NASA
SPACE VEHICLE
DESIGN CRITERIA
(STRUCTURES)

NASA SP-8057

STRUCTURAL DESIGN CRITERIA APPLICABLE TO A SPACE SHUTTLE

JANUARY 1971
REVISED
MARCH 1972

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

PREFACE

In 1969, when planning for the development of a manned space-shuttle vehicle began, it was evident that significant advances in structural design would be needed to combine a manned recoverable booster and a reusable orbital vehicle with conventional flight and landing capabilities. Accordingly, new structural design criteria would be required for use in the vehicle development program to obtain a flightworthy structure (i.e., a structure possessing sufficient strength and stiffness and all other physical, mechanical, and functional characteristics required to accomplish each vehicle mission without jeopardizing mission objectives).

Early in 1970, the National Aeronautics and Space Administration initiated a program to prepare structural design criteria applicable to a manned space-shuttle vehicle. With the aid of an industry-Government team formed of representatives of major aerospace companies, most NASA Centers, NASA Headquarters, and the USAF, the criteria were first published in January 1971.

Since then, three developments have occurred which created a need to revise the document. First, the space-shuttle concept changed in the ensuing time. The current NASA concept is a reusable orbital vehicle mounted on an expendable liquid-propellant tank with two recoverable solid-rocket motors used to assist in boosting the vehicle. Second, problem areas in structural design criteria for the space shuttle which were identified in the course of the initial effort have been resolved. And third, considerable progress has been achieved in shuttle-related design technology. This updated document reflects all three developments.

The structural criteria presented in this document are limited to general and mission-oriented criteria and are not configuration specific. Care has been taken to ensure that the criteria will not restrict configuration development and will not establish the overall risk level. In some instances, margins of confidence are indicated, not only because experience has shown them to be necessary but also because technology now permits quantitative values to be established.

The criteria and interpretative information presented herein do not represent structural requirements, structural specifications, or any type of contractual document, but rather are intended to assist in the preparation of such documents.

This document was revised by an industry-Government team similar to the group which prepared the initial edition. Meetings of industry, NASA, and liaison participants were held at Langley Research Center to review industry critiques of the original document and to coordinate changes in the text. The activity was managed and the document was edited by the Langley Structural Systems Office.

The following organizations and individuals participated in the development of the original document and/or its revision:

BELL AEROSPACE COMPANY
Wilfred H. Dukes (Industry Chairman)

GENERAL DYNAMICS CORPORATION
Michael Dublin**
Raymond Schuett

GRUMMAN AEROSPACE CORPORATION
Warner Lansing
Andrew Shreeves**

LOCKHEED AIRCRAFT CORPORATION
T. J. Harvey
A. E. Trapp**

**Contributor to both the original document and its revision.

MARTIN MARIETTA CORPORATION
Robert J. Heymans
Allan M. Norton
James L. Parham*
Donald J. Trent

McDONNELL DOUGLAS CORPORATION
H. P. Adam*
T. P. Brooks
Roy H. Christensen**
L. W. Davidson (Literary Editor)
Marilyn B. Harmon**
James Shepherd**
F. R. Smith** (Chief Editor)
Esther A. Spachner (Literary Editor)**

NORTH AMERICAN ROCKWELL CORPORATION
Len A. Harris
Harvey J. Hoge
Richard Schleicher
R. F. Stevenson
R. Westrup*

THE AEROSPACE CORPORATION
N. N. Au*
K. G. Graff

THE BOEING COMPANY
S. I. Gravitz
William L. Gray
Harold J. Runstad
D. K. Zimmerman*

TRW Inc.
H. L. Sujata

AIR FORCE FLIGHT DYNAMICS LABORATORY
Frank D. Boensch

KENNEDY SPACE CENTER, NASA
H. C. Shoaf

LANGLEY RESEARCH CENTER, NASA
A. L. Braslow (NASA Cochairman)
J. P. Dickson, Jr.
Philip Donely
J. R. Hall (NASA Cochairman)**
D. H. Humes*
R. L. Jackson*
G. W. Jones, Jr.*
E. T. Kruszewski*
S. A. Leadbetter*
R. W. Leonard**
C. C. Poe, Jr.*
W. H. Reed*
E. D. Schult
W. C. Thornton*
L. F. Vosteen
E. S. Wolff*

LEWIS RESEARCH CENTER, NASA
M. J. MacKinnon

MANNED SPACECRAFT CENTER, NASA
L. G. St. Leger

MARSHALL SPACE FLIGHT CENTER, NASA
Charles E. Lifer

OFFICE OF AERONAUTICS AND SPACE TECHNOLOGY, NASA
Thomas V. Cooney
William Underwood

OFFICE OF MANNED SPACE FLIGHT, NASA
Kenneth L. Turner

---

*Contributor to the revised document.

**Contributor to both the original document and its revision.

For sale by the National Technical Information Service
Springfield, Virginia 22151 — Price $3.00

CONTENTS

1. INTRODUCTION

1.1 PURPOSE

This document is applicable to manned space-shuttle missions, but not to any specific vehicle configuration. The information in the document reflects the experience of the aerospace industry and NASA in the design, development, and operation of aircraft and space vehicles; it is intended as a starting point for preparation of requirements and specifications for the space shuttle. It can also provide a basis for design review between hardware contractors and NASA, and should increase confidence that the critical problem areas in shuttle design are not being overlooked.

1.2 SCOPE

This document presents structural design criteria and interpretive information for the structural design of an earth-to-orbit space shuttle in all configurations (e.g., in the launch, entry, or ferry configuration). The criteria also treat structural characteristics of materials and functional systems, including propulsion systems. The criteria and supporting information apply to all phases of the shuttle life, independent of external vehicle configuration. The document covers:

- Basic definitions
- Related documents
- Design objectives
- Design characteristics
- Design conditions
- Natural environments
- Proof of design.

1.3 APPROACH

In this document, statements in bold type are design criteria and statements in lightface type provide guidance for interpretation of the criteria. Related documents drawn from structural design criteria experience with aircraft, spacecraft, and launch vehicles are listed in Section 2.

The design objectives are presented separately in Section 3.

Section 4 defines the structural design characteristics required of the space shuttle, such as sufficient strength and stiffness to meet mission objectives under expected service environments, including conditions imposed by the shuttle systems.

Section 5 defines the design conditions (i.e., phenomena, events, induced environments, and hazards) to be accounted for in the various phases of the vehicle's service life.

Section 6 identifies the natural environments to be accounted for in the design of the space shuttle.

Section 7 defines the tests, analyses, and procedures to be performed and documented to prove the adequacy of the structural design of the space shuttle. This section also defines the measurements to be taken during vehicle operation.

1.4 PRECEDENCE

In the event of conflict between information in this document and in the contract specifications, the information in the specifications shall take precedence.

1.5 DEFINITIONS

For purposes of interpreting this document, the following definitions will apply. Considerable attention was given to these definitions since precision of meaning and consistency of usage are vitally important to the expression of powerful, terse, and unambiguous criteria.

ABORT. A termination of a mission due to malfunction or failure.

ASCENT PHASE (See Life Phases)

ASSEMBLY. A combination of two or more components that function as a discrete element of a system. (See Component and System)

ATMOSPHERIC FLIGHT PHASE (See Life Phases)

BUCKLING. An elastic instability phenomenon in a plate or shell where an infinitesmal increase in the external loading produces a sudden, large, nonlinear deformation in the structure.

BUFFET. A repeated loading of a structure by an unsteady aerodynamic flow.

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. A separate element, member, or part of an assembly. (See Assembly and System)

CONTROL EFFECTIVENESS. The control movement per unit of control deflection. It is affected by structural deformation caused by the reaction to the control force.

CREEP. A time-dependent deformation under load and thermal environments which results in cumulative, permanent deformation.

CRIPPLING. An inelastic deformation (i.e., collapse) of a plate or shell which occurs after buckling and substantially reduces the ability of the structure to withstand loads.

CRITICAL. The extreme value of a load or stress, or the most severe environmental condition imposed on a structure during its service life. The design of the structure is based on an appropriate combination of such critical loads, stresses, and conditions.

CRYOGENIC TEMPERATURE. A temperature below about -100°C.

DESIGN CONDITION. A phenomenon, event, time interval, or combination thereof important in structural design. It may involve a specific point in time or integrated effects over a period of time in terms of physical units such as pressure, temperature, load, acceleration, attitude, rate, or flux.

DESIGN FACTORS. A multiplying factor applied to limit loads or pressures to account for design uncertainties that cannot be accounted for in a rational manner. For example, a factor of safety would be used because of the designer's inability to predict residual stresses or because fabrication processes cannot be controlled to produce identical structure.

YIELD FACTOR OF SAFETY. A multiplying factor applied to limit load (or pressure) to obtain yield load (or pressure).

ULTIMATE FACTOR OF SAFETY. A multiplying factor applied to limit load (or pressure) to obtain ultimate load (or pressure).

PROOF FACTOR. A multiplying factor applied to limit load (or pressure) to obtain proof test load (or pressure).

SPECIAL FACTORS. Factors which may be applied for special purposes other than those normally included in the ultimate or yield factor of safety.

DETERMINISTIC. Denotes that values used in design are discrete and not random. Deterministic values are based on available information and experience. (See Probabilistic)

DETRIMENTAL DEFORMATIONS. Deformations, either elastic or inelastic, resulting from the application of loads and temperatures which prevent any portion of the vehicle structure from performing its intended function. Examples include structural deformations, deflections, or displacements which (l) cause unintentional contact, misalignment, or divergence between adjacent components; (2) cause a component to exceed its established dynamic space envelope; (3) reduce the strength or related life of the structure below specified levels; (4) degrade the effectiveness of thermal protection coatings or shields; (5) jeopardize the proper functioning of equipment; (6) endanger personnel; (7) degrade the aerodynamic or functional characteristics of the vehicle; (8) reduce below acceptable levels confidence in the ability to ensure flightworthiness by use of established analytical or test techniques; or (9) induce leakage above specified rates.

DIVERGENCE. A nonoscillatory instability which occurs when the external aerodynamic upsetting moments exceed the internal structural restoring moments within a system.

ELASTIC MODE. Same as Vibration Mode.

EMERGENCY CONDITION. An unforeseen condition in which structural limits on quantities such as loads, temperatures, or combinations thereof are exceeded.

ENTRY PHASE (See Life Phases)

ENVIRONMENTS

NATURAL ENVIRONMENT. A condition that exists in nature independent of the vehicle, such as temperature, atmospheric pressure, radiation, winds, gusts, precipitation, meteoroids, and dust.

INDUCED ENVIRONMENT. A condition created by the vehicle, or its systems, or by the response of the vehicle to the natural environment; for example, aerodynamic pressures and forces, aerodynamic heating, rocket-exhaust pressures and heating, wind-induced bending loads, and differential pressures during ascent; also, a man-made condition which may affect the vehicle, such as automobile exhaust products or noise.

FACTORS (See Design Factors)

FAIL-SAFE. A design philosophy under which the failure of any single structural component will not degrade the strength or stiffness of the remainder of the structure to the extent that the vehicle cannot complete the mission at a specified percentage of limit loads.

FAILURE. A rupture, collapse, or seizure, an excessive wear, or any other phenomenon resulting in an inability to sustain design loads, pressures, and environments without detrimental deformation.

FATIGUE. In materials and structures, the cumulative irreversible damage incurred by the cyclic application of loads and environments. Fatigue can cause cracking and degradation in the strength of materials and structures.

FATIGUE LIFE. The number of stress cycles required to produce either cracking or rupture in materials and structure. It is also the number of service hours required to reach that number of stress cycles.

FLUTTER. A self-excited oscillation caused and maintained by the aerodynamic, inertia, and elastic forces in the structural system of the vehicle.

FRACTURE CONTROL. A set of policies and procedures intended to prevent structural failure due to the initiation or propagation of cracks or crack-like defects during fabrication, testing, and operation.

FRACTURE MECHANICS. An engineering concept used to predict fracture and flaw-growth behavior of materials and structure containing cracks or crack-like flaws.

HORIZONTAL TAKEOFF PHASE (See Life Phases)

INTERFACE. The common boundary between components, assemblies, or systems of a space vehicle. An interface may be physical, functional, or procedural.

LANDING PHASE (See Life Phases)

LAUNCH PHASE (See Life Phases)

LIFE PHASES. Subdivisions of vehicle flight which are characterized by a related set of design conditions. Two categories of life phases may be identified: (1) those related to flight operations, including prelaunch, launch, ascent, space, entry, and atmospheric flight; and (2) those related to ground operations, including manufacturing, storage, refurbishment, transportation and ground handling, landing, and horizontal takeoff. The flight phases are listed in their order of appearance in a program, as follows:

MANUFACTURING PHASE. The interval beginning with the manufacture of vehicle hardware and terminating when the vehicle or its systems, assemblies, or components are accepted for shipment from the manufacturing facility to the launch site or storage area. Manufacturing includes receiving, inspection, fabrication, assembly, and checkout operations.

REFURBISHMENT PHASE. An interval during which the vehicle or its systems, assemblies, or components are repaired, replenished, inspected, or tested.

STORAGE PHASE. An interval during which the vehicle or its systems, assemblies, or components are stored in an inactive condition.

TRANSPORTATION AND GROUND HANDLING PHASE. Intervals and events during which the vehicle or its systems, assemblies, or components are handled, transported, or erected. Each transport interval begins when the vehicle is accepted or certified for shipment and terminates when the shipment is received at its destination. Ground handling includes such events as towing, hoisting, reorienting, carrying, erecting, jacking, and mooring.

PRELAUNCH PHASE. The interval beginning with completion of vehicle installation on the launch pad and terminating with commencement of final countdown.

LAUNCH PHASE. The interval beginning at final countdown and terminating at the instant of vertical liftoff, holddown release, or engine shutdown for an on-pad abort.

ASCENT PHASE. The interval beginning at the instant of vertical liftoff or holddown release and terminating with the decay of thrust-cutoff transients at insertion into orbit for the orbiter or at separation for the boost stages. It also includes in-flight abort during ascent.

SPACE PHASE. The interval beginning with the decay of thrust-cutoff transients at insertion into orbit and terminating with initiation of deorbit retrorocket impulse. The space phase includes orbit, rendezvous, docking, undocking, meteoroid impact, cargo transfer, and all other operations in space.

ENTRY PHASE. For the orbiter, the interval beginning with the initiation of deorbit retrorocket impulse and terminating after the transition to aerodynamically controlled flight. For the boost stages, the interval beginning with separation and terminating with water impact.

ATMOSPHERIC FLIGHT PHASE. The interval beginning with the transition to aerodynamically controlled flight or when the orbiter becomes airborne in horizontal takeoff and terminating the instant before touchdown. It also includes ferrying, maneuvering, deployment of recovery and landing devices, and emergency aborts.

LANDING PHASE. For the orbiter, the interval beginning with touchdown and terminating after landing and taxi run, or for boost stages, the interval beginning with touchdown and terminating after water recovery. Orbiter landing includes landing roll, braking, and taxiing, as well as touchdown.

HORIZONTAL TAKEOFF PHASE. The interval beginning with taxiing and terminating when the orbiter becomes airborne. Horizontal takeoff includes towing, braking, and takeoff roll, as well as taxiing.

LIMIT CYCLE. An oscillatory response of limited amplitude, usually due to a nonlinear parameter in a system.

LOADS

LIMIT LOAD. The maximum anticipated load on a structure in the expected operating environments.

ULTIMATE LOAD. The product of the limit load and the ultimate factor of safety.

YIELD LOAD. The product of the limit load and the yield factor of safety.

ALLOWABLE LOAD. The maximum load that can be permitted in a structure for a given design condition.

PROOF TEST LOAD. The product of the limit load and the proof factor.

LOAD FACTOR. The ratio of the vector sum of the external forces acting on a mass to the weight of the mass.

LOAD REDISTRIBUTION. The changes in load distribution due to local inelastic or elastic deformation across a multiple load path in a structure.

LOAD SPECTRA. Representations of the cumulative static and dynamic loadings expected for a structural component or assembly under all expected operating environments for a prescribed mission.

LOAD TYPES

STATIC LOAD. A static load may be a steady load, a quasi-steady load, or a combination of both.

Steady Load. A load of constant magnitude and direction with respect to the structure. Examples are loads caused by joint preloads, clamping, and constant thrust.

Quasi-Steady Load. A time-varying load in which the duration, direction, and magnitude are significant, but the rate of change in direction or magnitude and the dynamic response of the structure are not significant. Examples are loads caused by wind shear, changing thrust, lift, and drag.

DYNAMIC LOAD. A dynamic load may be an impulse load, a fluctuating load, or a combination of both.

Impulse Load. A suddenly applied pulse or step change in loading in which the duration, direction, magnitude, and rate of change in direction or magnitude are significant, and the dynamic response of the structure is also significant. Examples are loads produced by physical impact, vehicular pyrotechnics, and external explosions.

Fluctuating Load. An oscillating load in which the duration, direction, magnitude, frequency content, and phase are significant. Dynamic response of the structure may or may not be significant. Examples are loads caused by pogo-type instability, buffeting, aerodynamic noise, acoustic noise, and rotating equipment.

MALFUNCTION. A failure of any functional component, assembly, or system to operate in accordance with applicable procedures, drawings, and specifications.

MANUFACTURING PHASE (See Life Phases)

MARGIN OF SAFETY. The increment by which the allowable load exceeds the applied load for a specific design condition, expressed as a fraction of the applied load.

$$MS = \frac{A - D}{D} = \frac{1}{R} - 1$$

where

A = allowable ultimate or yield load
D = actual or applied load
R = ratio of D/A

Thus, the strength or stiffness capability of the structural components or assemblies can be evaluated at various times to assess the relative strength or stiffness of these elements at all critical service conditions. The margins so determined are used as final indicators of available strength or adequate stiffness after all other design characteristics, conditions, and factors have been accounted for.

MISSION. A single flight endeavor undertaken by the vehicle.

PRELAUNCH PHASE (See Life Phases)

PRESSURES

DESIGN PRESSURES FOR PRESSURE VESSELS.

Limit Pressure. The maximum differential pressure that can be anticipated to occur while the vehicle is in service in the expected operating environments. Limit pressures include combinations of such pressures as maximum operating pressure, transient pressure, and head pressure.

Ultimate Pressure. The product of the limit pressure and the ultimate factor of safety.

Yield Pressure. The product of the limit pressure and the yield factor of safety.

DUE TO PRESSURIZATION EFFECTS ONLY.

Nominal Operating Pressure. The maximum pressure applied to a pressure vessel by the pressurizing system with the pressure regulators and relief valves at their nominal settings and with nominal fluid flow rate.

Maximum Operating Pressure. The maximum pressure applied to a pressure vessel by the pressurizing system with the pressure regulators and relief valves at their upper limit and with the maximum fluid flow rate.

Transient Pressure. Time-dependent pressure in which the characteristic time of fluctuation is comparable to significant dynamic time constants of the structure and vehicle systems; for example, the pressure fluctuation caused by the opening and closing of valves, pump surges, flutter of check or relief valves, engine-thrust transients, engine gimbaling, and fluid sloshing.

Head Pressure. Static head pressure is the pressure at any point in a pressure vessel due to the height of the column of liquid in a gravity field. Dynamic head pressure is the additional pressure caused by acceleration.

TEST PRESSURES.

Proof Test Pressure. The product of the limit pressure and the proof factor.

Burst Test Pressure. The pressure at which a pressurized component ruptures.

PRESSURE VESSEL. A container designed primarily to carry fluids at sustained internal pressure, but which may also carry some vehicle loads.

PRESSURIZED STRUCTURE. A structure designed primarily to carry vehicle loads, but which may also be subjected to internal pressure (e.g., cabins, interstages, heat shields, insulation panels, and honeycomb structure).

PROBABILISTIC. Denotes that the values used in design are random, not discrete. Probabilistic values are chosen on the basis of statistical inference. (See Deterministic)

SAFE-LIFE. A design philosophy under which crack propagation to failure will not occur in the expected operating environments during the specified service life of the vehicle; also, the period of time for which the integrity of the structure can be ensured in the expected operating environments.

SERVICE LIFE. The interval beginning with manufacture of a vehicle and ending with completion of its specified missions.

SPACE PHASE (See Life Phases)

SPEEDS. (The following definitions apply while the space shuttle is operating within the dynamic pressure-load factor-temperature envelope and is relying on aerodynamic forces to sustain flight.) Speed is expressed in terms of equivalent air-speed (EAS).

DESIGN SINK SPEED. The maximum vertical descent speed at touchdown in the landing configuration.

LEVEL FLIGHT MAXIMUM SPEED, V_H. For the basic configuration, the maximum speed attainable in level flight at any altitude with maximum thrust.

LIMIT SPEED, V_L. For the basic and landing configurations, the maximum speed attainable by the vehicle in normal use.

LIMIT SPEED, V_{LF}. The maximum speed for the landing approach and takeoff configurations: a value of (1) 120 percent of the maximum speed attainable without exceeding 200-ft altitude after takeoff from a runway or from an aborted landing in the period of time required to convert from the takeoff condition to the basic flight configuration, or (2) 1.75 times the stalling speed, V_S, whichever is higher.

STALLING SPEED, V_S. For the basic flight configuration, the minimum speed for level flight at sea level with zero thrust.

STALLING SPEED, V_{SL}. For the basic landing-approach configuration, the minimum speed for level flight at sea level with zero thrust.

STALLING SPEED, V_{SPA}. For the basic landing configuration, the minimum speed for level flight at sea level with the power or thrust required to provide satisfactory go-around characteristics.

SPEED FOR MAXIMUM GUST, V_G. For the basic configuration, the speed determined either by the intersection of the line representing C_N maximum and the 66-fps gust line on the V-n diagram (fig. 5-4) or $V_{S_1}\sqrt{n_g}$ where n_g is the gust load factor at V_H in accordance with the criteria presented in Section 5.2.10.1.3.1 and V_{S_1} is the stalling speed of the basic configuration at the particular weight and altitude under consideration.

STIFFNESS. Structural resistance to deflection under an applied force or torque.

STORAGE PHASE (See Life Phases)

STRENGTH

MATERIAL STRENGTH. The stress level that the material is capable of withstanding in the local structural configuration in the expected operating environments. Units are expressed in pounds per unit area (original unloaded cross-sectional area).

YIELD STRENGTH. Corresponds to the load or stress in a structure or material at which permanent set occurs.

ULTIMATE STRENGTH. Corresponds to the maximum load or stress that a structure or material can withstand without incurring rupture or collapse.

STRESSES

ALLOWABLE STRESS. The maximum stress that can be permitted in a material for a given design condition.

APPLIED STRESS. The structural stress induced by the applied load and environment.

RESIDUAL STRESS. A stress that remains in a structure due to local yielding or creep after processing, fabrication, assembly, testing, or flight.

THERMAL STRESS. The structural stress arising from temperature gradients and differential thermal expansion in or between structural components, assemblies, or systems.

STRUCTURAL DESIGN TEMPERATURES (See Design Condition)

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

SYSTEM. A major combination of components and assemblies that functions as a unit. (See Assembly and Component)

TRAJECTORY. The flight path of the vehicle or its jettisoned stages.

NOMINAL TRAJECTORY. The ideal trajectory the vehicle would follow if external and internal characteristics and conditions were exactly as programmed.

DISPERSED TRAJECTORIES. Vehicle trajectories which vary from the nominal trajectory because of variations in tolerances of internal and external characteristics and conditions.

TRANSPORTATION AND GROUND HANDLING PHASE (See Life Phases)

UNIPOTENTIAL STRUCTURE. A structure in which all components are electrically continuous with very low impedance between the structural components.

VEHICLE. The space shuttle in any configuration.

VIBRATION MODE. A characteristic pattern of displacement and frequency assumed by a vibrating system in which the motion of every particle is simple harmonic with the same frequency. (Also referred to as Elastic Mode)

2. RELATED DOCUMENTS

NASA SPACE VEHICLE DESIGN CRITERIA SPECIAL PUBLICATIONS

SP-8001	Buffeting During Atmospheric Ascent. May 1964 – Rev. Nov. 1970.
SP-8002	Flight-Loads Measurements During Launch and Exit. Dec. 1964.
SP-8003	Flutter, Buzz, and Divergence. July 1964.
SP-8004	Panel Flutter. July 1964 – Rev. June 1972.
SP-8005	Solar Electromagnetic Radiation. June 1965 – Rev. May 1971.
SP-8006	Local Steady Aerodynamic Loads During Launch and Exit. May 1965.
SP-8007	Buckling of Thin-Walled Circular Cylinders. Sept. 1965 – Rev. Aug. 1968.
SP-8008	Prelaunch Ground Wind Loads. Nov. 1965.
SP-8009	Propellant Slosh Loads. Aug. 1968.
SP-8012	Natural Vibration Modal Analysis. Sept. 1968.
SP-8013	Meteoroid Environment Model – 1969 (Near Earth to Lunar Surface). Mar. 1969.
SP-8014	Entry Thermal Protection. Aug. 1968.
SP-8015	Guidance and Navigation for Entry Vehicles. Nov. 1968.
SP-8016	Effects of Structural Flexibility on Spacecraft Control Systems. Apr. 1969.
SP-8017	Magnetic Fields – Earth and Extraterrestrial. Mar. 1969.
SP-8019	Buckling of Thin-Walled Truncated Cones. Sept. 1968.
SP-8021	Models of Earth's Atmosphere (120 to 1000 km). May 1969.
SP-8022	Staging Loads. Feb. 1969.
SP-8025	Solid Rocket Motor Metal Cases. Apr. 1970.
SP-8028	Entry Vehicle Control. Nov. 1969.
SP-8029	Aerodynamic and Rocket-Exhaust Heating During Launch and Ascent. May 1969.
SP-8030	Transient Loads from Thrust Excitation. Feb. 1969.
SP-8031	Slosh Suppression. May 1969.
SP-8032	Buckling of Thin-Walled Doubly Curved Shells. Aug. 1969.
SP-8033	Spacecraft Earth Horizon Sensors. Dec. 1969.
SP-8034	Spacecraft Mass Expulsion Torques. Dec. 1969.
SP-8035	Wind Loads During Ascent. June 1970.
SP-8036	Effects of Structural Flexibility on Launch Vehicle Control Systems. Feb. 1970.
SP-8037	Assessment and Control of Spacecraft Magnetic Fields. Sept. 1970.
SP-8038	Meteoroid Environment Model – 1970 (Interplanetary and Planetary). Oct. 1970.

SP-8039	Solid Rocket Motor Performance Analysis and Prediction. May 1971.
SP-8040	Fracture Control of Metallic Pressure Vessels. May 1970.
SP-8041	Captive-Fired Testing of Solid Rocket Motors. Mar. 1971.
SP-8042	Meteoroid Damage Assessment. May 1970.
SP-8043	Design-Development Testing. May 1970.
SP-8044	Qualification Testing. May 1970.
SP-8045	Acceptance Testing. Apr. 1970.
SP-8046	Landing Impact Attenuation for Non-Surface-Planing Landers. Apr. 1970.
SP-8048	Liquid Rocket Engine Turbopump Bearings. Mar. 1971.
SP-8049	The Earth's Ionosphere. Mar. 1971.
SP-8050	Structural Vibration Prediction. June 1970.
SP-8051	Solid Rocket Motor Igniters. Mar. 1971.
SP-8052	Liquid Rocket Engine Turbopump Inducers. May 1971.
SP-8053	Nuclear and Space Radiation Effects on Materials. June 1970.
SP-8054	Space Radiation Protection. June 1970.
SP-8055	Prevention of Coupled Structure-Propulsion Instability (Pogo). Oct. 1970.
SP-8056	Flight Separation Mechanisms. Oct. 1970.
SP-8058	Spacecraft Aerodynamic Torques. Jan. 1971.
SP-8059	Spacecraft Attitude Control During Thrusting Maneuvers. Feb. 1971.
SP-8060	Compartment Venting. Nov. 1970.
SP-8061	Interaction with Umbilicals and Launch Stand. Aug. 1970.
SP-8062	Entry Gasdynamic Heating. Jan. 1971.
SP-8063	Lubrication, Friction, and Wear. June 1971.
SP-8064	Solid Propellant Selection and Characteristics. June 1971.
SP-8065	Tubular Spacecraft Booms (Extendible, Reel Stored). Feb. 1971.
SP-8066	Deployable Aerodynamic Deceleration Systems. June 1971.
SP-8067	Earth Albedo and Emitted Radiation. July 1971.
SP-8068	Buckling Strength of Structural Plates. June 1971.
SP-8072	Acoustic Loads Generated by the Propulsion System. June 1971.
SP-8077	Transportation and Handling Loads. Sept. 1971.
SP-8079	Structural Interaction with Control Systems. Nov. 1971.
SP-8082	Stress-Corrosion Cracking in Metals. Aug. 1971.
SP-8083	Discontinuity Stresses in Metallic Pressure Vessels. Nov. 1971.
SP-8084	Surface Atmosphere Extremes (Launch and Transportation Areas). May 1972.
SP-8092	Assessment and Control of Spacecraft Electromagnetic Interference. June 1972.
SP-8095	Preliminary Criteria for the Fracture Control of Space Shuttle Structures. June 1971.
SP-8098	Effects of Structural Flexibility on Entry Vehicle Control Systems. June 1972.
SP-8099	Combining Ascent Loads. May 1972.

(The following NASA Space Vehicle Design Criteria Special Publications, not yet published, are available in draft form from the Structural Systems Office at the NASA-Langley Research Center.)

SP-80XX Structural Design Factors.

SP-80XX Advanced Composite Structures.

SP-80XX Structural Interaction with Transportation and Handling Systems.

OTHER NASA PUBLICATIONS

TM X-64589. Daniels, G. E., ed.: Terrestrial Environment (Climatic) Criteria Guidelines for Use in Space Vehicle Development, 1971 Revision. May 10, 1971. Addendum on Water Impact and Recovery Conditions, Feb. 1972.

TM X-64627. Smith, R.E., ed.: Space and Planetary Environment Criteria Guidelines for Use in Space Vehicle Development, 1971 Revision. Nov. 15, 1971.

Space Shuttle System Level II Requirement. (Internal NASA document) June 15, 1970 (including revisions through Change 13 dated Feb. 9, 1971).

TN D-5864. Trout, Otto F., Jr.: Vacuum Leakage Tests of a Simulated Lightweight Spacecraft Air Lock. July 1970.

TN-3030(NACA). Grey, W.L.; and Schenk, K.M.: A Method for Calculating the Subsonic Steady-State Loading on an Airplane with a Wing of Arbitrary Plan Form and Stiffness. Dec. 1953.

TN-3781(NACA). Gerard, George; and Becker, Herbert: Handbook of Structural Stability, Part I – Buckling of Flat Plates. July 1957.

TN-3782(NACA). Becker, Herbert: Handbook of Structural Stability, Part II – Buckling of Composite Elements. July 1957.

TN-3783(NACA). Gerard, George; and Becker, Herbert: Handbook of Structural Stability, Part III – Buckling of Curved Plates and Shells. Aug. 1957.

TN-3784(NACA). Gerard, George: Handbook of Structural Stability, Part IV – Failure of Plates and Composite Elements. Aug. 1957.

TN-3785(NACA). Gerard, George: Handbook of Structural Stability, Part V – Compressive Strength of Flat Stiffened Panels. Aug. 1957.

TN-3786(NACA). Handbook of Structural Stability, Part VI – Strength of Stiffened Curved Plates and Shells. July 1958.

SP-3024. Vette J. I.; Lucero, A. B.; and Wright, J. A.: Models of the Trapped Radiation Environment, Vol. II—Inner and Outer Zone Electrons. 1966. Vol. III—Electrons at Synchronous Altitudes. 1967.

SP-3024. King, J. H.: Models of the Trapped Radiation Environment, Vol. IV—Low-Energy Protons. 1967.

SP-3024. Lavine, J. P.; and Vette, J. I.: Models of the Trapped Radiation, Vol. V—Inner Belt Protons. 1969. Vol. VI—High-Energy Protons. 1970.

SP-3024. Imhof, W. L.; Bostrom, C. O.; and Beall, D. S.: Models of the Trapped Radiation Environment, Vol. VII—Long-Term Time Variations. 1971.

CR-626. Bies, D.A.: A Review of Flight and Wind Tunnel Measurements of Boundary Layer Pressure Fluctuations and Induced Structural Response. Oct. 1966.

CR-1596. Himelblau, H.; Fuller, C.M.; and Scharton, T.: Assessment of Space Vehicle Aeroacoustic-Vibration Prediction, Design, and Testing. July 1970.

CR-112033. Kuchta, B.J.; Howell, L.J.; and Sealey, D.M.: Determination of Methods for Establishing Space Shuttle Load Spectra. Mar. 1972.

NHB 5300.4(1A). Reliability Program Provisions for Aeronautical and Space System Contractors. Apr. 1970.

NHB 5300.4(1B). Quality Program Provisions for Aeronautical and Space System Contractors. Apr. 1969.

NHB 8080.1. Apollo Test Requirements. Mar. 1967.

NHB 8080.3. Apollo Applications Test Requirements. Oct. 13, 1967.

NPC 200-2. Quality Program Provisions for Space System Contractors. Apr. 20, 1962.

Safety Program Directive No. 1 – Revision A (SPD-A). System Safety Requirements for Manned Space Flight. Dec. 12, 1969.

DEPARTMENT OF DEFENSE PUBLICATIONS

MIL-A-008860A(USAF). Airplane Strength and Rigidity – General Specification for. Mar. 31, 1971.

MIL-A-008861A(USAF). Airplane Strength and Rigidity – Flight Loads. Mar. 31, 1971.

MIL-A-008862A(USAF). Airplane Strength and Rigidity – Landing and Ground Handling Loads. Mar. 31, 1971.

MIL-A-008865A(USAF). Airplane Strength and Rigidity – Miscellaneous Loads. Mar. 31, 1971.

MIL-A-008866A(USAF). Airplane Strength and Rigidity – Reliability Requirements, Repeated Loads, and Fatigue. Mar. 31, 1971.

MIL-A-008867A(USAF). Airplane Strength and Rigidity – Ground Tests. Mar. 31, 1971.

MIL-A-8868(ASG). Airplane Strength and Rigidity – Data and Reports. May 18, 1960.*

MIL-A-008870A(USAF). Airplane Strength and Rigidity – Flutter, Divergence, and Other Aeroelastic Instabilities. Mar. 31, 1971.

MIL-A-8871A(USAF). Airplane Strength and Rigidity – Flight and Ground Operations Tests. July 1, 1971.

MIL-A-8892(USAF). Airplane Strength and Rigidity – Vibration. Mar. 31, 1971.

MIL-A-8893(USAF). Airplane Strength and Rigidity – Sonic Fatigue. Mar. 31, 1971.

MIL-B-5087B(ASG). Bonding, Electrical, and Lightning Protection for Aerospace Systems. Oct. 15, 1964.

MIL-C-6021G. Casting, Classification and Inspection of Sept. 9, 1967.

MIL-HDBK-5B. Metallic Materials and Elements for Aerospace Vehicle Structures. Vols. 1 and 2, Sept. 1971.

MIL-HDBK-17. Plastics for Flight Vehicles. Aug. 14, 1961.

*Document in revision.

MIL-HDBK-23A. Structural Sandwich Composites. Dec. 30, 1968.

MIL-STD-143B. Specifications and Standards, Order of Precedence for the Selection of. Nov. 12, 1969.

MIL-STD-470. Maintainability Program Requirements for Systems and Equipments. Mar. 21, 1966.

MIL-STD-785A. Reliability Program for Systems and Equipment, Development and Production. Mar. 28, 1969.

MIL-STD-810B. Environmental Test Methods. Sept. 29, 1969.

MIL-STD-1530(USAF). Aircraft Structural Integrity Program: Airplane Requirements. Sept. 1, 1972.

AFML-TR-66-386. MIL-HDBK-5 Guidelines for the Presentation of Data. USAF, Feb. 1967.

AFFDL-TR-67-167. Lowson, M.V.: Prediction of Boundary Layer Fluctuations. Apr. 1968.

AFML. Advanced Composite Design Guide, Vol. 1, 3d ed., Nov. 1971.

AFSC DH 3-2. Design Handbook Series 3-0, Space Vehicles. USAF, Mar. 20, 1969.

OTHER PUBLICATIONS

FAA-FAR Part 25. Airworthiness Standards: Transport Category Airplanes (including changes through Change 19). Apr. 23, 1969.

U.S. Standard Atmosphere, 1962. U.S. Government Printing Office, Washington, D.C.

U.S. Standard Atmosphere Supplements, 1966. U.S. Government Printing Office, Washington, D.C.

Recommended Practice for Combined, Simulated Space-Environment Testing of Thermal Control Materials. 1969 Book of ASTM Standards, Pt. 30, ASTM E 332-67, Sept. 8, 1967, pp. 1122-1129.

Tension Testing of Metallic Materials, ASTM E8-69, Nov. 14, 1969.

Compressive Testing of Metallic Materials at Room Temperature, ASTM E9-70, June 18, 1970.

Bertram, M. H., et al.: Effects of Two Dimensional Multiple-Wave Distortion on the Heat Transfer to a Wall in Hypersonic Flow. (Presented at the Fifth AIAA Aerospace Science Meeting, New York, N.Y., Jan. 23-26, 1967). AIAA Paper No. 67-164.

Doyle, D.P.; and Godard, H.P.: A Rapid Method for Determining the Corrosivity of the Atmosphere at any Location. Nature, vol. 200, no. 4912, Dec. 21, 1963, pp. 1167-1168.

Pugsley, A.: The Safety of Structures. Edward Arnold, Ltd. (London), 1966.

Rain Erosion and Associated Phenomena, 2. Forschungskonferenz Regenerosion, Meersburg, Germany, Aug. 1967.

3. DESIGN OBJECTIVES

Structural design is strongly affected by objectives which cannot be absolutely defined or imposed because of performance, risk, cost, or other factors that depend on the hazards involved, the mission constraints, or details of the vehicle, its structure, and mode of operation. The primary objectives in the design of the space shuttle are to develop a lightweight vehicle that can safely complete the required number of missions in its specified life and to accomplish this at minimum cost. The following paragraphs present the design goals to be pursued to achieve these primary objectives.

3.1 WEIGHT

Because of the significant influence of structural weight on shuttle performance, the design of structure other than pressure vessels should be based only upon critical flight, landing, and takeoff conditions, including the cumulative effect of repeated service environments. So far as practicable, designs should be selected so that the burden of accommodating nonflight loads is borne by ground equipment, rather than by flight equipment and structure.

Vehicle loads associated with ferry conditions should not exceed design levels for other flight phases.

3.2 COST

All design objectives other than the safe and successful completion of the required missions should be weighed for their effects on cost and the overall design should be optimized on this basis. Costs of development, production, and any servicing, inspection, repair, or refurbishment necessary to carry out the missions should be considered in structural design to minimize the total cost of the space shuttle.

3.3 SIMPLICITY

The structural design should emphasize simplicity in the form and combination of components, assemblies, and systems to facilitate accurate determination of load paths and to increase confidence in the calculated stresses, strains, and structural response.

3.4 MANUFACTURABILITY

The structural design should employ proven processes and procedures for manufacture and repair. Provision should be made for inspection during manufacture.

3.5 MAINTAINABILITY

The structural design should permit the vehicle structure to be maintained in or restored to a flightworthy condition with a minimum of manpower and equipment. The design should emphasize structural materials, forms, fasteners, and seals which minimize the need for maintenance and which properly consider the needs for access, inspection, service, replacement, repair, and refurbishment.

3.5.1 ACCESSIBILITY

Structural design should permit adequate access to components and to structure for inspection or refurbishment for reuse. The structure should be designed so that no specific order of removal and reinstallation of access doors and panels is imposed only for structural considerations. Components with a high probability of replacement should be located so they can be readily replaced.

3.5.2 INTERCHANGEABILITY

The design should provide that similar components, assemblies, or subsystems be interchangeable wherever possible without degrading structural capability.

3.5.3 TANK SERVICEABILITY

The structural design should permit filling and emptying tanks in any order while the vehicle is on the launcher. Provision should be made to prevent the absolute internal pressure from decreasing to a value less than the external ambient pressure when tanks are being emptied.

3.5.4 REPAIR AND REFURBISHMENT

The structural capability should not be degraded by repair nor should the design include allowances for possible degradation from repair. Repaired or refurbished structure should meet all stipulated conditions of flightworthiness.

3.6 COMPATIBILITY

To facilitate the development of compatible structure, at least the following requirements, constraints, and system interactions should be established as early as possible in the design process:

- Safety
- Life
- Risk vs reliability
- Mission abort
- Reusability
- Turnaround time
- Load factors
- Thermal control
- Propulsion system
- Guidance and control system
- Allowable leakage rates
- Landing surface.

4. DESIGN CHARACTERISTICS

The vehicle structure shall possess adequate strength and stiffness to withstand limit loads and pressures in the expected operating environments throughout its service life without experiencing detrimental deformation. The structure shall be capable of withstanding the combined ultimate loads and pressures in the expected operating environments without experiencing collapse or rupture.

All pressure vessels in the vehicle shall sustain proof-test pressure without incurring detrimental deformation. When proof tests are to be conducted at temperatures other than design temperatures, the degradation of material properties at design temperatures shall be accounted for in determining the proof-test pressure.

The structure shall not be designed to withstand loads, pressures, or environments due to malfunctions that would create conditions outside the expected mission design envelope.

Pressure vessels under destabilizing pressure shall be capable of withstanding ultimate pressure in combination with ultimate load without experiencing rupture or collapse. Under stabilizing pressure, the vessels shall be capable of withstanding the minimum anticipated operating pressure in combination with ultimate load without experiencing rupture or collapse. The most probable failure mode for pressure vessels shall be leakage, rather than rupture.

The correction factor to account for material degradation is equal to the ratio of calculated burst pressure at proof-test temperature to the burst pressure at critical design temperature.

If the protection against environments afforded by the overall vehicle design is not sufficient to limit detrimental effects to specified levels, provision shall be made for protection against these environments.

Pertinent mass, physical, mechanical, thermal, and dimensional properties of the vehicle shall be identified and accounted for under all the design conditions anticipated in the service life of the vehicle.

4.1 DESIGN FACTORS

Any design factors used shall be identified, including factors of safety and special factors. The basis for selecting values of all design factors shall be identified and approved by NASA.

Design factors shall be used to account for uncertainties in design which cannot be analyzed or otherwise accounted for in a rational manner. Design factors shall be applied to limit loads and pressures and to the stresses arising from temperature differences and gradients, but not to the temperatures and temperature differences.

Design Factors. The selection of values for design factors is presently arbitrary and the rationale varies with NASA center, project, and contractor. The values given in table 4-1 are recommended for application to limit loads or pressures in initial design. It is intended that these factors be verified or modified on the basis of the best available design techniques (e.g., fracture mechanics and statistical analyses) and that the values be consistent with the desired level of structural reliability.

Special Factors. It is recommended that the factors in table 4-2 and others relating to personnel safety and to strength, compatibility of materials, or type of construction be defined separately from the ultimate or yield factors of safety and applied in design, where appropriate. These special factors should be used only when the value has been reliably established by test or prior experience. When the validity of a special factor cannot be confirmed, the variations should be assumed to be covered by the design factors of table 4-1.

TABLE 4-1 **DESIGN FACTORS**

COMPONENT	FACTORS		
	YIELD	ULTIMATE	PROOF
General structure	≥ 1.0	≥ 1.4	—
Main propellant tanks:			
Combined loads and pressures	1.1	≥ 1.4	
Pressure alone	—	*	1.05
Pressurized windows, doors, and hatches	—	≥ 3.0*	2.0
Pressurized structure:			
Combined loads and pressures	≥ 1.0	1.5**	—
Pressure alone		2.0	1.5
Pressure vessels (other than main propellant tanks)	—	2.0*	1.5
Pressurized lines and fittings:			
Less than 1.5 in. in diameter	—	4.0	1.5
1.5 in. in diameter or larger	—	2.0	1.5

*In addition to including the design factors in this table, designs for major load-carrying structure, windows, doors, hatches, and tanks should use fracture-control procedures to account for sharp cracks, crack-like flaws, and other stress concentrations in a manner that ensures the structural life meets mission requirements.

**Factor applied to limit load at limit pressure.

TABLE 4-2 **SPECIAL FACTORS**

FACTOR	ACCOUNTS FOR
Hazard	Personnel safety when structure contains pressure or other stored energy
Stress concentration	High local-stress concentrations (e.g., at holes, corners, or fillets)
Fitting	Unknown stresses in complex joints or fittings
Material	Material-property scatter, flaws, brittle or fragile materials, and variations in process control
Casting	Process-control variations such as sensitivity to cooling rate and size
Weld	Variations in process control and reweld
Buckling	Unknown strains including those introduced by end conditions, construction, and cutouts
Uncertainty	Inability of analysis or test to predict loads or stability margins with desired degree of certainty (e.g., a factor of 1.32 times the maximum dynamic pressure of the flight boundary is applied to determine a flutter-free or divergence-free margin)

4.2 MARGIN OF SAFETY

The margin of safety shall be positive and shall be determined at allowable ultimate levels and yield levels, when appropriate, and at the temperatures expected for all critical conditions. A high margin of safety shall not be used as a substitute for a design factor.

For minimum-weight design, the margin of safety should be as small as practicable.

4.3 STATIC ELASTICITY

The vehicle structure shall be stiff enough so that static elastic deflection will not cause structural failure or detrimental deformation, or degrade stability and control below specified levels.

4.3.1 DIVERGENCE

The vehicle 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. When establishing (3), the dynamic-pressure margin shall be determined separately at constant density and at constant Mach number.

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.

4.3.2 CONTROL-SURFACE EFFECTIVENESS

For any given flight regime, the active aerodynamic control surfaces shall not exhibit reversal up to the maximum dynamic pressure expected at any Mach number within the dispersed flight envelope. The control effectiveness of the control system and flexible structure, interacting together, shall be sufficient to provide adequate stability and response for these conditions.

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.

4.3.3 BUCKLING AND CRIPPLING

Buckling shall not cause components that are subject to instability to collapse when ultimate loads are applied, nor shall buckling deformation from limit loads degrade the functioning of any system or produce changes in loading that are not accounted for.

Evaluation of buckling strength shall consider the combined action of primary and secondary stresses and their effects on (1) general instability, (2) local or panel instability, (3) crippling, and (4) creep.

All structural components that are subject to compressive in-plane stresses under any combination of ground loads, flight loads, or loads resulting from temperature changes shall be analyzed or tested for buckling failure. Design loads for buckling shall be ultimate loads, except that any load component that tends to alleviate buckling shall not be increased by the ultimate factor of safety. Destabilizing external pressure or torsional limit loads shall be increased by the ultimate factor of safety, but stabilizing internal-pressure loads shall not be increased unless they reduce structural capability.

The analysis of all structural members shall include consideration of the relative deflection of adjacent members and the resulting loads imposed on all members. In addition, deflections of all major load-carrying structure and equipment-support structure shall be calculated to ensure that the structure does not interfere with an adjacent system and to ensure that equipment is not adversely affected by motion of the equipment-package support points.

For recommended practices, refer to NASA SP-8007, SP-8019, SP-8032, SP-8068, and NACA TN-3781 through TN-3786.

4.4 DYNAMIC ELASTICITY

The structure shall be designed to: (1) prevent all detrimental instabilities of coupled vibration modes; (2) minimize detrimental effects of the loads and dynamic responses associated with structural flexibility; and (3) minimize adverse interaction between the structure and other vehicle systems. Analyses shall account for:

1. **Configuration effects, such as center-of-gravity offset leading to coupled response.**
2. **Unsymmetrical stiffness distribution.**
3. **Variations in characteristics of the release-restraint device on the vehicle pad.**
4. **Variations in the thrust loads and unsymmetrical thrust effects resulting from engine sequencing and nonuniformity in combustion (including engine-out conditions).**
5. **Unsymmetrical aerodynamic effects.**

In addition, the following items should be evaluated: (1) changes in stiffness due to structural temperatures and internal stress redistribution with increasing load level; and (2) effects of clearances and mechanical play.

4.4.1 DYNAMIC AEROELASTIC INSTABILITIES

4.4.1.1 CLASSICAL FLUTTER

The vehicle 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. When establishing (3), the dynamic-pressure margin shall be determined separately at constant density and at constant Mach number.

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, booster-orbiter interface stiffness, 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 space-shuttle stages. For recommended practices, refer to NASA SP-8003.

4.4.1.2 STALL FLUTTER

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. The vehicle shall be free of stall flutter at 1.32 times the dynamic pressure expected for this type of maneuver.

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.

4.4.1.3 PANEL FLUTTER

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. When establishing (2), the dynamic-pressure margin shall be determined separately at constant density and at constant Mach number. During abort, an additional positive dynamic-pressure margin shall be provided unless it can be demonstrated that any panel flutter occurring will not endanger the crew.

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. For recommended practices, refer to NASA SP-8004.

4.4.1.4 CONTROL-SURFACE BUZZ

The vehicle, 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. When establishing (2), the dynamic-pressure margin shall be determined separately at constant density and at constant Mach number.

Control surfaces shall 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.

For recommended practices, refer to NASA SP-8003.

4.4.2 DYNAMIC COUPLING

4.4.2.1 FLIGHT-CONTROL SYSTEM AND ELASTIC MODES

The vehicle shall be free of instability or other interactions of the control system with the elastic modes which could impair flightworthiness. Structural characteristics shall be defined in sufficient detail to permit analytical prediction of interactions of the control system with elastic modes. Freedom from undesirable interactions shall be demonstrated by analysis, supplemented by tests. The analysis shall account for the effect of engine thrust and the most adverse possible values shall be assumed for structural damping and stiffness at critical times during flight.

The influence of the control system upon loads and dynamic response should be evaluated. Detrimental effects should be prevented by specifying appropriate control-system parameters such as stability and phase margins when this can be accomplished without degradation of performance. Load-alleviation control systems should be evaluated in the context of overall system performance, including evaluation of parameter sensitivity to the system. The evaluation should consider the effects of: (1) excitation of the structure and control system by induced and natural environments; (2) changes in configuration and parameters of the vehicle and control system; (3) elastic modes (reflecting mated vehicle coupling, where appropriate); (4) nonlinear and time-variant factors; (5) pilot-in-the-loop, and (6) actual hardware.

Detrimental interaction of the following components and the guidance and control system should be minimized in design: (1) actuators, (2) sensor mounts, (3) joints, (4) engine-support structure, (5) structural components of the passive control systems, (6) control and retrorocket mounts, (7) rotating machinery, (8) control surfaces, and (9) appendages. 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. For recommended practices, refer to NASA SP-8016 and SP-8036.

4.4.2.2 SLOSH

Tanks shall be designed to prevent or suppress coupling between liquids and vehicle structure and between liquids and the flight-control system.

The need for slosh-suppression devices should 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. If found to be necessary, the slosh-suppression devices should 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.

The following shall be accounted for in design of slosh-suppression devices:

1. **Tank characteristics, including size, geometry, internal hardware and structure, structural stability, internal insulation, and venting provisions.**
2. **Liquid-system characteristics, including liquid boiling, bubble entrapment, draining and settling, liquid level, fluid-material compatibility, and slosh frequencies.**
3. **Environmental conditions, including tank motions, temperature and pressure variations, thermal shock, and repeated loads.**
4. **Control-system parameters, such as frequencies and sensor-gain settings, characteristics, and locations.**

For recommended practices, refer to NASA SP-8009, SP-8031, and SP-8036.

4.4.2.3 STRUCTURE AND PROPULSION SYSTEM (POGO)

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

Coupling of the structure with the liquid-propulsion system shall be evaluated with the aid of a mathematical model that incorporates physical characteristics determined by experiment, where possible, and accounts for the following:

1. **Elastic-mode coupling of the vehicle structure, propellant feedlines, and tank-fluid system.**
2. **Engine characteristics, including engine-mounting flexibility, turbopump transfer functions, cavitation characteristics, and propellant flow rates.**
3. **Delivery-system characteristics, including flexible supports, accumulators, pressure-volume compensators, fluid or gas injection, fluid damping, and flow resistances.**

Stability analysis shall be performed using mathematical models to cover the entire rocket-powered flight regime. Uncertainties in the parametric values shall be accounted for by appropriate statistical means for establishing that the probability of a pogo instability during a space-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 deg). When possible, the stability analysis shall be checked by a comparative analysis of the stability characteristics of closely related vehicles that have flown.

For recommended practices, refer to NASA SP-8055.

4.4.3 DYNAMICALLY INDUCED ENVIRONMENTS

4.4.3.1 NOISE, VIBRATION, AND SHOCK

The structural response to acoustic and aerodynamic noise, vibration, and shock shall not cause structural failure or system or component malfunction, nor degrade performance below specified limits, nor shall it reduce the service life of the vehicle, impair the performance of personnel, or endanger them.

The structural stiffness and transmissibility characteristics of local structure and equipment-mounting hardware (e.g., brackets, panels, or trusses) should be considered, using suitable impedance techniques, when establishing shock and vibration requirements for component and system specifications.

The local resonances of the equipment mounts should be separated from the vehicle resonances and from the resonances of the structure and nearby equipment. Equipment-mounting hardware should be preloaded at installation to prevent gaps between mounting flanges and mounting structure during exposure to limit dynamic environments.

For recommended practices, refer to NASA SP-8012, SP-8050, and SP-8072.

4.4.3.2 BUFFETING

The design of the vehicle shall minimize the detrimental effects of buffeting on the fuselage and the aerodynamic surfaces at any point, including high angle-of-attack and transonic Mach-number environments. Buffeting phenomena shall not impair vehicle control or structural

integrity, nor shall they impose a hazard to or accelerations on the personnel or cargo in excess of specified values.

For recommended practices, refer to NASA SP-8001.

4.5 THERMAL PROTECTION SYSTEM CHARACTERISTICS

The thermal protection system shall be designed to withstand without failure the effects of thermal-energy transfer from natural and induced environments.

The thermal protection system shall maintain the vehicle structure and components at temperatures within the design constraints for all ground operation and flight conditions. Thermal-protection-system performance and the temperatures and temperature gradients of the system and its structure shall be predicted from transient analyses that include thermal-energy sources and sinks.

The structural components of the thermal protection system shall be designed to withstand aerodynamic, acoustic, vibration, and shock loads under all expected operating conditions. In addition, these components shall be designed so that panel flutter is prevented, with consideration given to at least the following parameters: (1) spacing of panel-support brackets, (2) stiffness of panel-supports, and (3) rotational constraints imposed on panel edges by support brackets.

The design and analysis of the thermal protection system shall reflect the applicable requirements of the primary structure. In addition, they shall account for:

1. Thermal characteristics that vary with time and temperature (e.g., emissivity and absorptivity).
2. Interdependent effects (e.g., the influence of stress-accelerated oxidation on thermal properties).
3. Dimensional stability of contours, especially contours of leading edges, nose regions, and control surfaces.
4. Sealing requirements.
5. The effect of local or distributed roughness. External discontinuities shall be small compared with the boundary-layer displacement thickness. External surface discontinuities shall be aft-facing steps with respect to the local aerodynamic flow at critical heating conditions. Beads, waves, or corrugations in skin panels shall be aligned as nearly parallel as possible to the local flow at the critical heating conditions.
6. Effects on heating rates of mismatch between separate surface panels and between skin sheets on the same panel, and effects of protrusions due to fasteners.
7. Deflection from prior creep as well as deflection from applied loads and temperatures.
8. Compatibility of strains and deformations induced by differential thermal expansions and contractions of adjacent elements of the heat shield or substructure.
9. Moisture absorption.

Stiffening and expansion-accommodating features in skin design shall be investigated by analysis and tests.

Nonablative Heat Shields. Nondestructive inspection procedures shall be developed to verify integrity for acceptance and for reuse.

Ablative Heat Shields designed to last more than one mission shall have provision for nondestructive inspection between missions to determine their adequacy for reuse, considering such parameters as unpyrolized thickness, remaining char layer, and outgassing and related effects.

Cryogenic Thermal Protection Systems, including purge-gas systems, shall be designed to prevent or limit atmospheric gases not sealed in the system (including water vapor) from condensing or freezing on the vehicle.

Insulation. Insulative materials for metallic heat shields shall be selected and sized for adequate performance in the anticipated operating environments throughout the service life of the vehicle, if practicable. Consideration shall be given to possible material degradation due to thermal cycling, noise and vibration environments, and moisture absorption. The adequacy of the insulation assembly shall be demonstrated in ground simulation tests of the environments expected throughout the service life of the thermal protection system.

4.6 MATERIAL CHARACTERISTICS

Materials shall be characterized in sufficient detail to permit reliable and high-confidence predictions of their properties in the expected operating environments.

Materials shall have adequate structural properties to withstand their anticipated loads, environments, and temperatures, and their variations with time.

Material characterization shall include determination of: (1) general physical properties, including thermal characteristics; (2) allowable mechanical properties; and (3) material failure mechanisms.

An integrated plan which includes material processing and quality control (e.g., for both structure and the thermal protection system) should be followed throughout the design, manufacture, and test of the vehicle. This plan should also define inspection techniques, test procedures, accept-reject criteria, and requirements which must be met for substitute materials.

4.6.1 PHYSICAL PROPERTIES

Values for physical properties of structural materials shall be obtained from sources approved by NASA or determined by methods approved by NASA.

For additional information, refer to MIL-HDBK-5B, MIL-HDBK-17, MIL-HDBK-23A, and the AFML Advanced Composite Design Guide.

4.6.2 ALLOWABLE MECHANICAL PROPERTIES

Values for allowable mechanical properties of structure and joints in their design environment (e.g., subjected to a single stress or to combined stresses) shall be taken from sources approved by NASA, such as MIL-HDBK-5B, MIL-HDBK-17, MIL-HDBK-23A, or the AFML Advanced Composite Design Guide. When values for mechanical properties of materials or joints are not available because they are new or used in a new environment, they shall be determined by analytical or test methods approved by NASA. A sufficient number of tests shall be conducted to establish values for the mechanical properties on a statistical basis. The tests shall be performed in accordance with the procedures in ASTM E8-69 and E9-70 and AFML-TR-66-386. Both "A" values (99 percent nonexceedance with 95 percent confidence) and "B" values (90 percent nonexceedance with 95 percent confidence) for allowable stresses shall be obtained.

The effects of temperature, thermal cycling and gradients, processing variables, and detrimental environments shall be accounted for in defining allowable mechanical properties.

4.6.2.1 STRUCTURAL COMPONENT ALLOWABLES

Material allowable "A" values shall be used whenever failure of a single load path would result in loss of structural integrity.

Material allowable "B" values may be used in redundant structure in which the failure of a component would result in a safe redistribution of applied loads to other load-carrying members.

4.6.2.2 FULL-SCALE ASSEMBLY ALLOWABLES

The allowable strength for assemblies under tensile or compressive loads shall be determined by test and shall be corrected in accordance with the procedures in MIL-HDBK-5B.

The procedures call for a correction factor to be applied to the strength values based on compression tests on coupons taken from material in the structure and related to the minimum guaranteed properties for "A" or "B" values, as applicable.

The allowable strength for assemblies under tensile loads shall be determined by test. It shall be demonstrated that the material properties are at least equal to the appropriate guaranteed values given in MIL-HDBK-5B.

4.6.3 FAILURE MECHANISMS

Structural materials shall not fail from any form of cracking, corrosion, creep, meteoroid impact, or irradiation during the service life of the vehicle.

4.6.3.1 FATIGUE

The fatigue-life characteristics of structural materials shall be determined by experiment for appropriate cyclical loading and loading rates in the applicable environments.

Crack-incubation, initiation, and crack-propagation characteristics should be determined. It should be assumed that fabricated structures contain flaws that are just small enough to remain undetectable by ordinary inspection procedures or by proof test. The number of stress cycles required to grow these initial flaws of maximum undetectable size to a size sufficient to initiate fracture should exceed the specified fatigue life. All the environments in which the structure operates should be accounted for by analysis or test to ensure that the environments will not accelerate flaw growth.

For information on service life, refer to Section 4.7.

4.6.3.2 BRITTLE FRACTURE

The structural design shall account for the susceptibility of materials to brittle fracture. Fracture analyses shall be performed to determine critical flaw sizes, allowable initial flaw sizes, and probable fracture modes for candidate structural materials. Tests shall be performed to determine fracture toughness, flaw-growth characteristics, and threshold stress intensity of structural materials.

When possible, the metals selected for a given tension application should have sufficient fracture toughness at the intended operating temperatures so that the predicted critical sizes for surface and embedded flaws at the design-limit stress levels exceed the section thickness. The critical through-the-thickness crack lengths should be of a size easily detectable by ordinary inspection. When this is not possible, consideration should be given to the use of proof testing as a means of determining the possible existence of a flaw of critical size.

Values of allowable stresses for brittle nonmetallic materials such as ceramics shall be selected on a statistical basis, recognizing that considerable scatter exists in the mechanical properties of these materials even when they are produced by closely controlled processes. Stress levels to be used with limit loads shall not permit a probability of more than one failure in a million components.

In designs using brittle nonmetallic materials, careful consideration should be given to the effects of repeated loads, process control, nondestructive inspection, and proof testing on the selection of allowable stresses.

For recommended practices, refer to NASA SP-8040.

4.6.3.3 STRESS-CORROSION CRACKING

The sustained-stress crack-growth characteristics of structural materials shall be determined by experiment in the anticipated service environments and at critical temperatures. Surface coatings used for inhibiting general corrosion shall not be relied upon to prevent stress-corrosion cracking.

Stress-versus-time behavior should be examined for all material, whether or not it exhibits threshold stress. In general, materials with threshold-stress values of less than 50 percent of the critical crack-intensity factor should be avoided. Materials with low threshold stresses should be used only when it can be shown by a "worst-case" fracture analysis that the low threshold stresses will not precipitate premature structural failure.

Alloys and other materials which are subjected to different heat-treat levels and tempers and are susceptible to stress-corrosion cracking in the anticipated environments (including cleaning and test fluids) should not be utilized, unless it can be shown by analysis or test that sustained surface-tensile stresses (from residual stresses, operating loads, assembly stresses, or any other source) are below the threshold stress-corrosion cracking level for the specific environment. Metal fabrication techniques and material processes should be used which minimize sustained residual surface-tensile stresses, stress concentrations, and incompatible environments.

For recommended practices, refer to NASA SP-8082.

4.6.3.4 HYDROGEN EMBRITTLEMENT

The design shall account for the susceptibility of structural materials to hydrogen-embrittlement failure.

Steels, titanium, and copper alloys are particularly susceptible to hydrogen embrittlement.

Where fabrication processes that can introduce hydrogen into the material are used, the material should be baked to eliminate the hydrogen. When the baking procedure is shown to be inadequate, the correct procedure should be determined by performing sustained threshold-stress-intensity tests. Where gaseous hydrogen can come in contact with metallic structure during vehicle operation, the susceptibility of the material to hydrogen embrittlement in the expected operating environments should be evaluated by tests when applicable data are not available. Precracked sustained-stress specimens should be used for all tests.

test. The effects of simultaneously applied loads and environments shall be accounted for. The sequence of the cyclic loads as well as their amplitude, duration, and rate of application shall be accounted for in fatigue analyses and tests.

4.7.6 SUSTAINED LOADS

The design shall account for creep-induced phenomena, including cracking and deformation of the vehicle structure. The allowable deformations shall be determined and it shall be demonstrated by analysis and test that the allowable values will not be exceeded in the service life of the structure.

Particular attention should be given to materials that will be exposed for prolonged times to elevated temperatures under sustained loads to ensure that excessive deformation or actual rupture does not occur.

Flaw initiation or growth under sustained loads induced by such phenomena as stress-corrosion cracking, hydrogen-embrittlement cracking, and growth in high-stress inert environments shall be accounted for in the service-life prediction.

Analyses or tests shall be conducted to demonstrate that the threshold-stress intensities (K_{ISCC} or K_{TH} values) of the structure are sufficiently high to prevent unacceptable flaw growth during the service life. The K_{ISCC} or K_{TH} values shall be determined for the representative environment and temperature conditions. (These values are defined as follows: K_{ISCC} is the critical stress intensity for opening-mode cracking, Mode I, in corrosive environmental conditions, and K_{TH} is the threshold value of the stress-intensity factor.)

For composite materials, crack formation and crack propagation generated by differential thermal expansion under cryogenic temperatures should be investigated.

4.7.7 CUMULATIVE COMBINED DAMAGE

Structural service-life predictions shall account for the effects of cumulative combined cyclic and sustained loads under the environmental conditions expected in service.

4.8 INTERFACE COMPATIBILITY

The vehicle structure shall be physically and mechanically compatible with functional components, assemblies, systems, and fluids. The design shall account for: (1) direct physical interaction of vehicle structure and components, assemblies, and systems; and (2) indirect interaction of the structure with two or more components, assemblies, or systems. Interface compatibility shall be verified by experiment.

4.8.1 STRUCTURAL INTERACTIONS WITH SYSTEMS

4.8.1.1 PERSONNEL AND THE LIFE-SUPPORT SYSTEM

Structural design shall be compatible with the constraints imposed by personnel and the life-support system.

Constraints include physiological limits on noise, vibration, shock, and load levels, provision for appropriate hand holds, and restraint points for operations.

4.8.1.2 ELECTRONIC AND ELECTRICAL SYSTEMS

The design shall provide a unipotential structure and freedom from radio-frequency interference.

An electrical connection should be provided between equipment mounts and cases and the unipotential structure which has sufficient strength to withstand applied loading and shock and vibration environments.

4.8.1.3 POWER SYSTEM

The vehicle structure shall be designed to withstand the effects of integration of the power system, including all power-system-induced environments, loads, and configuration interactions. The mechanical, fluid, thermal, and radiation environments and loads generated by the power system for all mission phases shall be identified and accounted for in the design.

4.8.1.4 PROPULSION SYSTEM

The vehicle structure shall be designed to withstand the effects of integration of the propulsion system, including all propulsion-system-induced environments, loads, configuration interactions, and dynamic coupling (pogo).

4.8.1.5 GUIDANCE AND CONTROL SYSTEM

The vehicle structure shall be designed to withstand the effects of integration with the guidance and control system. All control-surface structures, including hinges and brackets, shall be designed fail-safe where feasible. The structure shall be strong enough to withstand the loads resulting from:

1. **Surface displacements occurring when the power-control system is operating at its maximum rate.**
2. **Surface displacements at their maximum deflection, limited by the stops.**
3. **Available hinge moment.**

For recommended practices, refer to NASA SP-8036.

4.8.1.6 THERMAL PROTECTION SYSTEM

All structural components interfacing with the thermal protection system shall be designed so that differential thermal-expansion effects are accounted for. Provision shall be made for sealing when necessary to avoid high-enthalpy gas flow.

4.8.1.7 PAYLOAD

The design shall prevent payloads from impairing the vehicle's structural integrity or control-system stability, and shall minimize the structural coupling between the shuttle and the payload.

Clearance shall be maintained between the specified dynamic envelope of the payload exterior and the cargo compartment under all loading and environmental conditions. Specified payload dynamic envelopes shall be confirmed by test or analysis.

Payload-support structure shall be designed to accommodate the range of shapes of payloads and their attach-point locations which are specified by NASA, and to prevent transmission of loads which exceed the maximum levels specified for the payload.

The design of the cargo compartment, including doors, rails, and payload-support structure, shall account for venting, handling, loading, and unloading the payload in orbit and on the ground.

An effective technique to minimize coupling between the shuttle and the payload is to support the payload in a determinate manner relative to the shuttle vehicle. This technique should be used where practicable.

4.8.1.8 GROUND SUPPORT EQUIPMENT

Wherever possible, the vehicle structure shall be designed only for the critical flight conditions. The influence of nonflight conditions and environments on the structural design shall be kept to a minimum. Vehicle flight weight shall not be increased by requirements for assembly, handling, transportation, and storage.

In the event that this design objective cannot be fulfilled, then the vehicle structure shall be designed with the concurrence of NASA to withstand loads induced by ground support equipment and the related handling, transportation, and storage environments.

Recommended practices for structural interaction with transportation and handling systems are to be given in a forthcoming NASA special publication.

4.8.1.9 STRUCTURE-FLUID COMPATIBILITY

Structural materials shall be compatible with propellants and other fluids used in the vehicle.

Fluids used for cleaning, lubricating, or proof-testing vehicle structure (e.g., tanks, pressure vessels, plumbing, or highly stressed parts) shall be compatible with structural materials or their protection systems.

4.8.1.10 REFURBISHMENT

Refurbishment processes and materials shall be compatible with the vehicle structure.

4.8.2 STRUCTURAL INTERACTIONS BETWEEN MATED VEHICLE STAGES

Physical interfaces between mated vehicle stages and clearances required between boost stages and the orbiter shall be identified and accounted for in vehicle design.

4.8.2.1 LOADS

The structure of mated vehicle stages shall be designed to withstand the loads and environments induced during applicable mission phases. Loading and temperature-induced deformations that may cause loading across interfaces or restrict clearances shall be determined and accounted for in design.

The following noise and vibration environments shall be evaluated: (1) mixing of the turbulent boundary layer of the boost-engine exhaust-stream; (2) turbulent boundary-layer noise resulting from convection of random-sized eddies along the vehicle surfaces; (3) interaction of shocks and turbulent boundary layer; (4) primary impact and reflection of compression and expansion shocks on vehicle surfaces; and (5) wake excitations. Account shall be taken of the boost-stage propulsion-system configuration, launch-pad and exhaust-deflector configuration, ascent trajectories, and composite vehicle-profile shape.

Shock evaluation of the mated vehicle stages shall include the following: (1) engine-ignition and -shutdown impulses; (2) impulses resulting from activation of separation mechanisms; (3) shocks resulting from handling, matings, and transportation in the mated condition; and (4) detonation of pyrotechnic devices.

4.8.2.2 PRESSURES

The design shall account for nonregulated pressures induced by the mated vehicle stages.

Design practices should be followed which minimize the effects of detrimental nonregulated pressures, such as lateral venting.

4.8.2.3 STATIC ELASTICITY

Static-elasticity effects induced by the mated vehicle stages shall be accounted for in design.

The design analyses should consider all loads, temperatures, and other environments from mating which result in more severe design conditions than for the unmated vehicle. Accumulated deformations incurred in successive missions should be anticipated and accounted for.

4.8.2.4 DYNAMIC ELASTICITY

The design shall account for dynamic-elasticity interactions between the mated vehicle stages. The effect of the products of inertia of the mated configuration on control-system capability shall be evaluated, including the accelerations and motions induced during the time lag between applied and corrective forces.

Mated configurations may have an unsymmetrical profile, resulting in extremely large products of inertia. Forces applied in any plane other than the profile plane may therefore induce very significant accelerations in mutually perpendicular planes. Any appreciable time lag between applied and corrective forces may result in uncontrollable unstable motions. Time should be allowed for deflecting the structure to provide for the reaction to the corrective forces. Tests should be made on the mated configuration when necessary to verify analytical results.

4.8.2.5 THERMAL CHARACTERISTICS

Mated stages and their connecting structure shall be designed to withstand gross and local heating effects caused or induced by the proximity of each vehicle stage to the other.

The design shall account for heat exchange between mated vehicle stages from aerodynamic heating and propulsion-system heating and cryogenics, and for heat exchange between systems in one vehicle or stage.

4.8.2.6 CLEARANCE

The design shall provide adequate clearance between the boost stages and the orbiter to prevent functional interference.

Accumulated deformations resulting from successive missions shall be determined and accounted for in the design. Load- and temperature-induced deformations that may cause loading across interfaces or restrict clearances shall be determined and considered in the design. Dynamic-response effects of mated and proximate vehicles shall be determined and accounted for.

4.8.3 STRUCTURAL INTERACTIONS WITH EXTERNAL SPACE VEHICLES

The vehicle and its interconnecting structures shall be designed to withstand the loads and environments encountered while docking and undocking, and while mated with other space vehicles. Evaluation shall include at least the following factors: (1) relative vehicle displacement, velocity, and acceleration; (2) vehicle inertial and elastic properties; (3) docking-mechanism forces; (4) seal flexibility; and (5) fluid effects.

Forces should be limited or otherwise controlled so that vehicle motions can be stabilized by control systems and the structural and functional capability of all vehicle systems remains intact.

4.9 SUPPLEMENTARY CHARACTERISTICS

4.9.1 DESIGN THICKNESS

The design thickness, t_d, for each metallic structural member other than mechanically or chemically milled pressure vessels shall be the minimum thickness obtained by either of the following relationships:

t_d = mean thickness based on equal plus and minus tolerances

or

t_d = n times the minimum thickness

where

n = 1.10 for strength design
n = 1.05 for stability design

The mean and minimum design thicknesses shall include allowances for cumulative material damage or loss resulting from repeated exposure to the design environment. The design thickness for mechanically or chemically milled pressure vessels shall be the minimum thickness (i.e., mean minus the lower tolerance).

The design thickness for nonmetallic structural members shall be based on rational analysis.

The design thickness for ablation materials shall be subject to approval by NASA.

4.9.2 SAFETY

Structural design shall account for the safety requirements imposed by NASA and the test range from which the vehicle is launched.

Of principal concern are hazards faced by personnel during the storage, assembly, refurbishment, field test, launch, and flight of space vehicles. Personnel safety should be considered by use of the following design practices: (1) minimum proof factors for pressurized structure; (2) constraints on using or handling explosive, toxic, incendiary, or radioactive materials; (3) provisions for escape, access, and flight termination in the event of a system malfunction; and (4) provisions to prevent unsafe or undesirable effects from magnetic fields, static electricity, nuclear radiation, heat transfer, vibration, shock, radio-frequency radiation, and earthquakes.

Materials that present a hazard of a noxious, toxic, or flammable nature under the expected operating environments shall not be used in crew and passenger compartments. For other portions of the structure, adequate protective covers over wiring and plumbing, fire walls, or other equipment shall be provided to control or inhibit the propagation of fire.

4.9.3 METEOROID PROTECTION

The probability of unacceptable damage from meteoroid impact shall be specified and the vehicle shall be designed so that this probability is not exceeded.

The vehicle shall be designed to prevent meteoroid damage to structure or components which could impair flightworthiness or reduce the vehicle's service life. The meteoroid model identified in Section 6.7 shall be used.

The analysis should account for shock loads resulting from particle impact which may induce spallation or cracking. The design of pressure vessels containing fluids should account for pressure pulses resulting from meteoroid impact which can cause structural failure when the pulses are transmitted through the fluids.

The meteoroid environment and the structural response to meteoroid impact are not precisely known, particularly for the more complicated multiwall structures. These unknowns reduce confidence in the calculated reliabilities. Perhaps some method of onboard repair of noncatastrophic holes in enclosures for personnel should be considered during design, inasmuch as an emergency repair capability could increase the reliability of the design.

4.9.4 RADIATION PROTECTION

Radiation shielding shall be provided if the inherent protection afforded by the vehicle is not sufficient to prevent the allowable radiation doses and dose rates from being exceeded during a mission. Any shielding provided shall be compatible with the combined radiation, thermal, and mechanical environments.

4.9.5 CRASHWORTHINESS AND DITCHING

Seats, harness-support structure, equipment-support structure, instrumentation, mechanisms for holding canopies and doors in their open positions, and any other items whose failure could result in injury to

personnel during a crash or prevent egress from the crashed vehicle shall be designed to resist crash loads.

Ditching loads applied to the structure shall not cause structural failure which would make the vehicle sink rapidly, injure the occupants, or in any other way prevent them from escaping safely from the ditched vehicle.

Structural requirements for crash landing on land or water will depend strongly on the relationship between vehicle weight and risk. It is expected, however, that if structural crashworthiness requirements are specified, they will only apply to local structure needed to prevent failures that would endanger occupants.

4.9.6 LEAKAGE

Pressurized structure shall be designed to restrict leakage to a level that will permit successful completion of the mission. Where a specified pressure must be maintained, leakage rates shall be established experimentally for structural joints, seals around doors and access hatches, skin penetrations, and pressure fittings.

In no case shall leakage exceed levels stated in safety requirements for toxic and explosive fluids, or levels which might jeopardize system function or rated life.

4.9.7 VENTING

Adequate venting of compartments (including interstages, payload shrouds, fairings, heat shields, housings for electronic equipment, conduits, and insulation panels) shall be provided to restrict pressure differentials across all compartment walls to within allowable limits.

Vents shall not induce undesirable aerodynamic effects on the vehicle nor shall they restrict trajectories in which the vehicle may be operated.

The design of compartment vents shall, as a minimum, account for the following requirements and constraints, as applicable: (1) the effects of vent fluid injected into the compartment on equipment in the compartment; (2) the interaction of the ejected fluid and the external flow fluid; (3) compatibility with prelaunch and launch gas-flow systems (e.g., ground air conditioning, insulation purging, and propellant-fume ventilation); (4) the environment needed for compartment equipment; (5) the strength and structural characteristics of the compartment walls, including panel flutter and response to random noise; and (6) the strength and structural characteristics of equipment in the compartment.

If sandwich panels are vented, the possibility of a mechanically induced failure due to freezing of ingested moisture should be considered. If sandwich panels are unvented, the magnitude of the differential pressures across the skins may be limited by use of an internal vacuum.

Pressure-vessel design shall account for differential pressures which can cause the vessel to collapse when it is being emptied.

Recommended practices for compartment venting are presented in NASA SP-8060.

4.9.8 DOORS AND WINDOWS

Doors and windows shall be designed to withstand the maximum pressure differential across them, static and dynamic loads, and thermal loads and thermal gradients. Window panes and surrounding structure shall be designed to prevent stresses in the panes induced by adjacent structural loads and deformations, and to accommodate differential thermal expansion. If applicable, window covers shall be designed to avoid imposing increased heating rates on surrounding structure.

Window panes shall be designed using fracture mechanics techniques.

Redundant panes should be used in window design for the cabin. For recommended practices, refer to NASA SP-8040.

Doors and windows shall remain in place and locks and actuating mechanisms shall not unlatch under ultimate design conditions.

Mechanical backlash shall be minimized.

4.9.9 DECELERATORS

The decelerator devices shall be considered as a structural system subject to the same criteria as hard structure. The devices shall be designed to decelerate, stabilize, and control the descent of the vehicle in the service environment within prescribed limits without imposing detrimental deformations, vibrations, or

impact shocks on the vehicle. Loads and stresses imposed by deployment of accelerators shall be determined by analysis and test for both the vehicle's structure and the decelerators themselves.

Structural-design factors shall be identified and applied as necessary to decelerators to account for known deleterious phenomena such as abrasion, fatigue, humidity, vacuum, radiation, joint efficiency, nonuniform loading, line convergence, and material-property degradation due to temperature.

4.9.10 LANDING GEAR

The landing-gear doors shall provide the prescribed thermal protection and shall be capable of reopening after entry. The landing gear and supporting structure shall be designed to withstand the appropriate design environments, including the residual entry temperatures.

4.9.11 ANTENNAS

Antennas shall be designed to withstand the anticipated static and dynamic loads and environments throughout the service life of the vehicle.

Antennas shall be designed to prevent detrimental coupling with the vehicle structure or vehicle control system at any stage of deployment.

If antennas are retractable, deployable, or movable, their operating characteristics shall not be impaired by use or by the environment.

If protective antenna windows are employed, the window material shall be compatible with the surrounding structure and the thermal protection system. The design shall not be adversely affected by degradation of functional properties due to induced loads or deflections.

4.9.12 CASTINGS

Only high-quality castings shall be utilized for structural components. The use of castings in primary structural components shall be subject to NASA approval. At least one sample of each casting design shall be qualified to ultimate load level at critical temperature. All castings shall be subjected to acceptance testing to limit load at critical temperature.

4.9.13 FORGINGS

Only high-quality forgings shall be used for structural components.

At least one sample of each forging shall be sectioned in order to verify that the inherent characteristics such as grain flow, parting-line end-grain, and internal defects will not adversely influence the load-carrying ability of the design.

All forging designs shall be qualified to ultimate load levels at critical temperatures.

4.9.14 FRICTION AND WEAR

All contacting surfaces designed to undergo a sliding or rolling motion shall be lubricated.

When data on friction and wear are not available, tests shall be conducted to demonstrate that the friction and wear characteristics of contacting surfaces are acceptable and in accordance with analytical predictions.

Analyses and tests shall be conducted to demonstrate that actual friction forces will not exceed the limitations of available power, and that actual wear will not impair the performance of sliding or rolling surfaces.

The performance of lubricants shall not be degraded below minimum design requirements as a result of multiple exposures to service environments such as high temperature, vacuum, pressure, propellants, purge gases, moisture, or contaminants. Where exposure to the environments could be expected to degrade performance of seals and lubricants, adequate protection systems shall be provided to prevent degradation. Design provisions shall be made for inspection, refurbishment, maintenance, and replacement of the protection systems, as appropriate, to ensure that the contacting surfaces are effective throughout their service lives.

4.9.15 PROTECTIVE FINISHES AND SURFACE TREATMENTS

Finishes and treatments for metallic and nonmetallic surfaces of the vehicle shall be adequate to prevent unacceptable degradation of structural strength in all expected operating environments throughout the vehicle's service life.

Possible changes in absorptivity and emissivity characteristics from exposure to the mission environments shall be accounted for in the selection of thermal-control coatings. Degradation of the substrate or surrounding structure from condensation, impingement, or sublimation of a coating or from diffusion of coating or substrate elements shall be accounted for in the selection of coating materials. Resistance of the coating to environmental conditions, erosion, handling, and cleaning shall also be considered when selecting a coating.

The toxicity of outgassing products from heated coating materials shall be accounted for.

Use of coatings that may produce toxic, noxious, or corrosive products shall be approved by NASA.

4.9.16 REFURBISHMENT

Refurbished components shall meet acceptance specifications for new parts. Materials and processes used in refurbishment of the vehicle shall comply with approved control procedures. Distortions and protrusions shall be no greater than the tolerances specified for the original configuration. Refurbishment shall not reduce the service life of the component, assembly, or system.

4.9.17 COMPOSITE, BONDED, AND BRAZED CONSTRUCTION

Procedures shall be devised for reliable detection of flaws in composite, bonded, and brazed construction. Nondestructive testing of all composite structure and of all bonded and brazed sandwich structures shall be performed in accordance with a plan approved by NASA.

For recommended practices on composites, see the forthcoming NASA special publication on advanced composite structures.

4.9.18 REWELDING

Rewelding shall not reduce the probability of successfully completing the mission. Materials and procedures employed for the rewelding of space-vehicle structure shall be approved by NASA.

The effects of rewelding shall be accounted for in determining weld design allowables and fracture control.

4.9.19 EUTECTIC MELTING

The design shall avoid eutectic melting of dissimilar materials which are joined by welding.

Consideration should be given to the reduction in ductility in welded joints that accompanies eutectic melting.

4.9.20 FASTENER REUSE

The probability of successfully completing the mission shall not be reduced by requirements for reuse of fasteners. The type and location of critical fasteners and the conditions for their reuse shall be identified.

Confidence in reusability of fasteners depends on load level, degree of redundancy, degree of inspection, and procedural controls on installation and use.

5. DESIGN CONDITIONS

5.1 GENERAL CONDITIONS

5.1.1 LOADS AND PRESSURES

All static and dynamic loads and pressures (external and internal) which may affect structural integrity or influence design shall be defined and accounted for. The effects of thermally and mechanically induced structural deflections, allowable structural and thrust-vector misalignments, and structural offsets and dimensional tolerances shall be included in analyses of all loads, load distributions, and structural adequacy.

Loads shall be distributed throughout the structure by rational analyses which include the effects of structural nonlinearities and temperature gradients.

Analyses of dynamic loads shall account for all significant changes in vehicle mass properties with time and all significant structural flexibilities, damping, and load spectra. These analyses shall also account for coupling of the vehicle with the launch system during static test firings and during normal operation.

Recommended practices for analytically modeling the structure to determine the mode shapes, frequencies, and damping are given in NASA SP-8012.

All significant loads and pressures identified for each of the life phases and events cited in Section 5.2 shall be accounted for. In addition, loads and pressures induced by liquid slosh, noise, vibration and shock, and buffeting during the vehicle's service life shall be accounted for.

Additional conditions that should be accounted for in only one life phase are identified, as appropriate, in Section 5.2.

Considerable emphasis is being placed on automated methods and finite-element computer programs such as NASTRAN to speed up and improve the process of determining loads and pressures. In particular, there is need for a rational approach for defining and treating uncertainties to replace the use of arbitrary design factors or arbitrary methods of load combination (e.g., peak on peak). Attempts to achieve such an approach include refinement of the probabilistic values to better characterize the environments and to define the limit load statistically in terms of its probability of occurrence at a specified confidence level. This approach requires extensive test data on all load-input parameters to describe the loads properly: a requirement that presently limits its use during preliminary design.

The present state of quantitative knowledge of load conditions for shuttle-type vehicles leads to a structure for which the uncertainties can be assessed only with a low level of confidence. However, probabilistic methods may provide insight into the sensitivity of the structure to loads, environments, and other variables, and they may be used to establish reliability goals and for design evaluation *after* experimental data become available. An overall nonexceedance probability level may be specified and individual load levels reduced so that this value is not exceeded.

5.1.1.1 LIMIT LOADS

Limit loads shall be determined for the vehicle in all configurations for the design conditions identified in this document. At least the following effects and their perturbations, dispersions, and variations with time shall be accounted for, as appropriate: (1) the vehicle's external and internal geometry; (2) mass distribution; (3) stiffness and damping of the vehicle, including changes in properties due to load level and thermal environment, and load redistribution from elastic deformation; (4) aerodynamic characteristics; (5) natural and induced environments; (6) interactions of propulsion, control, and other vehicle systems; and (7) trajectory characteristics.

The limit loads shall be based on properly sequenced combinations of these parameters which account for

operational procedures. Commanded values of variables such as engine-ignition sequence, launch release, navigation, attitude control, staging, and docking shall be used in establishing the loads.

Limit loads are derived by combining external and internal loads at potentially critical flight conditions. Traditionally, several cycles of load prediction and assessment are required. Starting with idealized structure, the limit load is based initially on steady and quasi-steady *externally* applied loads obtained from preliminary information on rigid-body aerodynamics, vehicle contours, flight profiles, and weights. The *internal* and dynamic load contributions to limit load are then determined from more detailed knowledge of substructure, load paths, and elastic response. Next, as the structure is refined, the loads are redistributed. Additional load cycles are required to account for major changes in design or in the definition of the environment. The final load cycle uses the revised definition of the structure and of the environments.

5.1.1.2 LIMIT PRESSURES

The design-limit values for regulated pressure in the structure (e.g., in propellant tanks) shall be based on the upper limit of the relief-valve setting when pressure is detrimental to structural load-carrying capability. When pressure increases the structural load-carrying capability, as in buckling, the lower limit of the operating pressure shall be used in determining the critical limit-pressure value.

Nonregulated pressures in the structure (e.g., in vented compartments or rocket-motor cases) shall be determined and accounted for in a rational manner. Where a range of pressure exists for a particular design point, an upper and a lower bound of pressure shall be established for use in design. When pressure decreases the structural load-carrying capability, the maximum pressure shall be the limit value. When pressure increases the structural load-carrying capability, the minimum pressure shall be accounted for in determining the critical limit value.

5.1.1.3 VENTING LOADS

Venting analyses shall be conducted on all compartments (including interstages, payload shrouds, fairings, heat shields, housings for electronic equipment, conduits, and insulation) to establish the variations of pressure differentials with time in structure subjected to pressure loading. The adequacy of planned and unplanned vents for meeting all vehicle and system requirements shall be verified by analysis, or test, or a combination of both.

Recommended practices for compartment venting are presented in NASA SP-8060.

5.1.1.4 SLOSH LOADS

Slosh loads for individual tank and baffle elements shall be accounted for and shall include, as a minimum, the effects of the physical properties of the liquid, the liquid level, and acceleration.

The theoretical and experimental design data presented in NASA SP-8009 can be used to check space-shuttle system designs for structural adequacy if the data are applicable, but tests should be conducted when existing information is not applicable to the tank or baffle designs. These tests shall simulate the natural slosh frequencies, effective liquid damping, and slosh loads on the tank and baffle system. For recommended practices, refer to NASA SP-8009 and SP-8031.

5.1.1.5 ACOUSTIC LOADS

Acoustic excitation from aerodynamic sources (e.g., base pressure and turbulent boundary-layer pressure fluctuations) occurring during ascent, entry, and atmospheric flight shall be accounted for. Acoustic excitation from other sources internal and external to the vehicle shall be accounted for during all phases of the vehicle's service life.

For recommended methods of obtaining acoustic loads from aerodynamic sources, see NASA CR-626 and AFFDL-TR-67-167.

The characteristics of the acoustic-pressure fields imposed by the propulsion systems shall be established and accounted for, including the effects of:

- **Free jet mass flow**
- **Exit velocity and density**
- **Nozzle exit-plane diameter**
- **Characteristics of the medium into which the exhaust gases flow**
- **Combustion processes in the jet stream**
- **Pressure of strong shock waves in the jet**
- **Distances and shapes of nearby surfaces (e.g., launch tower and ground).**

For recommended practices on acoustic loads generated by the propulsion system, refer to NASA SP-8072.

5.1.1.6 VIBRATION AND SHOCK LOADS

At least the following life phases and events shall be evaluated for potentially critical vibration and shock loads: (1) manufacturing, (2) transportation and ground handling, (3) static or captive firings, (4) motor or engine ignition and shutdown, (5) launch-stand release, (6) separation and abort, (7) docking and cargo transfer, (8) maneuvering, (9) deployment of recovery and landing devices, and (10) landing impact.

Recommended practices for analyzing, evaluating, predicting, and alleviating the response to vibration and shock loadings are treated in NASA SP-8030, SP-8046, SP-8050, and SP-8077.

5.1.1.7 BUFFETING

Low-frequency buffeting effects shall be examined in areas where separated flow or rocket-exhaust plume produce a gross bending response of the mated or unmated vehicle. High-frequency buffet loads resulting from local impingement of a turbulent flow shall be accounted for to prevent damage to structure or internal components.

The evaluation of buffeting effects should consider both local and overall vehicle response and stability, and should account for such factors as aerodynamic interference, vehicle cross-section shape and area changes, protuberances, and structural flexibility.

For recommended practices, refer to NASA SP-8001.

5.1.2 THERMAL EFFECTS

All thermal energy-transfer conditions which may influence yield and ultimate strength, material properties, stresses, and deflections shall be defined and accounted for. At least the following shall be evaluated: (1) gasdynamic heating; (2) solar and planetary thermal radiation; (3) structural conduction, heat capacitance, and radiation; (4) leakage and internal convection; and (5) internally induced heat transfer.

5.1.2.1 GASDYNAMIC HEATING

The external flow fields shall be defined during launch, ascent, and entry, and evaluations made of the magnitude of the aerodynamic and rocket-exhaust-plume heat transfer to the structure. When analysis indicates a critical effect of aerodynamic or rocket-exhaust-plume heating on design, and when previous test data are not applicable, tests shall be conducted to evaluate the external heating sources in at least the following: (1) areas adjacent to protuberances; (2) wake areas downstream of protuberances; (3) separated-flow and reattachment areas; (4) shock-wave impingement areas; (5) areas of base heating; and (6) areas subjected to three-dimensional exhaust plumes or to plume impingement.

For recommended practices, see NASA SP-8014, SP-8029, and SP-8062.

The analytical models for the inviscid-flow field employed for gasdynamic heating analyses shall, as a minimum, include; (1) the effects of vehicle attitude and shape on the inviscid-flow properties; (2) the effects of viscous interaction, mass transfer, and radiative cooling on the inviscid-flow properties; (3) appropriate thermodynamic, transport, and optical properties; and (4) finite-rate chemistry.

5.1.2.1.1 AERODYNAMIC

The convective-heat transfer and shear calculations shall include the effects of: (1) low-density flow, (2) continuum flow, (3) appropriate thermodynamic and transport properties, (4) complex flow regions, (5) boundary-layer transition, (6) mass transfer, and (7) finite-rate chemistry.

In the prediction of convective heating, the laminar, turbulent, and transitional boundary layers and the effects of surface roughness and interference shall be considered. Estimates of heating accounting for these effects shall be modified by appropriate factors based on the particular design requirements and the type of thermal protection system used. In addition, convective-heating predictions shall include the effects of structural thermal distortions. Extrapolations from heating rates measured in ground test facilities to flight predictions shall account for real-gas effects and any deficiencies in Mach number, Reynolds number, temperature ratios, and enthalpy levels due to ground tests.

As an interim method, uncertainty factors on heat-transfer coefficients for laminar, turbulent, or interference heating should be applied independently. The uncertainty factors to be used initially to obtain heat-transfer coefficients are:

Laminar heating in attached flow region	1.10
Turbulent heating in attached flow region	1.25
Heating in separated flow regions	1.50
Heating in interference regions	1.50

The factors should be used individually, and should not be combined. Where sufficient data exist on the type of interference under consideration to permit definition of trends with the primary variables, angle of attack, Mach number, Reynolds number, and boundary-layer conditions, the 1.50 factor can be reduced to 1.25.

In regions of localized roughness, the heat-transfer coefficient will include a correction to account for surface roughness. The method given in AIAA Paper No. 67-164 may be used to obtain the roughness correction factor. With the roughness criteria of Section 4.5, it is anticipated that this factor will not exceed 1.25 for metallic heat-shield areas. As indicated in Section 4.1, no factor or tolerance should be applied to predicted temperatures or temperature gradients.

Heating rates in the transition region should be based on a linear variation between the laminar prediction at the beginning of transition and the turbulent prediction at the end of transition.

The radiative-heat-transfer calculations shall include the effects of radiative cooling, nongray self-absorption, appropriate thermodynamic and optical properties, mass transfer, and nonequilibrium flow.

Detailed calculations of radiative-heat transfer are time-consuming and difficult. It is therefore recommended that simplified conservative calculations be performed for several altitudes and vehicle locations to indicate whether radiative heating is significant. If significant radiative heating is found, more detailed analyses should be performed.

The effects of direct convective heating of internal structural members shall be evaluated for configurations in which hot boundary-layer gases can be ingested into the interior.

Methods used to predict transition from laminar to turbulent boundary-layer flow shall be approved by NASA. The method shall account for effects of local Mach number, unit Reynolds number, wall temperature, and vehicle configuration, and shall include a means of predicting turbulent overshoot heating.

As an interim method, the location of the beginning of boundary-layer transition on the windward surface should be defined by:

$$\frac{Re_\theta/M_L}{\left[Re_X/X\right]^{0.2}} = f(\delta)$$

where

Re_θ	is local momentum thickness Reynolds number,
M_L	is local Mach number,
Re_X	is local Reynolds number,
X	is streamwise distance, in feet, along windward surface, from leading edge to beginning of transition, and
δ	is local flow deflection angle, in degrees.

The local angle-of-attack or correlation function, $f(\delta)$, is defined by a smooth curve with values of 10 for δ less than 20 degrees, 13 for δ equals 45 degrees, 21 for δ equals 60 degrees, and 30 for δ equals 65 degrees. For calculating heating rates, assume that the Reynolds number at the end of transition is twice its value at the beginning of transition.

As an interim method, turbulent-flow heat-transfer rates should be computed by the Spalding-Chi method, modified for real-gas effects.

5.1.2.1.2 ROCKET-EXHAUST PLUME

The rocket-exhaust-plume heating analysis shall include the influence of the vehicle's external flow field, nozzle configuration, propellant composition, and chamber pressure, as well as the effects of local, upstream, and base geometries, engine gimbaling, engine-out condition, secondary combustions and other chemical reactions, the adjacent launch-pad structure, and base or engine-compartment venting.

5.1.2.2 SOLAR AND PLANETARY THERMAL RADIATION

Direct solar radiation (insolation) and solar radiation reflected from the earth (albedo) shall be evaluated for the space phase of the mission. Insolation shall also be evaluated for the prelaunch and launch phases. The effects of the following on temperature distributions in the vehicle shall be determined: the time-varying geometric orientation of the vehicle to the heat sources, vehicle configuration, and absorptivity and emittance of vehicle surfaces.

5.1.2.3 STRUCTURAL RADIATION AND CONDUCTION

The thermal energy radiated by structural surfaces to other internal and external surfaces and to space, and

the thermal energy conducted through structural components and joints shall be accounted for.

5.1.2.4 INTERNALLY INDUCED HEAT TRANSFER

Heat transfer between the structure and engines, cryogens, environmental control systems, and internal equipment shall be evaluated, as appropriate. The effects of at least the following on the temperature distributions within a cryogen-containment system and on its adjacent structure shall be determined:

- **Cryogen loading at the maximum rate and the transient temperature distribution in the containment-system wall.**
- **Temperature variations in the loaded containment system due to liquid level and thermal stratification in the cryogenic liquid (including vapor in the ullage space).**
- **Warm gas injected locally into the tank, if any.**
- **Uncertainties in liquid position inside the containment system, in the absence of gravity or inertial forces.**
- **Extreme variations in tank warmup with time, based on the residual propellants for 99 percent engine-burnout conditions.**
- **Cooldown resulting from gas expansion during venting or pressure reduction.**
- **Any other phenomenon resulting in temperatures differing significantly from the temperature of the contained bulk liquid.**

When a component is critical at maximum internal temperature, the temperature shall be based on conservative assumptions from the preceding conditions, on rational analysis, or on testing when confidence is lacking in the analysis. When a component is critical at minimum internal temperature, the minimum bulk temperature of the contained cryogen shall be used, unless a higher minimum can be proven.

5.1.2.5 STRUCTURAL DESIGN TEMPERATURES

During ground phases, the design temperatures used in structural analysis shall be obtained from the external heat transfer. Mutually related values of the natural environment properties shall be used in heat-transfer analysis. Values shall be selected which result in maximum or minimum external surface temperature, whichever is critical.

During flight phases, the design temperatures shall be obtained from the external heat transfer determined using the design trajectories specified for each mission phase.

All convective-heat-transfer coefficients shall be multiplied by uncertainty factors to yield 99-percent-probability maximum or minimum values, whichever are critical. The effects of the 99th-percentile values of factors which significantly affect the heat transfer shall be combined, using a root-sum-squared technique to yield design temperatures.

At least the following shall be considered: material thermal properties, structural dimensions, joint conductance or total panel conductance, heating, and trajectory dispersions combined with atmospheric variations. Joint and panel conductances shall allow for variations in interface resistance with service life. No factor or tolerance shall be applied to predicted temperatures, temperature differences, or temperature gradients.

Where sufficient test data are not available, best-estimate values may be utilized, subject to NASA approval.

Structural temperature analyses shall consider the accumulated effects of external and internal heat transfer for the entire mission from the prelaunch phase through landing. Structural temperatures after landing shall be determined for a sufficient period of time to establish peak values of temperature, loads, and stresses induced by heating applied during entry.

Critical temperature conditions for some structural components may occur after landing because of soak-through of stored heat. Ground cooling is a possible means of maintaining peak values below flight levels.

5.1.3 APPLICATION OF NATURAL AND INDUCED ENVIRONMENTS

The structural effects of the environments (specified in Section 6 and shown in table 5-1) shall be evaluated for each phase of the vehicle's life indicated. The structure shall exhibit all of the characteristics identified in Section 4 after exposure to these environments.

The following paragraphs provide additional criteria and pertinent information on specific environments:

Rain and Hail. Thermal-protection-system materials may be significantly damaged by rain or hail. Particularly

TABLE 5-1 **STRUCTURAL ENVIRONMENTS APPLICABLE TO LIFE PHASES**

ENVIRONMENT / LIFE PHASE	ATMOSPHERIC PROPERTIES	WINDS AND GUSTS	RAIN	HAIL	BLOWING SAND AND DUST	SALT AIR	SALT WATER	HUMIDITY	FUNGUS	ATMOSPHERIC CONTAMINANTS	ATMOSPHERIC ELECTRICITY	SOLAR THERMAL RADIATION	ALBEDO	ELECTRO-RADIATION	METEOROIDS	NOISE	RUNWAY AND TAXIWAY ROUGHNESS
Manufacturing	X				X			X		X							
Refurbishment	X	X	X	X	X	X	X	X	X	X	X						
Storage	X	X	X	X	X	X		X	X	X	X						
Transportation and ground handling	X	X	X	X	X	X		X		X	X						X
Prelaunch	X	X	X		X	X		X		X	X	X					
Launch	X	X	X					X			X	X				X	
Ascent	X	X	X		X						X					X	
Space												X	X	X	X	X	
Entry	X	X	X								X					X	
Atmospheric flight	X	X	X	X	X	X		X		X	X					X	
Landing	X	X	X	X		X	X	X		X	X					X	X
Horizontal takeoff	X	X	X	X		X		X		X	X					X	X

susceptible are reusable external-insulation, coatings for metallic heat shields, and thin metallic heat shields.

Atmospheric Contaminants. **The atmospheric contaminants which the vehicle must withstand shall be specified.**

Contaminants which may be in the atmosphere in the various geographical areas in which the vehicle will operate (e.g., industrial and commercial contaminants and automobile-exhaust products) should be included.

Electromagnetic Radiation. **Electromagnetic and particulate radiation from onboard vehicle sources and from the natural environment shall be determined and accounted for. The effect of both dose rates and integrated doses on each potentially critical component over its life cycle shall be evaluated, accounting for the following factors, as applicable: (1) spectral, temporal, and directional characteristics of each type of radiation involved; (2) modification of the radiation environment or its effects by other environmental phenomena; (3) spatial distribution and composition of the vehicle mass and its contents; (4) time-dependence of significant masses (e.g., propellant, cargo, equipment, and jettisonable structure, if any) and their locations; and (5) the finite extent of surfaces or volumes of potentially critical components and systems.**

Meteoroid Impact. **The degree of structural damage expected from meteoroid impact shall be determined by analysis and experiment. The damage assessment shall, as a minimum, include the types of failure of the components indicated in table 5-2.**

5.1.4 LOAD AND TEMPERATURE SPECTRA

Load spectra and temperature spectra shall be defined using the appropriate loads, pressures, temperatures, and

TABLE 5-2 **PROBABLE FAILURE FROM METEOROID DAMAGE**

PROBABLE CRITICAL TYPES OF FAILURE	PRESSURE CABINS	TANKS	RADIATORS	WINDOWS	SPECIAL-PURPOSE SURFACES	ENTRY THERMAL PROTECTION
Catastrophic rupture	X	X		X		
Secondary fractures			X			
Leakage	X	X	X			
Vaporific flash	X					
Deflagration		X				
Deformation			X			
Reduced residual strength	X	X	X	X	X	
Fluid contamination		X	X			
Thermal insulation damage	X	X				X
Obscuration				X		
Erosion				X	X	

structural response which correspond to all life phases and events described in Section 5.2 except for emergency events.

For information on load spectra, see Section 4.7.4.

5.1.5 EQUIPMENT-SUPPORT STRUCTURE

Design conditions for equipment-support structure shall be estimated from past experience on similar structure and environments or by analysis of the response of the structure and equipment to specified input load spectra or discrete loading.

5.2 SERVICE CONDITIONS BY LIFE PHASES

Critical loads, pressures, temperatures, and structural response shall be investigated for at least the following phases of the vehicle life: (1) manufacturing, (2) refurbishment, (3) storage, (4) transportation and ground handling, (5) prelaunch, (6) launch, (7) ascent, (8) space, (9) entry, (10) atmospheric flight, (11) landing, (12) horizontal takeoff, and (13) emergency conditions. Unless otherwise specified or required for safety, the service conditions, loads, and environmental phenomena associated with all ground activity other than landing and takeoff shall not restrict the design of the flight structure, except in local areas around attachment points.

All structural weight penalties or special requirements for flight test conditions or handling equipment imposed on the vehicle in the interest of safety or by preflight events and phenomena should be identified and submitted to NASA for approval.

5.2.1 MANUFACTURING

Fabrication and assembly operations shall be evaluated for (1) critical stress conditions from material handling; (2) forming, stretching, or other processing; (3) clamping, misfit, and misalignments; (4) welding and rewelding; (5) heat treatment; (6) bonding; (7) brazing;

(8) coating; and (9) factory-checkout and acceptance operations, including pressurization cycles.

Effects of natural and induced environments on thermal coatings and on the strength and durability of bonding compounds or bonded structure shall be evaluated.

The loads from hoisting and assembly shall be determined using the load factors and conditions given in Section 5.2.4.1 for transportation and ground handling.

5.2.2 REFURBISHMENT

All loads and environments which the orbiter or boost stages may experience, including static and dynamic loads, temperatures, temperature and repeated-load cycles, and atmospheric, space, and corrosive environments (e.g., sea water during recovery of boost stages), shall be accounted for in the design and testing of refurbished structure.

Loads and environments which the orbiter or boost stages may experience during the period of refurbishment shall be accounted for or the structures shall be protected against them.

For a list of environments associated with refurbishment, see table 5-1.

5.2.3 STORAGE

Loads and environments which the vehicle structure may experience during storage shall be accounted for or the structure shall be protected against them. At least the following shall be considered:

1. **Pressure-differential loads, including the effects of venting.**
2. **Natural and induced environments. (See Section 5.1.3)**
3. **Environments and loads from stored propellants and fluids, considering pressure and temperature as well as chemical and physical effects on structural materials and adhesives.**

5.2.4 TRANSPORTATION AND GROUND HANDLING

During transportation and ground handling, the effects of natural and induced environments on the vehicle strength, deflection, and fatigue characteristics shall be evaluated.

Load oscillations should be counted and load amplitude should be measured and evaluated for all fatigue-critical structure. It may be necessary to monitor the handling and transportation loads on production vehicles to ensure that the actual loads are within acceptable limits. Rational analyses should be performed to determine the need for such monitoring.

For recommended practices, refer to NASA SP-8077 and to the forthcoming NASA special publication on structural interaction with transportation and handling systems.

5.2.4.1 TRANSPORTATION LOAD FACTORS

The limit-load factors for transportation of components presented in table 5-3 shall be applied at the support points of the transporting vehicle.

5.2.4.2 TOWING LOADS

The limit towing loads shall be as defined in table 5-4 and figure 5-1, based on the maximum weight of the applicable configuration, and shall act parallel to the ground. In addition,

- **The vehicle shall be in the three-point attitude, with the resultant of the vertical reactions at the wheels equal to the maximum flight gross weight (atmospheric).**
- **The side component of the tow load at the main gear shall be reacted by a side force at the static ground line at the gear to which the load is applied.**
- **When tow loads cannot be applied to the nose or auxiliary gear in a given direction because of the configuration or type of swiveling, the load which will not result in a side component on the wheels shall be applied at the maximum attainable angle.**
- **Reaction loads in addition to vehicle inertial loads shall be provided in the analysis when necessary for overall equilibrium.**
- **Additional loads which may be necessary for equilibrium shall be considered separately.**
- **If a tow point is at or near a main-gear unit, a force acting at the axle of the wheel**

TABLE 5-3 **TRANSPORTATION LIMIT-LOAD FACTORS***

MODE	LONGITUDINAL (g)	LATERAL (g)	VERTICAL (g)
Marine	±0.5	±2.5	+2.5
Air	±3.0	±1.5	±3.0
Ground			
Truck	±3.5	±2.0	+6.0
Rail (humping shocks)**	±6.0 to ±30.0	±2.0 to ±5.0	+4.0 to +15.0
Rail (rolling)	±0.25 to ±3.0	±0.25 to ±0.75	+0.2 to +3.0
Slow-moving dolly	±1.0	±0.75	+2.0

*For crash factors, see Section 5.2.12.3. The load factors in this table apply to the transport vehicle axes.
**These are shock conditions and should not be treated as quasi-steady accelerations.

nearest the tow point in the opposite direction and parallel to the plane of symmetry shall be combined with inertial loads necessary for equilibrium. The force shall be equal in magnitude to this component or to the vertical reaction at a main gear, whichever is less.

- **If a tow point is at the plane of symmetry, a force acting at the axle of the auxiliary wheel or nose wheel in a direction opposite to the tow load shall be combined with inertial loads necessary for equilibrium. The force shall be equal in magnitude to this tow load or to the vertical reaction at the auxiliary wheel, whichever is less.**

TABLE 5-4 **TOWING CONDITIONS**

TOW POINT	TOWING LOAD	
	MAGNITUDE*	DIRECTION OF LOAD APPLICATION
At or near each main gear	0.75 T per main gear unit	Positive, longitudinal Positive, at 30 deg to longitudinal Negative longitudinal Negative, at 30 deg longitudinal
At the nose gear	1.0 T	Positive, longitudinal Negative, longitudinal

*Value of T can be obtained from figure 5-1.

5.2.4.3 JACKING LOADS

Limit jacking loads shall be based on the maximum flight gross weight of the vehicle. The vertical load shall act singly and in combination with the longitudinal load, the lateral load, and both longitudinal and lateral loads. The horizontal loads at the jack points shall be reacted by inertial forces so as to cause no change in the vertical loads at the jack points. Load factors of 2.0 g shall be applied in the vertical direction and load factors of 0.5 g shall be applied in any horizontal direction.

5.2.4.4 HOISTING LOAD FACTORS

Limit-load factors for hoisting vehicle components shall be 2.0 g for land operations and 2.67 g for shipboard operations, applied upward in any direction within 20 degrees of vertical. The vehicle weight shall be the basic landing gross weight (see Section 5.2.10.2.4).

5.2.4.5 MATING AND ERECTING LOAD FACTORS

Limit-load factors for vertical mating and erecting of vehicle components shall be 2.0 g applied upward in the

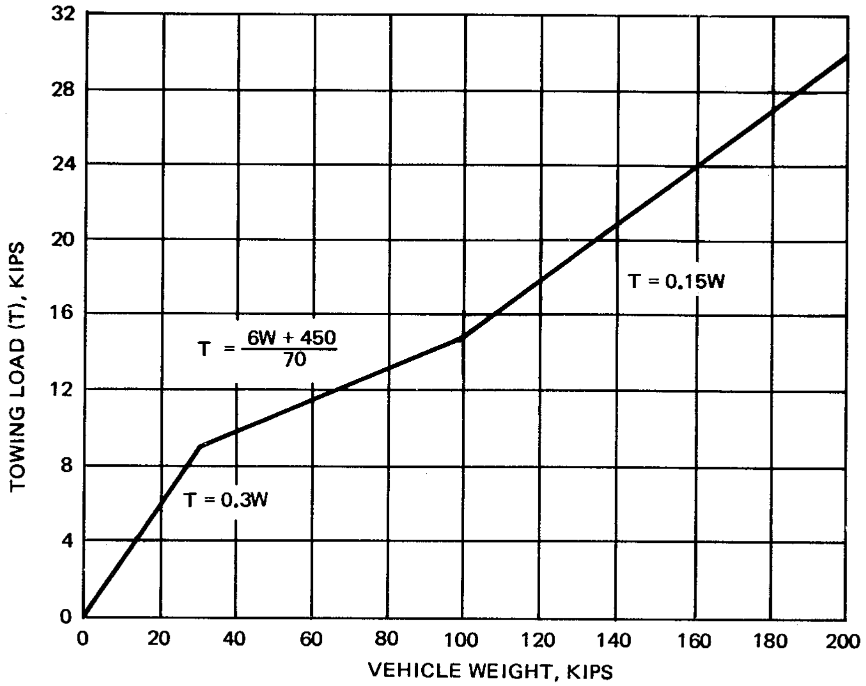


FIGURE 5-1 **TOWING LOADS**

vertical direction and 0.5 g in any horizontal direction. The vehicle shall be within the attitude envelope established for erecting and mating. The basic landing gross weight (atmospheric) shall be used, without an allowance for personnel.

5.2.4.6 MOORING

The vehicle shall be able to withstand ground winds while secured in the static horizontal or vertical position with control surfaces locked (see Section 6.1).

5.2.4.7 MASS PROPERTIES

Values of the design weights, centers of gravity, and mass moments of inertia to be used for all transportation and ground handling conditions shall include the mass properties of the segments of the flight vehicle being handled and transported, nonflight fluids (e.g., temporary pressurizing gases), and supports which are used during transportation and handling but are not part of the flight vehicle.

5.2.5 PRELAUNCH

5.2.5.1 WIND AND GUST LOADS

The design shall account for static and dynamic loads from ground winds and gusts and resulting vortex shedding with possible lateral force amplification from aerodynamic or gravity forces induced by the vehicle response motion during the prelaunch phase. At least the following effects shall be included: the forward profile shape of the vehicle; vehicle mass, stiffness, propellant loadings, and tank-pressurization conditions; protuberances and surface roughness; and proximity and shape of umbilical masts and other large structures. The turbulence loads and steady loads (including gravity effects) shall be suitably combined with the periodic vortex-shedding loads calculated from the peak-wind profile to obtain the resultant elastic-vehicle static and dynamic loads.

Tank-pressurization conditions shall account for the venting-system characteristics, including valve tolerances and settings for design ullage and vent pressure.

For recommended practices, see NASA SP-8008.

If a structural tie-off or damper is used with the launch-support structure to assist the vehicle in withstanding the wind loads, the vehicle attachment loads shall be included in the total vehicle loads.

5.2.5.2 UMBILICAL LOADS

Umbilical loads on the vehicle shall be accounted for and shall include the effects of umbilical configuration,

methods of attachment and separation, feed-line pressures, and wind loads.

For recommended practices, refer to NASA SP-8061.

5.2.5.3 GROUND-TEST FIRING LOADS

The following static and dynamic loads imposed on the vehicle during ground-test firing of engines shall be accounted for: (1) loads from ground winds and gusts; and (2) loads from thrust buildup and decay, including malfunction loads from any engine hard-over or out.

5.2.5.4 THERMAL EFFECTS

Thermal effects from at least the following sources shall be included in evaluation of temperatures and thermal stresses in critical areas of the structure:

- **Cryogens, including the effects of thermal cycling**
- **Environmental-control system, including the effects of cooling-air pressure, temperature, and humidity**
- **Engine test firing, including the effects of the test stand and ground**
- **Atmospheric density, humidity, temperature, and wind velocity**
- **Solar radiation.**

Refer to Section 5.1.2 for more detailed thermal-effects criteria.

5.2.5.5 MASS PROPERTIES

Values of the design weights, centers of gravity, and mass moments and products of inertia to be used for prelaunch conditions shall include: (1) the vehicle stages, mated and unmated; (2) level of propellants; (3) vehicle attitudes; (4) fueling sequences; (5) defueling sequences; and (6) payload configuration.

5.2.6 LAUNCH

5.2.6.1 WIND AND GUST LOADS

Static and dynamic loads from winds and gusts and resulting vortex shedding and possible lateral-force amplification during launch, as identified in Section 5.2.5.1, shall be accounted for.

Wind directions not parallel to the plane of vehicle symmetry, vortex shedding, and interference may cause large asymmetrical loads on the vehicle.

5.2.6.2 ENGINE FIRING LOADS

The following loads imposed on the vehicle as a result of engine firing during boost shall be accounted for:

- **Air loads induced by engine exhaust.**
- **Acoustic loads, including the effects of the launch system and the ground.**
- **Thrust-buildup loads, including deviations in engine start time, unsymmetrical side loads on the engine nozzle, and any engine rotation due to local deflections.**
- **Thrust-vector misalignment loads. The bounds of the total thrust-vector misalignment shall be established by statistical methods, considering all engines.** (The misalignment loads should be evaluated even though the total thrust vector is normally programmed to pass through the center of gravity of the mated vehicle for the launch-release condition.)
- **Loads resulting from engine hard-over or out after release. These loads shall be based on at least one engine hard-over or out, and on no more than the number of engines which will cause vehicle-control instability.**

The analysis of the engine hard-over or out condition should be in accordance with the procedure of Section 5.2.12.1. If abort specifications include engine conditions that result in vehicle instability, the analysis should be in accordance with the procedures of Sections 5.2.12.1 and 5.2.12.2.

The same loads shall be considered for engine hard-over prior to release as for ground-test firing in the prelaunch phase. In addition, rebound loads from emergency engine shutdown prior to release, including thrust-decay characteristics as well as all normal launch loads except vehicle-release loads, shall be accounted for.

For recommended practices, refer to NASA SP-8030.

5.2.6.3 VEHICLE-RELEASE LOADS

Vehicle-release loads, including the effects of the release mechanisms on the vehicle's dynamic response, shall be accounted for.

5.2.6.4 THERMAL EFFECTS

Thermal effects from at least the following sources shall be accounted for in determination of temperatures and thermal stresses in critical areas of the structure: (1) cryogens; (2) environmental-control system, including the effects of cooling-medium pressure, temperature, and humidity; (3) engine firing, including the effects of the launch tower and the ground; and (4) atmospheric temperature.

5.2.6.5 MASS PROPERTIES

The values of the design weights, centers of gravity, and mass moments and products of inertia to be used for the launch conditions shall be based on the nominal payloads and propellant loading. The mass properties shall include upper and lower boundary values to account for maximum and minimum payload weights and center-of-gravity locations as well as tolerances on propellants and other expendables. When pertinent data are available, these boundary values shall be established through statistical analysis of the tolerances.

5.2.7 ASCENT

5.2.7.1 LOADS AND PRESSURES

The determination of ascent loads and pressures shall include consideration of the trajectory conditions of Section 5.2.7.4 and of angles of attack in pitch, yaw, and roll within the operational flight envelope. In addition, the effects of the following shall be accounted for: (1) in-flight winds, wind shears, and gusts; (2) engine firing and shutdown; (3) staging; (4) interference from structure such as an attached stage, protuberances, and control surfaces; (5) separated flow regions and jet-plume interference on the flow fields; (6) adding to or removing mass from the flow fields; (7) shock impingement and interaction; (8) vent locations and sizes; and (9) vehicle flexibility on loading distributions.

Experimental data shall be utilized when validated theoretical or empirical data suitable to the configuration and expected flight conditions are not available, when the design angle of attack or yaw induces nonlinear aerodynamic behavior, when large flow separations are expected to occur, and when the configuration has large protuberances or severe wake generators. Experimental data shall also be utilized for the transonic-speed regime.

5.2.7.1.1 WINDS, GUSTS, AND TRAJECTORIES

The wind and gust data specified in Section 6.1.3 shall be used to determine structural loads during the ascent phase. The design trajectories for ascent flight shall include dispersions in the conditions that significantly affect structural loads and temperatures.

For additional information, see Section 5.1.2.1.

5.2.7.1.2 ENGINE FIRING

Engine-thrust magnitudes, engine-firing sequence, thrust transients, thrust-vector directional variations, and loads resulting from the engine-out condition shall be accounted for using the critical engine hard-over or out condition (e.g., firing at launch).

The dynamic inputs for thrust excitation should be derived from experimental data obtained from the engine under consideration, from similar engines, or from a logical extrapolation of related experimental data. For recommended practices, see NASA SP-8030.

5.2.7.1.3 STAGING

The following sources of loads imposed on the vehicle during staging shall be accounted for: separation or actuation devices, fluid slosh, exhaust-plume impingement, control system, and vehicle-separation dynamics.

Analyses should employ multidegree-of-freedom models incorporating coupled vibration modes of the continuing vehicle and of the jettisoned segments.

For recommended practices, refer to NASA SP-8022, SP-8030, and SP-8056.

5.2.7.2 THERMAL EFFECTS

Thermal effects from at least the following sources shall be included in evaluation of temperatures and thermal stresses in critical areas of the structure: cryogens; engines; and external flow field, including shock and engine-plume impingement areas.

For more detailed thermal-effects criteria, refer to Section 5.1.2.

5.2.7.3 MASS PROPERTIES

The values of the design weights, centers of gravity, and mass moments and products of inertia to be used for the ascent conditions shall be based on the nominal payloads and propellant loading. The mass properties shall include upper and lower boundary values to account for

maximum and minimum payload weights and center-of-gravity locations as well as tolerances on propellant and other expendables. When pertinent data are available, these boundary values shall be established through statistical analysis of the tolerances.

5.2.7.4 *DESIGN TRAJECTORIES*

The design trajectories for ascent flight shall satisfy mission requirements and shall include dispersions in trajectory parameters that have a significant effect on structural loads and temperatures.

In establishing the design trajectories for structural loads and thermal analyses, the effects of uncertainties in at least the following parameters shall be accounted for: aerodynamic characteristics, guidance and control system characteristics, thrust and thrust-misalignment tolerances, mass-property tolerances, atmospheric density dispersions, and wind dispersions.

In evaluation of loads, the loads and temperatures on all critical components shall be examined at a sufficient number of points along the design trajectory to ensure that all critical structural conditions are accounted for. The evaluation shall include at least the following trajectory points:

- **Maximum dynamic pressure**
- **Where the product of the dynamic pressure and angle of attack is a maximum**
- **Maximum longitudinal acceleration and deceleration**
- **Where centers of pressure are at extreme forward and aft locations**
- **Maximum heating rate**
- **Maximum temperature**
- **Maximum and minimum inertial loading**
- **Maximum differential pressure across the structure**
- **Transonic-speed regime (several points)**
- **Subsonic regime (one point)**
- **Pitch-yaw coupling for rolling vehicles**
- **Maximum and minimum pressure on compression and expansion surfaces**
- **Maximum fluctuating pressure.**

The effects of trajectory dispersion shall be determined for all critical external aerodynamic-heating areas. Laminar, transitional, or turbulent flow shall be considered in accordance with the transition criteria employed for design.

5.2.8 SPACE

5.2.8.1 *ORBIT TRANSFER AND DEORBIT LOADS*

The static and dynamic loads experienced by the vehicle during orbit transfer and deorbit shall be accounted for.

For recommended practices, see NASA SP-8058 and SP-8059.

5.2.8.2 *DOCKING AND UNDOCKING LOADS*

Loads imposed on the orbiter during docking and undocking shall be accounted for, including the effects of relative velocities and misalignments, liquid slosh produced by docking and undocking, latching and unlatching forces and torques, and engine thrust during undocking and maneuvers. The following configuration combinations shall be evaluated:

- **Orbiter – Orbiter.**
- **Orbiter – Space station or base.**
- **Orbiter – Space station or base – Other orbiters.**

The docking loads shall be evaluated using the relative velocities and misalignments in table 5-5, although lower values may be used if established by docking-simulator studies.

The velocities and misalignments should be considered in combinations limited by the following:

$$\frac{(V_L - V_{Lm})^2}{(\Delta V_L)^2} + \frac{V_R^2}{(\Delta V_R)^2} + \frac{D_R^2}{(\Delta D_R)^2} = 1$$

$$\frac{\omega_x^2 + \omega_y^2 + \omega_z^2}{(\Delta\omega)^2} + \frac{\theta_x^2 + \theta_y^2 + \theta_z^2}{(\Delta\theta)^2} = 1$$

where

V_L and V_R are the closing and lateral translation velocities

TABLE 5-5 **DOCKING LOADS**

PARAMETER	IMPACT VALUES
Closing velocity (parallel to docking port), fps	0.4
Lateral translation (in any direction perpendicular to closing velocity vector), fps	0.15
Angular velocity (in any plane), deg/sec	0.1
Linear misalignment, in.	±6.0
Angular misalignment (including roll), deg	±3.0

D_R is the linear misalignment,

V_{LM} is the mean closing velocity,

ω_x, ω_y, and ω_z are the angular velocities about the respective axes,

θ_x, θ_y, and θ_z are the angular misalignments about the same axes, and

Δ is the increment to be considered above and below the mean value or zero.

5.2.8.3 *CARGO TRANSFER LOADS*

All static and dynamic loads due to hatch opening and latch forces, movement of cargo, control-system interaction, and the absence of aerodynamic damping and gravity in orbit shall be accounted for.

5.2.8.4 *THERMAL EFFECTS*

Thermal effects from at least the following sources shall be included in evaluation of temperatures and thermal stresses in critical areas of the structure: (1) cryogens; (2) power supplies and other heat-producing equipment in orbiters and in the space station or base; (3) engines, including attitude-control and maneuvering engines; (4) solar radiation; (5) albedo of the earth, moon, and objects in interlunar space; and (6) radiation to space.

For more detailed thermal-effects criteria, refer to Section 5.1.2.

5.2.8.5 *MASS PROPERTIES*

The values of the design weights, centers of gravity, and mass moments and products of inertia to be used for the space-flight conditions shall be based on the nominal payloads and propellant loading. The mass properties shall include upper and lower boundary values to account for maximum and minimum payload weights and center-of-gravity locations as well as tolerances on propellant and other expendables. When pertinent data are available, these boundary values shall be established through statistical analysis of the tolerances.

5.2.9 ENTRY

All static and dynamic loads and pressures acting on the vehicle during entry, including their dispersions, shall be accounted for. The determination of air loads shall account for the effects of maneuvers, winds and gusts, vehicle attitude, and shock impingement and interactions associated with at least the following: protuberances, canopies, fins, nose cap, deflected control surfaces, engine plumes, and boundary layer. Auxiliary surface deployment, boundary-layer conditions, viscous-induced pressures, body flexibility, and vorticity resulting from leading edges, intersecting flow fields, and abrupt geometry changes shall also be accounted for.

Experimental data shall be utilized when validated theoretical analyses applicable to the configuration and flight conditions are not available and when the configuration has large flow separations, protuberances, or wake generators.

5.2.9.1 *THERMAL EFFECTS*

Thermal effects from at least the engines and the external flow field, including shock and engine-plume-impingement areas, shall be included in evaluation of temperatures and thermal stresses in critical areas of the structure and in evaluation of the effectiveness of thermal protection systems.

For more detailed thermal-effects criteria, refer to Section 5.1.2.

5.2.9.2 *MASS PROPERTIES*

The values of the design weights, centers of gravity, and mass moments and products of inertia to be used for the

entry conditions shall be based on the nominal payloads and propellant loading. The mass properties shall include upper and lower boundary values to account for maximum and minimum payload weights and center-of-gravity locations as well as tolerances on propellants and other expendables. When pertinent data are available, these boundary values shall be established through statistical analysis of the tolerances.

The analysis at each gross weight should include all reasonable distributions of payload and disposable items. These distributions should be presented in the form of plots showing the variations in center of gravity in the three planes of the body's axis system.

Minimum Entry Gross Weight. **Values of the minimum entry gross weight shall include an allowance for minimum crew, minimum propellant or other expendables, and for a full load of cruise-engine fuel and oil. It shall be assumed that no propellant remains for attitude control and that there is no payload or other useful load item.**

Maximum Entry Design Gross Weight. **Values of the maximum entry design gross weight shall include an allowance for full crew, full load of cruise-engine fuel and oil, maximum payload, and any propellant remaining in the primary propulsion system or other expendables. It shall be assumed that all of the attitude-control propellant remains and that there are other useful load items.**

5.2.9.3 DESIGN TRAJECTORIES

Entry-flight trajectories for use in determination of structural loads and aerodynamic heating shall include the dispersions in parameters in the design entry corridor which have a significant effect on loads and temperatures.

5.2.9.3.1 DESIGN ENTRY CORRIDOR

The design entry corridor, defined in terms of velocity versus altitude within the design atmosphere, shall be represented by an envelope of operational trajectories that satisfy the mission requirements.

Altitude margins for the nominal trajectory values should be derived from simulator studies involving tolerances and uncertainties in systems and environmental parameters that have a significant effect on loads and temperature conditions. The trajectories should include the ideal energy-management maneuver required during the initial entry period to establish the desired glide conditions. A design entry corridor (e.g., see figure 5-2) should be developed for NASA approval.

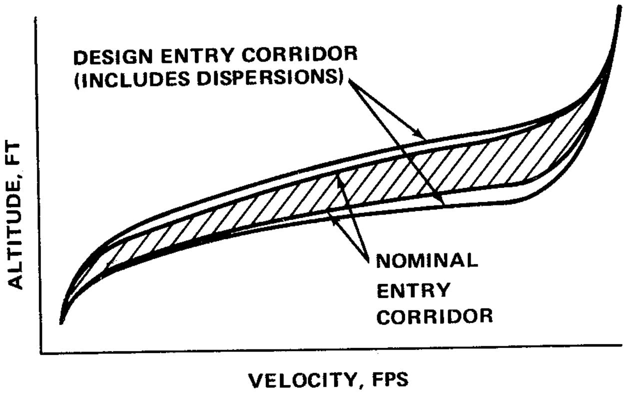


FIGURE 5-2 **DESIGN ENTRY CORRIDOR**

An acceptable approach to development of the corridor follows:

1. Define the nominal entry corridor for ideal conditions (no dispersions), using the ideal entry trajectories from the baseline orbit and from the critical orbits within the range of inclinations specified for design. The top (highest altitude) boundary is defined by an ideal minimum W/SC_L trajectory based on maximum C_L and minimum gross weight. The bottom boundary is defined by an ideal maximum W/SC_L trajectory for a maximum entry gross weight and a bank-angle history required for the specified cross range.

2. Establish the effect on trajectory altitude of incremental dispersions in each parameter that has a significant influence on loads and heating. As a minimum, incremental dispersions in the following parameters should be considered:

   A. Angle-of-attack dispersions due to tolerances and uncertainties in the pilot's instrumentation system, the autopilot, the guidance and control system, and the aerodynamic data.
   B. Angle-of-roll dispersions due to these tolerances and uncertainties.
   C. Flight-path-angle and velocity dispersions at entry due to tolerances in the effective retrorocket impulse resulting from dispersions in vehicle attitude, retrorocket thrust, or burn time.
   D. Aerodynamic-coefficient dispersions.

E. Atmospheric-property dispersions (including winds and gusts).
F. Uncertainty of orbit at retrorocket firing.

3. The boundaries of the nominal entry corridor should be expanded to account for the incremental dispersions, and the expanded boundaries should be based on statistical combinations of the dispersions, with consideration given to their coexistence at the same time.

5.2.9.3.2 DESIGN ENTRY TRAJECTORIES

Design entry trajectories shall be based on the ideal entry trajectories in the design atmosphere with transient excursions out to the boundaries of the design entry corridor. A sufficient number of trajectories shall be established to ensure that all critical structural heating and load conditions that occur in the design entry corridor have been adequately covered.

5.2.9.3.3 TRANSIENT MANEUVER ENVELOPE

A transient maneuver envelope for entry flight shall be established based on the aerodynamic capability of the vehicle, the aerodynamic environment, and the type of maneuver likely to be performed in each velocity range. The critical combinations of loads, temperatures, and other conditions represented in the transient maneuver envelope shall be accounted for.

Selection of the critical conditions should be based on analysis of coexisting structural temperatures, loads, pressures, and other parameters. The analysis should account for the time-dependency and phasing of these parameters.

A typical maneuver envelope (V-n diagram) for the entry vehicle is illustrated in figure 5-3. The values for the maximum normal load factors should include the vehicle's particular entry characteristics, pilot-control inputs, and the flight-control system characteristics for the initial entry and glide phases of flight.

During the initial entry period, prior to acquisition of the glide conditions, the precise roll angle and angle of attack should be modulated to avoid excessive structural loads and induced environments, and to prevent skipout. The load factors should be established for conditions at the boundaries of the design entry corridor and should include the load factor for the ideal maneuver at the boundary, plus an increment to provide capability to maneuver away from the boundary.

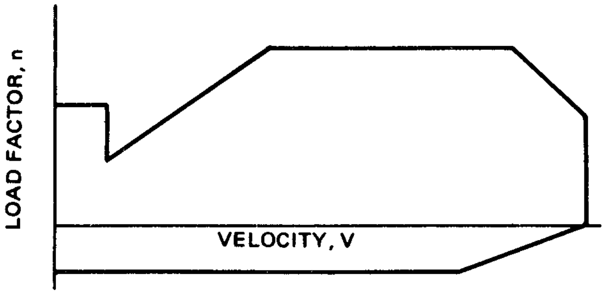


FIGURE 5-3 **TYPICAL ENTRY MANEUVER ENVELOPE SHAPE**

The transient maneuver envelope for the glide portion of the entry should be based on conditions at the boundaries of the design entry corridor. The load factor for each velocity range should be based on the attitude required for glide at conditions that define the design boundary, plus an increment to correct for deviations from the flight plan or to modify the flight plan.

Prior to completion of simulator studies conducted to develop the actual maneuver load-factor requirements, transient maneuver load-factor requirements may be defined by using the static loads based on the vehicle attitudes and conditions on the nominal entry boundary and increasing them by 10 percent.

5.2.10 ATMOSPHERIC FLIGHT

The loads and environments experienced by the orbiter structure in atmospheric flight and represented in the V-n flight envelopes shall be accounted for. Conditions imposed on the structure during atmospheric flight which are more severe than those experienced in any other flight phase shall be identified. The residual effects of loads and environments encountered in space and entry flight, including load redistribution from thermally induced deformations, reduced material allowables, and changes in vibration modes and frequencies, shall be accounted for.

5.2.10.1 LOADS AND PRESSURES

Loads shall be evaluated for the conditions identified for the entry phase and for at least the following speeds: level flight maximum speed, V_H; limit speed, V_L; stalling speeds, V_S, V_{SL}, and V_{SPA}; and the speed for maximum gust, V_G.

The speeds used to determine loads for atmospheric flight, not including takeoff and landing approach, shall be defined for the altitude at which the limit speed, V_L, is maximum, the altitude at which the Mach number is maximum, sea level, and for any intermediate altitude at which critical loads occur. Sea-level speeds shall be used for landing approach and takeoff loads.

Loads and pressures for both symmetrical and unsymmetrical flight maneuvers shall be accounted for.

5.2.10.1.1 SYMMETRICAL FLIGHT MANEUVERS

For a balanced maneuver, it shall be assumed that the vehicle is in the basic and landing configurations at all points on and within the maneuvering envelope illustrated in figure 5-4. The pitching velocity shall be the finite pitching velocity for the load factor developed. It shall be assumed that the elevator is deflected at a very slow rate so that no pitching acceleration will occur. In addition, at the limits of the envelope shown in figure 5-4, the pitching acceleration shall be the maximum attainable with the control system and in a direction that reduces the load factor. Balance shall be established between aerodynamic and inertial forces.

Except where vehicle design or the maximum static lift coefficient makes it impossible to exceed a lower value, the envelope shall be defined as follows:

- The positive limit-maneuvering load factor for any speed up to V_L may not be less than 2.5.
- The negative limit-maneuvering load factor may not be less than 1.0 at speeds up to V_H and must vary linearly with speed from the value at V_H to 0 at V_L.
- For a symmetrical maneuver with pitch, the vehicle shall be in the basic and landing configurations. The maneuver shall be based on a rational pitching-control-motion-versus-time profile.

Initially, the vehicle shall be in steady unaccelerated flight at the specified airspeed and fully trimmed, for zero control forces. The airspeed shall be constant until the specified load factor has been attained. The load factors to be obtained shall be all values on and within the envelope illustrated in figure 5-4. The load factor at each airspeed shall be obtained as indicated below for all center-of-gravity positions:

- By a control movement resulting in a triangular displacement-time curve, as illustrated by the solid heavy lines of figure 5-5(a), provided that the specified load factor can be attained by such control

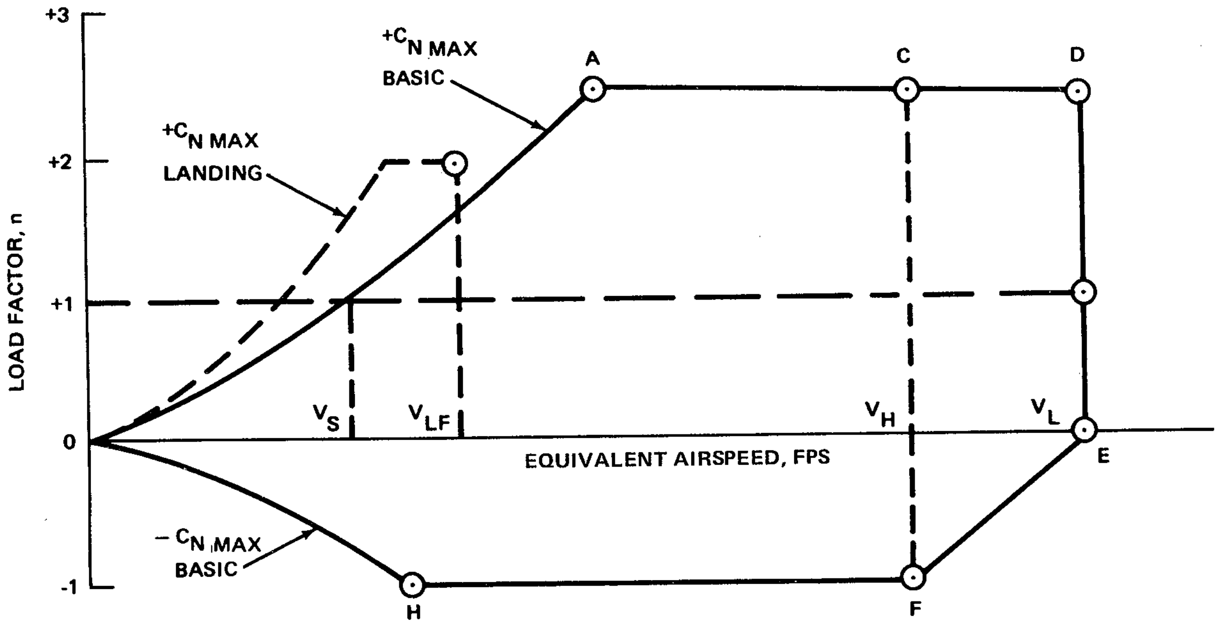
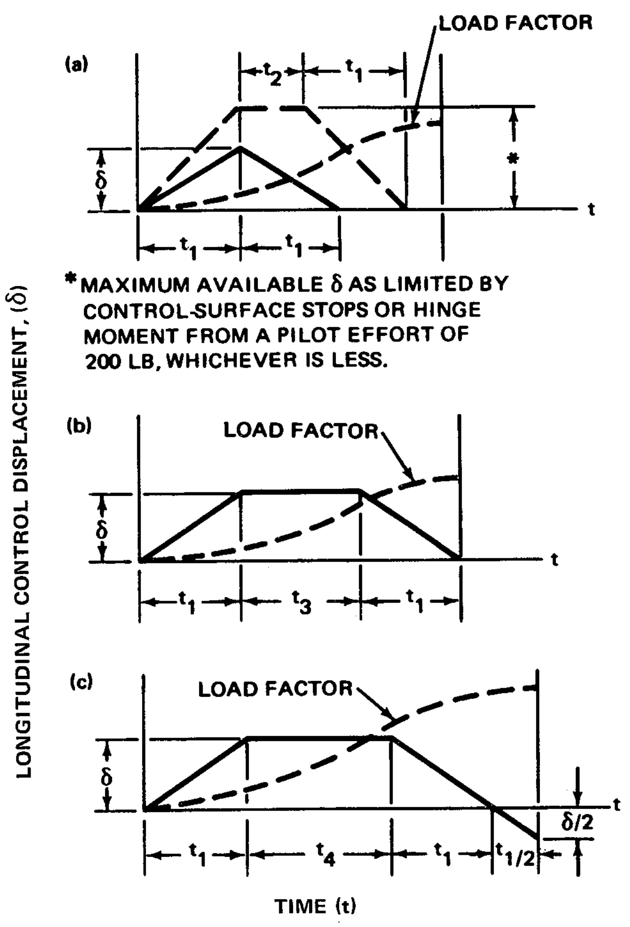


FIGURE 5-4 SYMMETRICAL MANEUVER ENVELOPE



*MAXIMUM AVAILABLE δ AS LIMITED BY CONTROL-SURFACE STOPS OR HINGE MOMENT FROM A PILOT EFFORT OF 200 LB, WHICHEVER IS LESS.

FIGURE 5-5 **LONGITUDINAL CONTROL DISPLACEMENT–TIME DIAGRAM**

movement; otherwise, by the ramp-style control movement illustrated by the dashed straight lines of this figure. The time t_1 is specified as 0.4 sec for the ramp-type control movement; the time t_2 shall be the minimum time required to attain the specified load factor while the control surface is held at the stops.

- By a control movement resulting in a ramp-type displacement-time curve, as illustrated by the solid heavy lines of figure 5-5(b). The time t_1 is specified as 0.4 sec. The time t_3 and the control displacement δ shall be sufficient to attain the specified load factor in time $2t_1 + t_3$.

- In addition, for maximum aft center-of-gravity position, the load factor shall be obtained by a control movement resulting in a ramp-type displacement-time curve, as illustrated by the solid heavy lines of figure 5-5(c). The time t_1 is specified as 0.4 sec. The time t_4 and the control displacement δ and $-\delta/2$ shall be sufficient to attain the specified load factor at the same time as $-\delta/2$ is attained.

For a symmetrical maneuver with the vehicle in the landing-approach configuration, the vehicle shall be at the limit speed, V_{LF}, and the load factors shall be all values from 0 to 2.0. Balanced and symmetrical maneuvers with pitch conditions shall be applied. The longitudinal control displacement shall be the same as indicated for the basic and landing configurations.

5.2.10.1.2 UNSYMMETRICAL FLIGHT MANEUVERS

For rolling pull-out, it shall be assumed that the vehicle is in the basic and landing configurations. The airspeeds shall be all airspeeds up to V_L and the directional control shall be held in a fixed position for trim in wings-level flight without rudder-control force and displaced as necessary to prevent sideslip. Cockpit lateral control shall be displaced to the maximum position, and the control force shall be applied for not more than 0.3 sec. The control force shall be maintained until the required change in angle of bank is attained, except that, if the roll rate would exceed a specified value, the control position may be reduced to produce the specified roll rate after the maximum rolling acceleration is attained. The maneuver shall be checked by application of the maximum displacement in not more than 0.3 sec.

For accelerated roll, it shall be assumed that the vehicle is in the basic and landing configurations. The airspeed shall be all airspeeds up to V_L and the initial load factor shall be all positive values between 0.8 and 1.0 of the maximum values in the maneuver envelope shown in figure 5-4. Initially, the vehicle shall be in a steady, constant-altitude turn at an angle of bank to attain the load factor at the specified airspeed. The vehicle shall roll out of the turn through an angle of bank equal to twice the initial angle. Constant airspeed and constant cockpit longitudinal-control position shall be maintained.

For roll in takeoff and landing configurations, the airspeed shall be V_{LF} in the landing-approach configuration. The load factor shall be unity. The lateral control shall be displaced in accordance with the rolling pull-out, and the roll need not be carried beyond a 60-degree angle of bank.

For sideslips and yawing, lateral control shall be displaced to maintain the wings in a level attitude, except that for high-speed rudder-kick conditions, an angle of bank of not more than 5 degrees shall be maintained.

The minimum speeds shall be the minimum speeds at which the angle of bank can be maintained. For all of the following conditions except one-engine-out operation, the normal load factor shall be unity:

1. Unsymmetrical thrust without sideslip. The critical engine shall not be operating and the vehicle shall be in the minimum drag configuration. All other engines shall deliver takeoff thrust or power. The vehicle shall be in the takeoff and landing configurations at V_{LF} and in the basic and high-drag landing configurations at the maximum flight speed obtainable with operating engines.

2. Engine failure. The vehicle shall be in the basic configuration. The airspeeds shall be all speeds from the approved minimum takeoff speed for the one-engine-out condition to V_H. The critical engine shall suddenly fail.

   If reverse thrust is possible because of automatic features, the failed engine shall deliver reverse thrust. All other engines shall then deliver normal-rated power or thrust, except that takeoff power or thrust is applicable at speeds up to 2 V_{SL}. Automatic decoupling or thrust-control devices shall be operating and alternately not operating. With these devices operating, the structure shall exhibit limit strength.

   The directional control shall:

   A. Be held in the neutral position until maximum sideslip is attained.
   B. Be moved to the position attainable with maximum rudder deflection.

3. Steady sideslip. The vehicle shall be in the basic and landing configurations. The airspeed shall be all speeds up to V_L. Rudder control shall be applied slowly to a maximum position.

4. Low-speed rudder kick. The vehicle shall be in the takeoff and landing configurations at speeds up to V_{LF}. The cockpit directional control shall be displaced to a maximum position in not more than 0.3 sec. (The maximum attainable displacement may be limited by stops, or by the capacity of the power-control system, or by a specified directional control force.) The displacement shall be maintained until the maximum overswing angle of sideslip is attained and the vehicle reaches a steady sideslip. Recovery shall be made by reducing the directional control to a 0-degree displacement angle in not more than 0.3 sec.

5. High-speed rudder kick. The vehicle shall be in the basic and landing configurations at speeds up to V_H. The cockpit directional control force shall be applied in not more than 0.2 sec. Recovery shall be made by reducing the directional control to a 0-degree displacement angle in not more than 0.3 sec.

6. One-engine-out. Sudden stopping of an engine at all speeds above the approved minimum takeoff speed for one-engine-out operation up to V_H shall not result in unacceptable vehicle motions or vibrations within this speed range. The limit loads on the vehicle shall not be exceeded in a symmetrical pullout to a load factor of 2.0, with each engine, one at a time, inoperative and all other engines delivering normal-rated power or thrust.

These criteria should not be used to impair flightworthiness or power-plant-installation requirements for one-engine-out operation, and should be reexamined after simulation studies are made.

5.2.10.1.3 GUSTS

Loads for at least the following gust conditions shall be accounted for: (1) symmetrical vertical gusts in level flight, (2) lateral gusts, and (3) continuous turbulence gusts.

5.2.10.1.3.1 Symmetrical Vertical

For symmetrical vertical gusts in level flight, the vehicle shall be in the basic flight and landing configurations.

The symmetrical gust envelope, illustrated in figure 5-6, shall be prepared in the following manner:

1. **Velocities shall be as specified in table 5-6 except that at altitudes greater than 20 000 ft, the specified equivalent gust velocity, U_{de}, shall be multiplied by the factors $\sqrt{\sigma_h}/\sqrt{\sigma_r}$, where σ_h is density at a given altitude and σ_r is density at 20 000-ft altitude.**

   If flaps are utilized in landing, the vehicle shall be assumed to encounter a head-on gust of 25 fps at V_{LF}.

2. **To calculate the gust load factor, the following assumptions shall be made: the shape of the gust is**

$$U = \frac{U_{de}}{2}\left(1 - \cos\frac{2\pi s}{\lambda}\right)$$

where

U = gust velocity, fps

U_{de} = derived gust velocity, fps

s = distance penetrated into gust, ft

λ = wavelength of gust that tunes lowest elastic mode of vehicle at the velocity of interest, ft

TABLE 5-6 **VELOCITIES FOR SYMMETRICAL VERTICAL GUSTS**

POINTS	CONFIGURATION	AIR SPEED (EAS)	GUST VELOCITY (EAS)
B ' and G'	Basic	V_G	U_{de} = 66 fps
C' and F'	Basic	V_H	U_{de} = 50 fps
D' and E'	Basic	V_L	U_{de} = 25 fps
I' and J'	Landing	V_{LF}	U_{de} = 50 fps

Gust load factors vary linearly between points B′ through G′, as shown in the gust envelope in figure 5-6.

3. **In the absence of a more rational analysis, the gust load factors shall be computed as follows:**

$$n = 1 + \frac{K_g U_{de} V_a}{498\ (W/S)}$$

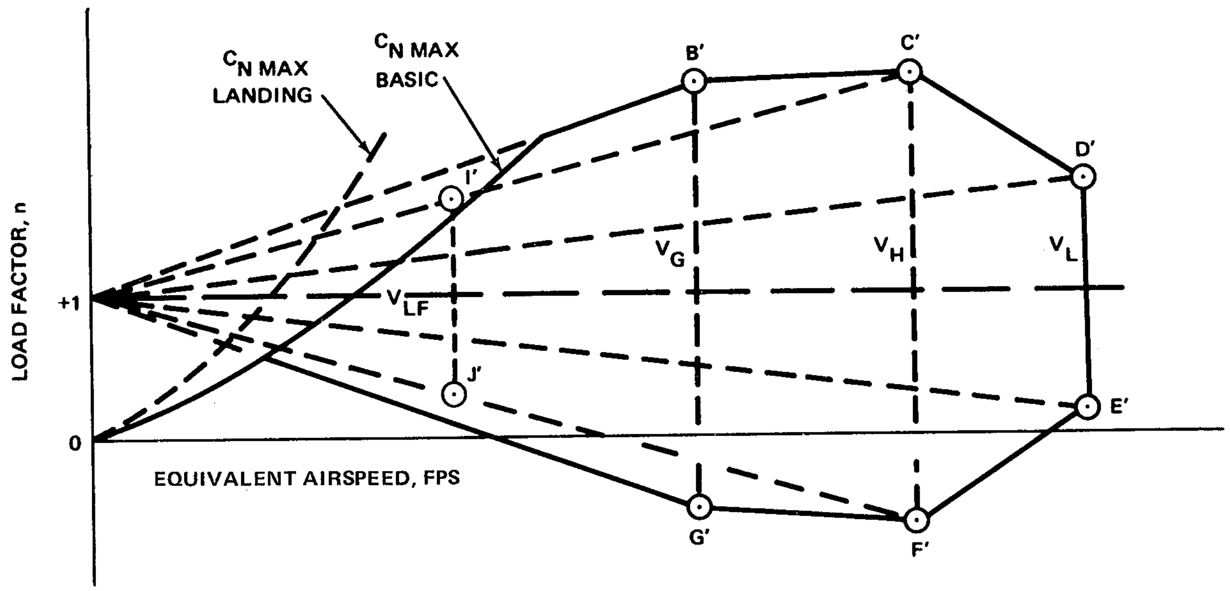


FIGURE 5-6 **SYMMETRICAL GUST ENVELOPE**

where

$$K_g = \frac{0.88\,\mu_g}{5.3 + \mu_g} = \text{gust alleviation factor}$$

$$\mu_g = \frac{2(W/S)}{\rho\, a\, \bar{C}\, g}$$

W/S = wing loading, psf

ρ = density of air, slugs/ft^3

g = acceleration due to gravity, fps^2

V = vehicle equivalent speed, knots

$\bar{C}$ = mean geometric chord of wing, ft

a = slope of the vehicle normal-force coefficient curve C_{N_A} per radian if the gust loads are applied to the wings and horizontal tail surfaces simultaneously by a rational method. (The wing-lift-curve-slope C_L per radian may be used when the gust load is applied to the wings only and the horizontal tail gust loads are treated separately.)

5.2.10.1.3.2 Lateral

The analysis shall consider that the vehicle encounters lateral gusts normal to the plane of symmetry while in unaccelerated wings-level flight (1) with all engines operating, (2) with all engines not operating, and (3) in a wings-level steady sideslip with the critical engine not operating. The derived gusts and vehicle airspeeds corresponding to conditions B′ through J′ (figure 5-6), as defined for symmetrical gusts, shall be investigated. The gust shape shall also be as specified for symmetrical gusts. If an adequate analysis of the vehicle response to a gust cannot be made, the gust loading on the vertical tail surfaces shall be computed as follows:

$$L = \frac{K_g\, U_{de}\, VaS}{498}$$

where

L = vertical tail load, lb

S = area of vertical tail, ft^2

and all other symbols are as defined for symmetrical gusts.

5.2.10.1.3.3 Continuous Turbulence

For continuous turbulence gusts, the gust-loads spectra shall be established using the normalized power spectra of atmospheric turbulence and the procedures defined in Section 5.3 of NASA TM X-64589. The vehicle structure shall be designed for a 1 percent or lower risk of exceeding limit loads during the expected time of atmospheric flight. The analysis shall include at least the dynamic response in the rigid-body modes of pitch and translation. The dynamic response of the elastic modes shall also be analyzed, as appropriate, and the analysis shall include interaction of the elastic body and the control system.

For information on winds and gusts, see Section 6.1.

5.2.10.1.4 MANEUVER AND GUST

Maneuver and gust envelopes shall be defined for at least the transition- and cruise-flight regimes and for landing. For transition flight, three envelopes shall be developed, one each at maximum transition altitude, midtransition altitude, and minimum transition altitude. The maximum normal load factor shall be derived from simulator studies of the transition maneuver.

Prior to completion of these studies, the normal load factor of 2.5 for the standard transport airplane (figure 5-4, line A-D) may be used.

For cruise flight, three envelopes shall be developed, one each at maximum cruise altitude, ideal cruise altitude, and sea level. The maximum normal load factor shall be 2.5 unless the vehicle has design features that make it impossible to exceed a lower value.

For landing, two envelopes shall be developed, one at sea level and one at 5 000-ft altitude.

A sufficient number of points on the maneuver and gust envelopes shall be investigated to ensure that the maximum load is obtained for each part of the vehicle structure.

A conservative combined envelope may be used.

The design loads and loading distributions shall include the significant forces acting on the vehicle and the effect of pitching velocities in turns and pull-ups. The forces shall be placed in equilibrium in a rational or conservative manner. The linear and angular inertial forces shall be in equilibrium with the externally applied aerodynamic forces and moments.

5.2.10.1.5 ENGINES

All engine-operating conditions from zero to maximum thrust and rpm values, including gyroscopic loads associated with maneuvers and gusts, shall be accounted for.

A limit lateral load factor shall be used which is at least equal to the maximum load factor obtained in the yawing conditions, but not less than 1.33.

The 1.33-limit lateral factor may be assumed to be independent of other flight conditions.

A limit torque load imposed by an abrupt engine shutdown from compressor jamming or other malfunction, or structural failure shall be accounted for.

5.2.10.1.6 DECELERATORS

Loads from the stowage and deployment of aerodynamic decelerators shall be accounted for. An analysis shall be performed accounting for the effects of deployment altitude, deployment rate, heating and heating rate, and dynamic loads. The analysis shall use the maximum dispersed velocity and altitude at initiation of recovery, and the vehicle weight, center of gravity, and tolerances at that time.

For recommended practices, refer to NASA SP-8066.

5.2.10.1.7 HORIZONTAL AND VERTICAL TAILS

The air loads on the horizontal tail shall be distributed symmetrically and unsymmetrically, in combination with the specified maneuver and gust conditions. In addition, the horizontal tail loads shall be distributed as follows: 100 percent of the maximum load intensity from the symmetrical flight conditions acting on one side of the plane of symmetry and 80 percent of this load intensity acting on the other side. The air loads on the vertical tail or tails resulting from unsymmetrical maneuvers and lateral gusts shall be determined.

5.2.10.1.8 PILOT-APPLIED LOADS

Pilot-applied loads (table 5-7) shall apply to manual, manual-backup, and manually reversible cockpit control systems having a conventional aircraft stick or wheel and rudder pedals. Other cockpit control systems shall be designed to a rationally determined set of control loads.

Dual Control Systems. For vehicles with dual control systems, 75 percent of the pilot-applied loads shall be applied simultaneously at both control stations.

Duplicate Control Systems. For vehicles with duplicate control systems, 100 percent of the pilot-applied loads shall be applied to each system, assuming the other system to be disconnected.

Powered Control Systems. For vehicles with powered control systems, the power system shall be considered as both operative and inoperative. For redundant systems, a single system shall be considered inoperative.

Reactions. Forces reacting to the pilot-applied loads shall be provided by:

- Control-system stops only.
- Control-system locks only.
- Components specifically designed to react to pilot-applied loads.
- Irreversible mechanism only, locked and with the control surface in all possible positions.
- Attachment of the longitudinal, lateral, and directional control systems to their control-surface horns when the corresponding cockpit controls are in all possible positions. Each control system shall act separately.

5.2.10.2 MASS PROPERTIES

The mass properties to be used for atmospheric flight conditions shall include all practical arrangements of movable items and all gross weights at the following configurations and all lower weights down to and including the minimum flying gross weight at which critical loads are achieved:

- Minimum flying
- Basic flight (atmospheric)
- Maximum flight (atmospheric)
- Basic landing (atmospheric)
- Maximum ferry and training flight
- Ferry and training-flight landing.

5.2.10.2.1 MINIMUM FLYING

The minimum flying gross weight shall include an allowance for:

- Minimum crew
- 5 percent of cruise-engine fuel

TABLE 5-7 **PILOT-APPLIED LOADS**

AIRPLANE CONTROL	COCKPIT CONTROL	NUMBER OF FORCES	MAGNITUDE OF EACH FORCE (LBF)	POINT OF APPLICATION	DIRECTION
Lateral	Stick	1	100	Top of stick grip	A lateral force perpendicular to a straight line joining the top of the stick grip and the pivot point
	Wheel	2	80	One force at any point on circumference of wheel, other force at diametrically opposite point	Each force tangent to wheel rim acting in the same rational direction
		1	100	On circumference of wheel	Tangent to wheel rim in plane of wheel
Longitudinal	Stick	1	250	Top of stick grip	A longitudinal force perpendicular to a straight line joining the top of the stick grip and the pivot point
	Wheel	2	150	One force at any point on circumference of wheel, other force at diametrically opposite point	Each force in same direction perpendicular to the plane of the wheel
		1	100	Any point on circumference of wheel	Perpendicular to the plane of the wheel
Directional	Rudder pedal	1	300	Point of contact of foot with pedal	Parallel to the projection on the airplane plane of symmetry of a line connecting the point of application and the pilot's hip joint, with the pilot's seat in its mean flying position
		2	300	Each force at point of contact of foot with each pedal	Each force in same direction parallel to the projection on the airplane plane of symmetry of a line connecting the point of application and pilot's hip joint, with the pilot's seat in its mean flying position
Brake	Brake pedal	1	300	Tip of pedal	Parallel to the projection on the airplane plane of symmetry of a line connecting the point of application and the pilot's hip joint, with the pilot's seat in its mean landing position
		2	300	Tip of pedal	Each force in same direction parallel to the projection on the airplane plane of symmetry of a line connecting the point of application and the pilot's hip joint, with the pilot's seat in its mean landing position
Flap, tab, stabilizer, spoiler, alighting gear, arresting hook, and wing-folding operating controls	Crank, wheel, or lever operated by push or pull force	1	$\left(1 + \frac{R}{3}\right) 50$ but not less than 50 nor more than 150 (R = radius in inches)	Circumference of wheel or grip of crank or lever	Any angle within 20 deg of plane of control
	Small wheel or knob	133 in.-lb if operated only by twisting 100 lb if operated only by push or pull			

- **Oil consistent with 5 percent fuel**
- **Hydraulic fluids**
- **Ballast.**

For flying qualities, flutter-and-divergence prevention, and vibration analyses, no fuel shall be assumed. No other useful load items shall be assumed.

5.2.10.2.2 BASIC FLIGHT (ATMOSPHERIC)

The basic flight gross weight (atmospheric) shall include an allowance for:

- **Full crew**
- **Full load of cruise-engine fuel and oil**
- **Maximum return payload**
- **Full load of auxiliary power fuel and fluids in other systems**
- **Any propellant remaining in the primary propulsion system or other expendables**
- **40 percent of the propellant remaining for attitude control.**

The basic flight weight is applicable to flight-loads computations, to flutter-and-divergence prevention, and to vibration analyses.

5.2.10.2.3 MAXIMUM FLIGHT (ATMOSPHERIC)

The allowance for maximum flight gross weight (atmospheric) shall be identical to the allowance for basic flight except that the propellant for attitude control shall be increased to 100 percent.

The maximum flight gross-weight allowance is applicable to taxiing, towing, ground handling, jacking, flutter-and-divergence prevention, and vibration analyses.

5.2.10.2.4 BASIC LANDING (ATMOSPHERIC)

The allowance for basic landing gross weight (atmospheric) shall be the basic flight allowance minus 50 percent of the cruise-engine fuel.

This weight allowance is applicable to orbiter landings after entry, return from an aborted mission, and taxiing and ground handling after landing.

5.2.10.2.5 MAXIMUM FERRY AND TRAINING FLIGHT

The maximum ferry and training flight gross weight shall include an allowance for:

- **Full crew**
- **Full load of cruise-engine fuel and oil, including auxiliary tanks**
- **Full load of auxiliary power-system fuel and fluids in other systems**
- **Auxiliary propulsion-system modules and ballast, if any.**

No weight reduction shall be permitted for fuel used during taxi, warmup, or climb-out.

The weight allowance for maximum ferry and training flight is applicable to taxiing and ground handling, takeoff, flight, flutter-and-divergence prevention, and vibration analyses.

5.2.10.2.6 FERRY AND TRAINING-FLIGHT LANDING

The weight allowance for ferry and training-flight landings shall be the maximum ferry and training-flight gross weight minus 50 percent of the cruise-engine fuel and oil.

5.2.11 LANDING AND HORIZONTAL TAKEOFF

All loads and environments imposed during landing and horizontal takeoff, including taxiing, braking, and takeoff run shall be accounted for. The residual effects of loads and environments in atmospheric, entry, and space flight shall be accounted for, including: (1) load redistribution due to thermally induced deformations; (2) reduced material allowables; (3) changes in vibration modes and frequencies; (4) changes in oleo strut characteristics; and (5) changes in tire characteristics.

5.2.11.1 LANDING LOADS

The range of expected landing velocities and their distribution shall include provision for clearing a 50-ft obstacle with power off.

At least the following landing loads shall be accounted for:

- **Maximum spin-up load and maximum spring-back load, each in combination with the vertical load occurring simultaneously. Dynamic analyses shall be made to obtain the combined loads. The spin-up and spring-back loads shall be the loads developed when** the sliding friction between the vehicle and landing surface equals 0.55 or any lower values that are critical. The touchdown speeds shall be all values from V_{SPA} to 1.3 V_{SPA}, but not less than 1.2 V_{SL}.

- Maximum vertical load, in combination with the drag load occurring at the instant of maximum vertical load. The drag load shall not be less than one-quarter of the maximum vertical load. Aerodynamic lift, acting through the vehicle's center of gravity and not exceeding the vehicle weight, may be assumed to exist during the initial landing impact.

5.2.11.1.1 SYMMETRICAL

Limit loads shall be determined for the weights of the basic landing configuration, the maximum flight gross weight configuration for taxiing, and for the following symmetrical landing attitudes at the design sink speed:

- Three-point landing, where the vehicle design permits the main wheels and nose wheels to contact the ground simultaneously.
- Two-point landing, where the main wheels are in contact with the ground at the lowest possible pitch angle, with the nose wheel clear and not carrying load throughout the landing impact.
- Tail-down landing, where the vehicle is assumed to be in an attitude corresponding to either the stalling angle or the maximum angle that allows each part of the vehicle except the main wheels to clear the ground, whichever is less. If the vehicle is equipped with a tail bumper, the tail bumper shall be completely compressed and in contact with the ground, but with no load imposed on the vehicle.
- Nose-gear impact loads shall be determined from analysis of the vehicle motion during a landing in the tail-down attitude, with appropriate applications of brake and nose-down pitch control.

5.2.11.1.2 UNSYMMETRICAL

Limit loads for unsymmetrical landing conditions shall include the effects of the vehicle motion in specified crosswind and landing velocities. Experience indicates the yaw attitude should be for a zero sideslip with a 5-degree roll attitude and a pitch attitude for a 1.1-g flare at a mean sink speed of 5 fps and a mean horizontal touchdown speed of 1.1 V_{SPA}.

Limit loads shall be determined for at least the unsymmetrical drift and one-wheel landing conditions. In drift landing, the vehicle shall be in the two-point symmetrical landing attitude and (1) the vertical reaction at each main gear shall be half of the maximum value defined for two-point symmetrical landing conditions; (2) the lateral load at one main gear shall consist of an inward-acting load 0.8 times the vertical reaction at that gear; (3) the lateral load at the other main gear shall consist of an outward-acting load 0.6 times the vertical reaction at that gear; (4) no drag load shall be applied; and (5) all external loads shall be considered to act simultaneously at the point of contact with the ground and to be balanced by vehicle inertia.

In one-wheel landing, the vehicle shall be in the symmetrical two-point and tail-down landing attitudes and (1) the loads shall be applied alternately to each main landing gear with the drag and lateral loads equal to zero; (2) with no load on the opposite main gear; and (3) all external loads shall be considered to act simultaneously at the point of contact with the ground and to be balanced by vehicle inertia.

5.2.11.2 TAXIING AND BRAKING LOADS

Loads from taxiing and braking, as well as loads from all ground operations where the vehicle is operating independently under its own power, shall be accounted for. The vehicle shall be at its maximum flight gross weight (atmospheric). For the braking conditions, the landing gear and tires shall be in their static positions.

In straight taxi, the vehicle shall be in the three-point attitude. No drag loads or lateral loads shall be applied, and the limit vertical-load factor shall be 2.0.

In turning, the vehicle shall be in the three-point attitude and shall execute steady turns by means of differential power or nose-gear steering. The vertical load factor at the center of gravity shall be 1.0; at the ground, lateral loads shall be applied so that the resultant of the vertical and side loads passes through the center of gravity. The same ratio of lateral-load to vertical-load components shall be applied to all gears; and the sum of the lateral loads shall be one half the vehicle weight, except that the side loads need not exceed a value which would result in overturning.

In pivoting, the vehicle shall be in the three-point attitude, the vertical load factor at the center of gravity shall be 1.0, and the tire coefficient of friction shall be 0.8. With brakes locked on the wheels of one gear about which the vehicle is rotating, the vehicle shall pivot about the centroid of the contact area of all wheels in the gear.

In two-point and three-point braked rolls, the vertical load factor acting at the center of gravity shall be 1.2 at the landing configuration gross weight and 1.0 at the maximum flight configuration gross weight. A drag reaction at each brake-equipped wheel on the ground shall be assumed to act at the point of contact with the ground at a magnitude of 0.8 of the vertical reaction and shall be combined with the vertical reaction.

In unsymmetrical braking, the vehicle shall be in the three-point attitude and the vertical load factor at the center of gravity shall be 1.0. One main gear shall be assumed to be braked and developing a drag load at the ground equal to 0.8 of the vertical reaction at that gear. The vehicle shall be placed in static equilibrium, with lateral loads at the main and nose gears reacting to the yawing moment, and with vertical loads at the main and nose gears reacting to the pitching moment. The forward-acting load at the center of gravity shall be 0.8 of the vertical reaction of the braked main gear. No lateral load shall act at the center of gravity, and the lateral load at the nose gear shall be acting at the point of contact with the ground and its magnitude need not exceed 0.8 of the vertical reaction. The nose gear shall be aligned in a fore-and-aft direction.

In reverse braking, the vehicle shall be in a two-point attitude and supported by the main gear, the vertical load factor at the center of gravity shall be 1.0, and a forward-acting drag reaction at the point of contact with the ground which is equal to 0.8 of the vertical reaction shall be combined with the vertical reaction for each brake-equipped gear.

5.2.11.3 TAKEOFF RUN AND ROTATION LOADS

For the takeoff run, the vehicle shall be in the three-point attitude. A dynamic analysis shall be performed using the runway profiles specified in Section 5.2.11.4 to obtain vehicle loads. The landing-gear drag loads due to discrete runway profile shapes shall be included in the analysis, but the drag loads due to friction shall be omitted. The analysis shall be conducted for at least three gross-weight conditions including the maximum takeoff gross weight and the most critical center-of-gravity location.

The dynamic analysis should include a minimum of six degrees of freedom for the flexible vehicle in addition to the landing-gear degrees of freedom.

The changes in landing-gear loads due to rotation, starting with the vehicle leaving the runway in a three-point attitude and ending when the climb angle is achieved, shall be accounted for in vehicle design.

5.2.11.4 RUNWAY AND TAXIWAY ROUGHNESS

A model for runway and taxiway roughness shall be specified for use in evaluation of ground loads.

5.2.11.5 SUPPLEMENTARY LOADS

In addition to the loads imposed on landing-gear assemblies by landing, taxiing, and braking, at least the following loads shall be accounted for:

Rebound Loads. **With the landing gear fully extended and not in contact with the ground, a rebound-load factor of –20.0 shall be assumed to act on the unsprung weight of the landing gear along the line of motion of the strut as it approaches the fully extended position.**

Extension and Retraction Loads. **With the landing gear in each critical position between fully extended and fully retracted, the loads shall consist of (1) aerodynamic loads up to the limit speed specified for the takeoff and landing configurations; (2) inertia loads corresponding to the maximum and minimum symmetrical limit-load factors specified for flight in the takeoff and landing configurations; (3) inertia loads resulting from maximum-powered accelerations of the landing-gear components that move during extension or retraction; and (4) gyroscopic loads resulting from wheels rotating at a peripheral speed of 1.3 times the stalling speed in the takeoff configuration while the wheels are retracting or extending at the maximum rate attainable.**

Loads from Braking Wheels in Air. **For the vehicle flying in the takeoff configuration with the landing gear in any position, the vertical load factor shall be 1.0. The airspeed and wheel peripheral speed shall be 1.3 times the stalling speed in the takeoff configuration. The maximum static braking torque shall be applied instantaneously to stop the wheel rotation.**

Tail Bumper Loads. **A dynamic analysis of motion shall be performed, considering: (1) that the vehicle rolls backward at 5 mph at zero ground slope and the**

maximum braking load based on a tire-to-ground coefficient of friction of 0.8 is suddenly applied; and (2) that for landings, the vehicle shall be in a tail-down attitude at touchdown with the main gear and bumper contacting the ground simultaneously.

5.2.11.6 LOAD DISTRIBUTION ON MULTIPLE WHEELS

The following load distributions for landing gears with two wheels per unit shall be evaluated. A rational approach shall be used for landing-gear configurations having more than two wheels per unit.

For Symmetrical Distributions, **the wheel loads shall be equally distributed at the wheels of each landing-gear unit.**

For Unequal Tire Inflation, **the wheel loads shall be distributed so that 60 percent are on one wheel and 40 percent on the other wheel, except in drift and turning conditions, when this distribution is not applicable.**

For Flat-Tire Landing, **the wheel loads resulting from landing, reduced to 60 percent of the limit load, shall be applied to each wheel separately.**

For Flat-Tire Taxiing, **the wheel loads resulting from taxiing, reduced to 50 percent of the limit load, shall be applied to each wheel separately.**

For Flat-Tire Towing, **the wheel loads resulting from towing shall be applied to each wheel separately.**

5.2.11.7 MASS PROPERTIES

The mass properties to be used for landing and horizontal takeoff conditions shall include all practical arrangements of movable items and all gross weights of the following configurations and all lower weights down to and including the minimum flying gross weight at which critical loads are achieved:

- **Minimum flying**
- **Basic flight (atmospheric)**
- **Maximum flight (atmospheric)**
- **Basic landing (atmospheric)**
- **Maximum ferry and training flight**
- **Ferry and training-flight landing.**

5.2.12 EMERGENCY CONDITIONS

Loads resulting from emergency conditions, including malfunction, abort, crash, and ditching, shall be accounted for.

5.2.12.1 MALFUNCTION

The transient conditions resulting from a malfunction shall be analyzed as a single event.

The analysis required for malfunction conditions should be conducted in conjunction with development of the malfunction-detection system, the malfunction-correction system, and the abort-initiation system. Based on the structural design requirements and the analysis of probabilities associated with malfunctions, the allowable bounds of the parameters defining the malfunction condition and the related time limits should be established. For cases where system performance is incompatible with the time limits, data relative to the tradeoff between mission degradation due to added weight and increased risk should be assembled to facilitate a choice.

5.2.12.2 ABORT

The transient conditions resulting from abort shall be analyzed as a single event, considering probabilities of occurrence of all loadings and environmental parameters and allowable risk for abort.

The analysis required for abort conditions, conducted in conjunction with development of the abort system and procedures, should include the following:

- Transient conditions resulting from emergency staging and separation of the vehicle stages at any time after liftoff or from another space vehicle.
- Effects of emergency systems and procedures, such as auxiliary propulsion or propellant dumping, developed to facilitate return of the vehicle to a stable cruise-flight condition.
- Initial transient and subsequent flight conditions for personnel-escape systems, such as ejection seats or escape pods.

All structural weight penalties imposed by abort conditions should be identified and submitted to NASA for approval.

5.2.12.3 CRASH

The ultimate crash load factors relative to body axes indicated in table 5-8 shall be used in design of structure whose failure could result in injury to occupants during a crash or prevent egress from a crashed vehicle.

The specified load factors are in the direction of the acceleration. Plus refers to forward, down, or right. The longitudinal load factor should be directed forward within a 20-degree semiangle cone whose axis is the vehicle's longitudinal axis.

It shall be assumed that the fuel tanks contain the cruise fuel which remains after half the internal cruise fuel has been expended in the normal manner. The boost or orbit-injection fuel shall not be included.

See Section 4.9.5 for additional information on crashworthiness.

5.2.12.4 DITCHING

The design shall minimize the probability that in an emergency landing on water, the behavior of the vehicle would cause immediate injury to the occupants or would make it impossible for them to escape.

The probable behavior of the shuttle in a water landing should be investigated by model tests or by comparison with airplanes of similar configuration for which the ditching characteristics are known. It must be shown that under probable water conditions, the flotation and trim of the vehicle will allow the occupants to leave it.

See Section 4.9.5 for additional information on ditching.

5.2.13 BOOST-STAGE LANDING AND RECOVERY

All static and dynamic loads and pressures acting on the boost stages which result from staging and from the post-staging trajectory, deployment of aerodynamic decelerators, landing and towing in water, and recovery shall be accounted for.

5.2.13.1 STAGING

The following additional sources of loads imposed on the boost stages during staging shall be accounted for: separation or actuation devices, exhaust-plume impingement, the flight control system, and vehicle-separation dynamics.

For recommended practices, refer to NASA SP-8022, SP-8030, and SP-8056.

5.2.13.2 POSTSTAGING ENTRY FLIGHT

All static and dynamic loads and pressures occurring during poststaging entry flight shall be accounted for. Heat transfer from engines and external flow fields shall be included in evaluation of the structural temperatures and thermal stresses.

5.2.13.3 AERODYNAMIC DECELERATOR DEPLOYMENT LOADS

Loads from the stowage and deployment of aerodynamic decelerators shall be accounted for. An analysis shall be performed accounting for the effects of deployment altitude, deployment rate, heating and heating rate, and dynamic loads. The analysis shall use the maximum dispersed velocity and altitude at initiation of recovery, and the weight, center of gravity, and tolerances at that time.

TABLE 5-8 **CRASH LOAD FACTORS**

AREA	LONGITUDINAL	VERTICAL	LATERAL
Crew and passenger compartments	+20	±10	±3
Cargo and equipment areas	+10	+5	–
Large mass equipment-support structure	+9 –1.5	–2.0 +4.5	+1.5 –1.5

For recommended practices, refer to NASA SP-8066.

5.2.13.4 WATER IMPACT LOADS

Limit static and dynamic loads and load spectra shall be determined analytically or experimentally for the boost stage for a sink speed of 150 fps, for an impact attitude of 20 degrees ± 10 degrees with respect to vertical, and for sea state Code 5.

Peak circumferential pressure distributions on the boost stages shall be based on experimental data and special structure such as a crushable shell shall be provided to accommodate local peak pressures of high intensity occurring for very short times.

For additional information, see the Addendum to NASA TM X-64589.

5.2.13.5 WATER TOWING LOADS

Limit static and dynamic loads and load spectra shall be determined for towing based on experimental pressure data for sea state Code 3 and for a 7-knot tow speed.

Limit static and dynamic loads and load spectra shall be obtained experimentally during wave slap in sea state Code 5.

Wave slap consists of wave pressures on the vehicle while it is floating in the water.

5.2.13.6 RECOVERY LOADS

Loads resulting from recovery of the boost stages from the water shall be accounted for in design. Stage weight shall be no greater than the weight required to withstand flight loads, insofar as practicable. Stage weight shall be prevented from increasing by changing the design, or the operation of the ground support recovery equipment, or both. (See Addendum to NASA TM X-64589.)

6. NATURAL ENVIRONMENTS

This section identifies the basic natural environments that must be accounted for in space shuttle design. These environments can be found in Appendix E of the NASA Space Shuttle Program Request for Proposal (No. 9-BC421-67-2-408), NASA TM X-64589, and NASA TM X-64627. The latter two documents and their addenda should be referred to for design values of natural environment parameters not presented in this section.

Where the criteria in this section are dependent on a specific launch site or landing site, they have been based on the Eastern Test Range, unless otherwise indicated. The criteria assume the space shuttle will avoid flight in thunderstorms.

6.1 WINDS DURING LIFE PHASES

The wind environment defined in NASA TM X-64589 shall be used for the space shuttle.

6.1.1 PRELAUNCH

All ground wind environments shall be as defined in Section 5.2 of NASA TM X-64589. In particular, the following environments shall be used: (1) peak wind speed for exposure periods and percentiles of wind exceedance and variation with height, (2) gust factors to be applied to the peak design wind speed to obtain mean wind speed, and (3) ground wind turbulence data.

Normal Wind Operations. Operations in normal wind are those that can be satisfied without reducing safety margins or adding special equipment beyond that provided for launch. Normal wind conditions include peak winds up to 17.7 m/sec (34.4 knots) at an altitude of 18.3 m (60 ft) above natural grade with the associated 3σ profile given in table 5.2.2 of NASA TM X-64589.

High Wind Operations. Operations in high wind are those that can be satisfied by reducing safety margins or providing special equipment for high wind conditions. These conditions include all vehicle ground operations in peak winds exceeding 17.7 m/sec at the 18.3-m reference altitude and associated 3σ profile.

For the unfueled vehicle on the launch pad, the peak ground wind speed should be 37.1 m/sec (72.1 knots) from any azimuth at the 18.3-m reference altitude with the associated 3σ profile shape given in table 6-1.

TABLE 6-1 **DESIGN PEAK WIND-SPEED PROFILES FOR A 1% RISK OF EXCEEDING THE 18.3-m REFERENCE LEVEL PEAK WIND SPEED FOR THE WINDIEST TWO-WEEK EXPOSURE PERIOD**

HEIGHT m	(ft)	PEAK WIND SPEED m/sec	(knots)
18.3	(60)	37.1	(72.1)
30.5	(100)	39.1	(76.1)
61.0	(200)	42.1	(81.9)
91.4	(300)	44.0	(85.5)
121.9	(400)	45.4	(88.2)
152.4	(500)	46.5	(90.3)

To calculate peak wind-speed profile values associated with the wind speeds up to 37.1 m/sec at the 18.3-m level, as given in table 6-1, the following equation should be employed:

$$U(h) = U_{18.3}\left(\frac{h}{18.3}\right)^{1.6\,(U_{18.3})^{-3/4}}$$

where

U(h) is the peak wind speed at height **h** in meters above natural grade

and

$U_{18.3}$ is the peak wind speed at the 18.3-m reference altitude in m/sec

Power spectral representations of the turbulent wind environment for elastic-body calculations should employ a 10-min. mean wind-speed profile. This is given in table 6-2.

TABLE 6-2 **10-MIN. MEAN WIND-SPEED PROFILE ASSOCIATED WITH THE 1% RISK PEAK WIND-SPEED PROFILE FOR THE WINDIEST TWO-WEEK EXPOSURE PERIOD**

HEIGHT m	 (ft)	MEAN WIND SPEED m/sec	 (knots)
18.3	(60)	24.7	(47.9)
30.5	(100)	27.2	(53.0)
61.0	(200)	31.0	(60.3)
91.4	(300)	33.3	(64.8)
121.9	(400)	35.1	(68.1)
152.4	(500)	36.4	(70.7)

To calculate values for the 10-min. mean wind-speed profile associated with peak wind speeds up to 37.1 m/sec at the 18.3-m level, the following equation should be used:

$$\bar{U}(h) = U(h)\left[1 + \frac{(18.3/h)^{0.283-0.435e^{-0.2U_{18.3}}}}{1.98 - 1.887e^{-0.2U_{18.3}}}\right]^{-1}$$

where

Ū(h) is the mean wind speed at height **h** in meters

U(h) is the peak wind speed at height **h** in meters

and

$U_{18.3}$ is the peak wind speed at the 18.3-m reference level in m/sec

The spectral ground-wind-turbulence model given in Section 5.2.6 of NASA TM X-64589 should be used to calculate the shuttle's power spectral response to ground winds. In applying this information, a reference height of h_r = 18.3 m and a surface roughness length of z_0 = 0.3 m (1.0 ft) should be used.

For the intermediate and fully fueled space shuttle, the peak wind-speed profile associated with a 1 percent risk of exceeding measured wind values and a windiest one-day exposure should be for 25.2 m/sec (49 knots) at the 18.3-m reference altitude. This profile is given in table 5.2.5 of NASA TM X-64589. The 10-min. mean wind-speed profile (16.7 m/sec or 32.5 knots) at the 18.3-m reference height is given in table 5.2.9 of the same document.

6.1.2 LAUNCH, LANDING, AND HORIZONTAL TAKEOFF

The wind environment for launch, landing, and horizontal takeoff shall be as defined in Section 5.2 of NASA TM X-64589.

The peak ground wind speed at launch release shall be 17.7 m/sec (34.4 knots) from any azimuth at the 18.3-m (60-ft) reference level with the associated 3σ profile shape for a 5 percent risk of exceeding the peak wind speed and windiest one-hour exposure period.

The preceding profile, given in table 5.2.2 of NASA TM X-64589, is recommended for calculations of vehicle drift immediately after launch. The wind shear recommended for calculations of the vehicle overturning moment immediately after launch release should be computed as follows: first, subtract the 10-min. mean wind speed at the height corresponding to the base of the vehicle from the peak wind speed at the height corresponding to the top of the vehicle and then divide the difference by the distance between the two heights. The wind speeds at the top and base of the vehicle can be found in tables 5.2.2 and 5.2.6 of NASA TM X-64589 (see 5 percent risk, 10-min. mean wind speed in table 5.2.6).

The peak and mean wind environments given in the preceding paragraph are recommended for takeoff and landing studies. In addition, for simulations of the orbiter landing and take-off-for-ferry, it is recommended that the 10-min. mean wind profile expressed by the last equation (Section 6.1.1) be used with a superimposed discrete or continuous gust, as described in Sections 5.3.13 and 5.3.14 of NASA TM X-64589. The strong wind-gust power spectra, as defined in Section 5.2.6 of NASA TM X-64589, are recommended for power spectral computations. A surface roughness length of $z_0 = 0.3$ m should be used in the gust definition.

Landing wind shear should be computed by taking (1) the mean wind speed at a height of 152.4 m (500 ft) and the peak wind speed at 18.3 m, and (2) the peak wind speed at an altitude of 152.4 m and the mean wind speed at 18.3 m for the design ground-wind-shear profiles. For analyses of vehicle response to ground winds in takeoff and landing while the orbiter is flying in the aircraft operational mode, the wind should be applied from the directions contained within the two quadrants perpendicular to and upwind of the runway.

For hot-day runway temperatures for orbiter performance calculations, see Section 15.4 of NASA TM X-64589.

6.1.3 ASCENT

The wind environments for ascent flight, including in-flight abort, shall be as defined in Section 5.3 of NASA TM X-64589. The winds used in establishing vehicle design during ascent shall be the 5-percent-risk directional winds for baseline missions launched from the Eastern Test Range and having flight azimuths of approximately: (1) 38 degrees with a 55-degree orbital inclination; (2) 90 degrees with a 28-1/2-degree orbital inclination; and (3) 180 degrees with a 90-degree orbital inclination. These winds shall be used to establish the synthetic wind profiles for vehicle design.

These directional design wind-speed-profile envelopes, valid for ±10 degrees of specified flight azimuths, are given in table 6-3. Also, see Section 5.3.5.2 of NASA TM X-64589. The design wind-shear values to be used with the wind speeds in table 6-3 are given in tables 5.3.11 and 5.3.12 of NASA TM X-64589.

On a mission launched from Vandenberg AFB, California at a 182-degree flight azimuth, the 5-percent-risk directional wind-profile envelopes given in table 5.3.10 of NASA TM X-64589 and the wind shears given in tables 5.3.13 and 5.3.14 of the same document should be used to establish control and structural design requirements.

Synthetic Profile with Discrete Gust. In the construction of a synthetic wind-speed profile, the degree of correlation between the wind shear and gusts should be taken into account. This is accomplished by multiplying the wind shears and the one-minus-cosine shaped discrete gust having an amplitude of 9 m/sec (30 fps) by a factor of 0.85 before constructing the synthetic wind-speed profile. This is approximately equivalent to taking the combined 1-percent-risk values for the gusts and shears. A series of synthetic wind-speed profiles should be constructed, each profile with a different reference height at which the design shear envelope intersects the design wind-speed-profile envelope.

To determine the gust depth or "thickness," a series of gusts, each with a different depth, should be calculated. The design value of the gust depth of 60 to 300 m (about 200 to 1 000 ft) should be determined by selecting the one associated with the most adverse condition. The design synthetic wind-speed profile should be determined by selecting the profile for the most adverse loading conditions as determined by load computations. Details on the construction of design synthetic wind-speed profiles for use in the space shuttle structural analyses are given in Section 5.3.8 of NASA TM X-64589.

Synthetic Profile with Gust Spectrum. The synthetic wind speed-wind shear profile without discrete gust and with an 0.85 factor on shears should be combined with calculations on the vehicle response to the gust spectrum. In place of the discrete gust, a spectral representation of

TABLE 6-3 DESIGN DIRECTIONAL STEADY-STATE WIND-SPEED-PROFILE ENVELOPES FOR BOOST PHASE

GEOMETRIC ALTITUDE km (ft)	HEAD WIND	TAIL WIND	RIGHT CROSSWIND	LEFT CROSSWIND
	meters per second (knots)			
38-deg Flight Azimuth (55-deg Orbital Incl.)				
80 (262 480)	30 (58)	70 (136)	34 (66)	50 (97)
75 (246 075)	30 (58)	70 (136)	34 (66)	50 (97)
60 (196 860)	47 (91)	95 (185)	65 (126)	97 (188)
50 (164 050)	47 (91)	95 (185)	65 (126)	97 (188)
23 (75 463)	17 (33)	18 (35)	18 (35)	15 (29)
20 (65 620)	17 (33)	18 (35)	18 (35)	15 (29)
14 (45 934)	20 (39)	63 (122)	13 (25)	54 (105)
10 (32 810)	20 (39)	63 (122)	13 (25)	54 (105)
1 (3 281)	11 (21)	16 (31)	9 (17)	14 (27)
90-deg Flight Azimuth (28-1/2-deg Orbital Incl.)				
80 (262 480)	50 (97)	90 (175)	30 (58)	20 (39)
75 (246 075)	50 (97)	90 (175)	30 (58)	20 (39)
60 (196 860)	72 (140)	120 (233)	52 (101)	30 (58)
50 (164 050)	72 (140)	120 (233)	52 (101)	30 (58)
23 (75 463)	25 (49)	25 (49)	8 (15)	7 (14)
20 (65 620)	25 (49)	25 (49)	8 (15)	7 (14)
14 (45 934)	20 (39)	75 (146)	28 (54)	29 (56)
10 (32 810)	20 (39)	75 (146)	28 (54)	29 (56)
1 (3 281)	11 (21)	20 (39)	13 (25)	9 (17)
180-deg Flight Azimuth (90-deg Orbital Incl.)				
80 (262 480)	30 (58)	20 (39)	90 (175)	50 (97)
75 (246 075)	30 (58)	20 (39)	90 (175)	50 (97)
60 (196 860)	52 (101)	30 (58)	120 (233)	72 (140)
50 (164 050)	52 (101)	30 (58)	120 (233)	72 (140)
23 (75 463)	8 (15)	7 (14)	25 (49)	25 (49)
20 (65 620)	8 (15)	7 (14)	25 (49)	25 (49)
14 (45 934)	28 (54)	29 (56)	75 (146)	20 (39)
10 (32 810)	28 (54)	29 (56)	75 (146)	20 (39)
1 (3 281)	13 (25)	9 (17)	20 (39)	11 (21)

gusts should be used. The loads resulting from the synthetic wind profile can be calculated with a rigid- or elastic-body trajectory.

The power spectrum recommended for elastic-body studies is given by the following equation:

$$E(\kappa) = \frac{683.4\ (4\ 000\kappa)^{1.62}}{1 + 0.0067\ (4\ 000\kappa)^{4.05}}$$

where the spectrum $E(\kappa)$ is defined so that integration over the domain $0 \leqslant \kappa \leqslant \infty$ yields the variance of the turbulence. In the preceding equation, $E(\kappa)$ is the power spectral density (expressed in $m^2\ sec^{-2}$/cycles per m) at wave number κ per m. The design turbulence loads for these calculations are obtained by multiplying the load standard deviation by a factor of 3. The loads obtained from application of this turbulence power spectrum should be added to the rigid-vehicle loads resulting from the use of the synthetic wind speed-wind shear profile (with an 0.85 factor on shears) without a discrete gust. This wind shear-spectrum combination will result in a 1-percent risk condition for the elastic-vehicle studies when employed with the design steady-state wind-speed envelope values.

For further information on spectra of detailed wind profiles, see Section 5.3.7.2 of NASA TM X-64589.

Vehicle Design Verification. It is recommended that a variety of detailed wind-profile data be used to calculate final vehicle launch capability for a given launch site. The data should be obtained from FPS-16 Radar/Jimsphere wind-velocity profiles representative of each month.

6.1.4 ENTRY

The wind environments for entry flight shall be as defined in Section 5.3 of NASA TM X-64589. The winds used in establishing vehicle design during entry shall be the 1-percent-risk, design-wind-speed-profile envelope given in table 6-4. The values given in this table, representing idealized steady-state horizontal scalar wind speeds, shall be applied without regard to flight azimuth to establish the design winds for orbiter entry.

Synthetic Wind Profile with Discrete Gust. The 1-percent design shear and gust values to be used with the wind-speed profile in table 6-4 for construction of synthetic profiles can be derived from tables 5.3.21 and 5.3.22 of NASA TM X-64589.

TABLE 6-4 **DESIGN STEADY-STATE WIND-SPEED-PROFILE ENVELOPE FOR ENTRY**

ALTITUDE km (ft)		WIND SPEED m/sec (knots)	
150	(492 150)	200	(389)
115	(377 315)	200	(389)
80	(262 480)	150	(291)
75	(246 075)	150	(291)
60	(196 860)	190	(369)
50	(164 050)	190	(369)
23	(75 463)	40	(78)
20	(65 620)	40	(78)
14	(45 934)	92	(179)
10	(32 810)	92	(179)
1	(3 281)	28	(54)

Synthetic Wind Profile with Gust Spectrum. For these calculations, the same winds should be used as for the rigid-vehicle studies for orbiter entry, with the exception of the discrete one-minus-cosine shaped gust. The discrete gust should be replaced with the design turbulence power spectrum presented for ascent flight.

Vehicle Design Verification. The entry winds for vehicle design verification for an altitude of 18 km (about 60 000 ft) or less should be 99 percent of the detailed in-flight wind profiles in each monthly reference period and for each specified entry flight azimuth.

6.1.5 ATMOSPHERIC FLIGHT

The expected gust exceedance rates given in table 6-5 shall be used to calculate limit and preliminary ultimate loads. The normalized power spectra and exceedance equation given in Section 5.3.12 of NASA TM X-64589 shall be used in horizontal or near-horizontal flight. A second set of ultimate loads shall be obtained by

applying appropriate design factors to the limit loads These loads shall be compared with the first set of ultimate loads calculated according to the appropriate exceedance rate in table 6-5, and the design ultimate loads shall be the larger of the two.

TABLE 6-5 **EXPECTED GUST EXCEEDANCE RATES**

LIMIT LOADS		ULTIMATE LOADS	
(exceedances per hr)			
Non-Ferry	Ferry	Non-Ferry	Ferry
2.22×10^{-3}	6.06×10^{-4}	1.11×10^{-6}	3.03×10^{-7}

For studies of the orbiter that do not include a ferrying requirement, the total cruise time over the life of the vehicle shall be considered to be 450 hr. For studies of the orbiter that include a ferrying requirement, the total flight time over the life of the vehicle shall be considered to be 1 650 hr. These flight times shall be used to define the expected shuttle gust exceedance rates for design.

The turbulence model which should be used with the flight simulator is given in Section 5.3.13 of NASA TM X-64589. This model can be used for landing and cruise flight simulations.

For certain horizontal flight studies, the use of a discrete gust in load and flight-control system calculations is desirable. Data on discrete gusts for horizontal flight studies are given in Section 5.3.14 of NASA TM X-64589.

6.2 WATER IMPACT AND RECOVERY

When determining the capability of the solid-rocket motors to withstand loads from water impact, recovery, and transportation, the information in the Addendum to NASA TM X-64589 shall be used.

6.3 NEUTRAL ATMOSPHERE DURING LIFE PHASES

The atmospheric properties of pressure, temperature, and density defined in the following sections shall be used in space shuttle design.

6.3.1 LAUNCH AND ASCENT

The data on the Cape Kennedy Reference Atmosphere (CKRA) in NASA TM X-64589, Section 14.7, shall be used as nominal values to determine surface-to-insertion, in-orbit, and abort trajectories and for analyses of vehicles launched from the Eastern Test Range.

This model is available from the Computation Laboratory at Marshall Space Flight Center as Computer Subroutine PRA-63.

For vehicles launched from other sites, the annual reference atmosphere given in Section 14.7 of NASA TM X-64589 shall be used.

For design conditions involving extremes of pressure, temperature, and density versus altitude, the coefficients of variation (CV) from table 14.9 of NASA TM X-64589 and the mean values from table 14.1 of the same document shall be applied as follows:

$$\text{Maximum parameter} = \text{CKRA}\left(1 + \frac{3CV}{100}\right)$$

$$\text{Minimum parameter} = \text{CKRA}\left(1 - \frac{3CV}{100}\right)$$

These extreme envelopes (mean ±3 standard deviations) should be used with caution. For example, extreme values of temperature, pressure, and density at a given altitude should not be used simultaneously. In addition, the extremes of one parameter cannot exist for the entire profile at a given time. However, if one is dealing with atmospheric extremes of pressure, temperature, and density independent of each other at discrete altitudes and that analysis does not depend on atmospheric conditions at other altitude levels, then the extreme values derived from these equations may be used.

6.3.1.1 EXTREME PROFILES

The hot and cold atmospheres given in Section 14.6 of NASA TM X-64589 shall be used to represent the atmospheric profiles for extreme density variation for such design analyses as aerodynamic heating, engine performance, and ferrying. The atmosphere producing the most severe vehicle design condition shall be utilized in vehicle design.

6.3.1.2 THERMODYNAMIC QUANTITIES ASSOCIATED WITH EXTREME PRESSURE, TEMPERATURE, AND DENSITY VALUES

For calculations in which two atmospheric variables are related to a third extreme variable at discrete altitudes, the functions given in Section 14.5 of NASA TM X-64589 shall be used. Values for the coefficients of variation and correlation for these calculations shall be obtained from table 14.9 of NASA TM X-64589, and the mean atmospheric values from table 14.11 of that document.

6.3.1.3 STANDARD DAY

For purposes of engine ratings, the sea-level values of temperature, pressure, and density as given by the U.S. Standard Atmosphere (1962) shall be used.

6.3.2 SPACE

The properties of the neutral atmosphere for the space phase of flight shall be taken from NASA TM X-64627.

6.3.2.1 SUBORBITAL AND ORBITAL (25- to-1 000-km Altitude)

In analyses of vehicle deorbiting conditions, the Marshall Space Flight Center model atmosphere given in Appendix B of NASA TM X-64627 shall be used to predict the nominal gas properties and their variations in the orbital altitude region of the atmosphere, plus the nominal gas properties in the 25-to-90-km (82 000-to-300 000-ft) region.

For calculations of the design steady-state values of gas properties of the orbital neutral atmosphere, a value of 230 shall be used for the mean 10.7-cm solar flux and a geomagnetic index (a_p) of 20.3 shall be used with a local time of 0900 hr.

Short-time extreme values of the atmospheric gas properties used for design shall be calculated with a value of 230 for the mean 10.7-cm solar flux and a geomagnetic index value of 400, and a local time of 1400 hr. (These gas-property values for the orbital neutral atmosphere represent an estimate of the conditions that may occur for a short period of time – say, 12 to 36 hr – during an extremely large magnetic storm.)

6.3.2.2 EXOSPHERE (37 000-km Geosynchronous Orbital Altitude)

The data given in Section 2.2.2 of NASA TM X-64627 shall be used to describe characteristics of the exosphere.

6.3.3 ENTRY AND ATMOSPHERIC FLIGHT

The U.S. Standard Atmosphere (1962) and dispersions in the atmosphere as given in Section 14.8.1 of NASA TM X-64589 shall be used for all orbiter entry heating and performance analyses.

6.4 LIGHTNING DISCHARGES

The atmospheric electrical parameters given in Section 9.2.2 of NASA TM X-64589 shall be used in all phases of design to ensure shuttle integrity under conditions of electrical discharges triggered by the atmosphere during prelaunch, launch, and flight operations. However, the design shall not provide for intentional penetration of thunderstorms during flight.

6.5 CHARGED PARTICLES

The electron density values and data in Section 2.3 of NASA TM X-64627 shall be used to define the charged-particle environment.

6.6 RADIATION

The radiation environment shall be defined from the following criteria and from information in Section 2.4 of NASA TM X-64627.

6.6.1 GALACTIC COSMIC RADIATION

Galactic cosmic radiation shall be accounted for in vehicle design.

Galactic cosmic radiation consists of low-intensity, extremely high-energy charged particles. These particles, about 85 percent protons, 13 percent alphas, and the remainder heavier nuclei, bombard the solar system from all directions. They have energies from 10^8 to 10^{19} electron volts per particle and are encountered nearly everywhere in space. The intensity of this environment in "free space" – that is, outside the influence of the earth's magnetic field – is relatively constant (0.2 to 0.4 particles per square centimeter per steradian per second) except during periods of enhanced solar activity. In these periods, the fluxes of cosmic rays have been observed to decrease due to an increase in the strength of the interplanetary magnetic field, which acts as a shield to incoming particles. Near the earth, cosmic rays are similarly influenced by the earth's magnetic field, resulting in a spatial variation in their intensity. The extreme of the galactic cosmic ray environment occurs when the sunspot activity is at a minimum. The environment is constant and may be scaled down to 24 hr.

For additional data on this subject, see Section 2.4.1 of NASA TM X-64627.

Estimates of the daily cosmic-ray dose for the various orbits are shown in table 6-6. These dosages should be considered in the space-shuttle design studies.

TABLE 6-6 **GALACTIC COSMIC RAY DOSAGE RATES**

	55-DEG INCL.	POLAR ORBIT	GEOSYNCHRONOUS ORBIT
	472 km (255 nmi)	370 km (200 nmi)	
	rems per day		
Solar maximum	0.005	0.008	0.024
Solar minimum	0.008	0.013	0.036

6.6.2 TRAPPED RADIATION

The trapped radiation environment shall be accounted for in vehicle design. This environment shall be taken from NASA SP-3024 or from the data obtainable from the TRECO computer code provided by the NASA Goddard Space Flight Center, and shall be merged with trajectory information to find particle fluxes and spectra.

The fluxes and spectra should be converted to dosages by using the NASA/MSC data or computer code. Only the most recent data in NASA SP-3024 (currently in six volumes) should be used.

For additional information on trapped radiation, see Section 2.4.2 of NASA TM X-64627.

Near-Earth Environment. The radiation belts trapped near the earth are approximately symmetric with respect to the azimuth except for the South Atlantic anomaly where the belts reach their lowest altitude. The natural trapped radiation in the anomaly region remains fairly constant with time, although it fluctuates with solar activity. Electrons will be encountered at low altitudes in the anomaly region as well as in the auroral zones. Design data requirements are given in Section 2.4.2.1 of NASA TM X-64627.

Synchronous Orbit Altitude Environment. The trapped proton environment at synchronous orbit altitude is of no direct biological significance, but may cause deterioration of material surfaces over long exposure times. The proton flux at this altitude is composed of only low-energy protons (less than 4 Mev) and is on the order of 10^5 protons/cm^2-sec. The trapped electron environment at synchronous altitude is characterized by variations in particle intensity of several orders of magnitude over periods as short as a few hours. However, for extended synchronous altitude missions, a local time-averaged environment can be used. See Section 2.4.2.2 of NASA TM X-64627 for additional data.

Solar Particle Events. The free-space particle event model which should be used for space-shuttle orbital studies is given in Section 2.4.3.1 of NASA TM X-64627. Solar particle events are emissions of charged particles from disturbed regions on the sun during solar flares. They are composed of energetic protons and alpha particles that occur sporadically and last for several days.

6.7 METEOROIDS

The meteoroid environment which the space shuttle must withstand shall be based on the meteoroid model defined in Section 2.5.1 of NASA TM X-64627.

6.8 ASTRODYNAMIC CONSTANTS

The astrodynamic constant values given in Sections 1.6 and 2.7 of NASA TM X-64627 shall be used.

6.9 RAIN

The rain environment defined in NASA TM X-64589 (tables 4.1 and 4.4) shall be used in evaluation of the accumulated damage from rain. The total vehicle exposures to rain shall be consistent with the data of table 4.3 of NASA TM X-64589 and with the specified intervals between refurbishment of components.

6.10 HAIL

The number of vehicle exposures to hail and the severity and duration of such exposures shall be specified for an evaluation of the potential damage from cumulative effects of hail. As an alternative, the hail environment which the vehicle must withstand or be protected against shall be equivalent to a single exposure to 50 mm (2 in.) of hail over a duration of 15 min., with a velocity of fall of 30.5 m/sec (100 fps), mass density of 0.80 g/cm^3 (50 lbm/ft^3), and wind speed of 10 m/sec (32.8 fps).

Size distributions shall be:

Diam Range cm (in.)		**Number of Hailstones per cubic meter (cu ft)**	
0 to 1	**(0 to 0.4)**	**22.00**	**(776.8)**
1 to 2	**(0.4 to 0.8)**	**0.80**	**(28.2)**
2 to 3	**(0.8 to 1.2)**	**0.17**	**(6.0)**

Variation in hail hardness with temperature shall be as indicated in table 6.2 of NASA TM X-64589.

6.11 BLOWING SAND AND DUST

Blowing sand and dust environments which the vehicle must withstand or be protected against shall be as defined in Section 6 of NASA TM X-64589.

Particle size, hardness, and distribution are indicated in the NASA document for windblown sand and dust. If qualification tests in a windblown-sand environment are required, the following conditions should be used: particle size, 0.08 to 0.12 mm (3×10^{-3} to 5×10^{-3} in.); hardness, 7 to 8 moh; distribution, 0.02 g/cm^3 (1.2 lbm/ft^3); wind speed, 10 m/sec (32.8 fps); duration of exposure, 10 hr.

If qualification tests in a windblown-dust environment are required, the following conditions should be used: particle size, 1×10^{-4} to 2×10^{-4} mm (3.94×10^{-6} to 7.88×10^{-6} in.); hardness, 7 to 8 moh; distribution, 6×10^{-9} g/cm^3 (3.744×10^{-7} lb/ft^3); wind speed, 10 m/sec (32.8 fps); duration of exposure, 10 hr.

6.12 SALT AIR

A model of the salt air environment which the vehicle must withstand shall be specified.

For further information, see Section 10 of NASA TM X-64589.

6.13 HUMIDITY

The humidity which the vehicle must withstand shall be specified.

For further information, see Section 3 of NASA TM X-64589.

6.14 FUNGI AND BACTERIA

Models of the fungi and bacteria which the vehicle must withstand or be protected against shall be specified.

For further information, see Section 11 of NASA TM X-64589.

7. PROOF OF DESIGN

Proof of structural adequacy of the design under all critical combinations of design loads and environmental conditions shall be provided by analyses and tests, all of which shall be documented.

7.1 DOCUMENTATION

Reports shall be prepared on analyses and tests conducted to verify the structural adequacy of the design. Assumptions, methods, and data used shall be defined. References cited in the reports which are not readily available shall be submitted to NASA with the reports. The reports shall cover at least the following:

- Integrated plan for proving structural adequacy
- Tests
  - Material characterization
  - Development
  - Qualification
  - Acceptance
  - Flight
  - Special
- Analyses
- Physical characteristics of structure
- Interfaces
- Operating restrictions
- Inspection and repair
- Operational-usage measurements.

Where appropriate to enhance understanding, the reports should be subdivided according to the life phases noted in Section 5.2.

7.1.1 INTEGRATED PLAN

An integrated plan shall be prepared which describes the total plan for verifying structural adequacy. All significant analyses and tests and the schedules for their accomplishment shall be identified for structure and structural characteristics requiring proof.

The test plan shall include tests to characterize materials, structural components, or assemblies; development tests; qualification tests; acceptance tests; flight tests; and special tests.

The plan shall be revised as necessary to reflect changes in schedules, requirements, objectives, design characteristics, and operational usage.

7.1.2 TEST DOCUMENTATION

7.1.2.1 TEST PLANS

A comprehensive test plan shall be prepared for each individual test prior to conducting the test. The plan shall include a description of the test purpose, test conditions, test procedures, test sequence, test articles, requisite data, instrumentation, accept-reject criteria, and provisions for complete documentation.

Where the test articles differ from the actual flight hardware and where design and test loads differ, such differences shall be identified and the consequences of these differences assessed. Test plans shall be approved by NASA.

7.1.2.2 TEST REPORTS

Test reports shall include the test results, conclusions, and recommendations; also, in case of failure, these reports shall describe the failure, the failure condition, the cause of failure, and the corrective action taken.

7.1.3 ANALYSIS DOCUMENTATION

Reports shall be prepared on analyses made to verify structural adequacy in compliance with the criteria of Sections 4 through 6. The reports shall be divided logically by subject and shall include the results of analyses to determine at least the following:

- Induced environment analysis (see Section 7.2.1)
- Natural environment analysis (see Section 6)
- Material selection and characterization analysis (see Section 7.2.2)
- Loads analysis (see Section 7.2.3)
- Thermal analysis (see Section 7.2.4)
- Structural analysis (see Section 7.2.5)
- Aeroelastic analysis (see Section 7.2.6).

The analyses shall be reported according to the life phases specified in Section 5.2 where appropriate.

7.1.4 PHYSICAL CHARACTERISTICS OF STRUCTURE

The physical characteristics of the boost stages and orbiter which are significant to the design of the vehicle structure shall be described and controlled by appropriate documentation, procedures, and policies. The physical description in the documentation shall include at least the following data for each stage: (1) vehicle dimensions, (2) aerodynamic surface areas, (3) station locations, (4) unit weights, (5) center of gravity, (6) distribution of mass and inertia, (7) distribution of stiffness, (8) detailed structural dimensions, and (9) physical interfaces with other systems. The detail and accuracy of the documentation shall be sufficient to provide a basis for all structural analysis.

7.1.5 INTERFACES

Physical and functional interfaces of the structure and other components, assemblies, systems, liquids, and gases shall be identified in the documentation. Interfaces within each vehicle, between vehicles, with external vehicles, and with test and ground support equipment shall be accounted for. Methods of controlling and accounting for interfaces shall be defined.

7.1.6 OPERATING RESTRICTIONS

Reports shall be prepared on vehicle-operating restrictions which state the strength of the structure and any limitations on preparation, testing, and operational use of the vehicle.

7.1.7 INSPECTION AND REPAIR

Reports shall be prepared on inspection and repair of the vehicle. The reports shall include: techniques for inspecting structure to locate hidden defects, deteriorations, and fatigue effects; and instructions for repair and replacement, modified as necessary on the basis of flight-test experience.

7.1.8 OPERATIONAL-USAGE MEASUREMENTS

A plan shall be prepared for measurement of loads and temperatures during vehicle operation.

Reports shall be prepared on operational-usage measurements. These reports shall define the recording and monitoring systems for evaluating structural adequacy during operational usage. In case of failure, these reports shall describe the failure, the failure condition, the cause of failure, and the corrective action taken.

7.2 ANALYSES

Analyses shall be performed to verify structural adequacy in compliance with the criteria of Sections 4 through 6. Where theoretical analysis is inadequate or where experimental correlation with theory is inadequate, the analysis shall be supplemented by tests.

7.2.1 ENVIRONMENTAL ANALYSES

Analyses shall be performed to define the induced environments acting on the vehicle.

7.2.2 MATERIALS ANALYSES

Analyses shall be performed in accordance with the criteria of Section 4.6 to determine the suitability of materials selected for use in the design environment and to define the allowable mechanical and physical properties of new materials or of existing materials in new environments.

7.2.3 LOADS ANALYSES

Loads analyses shall cover the static and dynamic loads and load spectra expected to be imposed on the vehicle during its service life. The analyses shall be made according to the life phases specified in Section 5.2. All critical loads and combinations shall be defined.

The analyses shall account for (1) vehicle geometry; (2) flight conditions such as altitude, velocity, and load factors; (3) weight conditions; (4) inertial properties; (5) vehicle and control-system stiffness distributions; (6) vehicle vibration-mode frequencies and structural damping; (7) structural interaction with the control system; (8) variation of loads with time for deterministic load analyses, and (9) all statistical loadings for probabilistic load analyses.

Computed static and dynamic loads and load spectra shall be combined with thermal effects to produce vehicle-critical design loads, test loads, and data for use in establishing strength and operating restrictions on the vehicle.

7.2.4 THERMAL ANALYSES

Thermal analyses shall be made of the induced thermal environment and of the vehicle response to this environment. The analyses shall be made in compliance with the criteria presented in Sections 4 through 6 and according to the life phases specified in Section 5.2.

These analyses shall account for the flight conditions which affect heating in all phases of the vehicle's life. These flight conditions shall include, but not be limited to (1) maximum heating trajectories, (2) aerodynamic heating, (3) exhaust-plume heating from the propulsion and control systems, (4) propellant-tank levels, and (5) orbit definition and orientation. The analyses shall also account for the effects of structural materials and their properties, structural components and their assembly, insulation materials, and internal energy sources.

7.2.5 STRUCTURAL ANALYSES

Structural analyses shall be made covering strength, deformation, leakage, and structural response to the critical loads, environments, and temperatures anticipated during the service life of the vehicle. These analyses shall define the critical combination of loads, conditions, material properties, and interactions which determine stress levels and margins of safety for all structural components.

The structural analyses shall also include investigations of fatigue, safe-life, and fail-safe considerations to establish the service life; tolerance of the structure to crack-like defects; and residual strength and damage tolerance.

Analyses shall also be performed to show that deformations do not cause degradation of vehicle performance.

7.2.6 AEROELASTIC ANALYSES

Static and dynamic aeroelastic analysis shall account for the following in all phases of the vehicle's life: vehicle geometry; flight conditions, weight conditions, and corresponding mass properties; vehicle and control-system stiffness distributions, structural interaction with the control system and the propellant system; stationary and nonstationary aerodynamic coefficients; interface with thermal characteristics; and stability margins.

7.3 MATERIAL CHARACTERIZATION TESTS

When structural material characteristics, including physical and allowable mechanical properties and failure mechanisms, are not available in NASA-approved references, tests shall be performed to characterize the materials in accordance with the criteria of Sections 4.6.1 through 4.6.3.

For recommended practices, refer to NASA NHB 8080.1, NHB 8080.3, MIL-HDBK-5B, and AFML-TR-66-386.

7.3.1 PHYSICAL PROPERTIES

Material physical properties, including thermal properties, shall be determined by test.

Physical properties should include, as appropriate: density, coefficient of thermal expansion, thermal conductivity, specific heat, solar absorptance, and infrared emittance. For recommended practices, refer to NASA SP-8014, SP-8043, NASA NHB 8080.3, MIL-A-008860A (USAF), MIL-STD-143B, MIL-STD-810B, and ASTM E 332-67.

7.3.2 ALLOWABLE MECHANICAL PROPERTIES

Allowable mechanical properties shall be determined by experiments that account for appropriate thermal and chemical environments.

Mechanical properties should include allowable values for tensile and compressive yield strengths, tensile and compressive ultimate strengths, bearing and shear strengths, strength under combined loads, moduli of elasticity, Poisson's ratio, and material elongation. Sufficient test data should be obtained to account for scatter in the data. Where applicable, inspection procedures, accept-reject criteria, the effect of manufacturing processes on material properties, and protective-surface treatments should be determined.

7.3.3 FAILURE MECHANISMS

Tests shall be performed on structural materials, as applicable, to determine their susceptibility to failure by the following failure mechanisms:

- **Fatigue**
- **Brittle fracture**
- **Stress-corrosion cracking**
- **Hydrogen embrittlement**
- **Temper embrittlement**
- **Creep**
- **General corrosion**
- **Galvanic corrosion**
- **Meteoroid-impact damage**
- **Radiation damage.**

Fatigue. **The fatigue characteristics of structural materials shall be determined by test. These tests shall be made in the combined environment used for design representing static loads, dynamic loads, temperature, vacuum, and corrosion. Provision shall be made to reduce allowable stresses to account for scatter in the test data.**

The test loading conditions, environments, and stress states should represent as accurately as possible those expected during the service life of the structure.

Brittle Fracture. The brittle-fracture characteristics of thick-wall and heavy-forged sections will be required for the vehicle structural design. The tentative standard testing procedures developed by ASTM Committee E-24 should be applied.

In conjunction with evaluation of brittle fracture, fracture toughness should be determined by experiment. Flaw-growth characteristics and the threshold stress intensity of materials should be determined by tests when the materials are used for structural components designed for safe-life.

When experimentally determining the fracture toughness of materials, the test specimens should be sufficiently wide to prevent in-plane bending and should be of the same material and thickness as the structural assemblies, and processed in the same manner. A sufficient number of specimens having flaws of various sizes and simulating the parent metal, weldments, and heat-affected zones of the pressure vessels should be tested to allow meaningful statistical values of fracture toughness to be established.

When experimentally determining the flaw-growth characteristics of material, the test specimens should be designed to eliminate detrimental effects such as in-plane bending and back-face corrections. A sufficient number of tests should be conducted in the simulated service environments and at the service load frequencies to allow meaningful statistical values of flaw-growth characteristics to be established. In addition, flaw-growth tests of specimens simulating the actual structural thickness, expected service loading and environment, and the anticipated flaw geometries should be conducted on critical structural components such as pressure vessels to verify the calculated flaw-growth predictions.

When experimentally determining the threshold stress-intensity characteristics and sustained-stress flaw-growth rates selected for assemblies subjected to sustained loads, the specimens should be tested in environments simulating the actual service environments as nearly as practicable. A sufficient number of specimens should be tested to allow meaningful statistical values of the material's threshold stress intensities to be established.

For recommended practices, refer to NASA SP-8040 and SP-8095.

Stress-Corrosion Cracking. There are no universally accepted test procedures to determine stress-corrosion cracking. The sample configurations most often used are identical to those used for hydrogen-embrittlement tests. Short-time cyclic immersion in salt water and exposure to the sea-salt environment are the most common types of tests.

The synthetic sea-water solution used should be as designated by the American Society of Testing Materials. Other corrosive environments such as air, gas, or fuel can also be used for test conditions, where appropriate.

Hydrogen Embrittlement. The sustained load-carrying ability of metals susceptible to hydrogen embrittlement (particularly, steels and titanium alloys) should be evaluated by laboratory tests.

A variety of specimen configurations such as the pre-stressed bent beam, split-ring, and notched types can be used. Safe threshold working-stress levels may be established for materials susceptible to hydrogen-induced embrittlement by subjecting specimens to the anticipated hydrogen environment. Safe or tolerable levels of hydrogen absorption should be determined for titanium alloys. The effects of possible hydrogen absorption from fabrication processes such as chemical milling, pickling, and cleaning prior to plating should be determined for steels and titanium alloys. For steels, no dangerous or embrittling levels of absorption should be permitted to occur from these processes. For titanium alloys, the level of hydrogen absorbed during processing should be determined by hydrogen analyses. This level must be safely below the previously determined tolerable limits.

Temper Embrittlement. Tests should be made on representative coupons to verify that temper embrittlement has not occurred.

Creep. Creep tests for candidate structural materials should be conducted at elevated temperatures unless valid comparisons can be made from results of prior tests that are acceptable to NASA. Standard procedures of the American Society of Testing Materials should be followed for creep tests on materials. (There are no established standard procedures for such tests on structural assemblies.)

The effects of temperature overshoot and temperature cycling on the creep properties of sensitive materials should be determined.

General Corrosion. Typical corrosion tests for evaluating material susceptibility to surface pitting and oxidation may be made using the well-known outdoor seashore rack for mounting unloaded panels. Structural material samples and small assemblies may be subjected to the salt-spray simulation test described in MIL-STD-810B.

Galvanic Corrosion. There are no standard tests for galvanic corrosion.

Meteoroid-Impact Damage. **If appropriate data do not exist, material constants such as K_∞ and K_1, used in analyses of meteoroid penetration, shall be determined from hypervelocity-impact tests on all metals used in components that are subject to failure from meteoroid impact. Test data shall be obtained for the highest possible impact velocities. The other test parameters shall be adjusted so that the response of the structure to the kinetic-energy distribution of meteoroids encountered in space can be determined.**

Radiation Damage. **When the degradation of material properties cannot be determined by analogy, comparison, or interpolation of data from previous tests, the materials shall be tested in radiation facilities that accurately represent the projected service environment.**

For recommended practices applicable to solar electromagnetic radiation, refer to AFSC DH 3-2(DN 4C3). For information on particulate radiation, refer to DN 4B4 in the same document.

7.4 DEVELOPMENT TESTS

Development tests shall be conducted as necessary to predict structural behavior with confidence. Specifically, tests shall be performed to:

- **Evaluate design concepts**
- **Verify analytical techniques**
- **Evaluate structural modifications for achieving desirable structural characteristics**
- **Obtain data for reliability predictions**
- **Determine failure modes or causes of failure.**

Development tests are not normally specified by contract and are not as closely controlled as qualification tests and acceptance tests. They are, however, defined in the integrated test plan. In general, development tests precede qualification and acceptance tests and are heavily oriented toward evaluations of the preliminary design.

Structural development tests may involve a wide range of disciplines. Representative development tests include: mock-ups to enhance visualization of structural concepts, strength tests, life tests, mechanism tests, tests to evaluate fabrication techniques, tests on models to evaluate man-machine interactions, and tests to verify loads, pressures, and environments. Specific tests are detailed in Sections 7.4.1 to 7.14.13.

The amount of development testing depends largely on the degree of sophistication of the structure, the quantity of qualified hardware, and the processes employed in the design. Conventional designs will obviously require less testing than designs which advance the structural technology.

Characterization of materials is sometimes considered as development testing, although these tests are classified separately in this document in Section 7.3.

For recommended practices, refer to NASA SP-8043.

7.4.1 TESTS TO VERIFY LOADS, PRESSURES, AND ENVIRONMENTS

Tests shall be conducted to assist in defining or verifying static and dynamic loads, pressures, load spectra, and environments which the vehicle will encounter throughout its service life. Tests shall be performed in accordance with the criteria of Sections 4 through 6, and in accordance with the integrated plan.

7.4.2 AIR LOADS AND PRESSURES

Wind-tunnel tests shall be performed to verify analytical estimates of the aerodynamic coefficients and pressures for both mated and unmated configurations. Proper allowance shall be made for scaling effects. These tests shall cover the vehicle operational speed, altitude, and angle-of-attack range. Load redistribution for the aeroelastically deformed vehicle shall be accounted for. Variation of local pressures with time at vent locations shall also be obtained.

For recommended practices, refer to NASA SP-8006 and SP-8060.

7.4.3 GROUND WIND LOADS

Dynamically similar wind-tunnel models of the vehicle and its restraint on the launch pad shall be used to obtain ground wind loads. The vehicle model shall incorporate all protuberances. The influence of adjacent towers and launch equipment shall be accurately simulated. Tests shall be conducted on both mated and unmated configurations for all orientations with respect to the wind at both subcritical and supercritical Reynolds numbers.

Full-scale ground wind loads shall also be measured to establish the validity of the wind-tunnel tests and analyses.

These measurements should include vehicle response, such as bending moment or accelerations, and simultaneous measurements of the frequency and damping of the relevant vibration modes of the vehicle on its launch pad.

Refer to NASA SP-8008 and AFSC DH 3-2(DN 3A3) for recommended practices.

7.4.4 BUFFET LOADS

Dynamically similar wind-tunnel models of the mated and unmated configurations shall be tested to obtain

buffet loads. Each ratio of the model to full-scale Mach number, to reduced frequency, and to Reynolds number (if possible) shall be unity. The tests shall cover the vehicle speed, altitude, and angle-of-attack range.

For recommended practices, refer to NASA SP-8001 and NASA CR-1596.

7.4.5 SLOSH LOADS

Scale-model tests shall be conducted on both mated and unmated configurations as required to verify analytical predictions of fuel-sloshing loads and to validate the effectiveness of the slosh-suppression devices used. Inertial, viscous, and interfacial characteristics of the liquid shall be scaled.

Reduced-scale-model tests, full-scale ground tests, or flight tests may be employed. Refer to NASA SP-8009 and SP-8031 for recommended practices.

7.4.6 SHOCK LOADS

Mechanical-shock tests shall be conducted to define the shock environment when it cannot be predicted by analysis or from previous tests, and to develop means for reducing excessive shock levels.

The tests should be conducted on full-scale structural components and assemblies. For recommended practices, refer to NASA SP-8043, MIL-A-008867A (USAF), and AFSC DH 3-2(DN 4C3).

7.4.7 ACOUSTIC LOADS

Acoustic tests shall be conducted to define the acoustic environment when it cannot be predicted by analysis or from previous tests on similar structure, and when there is a need to develop means for reducing acoustic-load damage.

The tests should be conducted on full-scale structural components and assemblies in an accurately simulated service environment.

For recommended practices, refer to NASA SP-8043, SP-8072, and NASA CR-1596.

7.4.8 BUCKING AND CRIPPLING

Representative structure shall be tested under the conditions cited in Section 4.3.3. Tests shall be conducted simulating the compressive design loads when: (1) configurations are shells of arbitrary shape; (2) configurations are of minimum weight, and coupling between the various modes of failure is possible; (3) no theory or correlation factor exists; (4) correlation factors used are less conservative than those recommended in NASA SP-8007, SP-8019, and SP-8032; and (5) cutouts, joints, or other design irregularities occur.

7.4.9 VIBRATION

Tests shall be conducted as required to verify the analytical predictions of the vibration environment and to develop techniques for suppressing excessive vibration.

The tests should be conducted on full-scale structural components and assemblies in an accurately simulated service environment.

For recommended practices, refer to NASA SP-8043, SP-8050, and NASA CR-1596.

7.4.10 MODAL SURVEY

Ground vibration tests shall be conducted as required to verify the vehicle's vibration modes, frequencies, and damping coefficients used for dynamic-load and dynamic-aeroelastic calculations. The full-scale vehicle or a replica which accurately models both the aeroelastic properties and the construction of the vehicle shall be used for these tests.

The modal surveys shall include the mated configurations or major assemblies, as appropriate, and shall be used to correlate with and confirm theoretical results obtained on mathematical models. Surveys shall be conducted at several weight conditions for each flight configuration, considering the effects of liquid expenditure, liquid sloshing, control-force application, programmed maneuvers, and engine thrust.

The vehicle or model shall be properly supported so that its rigid-body frequencies are approximately an order of magnitude lower than its free-free, flexible-body frequencies. Mass configurations shall conform to those

found to be critical from theoretical analyses. The tests shall be performed to obtain all significant symmetric, antisymmetric, and unsymmetric vibration modes and frequencies. Suitable instrumentation shall be used to measure all significant coupling responses.

For recommended practices, refer to NASA SP-8012, SP-8016, SP-8036, SP-8043, NASA CR-1596, MIL-A-008870A (USAF), and AFSC DH 3-2(DN 4C7).

7.4.11 STRUCTURE/PROPULSION SYSTEM INSTABILITY (POGO)

Analytical models of the vehicle longitudinal dynamics shall be verified by experiment.

For recommended practices, refer to NASA SP-8055.

7.4.12 HEATING

When analysis is not adequate to evaluate external heating sources, tests shall be conducted to verify that analytical models will satisfy the criteria of Sections 4.5 and 5.2. Tests shall be conducted to evaluate the external heating sources for the mated and unmated configurations in at least the following: (1) areas adjacent to protuberances; (2) wake areas downstream of protuberances; (3) separated-flow and reattachment areas; (4) shock-wave impingement areas; (5) areas of base heating; (6) areas subjected to three-dimensional exhaust plumes or to plume impingement; and (7) areas representative of heat-shield panel arrangements including gap patterns, surface waviness, flutes, laps, and corrugations under varying conditions of aerodynamic flow.

These flow and heating phenomena are not readily amenable to analytical prediction. Tests are often made on reduced-scale models or full-scale components and assemblies under accurately simulated flight conditions. Usually, a number of tests are required to evaluate all parameters of interest.

7.4.13 CRASHWORTHINESS AND DITCHING

Tests shall be conducted to verify analytical predictions of crashworthiness characteristics in accordance with the criteria of Section 4.9.5. Scale-model tests may be used to evaluate ditching characteristics in lieu of full-scale tests.

7.5 QUALIFICATION TESTS

Qualification tests shall be conducted on flight-quality hardware to demonstrate structural adequacy under more stringent loads than the worst expected loads. In defining the number and types of qualification tests, the highest practicable level of assembly shall be used. Test conditions shall be selected to demonstrate clearly that all elements of the structure satisfy the design criteria of Sections 4 and 5.

The test fixtures, support structure, and methods of environmental application shall not induce erroneous test conditions.

Support structure should be designed to simulate the flight-load distribution and stiffness of the vehicle at the support structure-specimen interface.

The types of instrumentation sensors and their location in qualification tests shall be coordinated with instrumentation for the flight-test vehicle and shall be provided to measure all applied loads and environments and the structural response. The instrumentation shall provide sufficient data to ensure proper application of the accept-reject criteria. The sequences, combinations, levels, and durations of loads and environments shall demonstrate that design requirements have been met.

For recommended practices, refer to NASA SP-8044.

Qualification should be accomplished by one of the following methods: (1) subjecting the components, assemblies, or systems to qualification tests; (2) qualification of higher structural levels of assembly; (3) basing qualification on tests conducted on similar configurations in a similar environment; (4) prior vehicle qualifications; or (5) basing the qualification on other tests or history, such as vendor tests, static firings, or flight tests. Hardware should be subjected to requalification tests when changes made in design or manufacturing processes affect functioning or reliability; when inspection, test, or other information indicates that a more severe environment or operating condition exists than that for which the hardware was originally tested; or when hardware is made by a different company than manufactured previous similar hardware.

During tests, input parameters, system outputs, and structural response should be monitored continuously.

Anomalous behavior during tests and its potential influence on the vehicle should be identified.

7.5.1 STATIC TESTS

7.5.1.1 LIMIT CONDITIONS

Tests shall be conducted to verify that the structure does not experience detrimental deformation at limit loads and pressures in accordance with the criteria of Sections 4 and 5.

Deformation of structural joints subjected to loads and elevated temperatures and to thermal stresses should be measured for all critical locations and conditions. An increased deflection of structure due to creep elongation of bolt holes should be evaluated by tests. Cumulative strain measurements should be made of test assemblies during periodic disassembly and reassembly of fabricated structure.

7.5.1.2 ULTIMATE CONDITIONS

Tests shall be conducted to verify that the structure does not rupture or collapse at ultimate load and pressures in accordance with the criteria of Sections 4 and 5.

For recommended practices, refer to NASA NHB 8080.1, NHB 8080.3, NASA SP-8040, AFSC DH 3-2(DN 4C3), FAA-FAR Part 25, MIL-A-008867A (USAF), and MIL-STD-1530 (USAF).

7.5.1.3 COMBINED LOADS AND INTERNAL PRESSURE

Tests shall be conducted to verify the capability of pressurized structure to withstand without failure combined internal pressure and external forces in accordance with the criteria of Sections 4 and 5.

When pressure combined with external forces is detrimental to structural stability or load-carrying capability, the ultimate pressure shall be combined with ultimate external forces in tests for strength without structural collapse or rupture. When pressure combined with external forces is beneficial to structural stability or load-carrying capability, the minimum operating pressure shall be combined with ultimate design external forces in tests for strength without structural collapse or rupture.

For additional information, refer to NASA SP-8040, AFSC DH 3-2(DN 4C3), and MIL-A-008867A (USAF).

7.5.1.4 COMBINED LOADS AND THERMAL EFFECTS

Tests shall be conducted to verify the capability of the structure to withstand without detrimental deformation the combined loads at the operating temperatures expected in the vehicle's service life.

Test loads and temperatures should be distributed in a manner representing actual service distributions as nearly as possible. The load distributions may be simplified in noncritical structural areas or for previously qualified structure. Load simplifications which result in deformations or possible failures not met during mission conditions should be avoided. More than one loading condition may be applied simultaneously to different portions of the structure, providing the combined loads do not exceed the design load on any portion of the structure. Unaccountable effects, such as combined loads and material behavior, should be provided for in all test loads and procedures where such effects cannot be properly simulated. All prior load history affecting structural adequacy should be simulated.

Load and thermal distributions are more easily and accurately applied to the unshielded structure. The difficulties involved in simultaneously applying the severe entry heating pulse, coexisting aerodynamic forces, and inertia loads are likely to cause erroneous test conditions. In many tests, better simulation may be achieved without the heat shield because the relatively mild back-face temperature distributions can be applied, permitting access to the structure without penetration of the heat shield. The dynamic characteristics of the structure may be significantly different with and without the heat shield. This difference should be taken into account in tests without the heat shield.

For recommended practices, refer to NASA SP-8004, SP-8007, SP-8019, SP-8045, AFSC DH 3-2(DN 4C3), and MIL-A-008867A (USAF).

7.5.1.5 ULTIMATE PRESSURE

At least one specimen typical of flight hardware shall be tested to demonstrate that each structure is capable of sustaining ultimate pressure without rupturing, in accordance with the criteria of Section 4. Each test specimen shall be of the same design as planned for flight hardware and shall be fabricated from the same materials and by the same processes planned for production of flight hardware. The effects of operating temperatures and environments shall be accounted for in the tests.

7.5.2 STATIC-ELASTICITY TESTS

7.5.2.1 DIVERGENCE

Wind-tunnel tests shall be conducted to demonstrate that the vehicle is free of divergence under the conditions cited in Section 4.3.1 when this cannot be proven by analytical methods (i.e., when they are not available, not accurate, or not corroborated by experimental data).

The test specimens should be either dynamic models or full-scale components. If dynamic models are used, the adequacy of the structural simulation should be verified by influence-coefficient, structural-stiffness, and/or vibration tests.

For recommended practices, refer to NASA SP-8003, AFSC DH 3-2 (DN 4C7), FAA-FAR Part 25, and MIL-A-008870A (USAF).

7.5.2.2 CONTROL-SURFACE REVERSAL

Wind-tunnel tests shall be conducted to demonstrate that the vehicle is controllable at all points along the dispersed trajectory during atmospheric flight under the conditions cited in Section 4.3.2 when controllability cannot be shown by analytical methods (i.e., when they are not available, not accurate, or not corroborated by experimental data).

For recommended practices, refer to FAA-FAR Part 25 and MIL-A-008870A (USAF).

7.5.2.3 BUCKLING AND CRIPPLING

Tests on flight-quality hardware shall demonstrate that the structure is free from buckling and crippling, in accordance with the criteria of Section 4.3.3.

Tests to demonstrate freedom from buckling and crippling are readily performed in connection with static tests required under Section 7.5.1.

For recommended practices, refer to NASA SP-8007, SP-8019, SP-8032, SP-8068, and MIL-A-008867A (USAF).

7.5.3 DYNAMIC AEROELASTIC INSTABILITY TESTS

Tests shall be conducted as a supplement to analysis to verify freedom from undesirable axial-lateral coupling in accordance with the criteria of Section 4.4. Scaled dynamic and aeroelastic models shall be used, as appropriate.

7.5.3.1 CLASSICAL FLUTTER AND STALL FLUTTER

Wind-tunnel tests shall be conducted to demonstrate that the vehicle is free of flutter under the conditions cited in Sections 4.4.1.1 and 4.4.1.2 when analytical methods are not adequate (i.e., not available, not sufficiently accurate, or not corroborated by experimental data) or when analysis indicates marginal stability.

Test specimens should be either dynamic models or full-scale elements of the vehicle. It should also be demonstrated by influence-coefficient, structural-stiffness, and/or vibration tests of full-size vehicles in the flight configuration that the scale models adequately simulate the dynamic characteristics of the vehicle. Dynamic characteristics of the scale models should also reflect the variation in modulus of elasticity with the anticipated service temperatures.

For additional information, see NASA NHB 8080.1, NHB 8080.3, NASA SP-8003, AFSC DH 3-2 (DN 4C6), FAA-FAR Part 25, and MIL-A-008870A (USAF).

7.5.3.2 PANEL FLUTTER

If test data do not exist for panels of similar structural configuration, edge-support conditions, and aerodynamic parameters, wind-tunnel tests shall be conducted on dynamically scaled models or full-scale components to demonstrate that external panels are free of panel flutter under the conditions of Section 4.4.1.3.

At least one panel of each structural type on the vehicle for which flutter data do not exist should be tested at dynamic pressures up to 1.5 times the maximum local dynamic pressure expected to be encountered at any Mach number within the normal operating envelope. Thermally induced loads, mechanically applied loads, and pressure differentials across the panels should be simulated in the tests.

For additional information, refer to NASA SP-8004 and AFSC DH 3-2 (DN 4C6).

7.5.3.3 CONTROL-SURFACE BUZZ

Wind-tunnel tests shall be conducted to demonstrate that the vehicle is free of control-surface buzz under the conditions cited in Section 4.4.1.4.

The test specimens should be either dynamic models or full-scale components, and both Mach number and Reynolds number should be simulated in the tests. At least one flight-test vehicle should be instrumented to detect control-surface buzz in flight-test regions of greatest dynamic pressure.

For recommended practices, refer to NASA SP-8003.

7.5.4 DYNAMIC-COUPLING TESTS

Ground dynamic tests shall be conducted on representative vehicle structure in the mated and unmated configurations to assess compatibility of the flexible structures with functional systems.

For recommended practices, refer to NASA NHB 8080.1, NHB 8080.3, NASA SP-8016, AFSC DH 3-2 (DN 4C7), ASD-TR-66-57, and MIL-A-8871A (USAF).

7.5.5 CONTROL SYSTEM AND ELASTIC MODES

Ground tests shall be conducted as a supplement to analyses to demonstrate that the vehicle is free of undesirable coupling between the control system and vehicle elastic modes in accordance with the criteria of Section 4.4.2.1.

Ground tests for this type of coupling should include tests of components, vibration tests of the structure, closed-loop simulation tests with as much flight hardware as possible included, and overall vehicle system tests, including both the structure and control systems.

For recommended practices, refer to NASA SP-8016.

7.5.6 DYNAMICALLY INDUCED ENVIRONMENT TESTS

7.5.6.1 VIBRATION

Ground vibration tests shall be conducted to verify: (1) structural adequacy in the vibration environment; (2) predicted structural response to the vibration environment; (3) efficiency of vibration-isolation mounts and panels; and (4) proper damping and vibration-transmission characteristics.

Vibration fixtures shall be designed to avoid fixture-induced attenuation, amplification, or resonance within the range of test conditions.

Particular consideration should be given to structure supporting massive equipment or equipment sensitive to discrete frequency bands. Service environments should be closely simulated in ground vibration tests determining structural strength.

For recommended practices, refer to NASA SP-8043, SP-8044, FAA-FAR Part 25, and MIL-A-008870A (USAF).

7.5.6.2 EQUIPMENT MOUNTS

Tests shall be conducted to verify that the equipment-support structure with the applicable equipment mounted will be adequate for the service life of the vehicle.

Local resonances of the supporting structure should be determined to permit comparison with the resonances of the vehicle structure or equipment in close proximity.

For recommended practices, refer to NASA SP-8044. Additional information on equipment mounts is presented in AFSC DH 3-2 (DN 4B5).

7.5.6.3 ACOUSTIC

Acoustic tests shall be conducted to verify the adequacy of the structure to withstand the acoustic environment.

Particular consideration should be given to structure characterized by lightly stiffened surface areas and equipment susceptible to high-frequency excitation. Service environments and in-service boundary conditions should be closely simulated on test specimens.

Applicable tests on similar configurations may be utilized, subject to NASA approval.

For recommended practices, see AFSC DH 3-2 (DN 4C4).

7.5.6.4 SHOCK

Mechanical shock tests shall be conducted when analyses or previous tests on similar structure do not clearly demonstrate structural adequacy or adequately define structural response to nonexplosive mechanical shock.

Pretest documentation should show that the test input, model, instrumentation, and procedures will be sufficient to demonstrate structural adequacy for mechanical shock.

For recommended practices, refer to NASA SP-8050.

Impact tests shall be conducted when analyses or related tests do not clearly demonstrate the adequacy of structure to withstand impact loads in combination with other design loads and environments.

Pretest documentation should show that the test boundary conditions are valid and that the test input, test specimen, mounting fixture, instrumentation, and procedures are appropriate. For additional information, refer to AFSC DH 3-2 (DN 4C3).

Explosive shock sources and responses, potential damage from explosive shock, and techniques to suppress and control damage shall be evaluated by tests if adequate analytical techniques are not available.

For additional information, see AFSC DH 3-2 (DN 4C1).

Components and assemblies subject to possible dropping or tumbling shall be tested to the drop-test requirements of MIL-STD-810B. The shock levels transmitted to critical cushioned or packaged components shall be determined from rational analysis to verify that the protected components are not damaged.

7.5.7 THERMAL TESTS

7.5.7.1 STRUCTURAL TEMPERATURES

Full-scale tests shall be conducted to verify predicted structural temperatures. When the size of the structure makes it impractical to conduct full-scale ground tests or when heating conditions cannot be accurately represented in such tests, flight tests shall be employed. Any of these tests shall include high and low temperature extremes. Scatter in the test data shall be defined and deficiencies in the simulation of the operational environment shall be analyzed.

Tests shall be conducted to verify joint conductance.

For recommended practices, refer to NASA NHB 8080.1, NHB 8080.3, NASA SP-8014, SP-8029, SP-8040, SP-8062, ASFC DH 3-2 (DN 4C3), MIL-A-008860A (USAF), MIL-A-008867A (USAF), MIL-STD-470, and MIL-STD-1530 (USAF).

7.5.7.2 EXHAUST-PLUME IMPINGEMENT

The effects of exhaust-plume impingement from rocket motors on vehicle structure shall be experimentally determined, including the effects on skin and on radiation coatings or temperature-control surfaces.

For recommended practices, refer to NASA SP-8029.

7.5.7.3 THERMAL BUCKLING OF PANELS

The effects of high rates of heating on the buckling strength of stiffened panel construction shall be determined by test.

Thermal stresses interacting with load stresses for both uniform and nonuniform heating can have significant effects in reducing the buckling load of structure. Depending upon the mode of buckling, the thermal stresses may or may not affect the magnitude of the maximum load.

For recommended practices, refer to NASA SP-8044 and AFSC DH 3-2 (DN 4C3).

7.5.7.4 THERMAL PROTECTION SYSTEMS

Thermal tests shall be conducted to verify the analyses employed for each design heating condition up to the most severe anticipated heating environment. Physical and thermal adequacy shall be demonstrated under the simulated operating environments, both for high-temperature and low-temperature applications.

Frequently, tests cannot be performed in a completely simulated flight environment. Transient effects, for example, are frequently important during the period of maximum flight heating, but test conditions duplicating the extremes of the flight environment can usually be achieved only as steady states. It is therefore often desirable to try to duplicate the predicted total heat input by various combinations of heating rates and exposure times. In this manner, the transient effects of char formation on the ablative material can be at least partially simulated. If the test models are instrumented with thermocouples and the measured temperature histories, and the mass loss and surface recession are analytically matched, much insight can be gained into the material properties and the analytical model.

For additional information, refer to NASA SP-8014.

7.5.7.5 INSULATION

Tests shall be conducted to demonstrate the thermal and structural adequacy of insulation systems under repetitive cycles of the heating or cooling expected throughout the service life of the vehicle.

For recommended practices, refer to NASA SP-8044 and AFSC DH 3-2 (DN 4C3).

7.5.8 LIFE TESTS

Fatigue tests shall be performed in accordance with the criteria of Section 4.7 to establish the service life of structure designed utilizing safe-life or fail-safe concepts.

The test-loading conditions, environments, and stress states, and their distributions and combinations shall represent as accurately as possible those expected during the service life of the structure.

For recommended practices, refer to MIL-A-008867A (USAF), FAA-FAR Part 25, AFSC DH 3-2 (DN 4B2), and MIL-STD-1530 (USAF).

For some conditions, the behavior of structural assemblies may be determined from tests of simple coupons containing various geometric stress concentrations.

7.5.8.1 SAFE-LIFE TESTS

Safe-life tests shall be conducted in accordance with the criteria of Section 4.7 for structural components, assemblies, and systems that have little or no tolerance to damage during operation.

The fatigue-test life with appropriate reduction factors for inherent structural strength scatter may be used to establish the safe-life of assemblies and systems.

For safe-life design concepts that depend on nondestructive inspection and flaw-growth predictions for structural life assurance, safe-life tests of the structure with artificial flaws shall be conducted to verify the safe crack-growth predictions and to demonstrate that nondestructive inspection techniques are adequate. These induced flaws shall simulate the flaws created by manufacturing or service conditions and shall not exceed the maximum permissible flaw sizes established as nondestructive inspection standards for design of the assembly or system.

For safe-life design concepts that depend on the proof test as the final inspection, the amount and type of preproof nondestructive inspection required should be determined considering the impact of a proof-test failure on vehicle and program costs and schedules.

For safe-life design concepts that depend on nondestructive inspection alone for structural life assurance, it shall be demonstrated that the techniques are adequate to ensure detection of significant defects.

The more important defects for which inspection techniques should be defined are noted in Section 4.6.3.

7.5.8.2 FAIL-SAFE TESTS

Fail-safe tests shall be conducted in accordance with the criteria of Sections 4.7.2 through 4.7.7 to demonstrate structural tolerance to damage and the residual load-carrying ability at the specified percentage of limit loads for critical structure (excluding structure for which safe-life is applicable, such as metallic pressure vessels and landing gears).

Fail-safe tests may be conducted either on structure containing cracks in a single component developed during fatigue testing or on structure which has been purposely cut to simulate accidental severance of members.

During these tests, the load applied to the structure should not be greater than the specified fail-safe load.

7.5.8.3 CUMULATIVE COMBINED DAMAGE

Cumulative combined damage tests shall be performed in accordance with the criteria of Section 4.7.7.

7.5.9 INTERFACE-COMPATIBILITY TESTS

Tests shall be conducted to demonstrate that the vehicle structure is physically and mechanically compatible with functional components, assemblies, systems, liquids, and gases. As a minimum, the tests shall verify that the conditions and structural interactions identified in Section 4.8 have been adequately accounted for in design. The tests shall be conducted under environmental conditions that permit proper assessment of interactions.

Tests shall be conducted to verify that structural materials are compatible with all liquids and gases employed in the vehicle.

The performance of lubricants shall be determined by tests in the simulated service environment.

Refer to Section 4.9.14 for additional criteria on lubricant characteristics. For recommended practices, refer to NASA NHB 8080.1, NASA NHB 8080.3, and MIL-A-008867A (USAF).

7.5.9.1 METEOROID PROTECTION

Tests shall be conducted on the meteoroid shield in accordance with the criteria of Section 4.9.3 to demonstrate the capability of the shield to sustain impacts by projectiles having equivalent characteristics to meteoroids in space, without damaging the shield structure beyond prescribed limits or degrading the function of other vehicle systems.

Test specimens shall have the same geometry, material, temperature, and stress level as the structural component being represented. Test data shall be obtained for the highest possible impact velocities.

For recommended practices, refer to NASA SP-8042.

7.5.9.2 LEAKAGE

Leakage rates shall be determined in accordance with the criteria of Section 4.9.6 for structural joints, seals, access hatches, skin penetrations, and pressure fittings.

For additional information on leakage testing, refer to NASA TN D-5864.

7.5.9.3 VENTING

Tests shall supplement analysis if required to verify the adequacy of compartment-venting provisions in accordance with the criteria of Section 5.1.1.3. The largest practicable assemblies shall be employed in the tests.

7.5.9.4 DOORS AND WINDOWS

The structural integrity of doors and windows under ultimate conditions of load and pressure shall be demonstrated in accordance with the criteria of Section 4.9.8.

7.5.9.5 MISALIGNMENTS AND TOLERANCES

Tests shall be conducted to verify that specified structural and functional characteristics are not impaired by allowable accumulated misalignments and dimensional tolerances.

7.5.9.6 MECHANISMS

Tests shall be performed to ensure that mechanisms critical to mission success (e.g., separation and staging, docking, landing, and locking) shall function within prescribed tolerances after exposure to qualification-test levels.

7.5.9.7 DEPLOYABLE AERODYNAMIC DECELERATORS

Tests shall be conducted on deployable aerodynamic decelerator systems in accordance with the criteria of Section 4.9.9 to verify the structural integrity of components and analytical models used in design calculations of the system. Physical characteristics and mechanical properties of fabrics shall be verified by aerial deployment tests conducted under more severe conditions of dynamic pressure and velocity than anticipated, and approximating ultimate load conditions as closely as possible.

The following characteristics shall be evaluated: (1) ultimate strength and elongation; (2) tear resistance and tear-stop characteristics; (3) fabric porosity; (4) resistance to aerodynamic heating; (5) compressibility effects; and (6) opening shock loads and transients.

For recommended practices, refer to NASA SP-8066.

7.5.9.8 ANTENNAS

Tests shall be conducted in accordance with the criteria of Section 4.9.11 to verify the mechanical and functional performance of antennas and their deployment or aiming mechanisms.

7.5.9.9 CASTINGS

Each casting design shall be tested in accordance with the criteria of Section 4.9.12 to demonstrate structural integrity under ultimate loads at critical temperature conditions.

7.5.9.10 FRICTION AND WEAR

Tests shall be conducted on all contacting surfaces designed to undergo sliding or rolling motion in accordance with the criteria of Section 4.9.14. These tests shall show that the friction and wear characteristics are acceptable and in agreement with analytical predictions. Service-life usage, environment, and chronological sequence shall be simulated as realistically as possible in the tests. All variables that affect friction and wear shall be controlled, including vacuum, temperature, load, speed, cyclic behavior, material hardness and topography, and atmospheric pressure and composition. The friction and wear of mechanisms used during test and checkout shall be accounted for.

7.5.9.11 NATURAL AND INDUCED ENVIRONMENTS

Tests shall be conducted to demonstrate that the vehicle structure is capable of withstanding or that it is protected from the effects of the natural and induced environments identified in Sections 5.1.3 and 6.

7.6 ACCEPTANCE TESTS

Tests shall be conducted on flight hardware to verify that the materials, manufacturing processes, and workmanship meet design specifications. When verification cannot be obtained by in-process tests, component and assembly tests shall be conducted to verify that the structure has been manufactured to meet design requirements. Unless definite verification can be obtained by lower-level tests, full-system tests shall be conducted to verify the adequacy of the complete structure. The test loads shall not exceed the limit loads, except in pressure-proof tests.

Support structure should be designed to simulate flight-load distributions and the stiffness of the vehicle at the support structure-specimen interface. Captive firing, handling, and transport loads should also be accounted for. The hardware should not be significantly fatigued by acceptance testing so as to impair its service life.

Anomalous behavior during tests and its potential influence on the vehicle should be identified.

For recommended practices, refer to NASA SP-8045.

7.6.1 MISALIGNMENTS AND TOLERANCES

In-process measurements and inspections shall be made to verify that alignments and dimensional tolerances are within prescribed limits.

For recommended practices, see NASA NHB 8080.1, NHB 8080.3, NASA SP-8045, and NASA NPC 200-2.

7.6.2 THERMAL PROTECTION SYSTEMS

Materials used in the thermal protection system (including surface coatings) shall be shown by test measurements to possess the thermal properties and other characteristics assumed in the design calculations.

Both before and during manufacture of the thermal protection system, several steps should be taken to ensure that the flight hardware will possess the same properties obtained in laboratory or model-shop fabrication and used in the design calculations. The first step is to establish firm specifications for material procurement and processing. Following this, all steps in the manufacturing and assembly process should be reviewed with quality-control and inspection personnel to ensure that inspections will be performed and accurate records maintained of all pertinent properties and measurements.

7.6.3 PRESSURE VESSELS

All pressure vessels and pressurized structure intended for flight use shall be proof-tested in accordance with the criteria of Sections 4 and 5.

Pressure vessels and main propellant tanks shall be tested at proof pressures.

When it has been shown by test that the pressure-vessel materials exhibit a decreasing resistance to fracture with decreasing temperature, the proof test shall be conducted at a temperature equal to or below the lowest expected operating temperature.

The time for pressurization to the proof-pressure level and the time the pressure is sustained at that level shall be held to the minimum consistent with test-system limitations. Depressurization time shall also be held to a minimum.

Tests shall be conducted to verify that the probable failure mode in service will be leakage rather than catastrophic fracture when assurance of safe-life cannot be provided by proof test.

For recommended practices, refer to NASA SP-8040.

7.6.4 LEAKAGE

Tests shall be conducted on pressurized structure in accordance with the criteria of Section 4.9.6 to measure the leakage rate and to verify that leakage is within prescribed tolerances.

7.6.5 CASTINGS

All castings intended for flight use shall be proof tested to limit loads at critical temperature conditions in accordance with the criteria of Sections 4 and 5.

For recommended practices, see MIL-A-00860A (USAF).

7.6.6 DOORS AND WINDOWS

Functional tests shall be conducted to verify that doors, movable covers, and their actuating mechanisms, locks, and related items of mechanical equipment operate within prescribed tolerances.

7.6.7 MECHANISMS

Tests shall be conducted to verify that all mechanisms operate within prescribed tolerances.

7.6.8 RECEIVING AND IN-PROCESS INSPECTION

Receiving tests, in-process tests, environmental tests, and inspections shall be conducted to ensure that manufacturing processes and workmanship comply with prescribed design characteristics (Sec. 4) and procurement specifications.

For recommended practices, refer to NASA NHB 8080.1, NHB 8080.3, NASA SP-8040, and SP-8045.

7.7 FLIGHT TESTS

Flight tests shall be conducted to provide adequate confidence in the limit loads used in the design and in the test conditions used in the qualification tests.

At least one flight test shall be instrumented to collect data permitting an evaluation of each of the following:

- **Flutter in the region of greatest dynamic pressure and most severe heating**
- **Control-surface buzz in the region of greatest dynamic pressure**
- **Buffeting**
- **Elastic-mode coupling of structure and propulsion system (pogo)**
- **Control system-elastic mode coupling**
- **Fuel-slosh coupling**
- **Axial-lateral coupling**
- **Structural response to explosive shock**
- **Refurbishment techniques**
- **Heating.**

These flight tests should be closely integrated with the structural development and qualification tests and with flight tests for validation of other systems. Anomalous behavior during tests should be identified and its potential influence on the vehicle should be determined.

For recommended practices on flight-loads measurements, refer to NASA SP-8002.

7.8 SPECIAL TESTS

7.8.1 RELIABILITY

Useful life shall be verified by reliability tests.

For recommended practices, refer to NASA NHB 5300.4(1A), NHB 8080.1, NHB 8080.3, NASA SP-8043, SP-8044, and MIL-STD-785A.

Overstress tests shall be conducted to determine failure modes, failure rates, and safety margins of major structural assemblies.

For recommended practices, refer to NASA NHB 5300.4(1B), NASA NHB 8080.1, NHB 8080.3, NASA SP-8044, AFSC DH 3-2, and MIL-STD-785A.

Receiving tests, in-process tests, environmental tests, and inspections shall be conducted to verify production hardware reliability.

For recommended practices, refer to NASA NHB 5300.4(1B), NHB 8080.1, NHB 8080.3, NASA SP-8045, and MIL-STD-785A.

Reliability of processes and standards shall be verified by test.

For recommended practices, refer to NASA NHB 8080.1 and NHB 8080.3.

7.8.2 MAINTAINABILITY

Maintainability tests shall be integrated with qualification and acceptance tests and shall include tests for access and servicing, interchangeability, fault detection, repair, and replacement.

For recommended practices, refer to NASA NHB 8080.3 and MIL-STD-470.

7.8.3 INSPECTION

Techniques for inspection of vehicle structure shall be developed to locate hidden defects, deteriorations, and fatigue effects.

Nondestructive inspection techniques are not adequate for all purposes. Tables 7-1, 7-2, and 7-3 list available techniques for inspection of coated refractory alloys, ceramics, and composites, respectively, with an indication of their current practical applicability in the field.

7.8.4 OPERATIONAL-USAGE MEASUREMENTS

Measurements of loads and temperatures during vehicle operation shall be taken to: (1) enhance confidence in predicted loads and temperatures; (2) reevaluate service-life expectancy; (3) evaluate intervals between inspections, refurbishments, and repairs; (4) establish operational limitations; and (5) provide data for development of improved structural design practices. Measurements shall be made at fatigue-critical or thermal-critical points on each vehicle.

Location of fatigue-critical and thermal-critical points should be established on the basis of all prior development, qualification, acceptance, and flight-test results.

A log of structural load experience, such as can be derived from a v-n-h recorder, should be maintained for each operational vehicle. These data should be periodically evaluated to compare actual service damage with predicted levels.

For recommended practices on flight-loads measurements, refer to NASA SP-8002.

TABLE 7-1 NONDESTRUCTIVE INSPECTION OF COATED REFRACTORY ALLOYS

TECHNIQUE	INSPECTION FOR	APPLICABLE TO		REMARKS
		FACTORY	FIELD	
Visual	Coating defects		X	Very noticeable metal oxide
Dye penetrant	Cracks, holes	X		Possible contamination
Thermoelectric	Coating thickness	X	X	Slow; exterior surface only
Eddy current	Coating thickness	X	X	Slow; exterior surface only
X-ray backscatter	Coating uniformity	X		Applicable to simple shapes
Ultrasonic	Honeycomb bonds	X		Well developed
Radiograph	Fabrication defects	X		Well developed
Scintillators	Coating thickness	X	X	Requires radioactive substance in coating material; requires development

TABLE 7-2 NONDESTRUCTIVE INSPECTION OF CERAMICS

TECHNIQUE	INSPECTION FOR	APPLICABLE TO		REMARKS
		FACTORY	FIELD	
Dye penetrant	Cracks	X		Possible surface contamination
Sonic	Cracks	X	X	Well developed
Ultrasonic	Cracks	X		Well developed
Thermal	Uniformity	X		Infrared mapping required

TABLE 7-3 **NONDESTRUCTIVE INSPECTION OF COMPOSITES**

TECHNIQUE	INSPECTION FOR	APPLICABLE TO		REMARKS
		FACTORY	FIELD	
Resin matrix				
Sonic	Debonding, voids, cracks	X	X	Well developed
Ultrasonic	Debonding, voids, cracks	X		Well developed
Radiography	Uniformity, voids	X	X	Well developed
Dielectric	Moisture	X	X	Principle developed
Resistivity	Moisture	X	X	Principle developed
Microwave	Resin cure	X		Frequency response is unknown; complex equipment required
Thermal	Uniformity	X		Infrared mapping required
Metal matrix				
Sonic	Debonding, voids, cracks	X	X	Principle developed
Ultrasonic	Debonding, voids, cracks	X		Principle developed
Radiography	Uniformity, voids	X	X	Difficult in field
Thermal	Uniformity	X		Infrared mapping required

APPENDIX

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

U.S. CUSTOMARY UNIT	CONVERSION FACTOR*	SI UNIT
foot	0.3048	meter
inch	0.0254	meter
knot	0.51479	meter/second
mph (miles per hour)	0.447	meter/second
pound force	4.448	newton
psf (pounds/foot^2)	47.8803	newton/meter^2
psi (pounds/inch^2)	6894.757	newton/meter^2

* Multiply value given in U. S. customary unit by conversion factor to obtain equivalent value in SI unit.