those associated with launch and ascent loads analyses, provided the transportation environment is measured. Table 1, Transportation and Handling Limit Load Factors, defines transportation and handling load factors.

Table 1 (See Notes 1 thru 8)—Transportation and Handling Limit Load Factors

Transportation Mode/Vehicle	Load Occurrence	Fore/Aft g's	Lateral g's	Vertical g's
Water Craft	S	±0.75	±1.0	+2.5, -0.5
NASA Barge (MAF to KSC) (12)	S	±0.75	±1.0	+2.25, -0.25
NASA Barge Inland Waterway	S	±0.5	±0.5	+1.4, +0.6
Airplane (11)	S	±3.0	±1.5	+3.0, -1.0
Crash Landing (11)	I	+3.0, -1.5	±1.5	+4.5, -2.0
Ground:				
Truck or Air Ride Trailer	S	±2.0	±2.0	+3.0, -1.0
Rail (Humping) (13)	S	±30.0	±5.0	±15.0
Rail (Normal Operation)	S	±3.0	±1.5	+3.0, -1.0
Dolly (Max Velocity, 5 mph) (9)	I	±1.0	±0.75	+1.5, +0.5
Dolly (Hand Operated) (10)	I	±0.2V	±0.15V	+1.0
Forklift	S	±1.0	±0.5	+2.0, 0.0
Hoist	S	0	0	+1.33
Hoist (Heritage Hardware)	S	0	0	+1.0

Table 1 (See Notes 1 thru 8)—Transportation and Handling Limit Load Factors

Transportation Mode/Vehicle	Load Occurrence	Fore/Aft g’s	Lateral g’s	Vertical g’s

*Notes to Table 1:

1. All loads are to be applied as inertial loads.
2. Payload, as used in reference to this table, can be flight hardware, test articles, and/or any other structure intended to interface with and be transported on the GSE
3. The negative sense of the vertical acceleration vector is in the direction of the gravity vector.
4. S = Loads occur simultaneously in each of the three directions.
5. I = Loads occur independently in each of the three directions. Except that gravity (vertical) is always +1 g for fore/aft and lateral load cases.
6. For ground transportation, the GSE/vehicle should be designed for the occurrence of a 30-knot wind in combination with the load factors. Note that this wind load combination is only for the hardware during ground transportation; higher wind loads may exist during other operations, e.g., the hardware parked in an open lot. Other external loads may also need to be considered.
7. Cargo must be restricted from sliding or tipping during transportation. Restraints must be capable of withstanding cargo load factors shown in Table 1 combined with other applicable loads such as wind.
8. The GSE, vehicle and payload system design should be statically determinate. If that is not possible, then detailed loads analyses will be required.
9. In this context, Dolly represents any slow moving (≤5 mph) ground transporter that is not categorized by any other transportation mode in Table 1.
10. V is the expected max speed of the hand-operated dolly in miles per hour.
11. Airplane load factors envelope the Super Guppy and C17 operational loads. Crash landing is defined as an event where the aircraft may be damaged during landing but the event is survivable by the crew due to the protection provided by the aircraft structure. Therefore, for crew safety, any GSE and payload transported on an aircraft that could pose a risk to the crew in the event of a crash landing will be assessed to Crash Landing Limit Loads Factors (crash loads). Crash loads are to be assessed independently in the three orthogonal directions except gravity; vertical gravity load of 1.0g will be applied simultaneously with longitudinal and lateral crash loads. The crash load case is an ultimate load case.
12. Load factors were modified for MAF to KSC trips based on review of data from instrumented NASA Barge trips. Barge Sea Stage 6 (Douglas Sea Scale): Moderate Gale Wind 28-33 Knots (Beaufort No. 7); Wave Height 20 ft (Highest); Wave Length 285 ft (Typical).
13. These are shock conditions and should not be treated as quasi-static accelerations.

c. <u>Ground testing</u>. Testing of payloads and spacecraft involves a variety of excitation inputs that cover a range of amplitudes and frequencies. The loads experienced during testing may exceed flight loads and have to be considered in the design. All planned tests should be considered, including static, vibration (random, sine, etc.), acoustic, shock, pressure, spin balance, impact, and deployment tests. The effects of test configurations and boundary conditions should be assessed. Testing may require exposing payloads to operational thermal environments associated with cryogenics, orbital day/night transitions, extraterrestrial operations, etc.

d. On-orbit deployment. Deployable spacecraft, or items such as solar arrays, antennas, booms, radiators, etc., that deploy from a spacecraft have to be designed to account for loads induced due to their deployment action. Deployment may include initial release, extension, spinup, unfolding, and/or end of travel. For example, partially deployed Shuttle payloads experienced transient loads due to firings of the attitude control system and orbital maneuvering system.

e. On-orbit assembly. Assembly loads resulting from crew or robotics operations required to configure a payload or spacecraft to an intermediate or operational state have to be considered. Assembly loads also may occur due to docking of two spacecraft and from berthing of components with a robotics or otherwise automated device. Crew or robotics translation, manipulation, installation, and/or removal of equipment or components for maintenance or comparable activities require assessment. Loads from operations that may occur simultaneously or in close sequence have to be combined in a rational manner.

f. Terrestrial Descent and landing. Terrestrial descent and landing are transient loading environments where payloads and spacecraft will be subjected to static and dynamic loading. The descent maneuvers will produce static load conditions from inertial accelerations and pressure changes with altitude. The landing gear impact (touchdown) conditions produce significant dynamic loading. For example, for the Shuttle, the thermal environments resulting from orbit operations produced structural loads that were combined with other descent/landing loads. Loads induced by recovery operations after landing, including lifting and handling, should be considered.

g. Space operations. Spacecraft will generate or incur mechanically and thermally induced loads while operating in space. These loads may result from spacecraft booster thrust, spin/de-spin, and attitude control; from mechanical sources like rotating machinery and deployment or retraction devices; and from crew and robotics activity. Thermally induced loads encountered during flight operations may result from external sources such as day/night transitions associated with planetary orbit or internal heat sources and sinks.

h. Extraterrestrial operations. Extraterrestrial operations are those that occur in the atmosphere or on the surface of a planetary satellite or planet other than Earth. These operations can induce loading from descent and landing, surface excursion, mechanical functions, pressurization, and launch. The loads induced by these events are dependent on the design concept utilized. Load attenuation mechanisms are generally utilized to limit landing impact loads. Other spacecraft-unique functions or operations that produce structural loading should be considered.

i. Emergency escape/launch abort. Spacecraft will incur induced loads from emergency escape and abort scenarios. The loads induced depend on the conditions up to the point of separation and the initial conditions at separation for each scenario. Loads are developed for operations during and after separation.

B.3 LOAD CYCLES

In most cases, structural loads are dependent not only on the external environment but also on the structural properties of the spacecraft or payload. This means the sizing of structural members can influence the loads. At the same time, the sizing is often governed by the need to withstand the loads. As a result, structural design and load analysis are normally an iterative process. An example of a structural design cycle is shown in Figure 1, Structural Design Cycle Example.

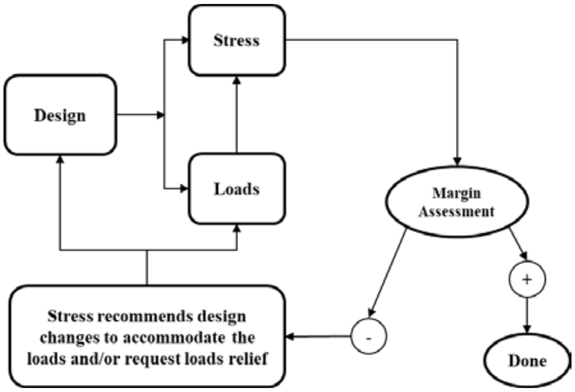

Figure 1—Structural Design and Loads Cycle Example

B.3.1 The Load Cycle Analysis Process

The load cycle analysis process is iterative and the number of iterations is variable. For programs that require optimization to achieve minimum weight for the structure, additional load cycles are typical.

The primary steps in a typical LV load cycle analysis process are shown in Figure 2, The Load Cycle Analysis Process. A similar approach may be used for any dynamic loading event for dynamic analysis.

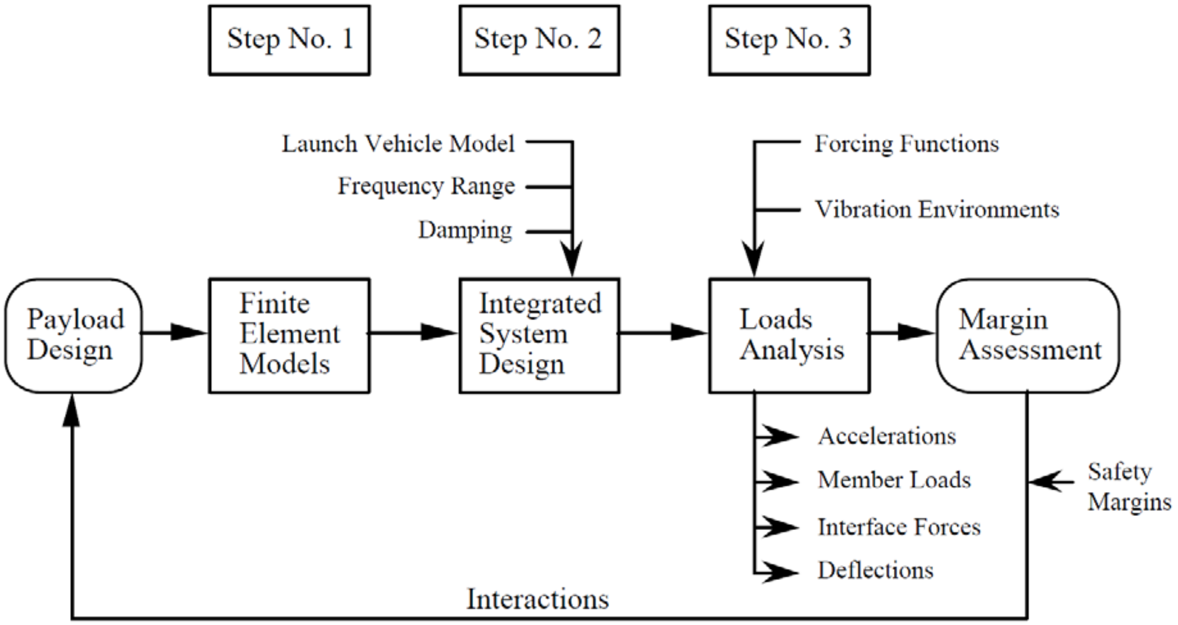

Figure 2—The Load Cycle Analysis Process

The steps of a CLA cycle process are described as follows:

a. Step 1: For the first load analysis cycle, use the properties and geometry of the initial design.

For subsequent load cycles, these models are updated. Finite element models of elements comprising the payload are developed from structural properties and geometry. This design should be based on preliminary design load factors discussed in section 4.3.

b. Step 2: Combine the payload element models with models of LV elements to form an integrated system model.

c. Step 3: Apply forcing functions representing the specific flight environments, along with appropriate uncertainty factors, to the integrated system model to obtain payload structural response and use the results of these analyses to update/revise the limit load data set following the initial structural sizing, as required, and subsequently for structural margin assessment.

Figure 3, Load Cycle Process – General Systems Engineering and Integration (GSE&I) with Independent Verification and Validation (IV&V), shows an example of a load cycle process that includes independent verification and validation analysis (source SMC-S-004, Independent Structural Loads Analysis).

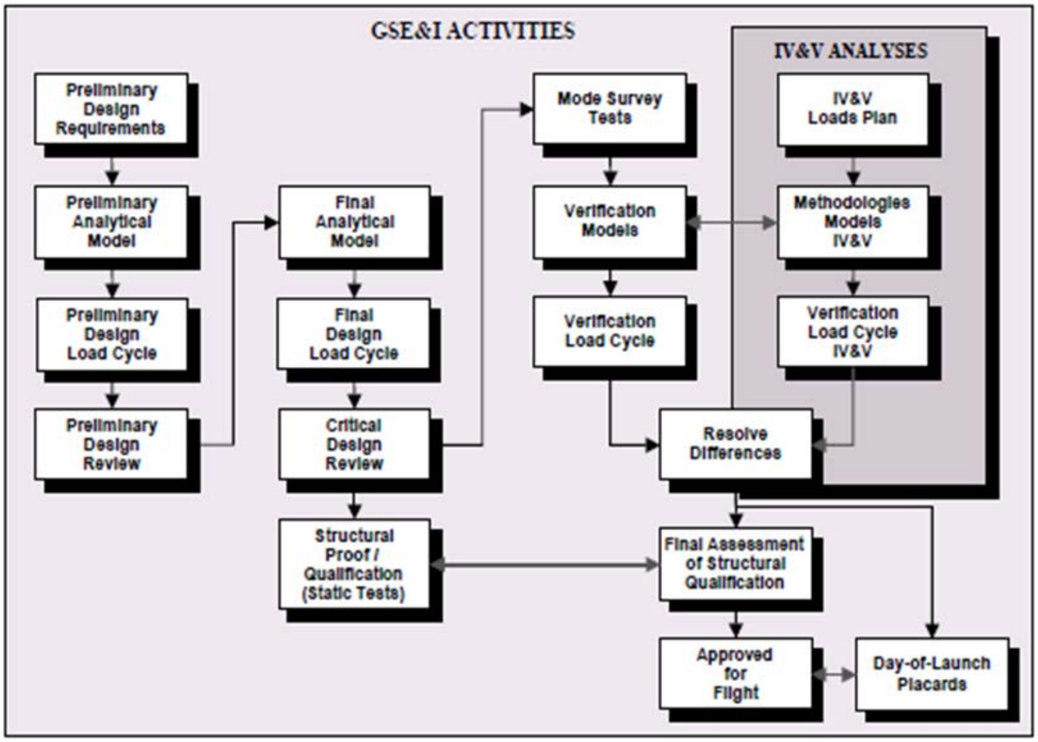

Figure 3—Load Cycle Process – General Systems Engineering and Integration (GSE&I) with Independent Verification and Validation (IV&V)

B.3.2 Load Cycle Types

B.3.2.1 Standard Load Cycles

For LV, three CLA cycles are required for a mission. More may be performed if reasons such as a major design change of the spacecraft/payload or an LV model or forcing function change. Fewer load cycles may be acceptable in special cases, as described below. The three required load cycles are:

a. Preliminary. The Preliminary Design Loads Cycle (PDLC) or Preliminary Loads Analysis Cycle (PLAC) is used for computing mission-specific expected loads on all parts of the spacecraft/payload from main structure to small appendages. These loads are used for identifying problems and modifying the preliminary design of the spacecraft/payload. Typical problems would include unexpected adverse coupling with the LV dynamics and unexpected tuning with a forcing function. A PDLC is required.

b. Final Design. The Final Design Loads Cycle (FDLC) or Final Loads Analysis Cycle (FLAC) serves two purposes. First, it is used for confirming that changes made since the PDLC are acceptable and, at this point, the design is typically finalized. The second purpose is to define verification test requirements for the spacecraft/payload; the FDLC is used to develop modal test analysis models, identify target modes for the modal test, and provide notching limits for sine vibration and random vibration testing. An FDLC is required.

c. Verification. The Verification Loads Cycle (VLC) is so called because all models used in the CLA are required to be verified through test. Because of this, the VLC provides results that can be trusted as reliable. The VLC serves many functions. The VLC is used to confirm that positive spacecraft and LV margins exist for launch. The output from the VLC is also used by the LV organization for the loss of clearance analysis. The modes from the VLC are also used by the LV organization in the controls analysis. A VLC is required.

B.3.2.2 Non-Standard Load Cycles

a. Omitting VLC. A VLC is required to qualify the vehicle for flight. However, in one case, a VLC can be omitted. If it is found during modal or vibration testing of the spacecraft/payload that the dynamic model used in the FDLC was accurate, and if the LV models and forcing functions have not changed, then running another loads cycle with the same models is pointless. In this case, the FDLC essentially becomes the VLC. In this way, the requirement for a VLC is satisfied.

b. Early CLA. In some cases, it may be necessary to run a load cycle before an LV has been selected or is under contract to perform the standard load cycles defined in Appendix B.3.2.1. This can be the case where preliminary design loads are considered to be too conservative and a more accurate assessment of launch loads is required in advance of having a PDLC performed. The cost and schedule for an early CLA are coordinated between the payload developer and the LV organization or launch services provider.

c. Intermediate CLA. An intermediate load cycle is one that is performed between the standard load cycles defined in Appendix B.3.2.1. The decision to perform an intermediate CLA is usually driven by a design change to the payload that is considered significant enough to impact predicted launch loads. An intermediate load cycle may also be driven by test results (i.e., modal survey or vibration test) showing the dynamic characteristics of a payload subsystem is different than represented in a previous load cycle or by the need to get the most accurate loads and environments to support testing of the payload or payload hardware. Like an early CLA, the cost and schedule for performing an intermediate CLA will be coordinated between the payload developer and the LV organization or launch services provider.

B.3.2.3 Schedule of Load Cycles

The schedule for the loads cycles varies by vehicle. The VLC schedule is based on when the LV provider needs the VLC results. The FDLC schedule is then defined to support spacecraft/payload environmental testing that will result in a verified model for the VLC. The PDLC schedule is spacecraft driven. It is usually used to support a spacecraft Preliminary Design Review (PDR). The PDLC should be performed as early as possible to obtain detailed loads and to identify any major design flaws, especially for spacecraft/payloads with fundamental frequencies less than those recommended by the LV organization or launch services provider where use of standard LV limit load factors is not valid. Also, a PDLC should be performed as early as possible for new spacecraft bus/core designs.

B.4 ANALYSIS TYPES

Analysis methods fall into three general categories: static, transient, and random vibration analyses. Static analysis is used to predict distribution of loads and displacements in a structure due to slowly varying applied forces. This type of analysis is also used for thermal loads, which arise from temperature changes in the structure. Transient analysis is used to predict loads resulting from applied forces that are rapidly varying and deterministic functions of time. Random vibration analysis deals with applied forces that are not deterministic but are known only in terms of statistical average properties. This type of analysis predicts statistical averages of loads in the structure resulting from applied random forces. NASA-HDBK-7005 can provide additional information on loads analysis methods.

B.4.1 Static Load Analysis

Static load analysis is suitable for load events in which the applied forces vary slowly with time. Such forces have frequency content much lower than the natural frequencies of the structure so that dynamic response is not induced. These events are commonly called quasi-static. Examples of static environments include maximum acceleration during ascent, descent maneuvers, steady spin, installation misalignment, and temperature variations.

The objective of static load analysis is to define the resulting load distribution throughout the structure. This load distribution may be defined using tools such as free body diagrams in simple cases. Finite element analysis is recommended for complicated or redundant load paths.

When performing static analysis with load factors, inertial (“g”) forces are applied to the structure along the various axes.

Static analysis is also used to predict forces and displacements due to specified temperature variations. The thermal strain caused by the specified temperatures, along with the system constraints, results in the predicted forces and displacements.

B.4.2 Transient Load Analysis

Transient analysis is appropriate when the loading environment can be represented by deterministic rapidly varying forces. Examples of transient events are engine ignition and shutdown, launch pad release, staging, control system operation, and landing impact.

This type of analysis requires development of a dynamic model of the complete dynamic system. In the case of launch load analyses, the model normally consists of the payloads coupled to the full LV. The forcing functions are applied; the equations of motion are solved; and time histories of the resulting displacements, accelerations, interface forces, and member forces are recovered. Statistical variation of parameters governing the forcing functions is accommodated by generating multiple cases of forcing functions for a single flight event. After all cases are analyzed, the peak responses for each parameter, e.g., load, of interest are combined statistically to yield the desired enclosure and confidence levels. The enclosure factors have to be consistent with the statistical distribution function of the loads event, which may not be normal. The frequency range of transient load analysis is limited by the accuracy of both the model and the forcing functions. For some expendable LV, significant axial loads are generated at higher frequencies during engine cutoff events; and transient analyses have to be run to 60 Hz or higher. For other events such as docking, robotics berthing, plume impingement, and spacecraft landing, the modal content has to be selected to adequately capture the dynamic response.

Damping may be incorporated into the transient analysis as modal damping on the coupled system modes or as modal damping on the modes of the components. In some cases, physical dampers may be included in the finite element models. When damping is applied to the component modes, the coupled system damping matrix is not diagonal.

The direct applicability of transient load analysis results to stress analysis is dependent on the fidelity of the dynamic model used in the analysis.

Maximum and minimum component accelerations may be used as a basis for component stress analysis using static load factors.

B.4.3 Random Vibration Load Analysis

Some load environments have to be treated as random phenomena when the forces involved are controlled by non-deterministic parameters. Examples include high frequency engine thrust oscillation, aerodynamic buffeting, and sound pressure on the surfaces of the payload.

Random vibration analysis describes the forcing functions and the corresponding structural response statistically. It is generally assumed the phasing of vibration at different frequencies is statistically uncorrelated. The amplitude of motion at each frequency is described by a power spectral density function. In contrast to transient analysis that predicts time histories of response quantities, random vibration analysis generates the power spectral densities of these response quantities. From the power spectral density, the root mean square (rms) amplitude of the response quantity is calculated. Random vibration limit loads are typically taken as the 3-sigma load (obtained by multiplying the rms load by 3) or are computed to the required statistical enclosure level. The multiplying factor on the rms values will depend on the statistical distribution function, e.g., normal, Rayleigh, gamma, and the required enclosure/confidence levels. Damping used for random vibration analyses will be based on test measurements or experience with similar types of structures, materials, and analysis methods.

The random vibration excitation may consist of accelerations at the interface degrees of freedom or sound pressure on the surfaces of the structure. Interface accelerations are represented by power spectral densities that envelop measured or predicted accelerations. Sound pressure levels are described in third-octave bands, representing average pressure amplitude over the band.

An important feature of random vibration analysis is the correlation between input accelerations and spatial correlation of pressure forces. A typical assumption for base drive analysis is that interface accelerations in different directions are uncorrelated.

In simple base drive cases, when the component can be represented as a single dynamic degree of freedom, the Miles equation gives a useful approximation to the rms response of the system. For more complicated structures, random vibration analysis can be performed when a finite element model with adequate fidelity exists.

A conservatism of performing random vibration base drive analysis is that dynamic coupling between the component and its supporting structure is not modeled. The impedance effect (vibration absorption) the component resonances have on the interface accelerations is not captured since there is no feedback between the response and the input. This is the same phenomenon that can cause component vibration tests to be overly conservative compared with the flight environment. The effect is most pronounced for primary modes of the payload or component (those with high effective mass), where the impedance can bring about a significant reduction in response in the true environment. Information on random vibration statistical energy analysis (SEA), boundary element analysis (BEA), and finite element analysis (FEA) methods can be found in NASA-STD-7001, Payload Vibroacoustic Test Criteria, and NASA-HDBK-7005.

Most payloads are acoustic tested to measure vibration levels associated with the acoustic environment (refer to NASA-STD-7001 and NASA-STD-7002). Such tests are typically late in the payload development and thus serve as verification of design environments used for spacecraft components.

B.5 MASS ACCELERATION CURVE

The concept of the mass acceleration curve has been successfully used for many years for the preliminary design of payloads. In essence, it has been observed that the acceleration of physical masses of a payload are bounded by a curve. The lighter the mass, the higher the corresponding acceleration. This observation is true for both transient and random vibration analyses.

In most cases, a single curve can be developed for a given LV configuration that applies to a broad class of payloads. Additional information on mass acceleration curve can be found in NASA-HDBK-7005 and JPL-D-5882, Mass Acceleration Curve for Spacecraft Structural Design.

B.6 UNCERTAINTY

Coupled loads analysis has uncertainty associated with both the LV and payload/spacecraft inputs to the CLA, which are typically accounted for by using uncertainty factors. From the spacecraft perspective, this uncertainty is due primarily to using an unverified dynamic model in the analysis. To mitigate the risk of generating surprisingly high loads late in the mission integration cycle at VLC, model uncertainty factors are used in all load cycles. These factors typically decrease with design maturity and by gaining confidence in the mathematical models via testing. Recommended values for the model uncertainty factors for different load cycles are:

a. For PDLC – this is typically the PDR level: 1.4 – 1.5 to account for future design changes and using mathematical models that are not test-verified.

b. For FDLC – this is typically the Critical Design Review (CDR) level when the design is finalized: 1.2 – 1.25 to account for using mathematical models that are not test-verified.

c. For VLC: factor decreased to 1.1 with test-verified models. Most test verification and correlation programs do not support reducing this factor to 1.0; this would imply that all dynamics are correlated.

While typical factors are identified here, the payload/spacecraft design strategy will determine appropriate factors. It should be noted that the model uncertainty factor can never be a substitute for model verification.

From the LV perspective, the uncertainty is due primarily to using approximate forcing functions and unverified models in the CLA, especially for vehicles with no flight history. The former of these is reduced only through test data analysis and flight data. The latter of these is initially reduced as the design stabilizes and later through verification testing and flight data.

Uncertainty factors play an important role in the CLA scheme. In each loads cycle, the loads differ. But because of the reduction in uncertainty factors, often the limit load (which depends on the uncertainty factor) has not increased. This is important in maintaining the payload/spacecraft project flow.

B.7 INDEPENDENT VERIFICATION AND VALIDATION (IV&V) OF LOADS ANALYSES

The LV organization generates primary loads information as required for normal LV and payload/spacecraft development. The LV organization's final VLC prediction of loads, typically supersedes all earlier predictions and forms the basis for commitment to flight. Because of its criticality, this final prediction of flight loads may be verified and validated by an independent source. This includes IV&V of test results, models, forcing functions, mass properties, analysis methodologies, load transformation matrices, etc., for all critical events. Any difference between LV and independent analyses would be resolved with minimum re-analysis. The requirement for an independent loads analysis should be identified early in the overall planning to assure the availability of adequate funding for this effort. Figure 1 shows an example of a loads process with IV&V.

APPENDIX C

REFERENCES

C.1 PURPOSE

This Appendix provides reference documents that may be useful to the user.

C.2 REFERENCE DOCUMENTS

NPR 8705.4	Risk Classification for NASA Payloads
NASA-STD-5001	Structural Design and Test Factors of Safety for Spaceflight Hardware
NASA-STD-7001	Payload Vibroacoustic Test Criteria
NASA-STD-7002	Payload Test Requirements
NASA-STD-7009	Standard for Models and Simulations
NASA-HDBK-7005	Dynamic Environmental Criteria
JPD 7120.9	Experimental Flight Hardware (Class I-E) Development Policy (https://nodis3.gsfc.nasa.gov/ under JSC Center Directives)
JPL-D-5882	Mass Acceleration Curve for Spacecraft Structural Design
SMC-S-004	Independent Structural Loads Analysis
MSFC Form 4657	Change Request for a NASA Engineering Standard