

# **Payload Flight Equipment Requirements and Guidelines for Safety–Critical Structures**

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## **International Space Station Program**

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PENDING EXPORT CONTROL CLASSIFICATION, THE INFORMATION CONTAINED IN THIS DOCUMENT MAY BE SUBJECT OF THE INTERNATIONAL TRAFFIC IN ARMS REGULATIONS (22 CFR 120 ET SEQ.) OR THE EXPORT ADMINISTRATION REGULATIONS (15 CFR 730 ET SEQ.).



**NASDA**

**National Space Development  
Agency of Japan**

**National Aeronautics and Space Administration  
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Houston, Texas  
Contract No. NAS15–10000 (PA16)**



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**INTERNATIONAL SPACE STATION  
PAYLOAD FLIGHT EQUIPMENT REQUIREMENTS AND GUIDELINES FOR  
SAFETY-CRITICAL STRUCTURES**

## **PREFACE**

The Payload Flight Equipment Requirements and Guidelines for Safety Critical Structures provides the composite structural, dynamic, and fracture control requirements for the design, analysis, fabrication, test and verification of payload flight hardware safety critical structures. The activities required to certify payloads for flight are defined. Payload Developers are to verify structural design compliance in accordance with this document as per NSTS 1700.7 ISS Addendum.

This document is invoked on payloads to be flown in ISS Pressurized Modules and U.S. Truss Locations and all the attached Payloads connected with the international partners. This document is controlled by the ISS Multilateral Payload Control Board.

**INTERNATIONAL SPACE STATION  
PAYLOAD FLIGHT EQUIPMENT REQUIREMENTS AND GUIDELINES FOR  
SAFETY-CRITICAL STRUCTURES**

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## PAYLOAD FLIGHT EQUIPMENT REQUIREMENTS AND GUIDELINES FOR SAFETY-CRITICAL STRUCTURES

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**INTERNATIONAL SPACE STATION**  
**PAYLOAD FLIGHT EQUIPMENT REQUIREMENTS AND GUIDELINES FOR**  
**SAFETY–CRITICAL STRUCTURES**

**LIST OF CHANGES**

All changes to paragraphs, tables, and figures in this document are shown below.

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## **1.0 INTRODUCTION**

### **1.1 PURPOSE**

This document provides the structural, dynamic, and fracture control requirements for the design, analysis, fabrication, test, and verification of payload Safety-Critical Structures (SCS) on flight hardware for the International Space Station (ISS). This document is applicable to payloads that fly in the Shuttle middeck, attached payloads in the Shuttle cargo bay (e.g., sidewall or carrier-mounted payloads), Expedite the Processing of Experiments to Space Station (EXPRESS) pallet, Spacelab pallet, in the Station-provided Multi-Purpose Logistics Module (MPLM) or on the Unpressurized Logistics Carrier (ULC). This document defines structural requirements, methodology for determining load factors, and factors of safety. It also defines the activities required for certifying safety-critical structural payload components for flight. Integrated payloads which span the Space Shuttle cargo bay, referred to herein as “cargo elements,” need to also consider NSTS 14046, NSTS 37329, and NASA-STD-5003 for the requirements and process for structural verification.

In the event of a conflict between the requirements of this document and the requirements shown in NSTS 1700.7 ISS Addendum and NASA-STD-5003, then the requirements in NSTS 1700.7, NSTS 1700.7 Addendum, then NASA-STD-5003/ECSS-E-30-01/NSTS 14046, then SSP 52005 shall govern.

the requirements in NSTS 1700.7 ISS Addendum then NASA-STD-5003/ECSS-E-30-01A/NSTS 14046, the requirement of SSP 52005 shall take precedence.

Instructions defining the methodology for performing SCS assessments are included. Additionally, instructions for preparation and delivery of safety-critical structural data are included. Peculiar requirements for the safety certification of composites, structural bonds, beryllium, and glass, especially fracture control and testing, are also included.

### **1.2 SCOPE**

This document is a compilation of the structural design and verification requirements (with sample solutions) to be used by the ISS Payload Developer (PD) to satisfy Space Shuttle and ISS safety criteria. It provides a single comprehensive document for payload structural design and analysis criteria, and a comprehensive set of structural design requirements for PDs to ensure successful fulfillment of safety requirements. Requirements dealing with reliability and performance of payload components are beyond the scope of this document and are levied individually by experiment performance specifications.

A compilation of considerations necessary to meet design, fabrication, and verification requirements on safety-critical flight structures is provided. These considerations begin with the definition of SCS. The required steps for safety qualification are outlined, directions are given for determining load factors (for lift-off, on-orbit, and landing conditions), and provides line guidelines for calculating stresses and margins of safety for all flight phases.

Design criteria which affect structural safety are emphasized, and material/process controls required for SCS are listed. Methodology guidelines and requirements are discussed for structural analysis/fracture control and test procedures are discussed. Reporting requirements are also included.

### **1.3 OVERALL REQUIREMENTS**

The responsible PDs will show by analysis or analysis supplemented by tests, that the hardware meets STS and ISS design requirements with sufficient margin of safety to ensure adequate strength and safety of the STS, ISS, and personnel at all times. Analysis and test reports will be submitted which will verify the capability of hardware to meet design requirements. Verification requirements may be met by a combination of analysis and test results.

The following loads and loads combinations will be considered during design:

- A. Assembly and Installation
- B. Testing
- C. Transportation
- D. STS flight (lift-off, ascent, descent, reentry, and landing)
- E. Emergency landing
- F. ISS on-orbit
- G. Crew-applied loads
- H. Pressure
- I. Thermal

The PD will perform and document adequate structural analyses and/or test results based on design load factors given in the applicable Interface Requirements Document (IRD). The design load factors for payloads located within the ISS are documented in the Pressurized Payload Interface Requirements Document, SSP 57000. Load factors for payloads located on the external payload attach sites are documented in the Attached Payload Interface Requirements Document, SSP 57003. The load factors to be used for “as-built” verification will be those in effect at the time of the verification analyses for the “as-built” hardware configuration. This

structural report will include identification of SCS and meet the minimum requirements of Section 9. Documentation drawings, analyses, and reports will be submitted in accordance with the requirements specified in the payload-unique verification plan.

Payload hardware which fails to meet the design, analysis, test, fracture control, and verification requirements specified herein must obtain approval for flight from the SSP Structures Working Group (SSP-SWG) and/or the PSRP.

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## **2.0 APPLICABLE DOCUMENTS**

The following documents of the latest issue or revision (and all changes thereto) are applicable to payload hardware as described in the body of this document. The documents are listed by subject category for convenience.

### **2.1 GOVERNMENT**

#### **2.1.1 SAFETY AND VERIFICATION REQUIREMENTS**

JSC 26943	Guidelines for the Preparation of Payload Flight Safety Data Packages and Hazard Report
NSTS 1700.7	Safety Policy and Requirements for Payloads Using the Space Transportation System
NSTS 1700.7 ISS Addendum	Safety Policy and Requirements for Payloads Using the International Space Station
NSTS/ISS 13830	Payload Safety Review and Data Submittal Requirements for Payloads Using the – Space Shuttle – International Space Station
NSTS/ISS 14046	Payload Verification Requirements
NSTS/ISS 18798	Interpretations of NSTS/ISS Payload Safety Requirements

#### **2.1.2 STRUCTURAL REQUIREMENTS**

ECSS-E-30-01A*	Fracture Control
JSC-22267	Fatigue Crack Growth Computer Program “NASGRO“
Letter MA2-00-057	Mechanical Systems Safety
MDC91W5023C	Spacehab/Experiment Interface Definition Document
MIL-STD-1522A	Standard General Requirements for Safe Design and Operation of Pressurized Missile and Space Systems
NASA-STD-5003	Fracture Control Requirements for Payloads Using the Space Shuttle

\* NASA letter OE-01-154 dated December 19, 2001, “Reciprocal Agreement NASA JSC/ESA-ESTEC Reciprocal Fracture Control Agreement.”

NSTS 21000-IDD-ISS	Shuttle/Orbiter International Space Station Cargo Standard Interfaces
NSTS 21000-IDD-MDK	Shuttle/Payload Interface Definition Document for Middeck Accommodations
NSTS 21000-IDD-SML	Shuttle/Payload Interface Definition Document for Small Payload Accommodations
SLP/2104	Spacelab Payload Accommodation Handbook
NSTS 37329	Structural Integration Analysis Responsibility Definition for Space Shuttle Vehicle and Cargo Element Developers
SSP 30425	Space Station Program Natural Environment Definition for Design

### **2.1.3 FASTENING SYSTEMS**

MIL-B-7883	Brazing of Steels, Copper Alloys, Nickel Alloys, Aluminum and Aluminum Alloys
MIL-N-25027	Nut Self-locking 250 Degrees Fahrenheit, 450 Degrees Fahrenheit, and 800 Degrees Fahrenheit
MIL-STD-1515	Fastener Systems for Aerospace Applications
MIL-W-6858	Welding, Resistance; Aluminum, Magnesium Non-hardening Steels or Alloys, Nickel Alloys, Heat Resisting Alloys, and Titanium Alloys; Spot and Seam
MS 33540	General Practices for Safety Wiring and Cotter Pinning
MSFC-SPEC-560	Specification, Welded Steels, Corrosion and Heat Resistant Alloy
MSFC-STD-486	Torque Limits for Threaded Fasteners
MSFC-STD-557	Threaded Fasteners 6AL-4V Ti Alloy — Usage Criteria for Spacecraft Application
MSFC-STD-561	Threaded Fasteners, Securing of Safety Critical Flight Hardware Structure Used on Shuttle Payloads and Experiment
MSFC-STD-655	Weld Filler Metal
MSFC-STD-969	Control of Braze Filler Metal
NSTS 08307	Criteria for Preloaded Bolts



## **2.1.4 MATERIALS**

MIL-HDBK-5	Metallic Materials and Elements for Aerospace Vehicle Structures
MIL-HDBK-17	Plastics for Flight Vehicles
MIL-HDBK-691	Handbook of Adhesive Bonding
MSFC-SPEC-504	Specification: Welding, Aluminum Alloys
MSFC-STD-3029	Guidelines for the Selection of Metallic Materials for Stress Corrosion Cracking Resistance in Sodium Chloride Environments
MSFC-HDBK-527F/JSC-09604	Material Selection List for Space Hardware Systems
SSP 30233	Space Station Requirements for Materials and Processes

## **2.1.5 NONDESTRUCTIVE EVALUATION**

MIL-STD-410	Nondestructive Testing Personnel Qualification and Certification
MIL-STD-2154	Inspection Process for Ultrasonic, Wrought Metals
MSFC-STD-366	Penetrant Inspection Method
MSFC-SPEC-259	Radiographic Inspection; Soundness Requirements for Fusion Welds in Aluminum and Magnesium Alloy Sheet and Plate Material
MSFC-STD-481	Radiographic Inspection Procedures and Acceptance Standards for Fusion Welded Joints in Stainless and Heat Resistant Steel
MSFC-STD-1249	Standard NDE Guidelines and Requirements for Fracture Control Program
ASNT-CP-189	ASNT Standard for Qualification and Certification of Nondestructive Testing Personnel

## **2.2 NON-GOVERNMENT**

### **2.2.1 FASTENING SYSTEMS**

SAE AS4536	Safety Cable Kit Procurement Specification and Requirements for Use
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## **2.2.2 STRUCTURAL REQUIREMENTS**

ATR-93(3827)-1	Guidelines for Design and Analysis of Large, Brittle Spacecraft Components, E. Y. Robinson, The Aerospace Corporation; report prepared for NASA/Johnson Space Center, September 1, 1993
COL-RIBRE-SPE-0164	Columbus Pressurized Payload Interface Requirements Document
COL-RIBRE-SPE-0165	Columbus External payload Interface Requirements Document
JCX-95006	JEM Payload Accommodations Handbook
SSP 52000-IDD-EPP	Interface Definition Document EXPRESS Pallet
SSP 52000-IDD-ERP	Interface Definition Document EXPRESS Rack
SSP 52000-PAH-PRP	International Space Station Payload Accommodations Handbook - Pressurized Payloads
SSP 57000	Pressurized Payloads Interface Requirements Document
SSP 57003	Attached Payload Interface Requirements Document

## **2.2.3 REFERENCE DOCUMENTS**

QQ-B-566	Rod and Electrodes, Welding Aluminum, and Aluminum Alloys
TN-ER-33-029-78	Penetration Possibility of Loose Parts through GAS (Getaway Special) Canister
SSP 30560	Glass, Windows, and Ceramic Structural Design and Verification Requirements
SSP 50200-03	Station Program Implementation Plan, Volume III: Cargo Analytical Integration

### 3.0 CLASSIFICATION OF SAFETY-CRITICAL STRUCTURES

This section provides an overview of the safety-critical structures process, including definitions and classifications, and forms the basis for further discussion. It is intended to introduce, not cover, the detailed requirements provided in later sections.

The structural integrity of payload flight equipment is a critical flight safety concern. Flight safety of the payload equipment shall be assured by structural analysis and/or tests. These analyses and/or tests are for the purpose of assuring that structural failure does not create a safety hazard. They are not, however, intended to cover the functional integrity of the experiment unless loss of functionality could create a hazard to the STS/ISS or crew.

All structural elements including associated interfaces, fasteners, and welds in the payload component primary load path, including pressure systems, uncontained glass, rotating machinery, mechanical stops, and containment devices, are safety critical and shall be analyzed. For cargo bay exposed payloads (i.e. payloads mounted to a side wall carrier or to an across the bay carrier), the definition of safety critical structure is expanded to also include all secondary structure that has significant dynamic response of its own or is important to the overall response of the carrier. Safety critical structural elements shall be shown to have positive margins of safety or, in the case of containment devices, be proven to be structurally adequate against penetration. The primary load path is defined as the collection of structural elements which transfer load from one part of a structure to another. Elements in the primary load path experience loading in excess of that created by their own mass. Examples of non-SCS hardware would include electronic components (which can be shown to be contained inside a box) whose failure would not create a hazard, printed circuit boards, switch covers, and their associated fasteners.

Stowed hardware which is packed in foam is generally considered to be non-safety critical. Items which are soft stowed in foam and bags do not need to consider random vibration loads in addition to the low frequency load factors of SSP 57000, table 3.1.1.3–4. This does not mean that there is no random vibration environment. It is assumed that the loads imposed by the random vibration environment as seen by the item encased by foam will be small enough (effectively zero) to be neglected in design consideration. Normally the payload developer will conduct a workmanship vibration test (strongly suggested for payloads containing moving parts, mechanisms, or electronics) to ensure that manufacturing defects are discovered and corrected. The vibration level and duration of workmanship vibration tests are determined by the payload developer or the sponsoring agency.

Stowed hardware which is “hard-mounted” in drawers, lockers, or similar containers is generally classified as safety critical and will require stress analysis or containment analysis. Stowed hardware which contains pressurized systems or other hazards (e.g., toxic materials, exposed glass) must be classified as safety critical and analyzed. Also stowed hardware mounted on orbit may be classified as safety critical.

SCS may include a subset of components whose failure would present catastrophic hazards. These components are termed “Fracture Critical” and shall be shown through analysis, inspection, and/or test to be safe from failure throughout the mission. The process flows for accomplishing this are defined below. Fracture-critical structural components shall be identified and listed (paragraph 3.2). It shall be proven that these listed components will not fail during all flight phases (paragraph 3.3).

Containment devices are shrouds, covers, housings, etc., which contain components or small items that, if released in a habitable area or in the cargo bay, would present a safety hazard. Broken glass in habitable areas and any item larger than 0.25 lb in the cargo bay is normally a concern. Plans to use a containment analysis in lieu of stress analysis to verify structural integrity (other than fracture screening) shall be submitted, along with supporting rationale, in accordance with Section 9.3 data submission requirements.

### **3.1 CATEGORIES OF SAFETY-CRITICAL STRUCTURES**

Four categories of SCS and their corresponding paths to the fracture-critical list are shown in Figure 3.1–1. These four are discussed below.

#### **3.1.1 PRESSURE SYSTEMS AND ROTATING MACHINERY**

The pressure systems and rotating machinery category includes:

- A. Pressure Vessels - Defined in NSTS 1700.7 ISS Addendum as containers storing pressurized gasses or liquids and which:
  - (1) Will experience a design limit pressure greater than 100 pounds per square inch absolute (psia), or
  - (2) Contain a fluid in excess of 15 psia which will create a hazard if released, or
  - (3) Contain stored energy of 14,240 ft-lb [0.01 lb of trinitrotoluene (TNT) equivalent] or greater, based on adiabatic expansion of a perfect gas.
- B. Lines, Fittings, and Components - Lines, fittings, and components of pressurized systems, excluding pressure vessels, are safety critical but are in a separate category from pressure vessels.

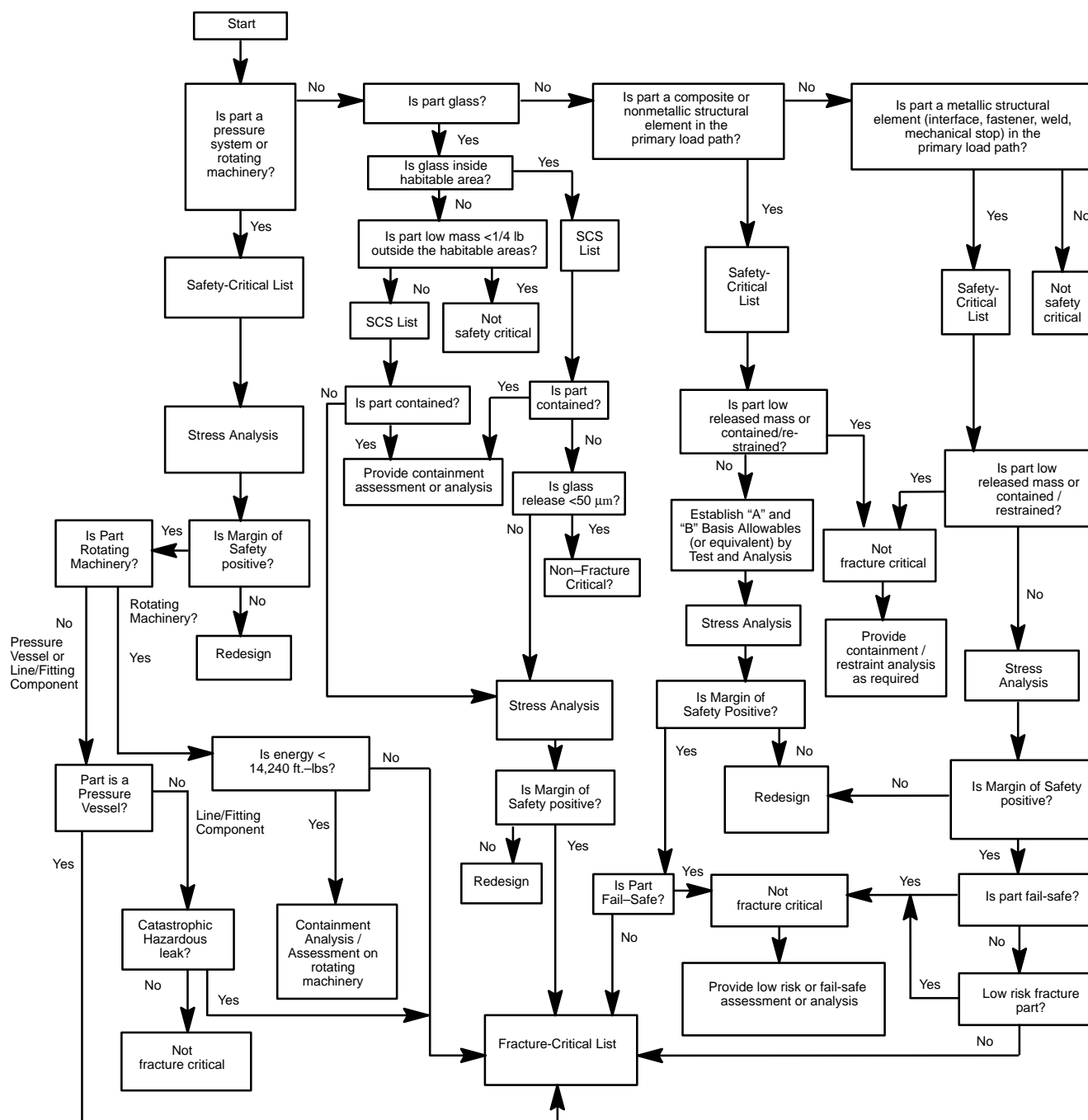
- C. Rotating Machinery - All rotating machinery are safety critical. A rotating mechanical assembly that attains kinetic energy ( $1/2 I\omega^2$ ) equal to or greater than 14,240 ft-lb is fracture critical.

Note: All pressure vessels and rotating machinery, as defined above, are fracture critical. Lines, fittings, and other components are fracture critical if leakage or loss of pressurization would result in a catastrophic hazard.

Rotating machinery shall be analyzed to demonstrate proof of containment, or shown to be acceptable by safe-life analysis and testing. As indicated in Figure 3.3-1, if the margin is negative, the part is not acceptable and shall be redesigned. If there is a positive margin of safety, it is still fracture critical and shall be so listed and treated. Rotating mechanisms with lower kinetic energy levels are to be classified by the same criteria as other structural components and must be contained.

Lines and fittings and other components (excluding pressure vessels) of pressurized systems shall be designed to the requirements given in paragraph 5.1.3.3. Stress analyses for these components shall be performed to include all loading events in addition to pressure loads (covered by 5.1.3.3). Safe-life analyses are not required for these components, and they are not fracture-critical unless a leak would result in a catastrophic hazard.

Propellant tanks or other pressure vessels which are pressure-stabilized must utilize a single-fault tolerant pressure monitoring technique to verify that appropriate minimum pressures are present in the tank or vessel prior to the application of launch or landing loads. A pressure-stabilized tank or vessel must contain a minimum internal pressure to maintain the required ultimate Factors of Safety (FS) to ensure structural integrity under launch and landing loads. Pressure monitoring may be implemented by using pressure transducers, strain gauges, or other equivalent techniques.



**FIGURE 3.1-1 SAFETY-CRITICAL/FRACTURE-CRITICAL SELECTION LOGIC DIAGRAM**

### **3.1.2 GLASS**

Glass inside a habitable area is always considered safety critical and shall be shown safe from breakage, shown to be contained or shown to release less than 50  $\mu\text{m}$  particles. If a payload with a glass component is carried in the crew module, positive protection to the crew against any breakage or release of shatterable material is required. Outside a habitable area, glass of low mass (less than 0.25 lb) is not safety critical. A glass part (not shown to be contained or low mass) shall be subjected to a stress analysis to determine its safety margin. If the margin is positive, the part is then screened for fracture criticality and for possible inclusion on the fracture-critical list. See Appendix F for additional requirements.

### **3.1.3 COMPOSITE OR NONMETALLIC STRUCTURAL COMPONENTS IN THE PRIMARY LOAD PATH**

A “composite” material is defined here as two or more materials combined on a macroscopic scale to yield useful structural properties. Composites or nonmetallic structural elements in the primary load path are always classified as safety critical and shall be subjected to stress analysis to determine safety margins. The PD shall conduct tests and analyses on the materials and parts to provide a statistically valid data set for an “A” and “B” Basis Allowables (or equivalent). Once the allowables have been established, a stress analysis using these criteria shall be performed for the part. If the stress analysis shows a negative margin, the part shall be redesigned. If the margin is positive, the part is then screened for fracture criticality and for possible inclusion on the fracture-critical list. See Appendix F for additional requirements.

### **3.1.4 METALLIC STRUCTURAL COMPONENTS IN THE PRIMARY LOAD PATH**

A stress or containment analysis shall be performed for all metallic structural components in the primary load path. If the analysis shows a negative margin of safety, the part shall be redesigned. If the margin is positive, the part is then screened for fracture criticality and for possible inclusion on the fracture-critical list.

## **3.2 FRACTURE SCREENING**

The objective of the fracture screening activity is to determine if structural failure due to the presence or propagation of flaws can cause a catastrophic hazard for the safety-critical part in question. If the part is shown to be of low released mass, contained, fail-safe, or low risk, then it is not fracture critical. Otherwise, it is fracture critical and shall be shown to be safe-life (with specific exceptions for pressure vessels and rotating machinery as described below).

## **3.3 FRACTURE CONTROL**

The requirements to be followed for fracture control and fracture mechanics analyses are specified in paragraphs 5.3 and 6.2, respectively. Figure 3.3–1 illustrates the logic flow for meeting fracture control requirements and ensures that failures due to pre-existing flaws in properly designed space hardware do not occur.

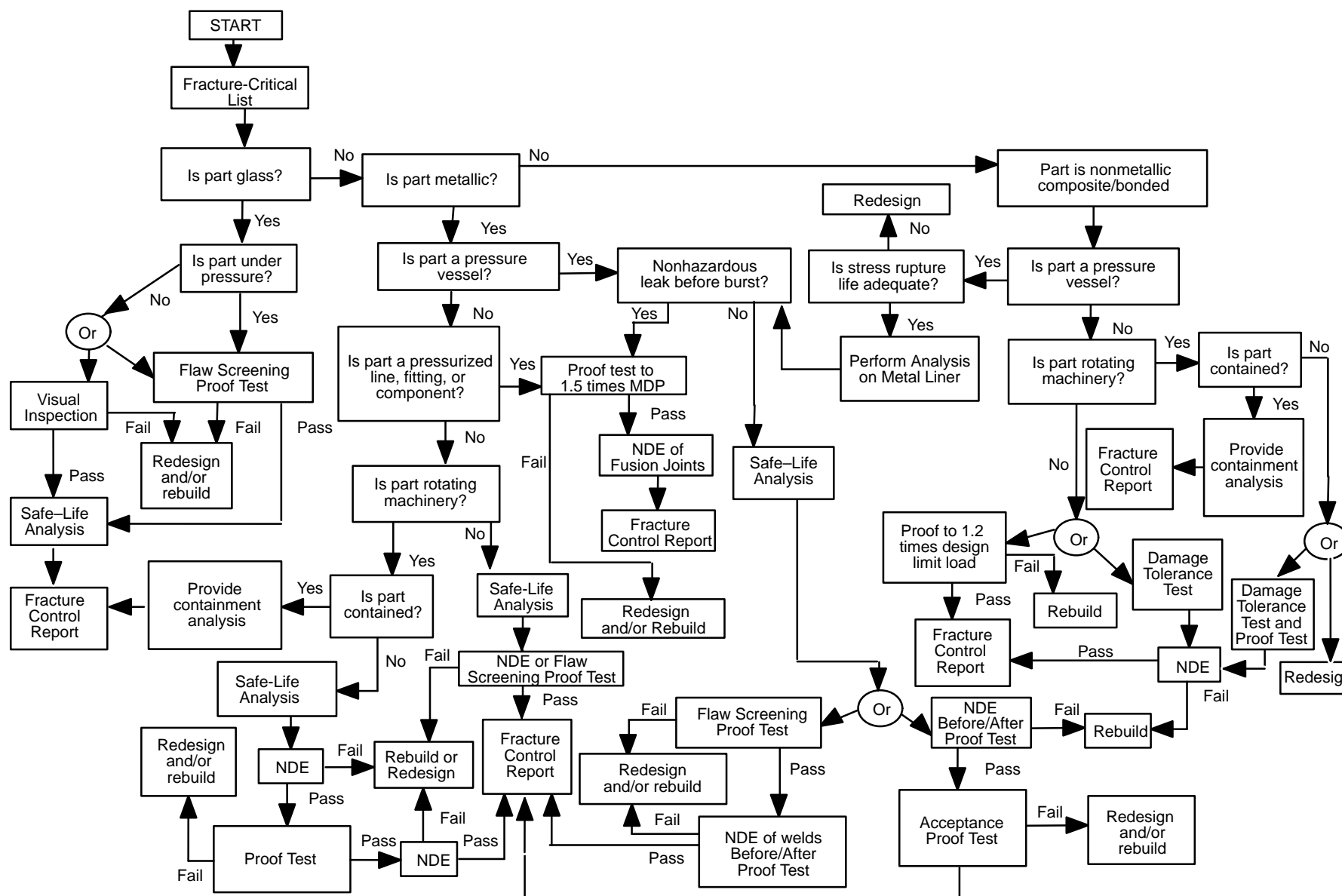


FIGURE 3.3-1 FLOW DIAGRAM FOR FRACTURE CONTROL



In addition to the oversight of the responsible fracture control authority (i.e., at the NASA Center or other Government agency), the PD shall designate a specific fracture control individual or group to be responsible for directing the payload fracture control program and for ensuring its effectiveness. This designee shall be responsible for monitoring, reviewing, and approving fracture control activities performed both internally and by subcontractors or other contributors to the payload system. As appropriate, concurrence is required by other key organizations including engineering; manufacturing; and safety, reliability, and quality assurance.

### **3.3.1 PRESSURE VESSELS AND ROTATING MACHINERY**

#### **3.3.1.1 PRESSURE VESSELS**

Fracture control of a pressure vessel begins by determining whether the only failure mode for the vessel at Maximum Design Pressure (MDP) is a Leak-Before-Burst (LBB) failure mode. If the pressure vessel is LBB, no additional analysis is required. If the pressure vessel is not LBB at MDP or if a leak would result in a catastrophic hazard, safe-life analysis and specific Nondestructive Evaluation (NDE) or flaw screening proof testing to establish potential maximum initial flaw size shall be performed. In both cases, results of the analyses, tests, and inspections shall be included in the Fracture Control Report.

#### **3.3.1.2 ROTATING MACHINERY**

The fracture control of rotating machinery involves either containment analysis or safe-life analysis and NDE, and proof test. Safe-life analysis and NDE are required unless: (1) loss of function of the rotating device does not result in a catastrophic hazard, and (2) containment is demonstrated by an acceptable analysis or test. In either case, results of the analyses and tests shall be included in the Fracture Control Report.

### **3.3.2 COMPOSITES**

The fracture control procedure for composites is accomplished through testing of the composite. These are either proof tests where 1.2 times the design limit load is applied to the flight parts, or damage tolerance tests of flight parts whose flaws have been identified and cataloged. If the part passes either of these tests, it is considered flightworthy, and the appropriate data shall be included in the Fracture Control Report. If the part does not pass its test, then it is unacceptable and the part shall be redesigned. As an alternative, flight hardware may also be approved for fracture control based on special considerations as given in Section 6.2.7, paragraph E.

### **3.3.3 METALLIC OR GLASS**

Fracture critical metallic or glass structural parts must be shown to meet all fracture control requirements detailed in sections 5.3 and 6.2. One way to show acceptability for fracture critical metallic or glass parts is by a fracture mechanics analysis which demonstrates the required safe-life is achieved and an Nondestructive Evaluation (NDE) inspection of the parts or a flaw screening proof test to inspect for crack-like flaws, and additional procedures as detailed in sections 5.3 and 6.2. If no crack-like flaws are found with the NDE, the part is deemed flightworthy, and the appropriate documentation shall be provided in the Fracture Control Summary Report. If any crack-like flaws are found, the part may not be useable, and it should be remanufactured and/or redesigned. Alternatively, a specific, detailed, fracture mechanics analysis (or test) shall be performed to justify the use of any fracture-critical flight part with detected crack-like flaws per the requirements of NASA-STD-5003 section 4.2.3.1.1.c.

### **3.4 EXAMPLE OF SAFETY-CRITICAL STRUCTURE**

Figure 3.4-1 represents an example of a payload flight equipment assembly which includes several categories of safety-critical structural interfaces, including examples of both fail-safe and single-point failure components. The payload depicted represents no particular payload, but was conceived to illustrate the various processes required to qualify payload equipment structures for flight aboard the STS and ISS. The example consists of several types of equipment mounted on a platform which could be attached to a support structure at standard attach points. Note that this experiment assembly attachment is statically determinate; therefore, each attachment interface is fracture critical since it represents a single-point failure.

The interfaces of the various equipment components with the mounting platform represent different categories of structural attachment criticality and fracture control requirements. Because the Data Retrieval Unit and the Motion Sensor Unit are attached to the mounting platform using redundant (more fasteners than needed to show positive Margin(s) of Safety (MS) using the required FS) attachments, they are not fracture critical but they are safety critical. If their contents cannot penetrate the container walls and the units are not pressure vessels, containment may be substituted for safety-critical structural analysis. Proof of containment will also remove the contents of the Power Supply and Electronics Box from the fracture-critical list. Since the box itself supports the Optical Pointing Assembly, the box, the structural support for the gimbals, and the gimbals themselves are safety and fracture critical (because they are part of a nonredundant load path up to the optics carrier).

The carrier, which supports the platform, requires safety-critical structural verification. The attachment provisions for the instruments mounted on it have been made redundant for the sake of simplification and, hence, are not fracture critical. The instruments, however, do contain SCS and will require analysis and verification to assure the structural integrity of appendages and parts not contained or restrained by redundant structural elements. Finally, the attachment of the

carrier retention fixture to the platform is redundant, therefore not fracture critical, but the carrier and its retention mechanism are fracture critical.

The retention mechanism is designed for power-on unlatching with power-off lock provisions; however, the drive mechanisms requires power to restow and relatch the optical carrier assembly for reentry and landing. To meet requirements for two failure tolerant safing, (1) the gimbal drives must be designed to withstand landing loads without essential power, such that no safety-critical failure occurs or, (2) emergency power from a redundant source must be provided for emergency restow operations in the event of primary power failure.

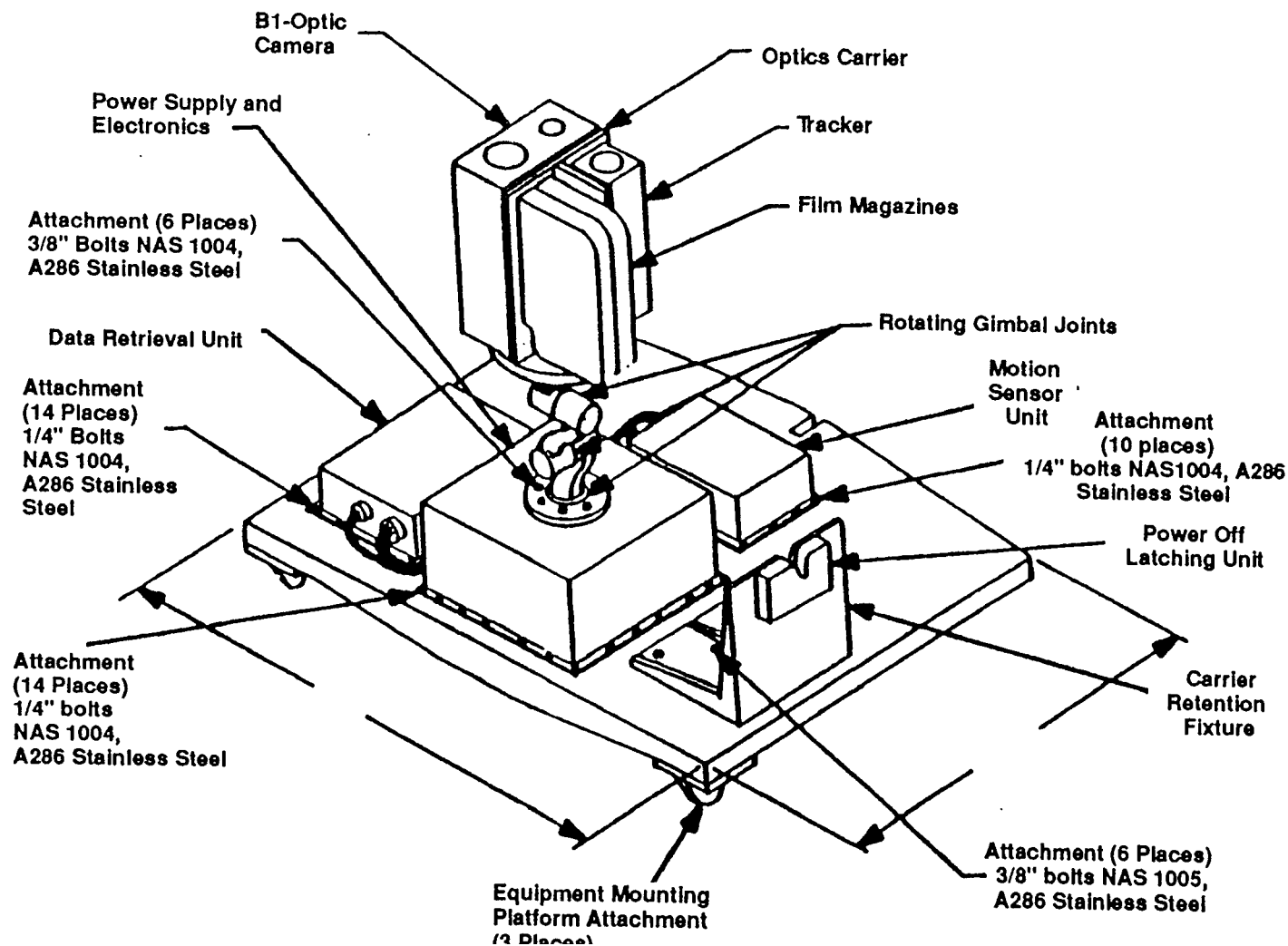


FIGURE 3.4-1 PAYLOAD FLIGHT EQUIPMENT ASSEMBLY EXAMPLE

## 4.0 DESIGN LOADS REQUIREMENTS

In order to design payload flight equipment (to assure adequate structural integrity for mission life), it is essential that a realistic set of loads be used in the structural analysis. Design loads that must be considered are encountered during ground handling/transportation, during liftoff and landing, and during on-orbit operations. Liftoff/landing loads criteria discussed herein are applicable to Shuttle launch and Orbiter landing. On-orbit operations loads are presented for payloads on both the Orbiter and ISS (US elements only). Table 4-1 addresses the “Flight” and “Stage” phases for the ISS. The “Flight” phase denotes the activities associated with the Shuttle launch, Orbiter on-orbit operations, and Orbiter landing. The “Stage” phase denotes the time when a payload is aboard the ISS between its Shuttle launch and Orbiter landing flights. Payload flight equipment shall be designed and verified, for interface and safety considerations, to the combined loads environment for each flight/stage phase.

This section describes the design loads requirements, explains where to get specific data, and gives guidelines for the calculations and use of the data. Section 4.1 delineates sources of generic design/loads criteria for common ISS payloads.

**TABLE 4-1 APPLICABLE ENVIRONMENTS FOR EACH FLIGHT/STAGE PHASE**

PHASE	ENVIRONMENT						
	LOW FREQUENCY	RANDOM	ACOUSTIC	CREW/ EVR INDUCED	THERMAL	PRESSURE	SHOCK
Ground Transportation	X	X			X		X
Lift-off/Ascent	X	X	X			X	
On-Orbit (Orbiter)	X*			X	X	X	
On-Orbit (ISS) (US Element only)	X*	X*		X	X	X	X
Descent	X*				X	X	
Landing (Nominal)	X				X	X	
Landing (Emergency)	X				X	X	
Landing (Contingency De-orbit)	X				X	X	

#### 4.1 SOURCES FOR DESIGN/LOADS CRITERIA

A generic set of design loads for each class of payload is provided in the following carrier-specific Interface Requirements Document (IRD) or payload Interface Definition Document (IDD). These documents address ISS facilities, payloads on or in ISS facilities, and payloads that attach directly to the Orbiter.

- A. SSP 57000, Pressurized Payloads Interface Requirements Document. The load factors contained in this IRD are appropriate for components mounted to ISPR posts.
- B. NSTS 21000-IDD-ISS, Shuttle Orbiter/International Space Station Cargo Standard Interfaces. The load factors in this document are appropriate for all cargo elements which are mounted across the payload bay.
- C. NSTS 21000-IDD-SML, Shuttle/Payload IDD for Small Payload Accommodations. The load factors in this document are appropriate for all payloads which mount to an Orbiter payload by a sidewall carrier. The list of sidewall carriers includes the Adaptive Payloads Carrier (APC), the Increased Capability Adaptive Payload Carrier (ICAPC) and the Get-Away Special (GAS) beam.
- D. NSTS 21000-IDD-MDK, Shuttle/Payload IDD for Middeck Accommodations. The load factors contained in this IDD are appropriate for payloads or components mounted in the Orbiter Middeck.
- E. SSP 52000-IDD-ERP, EXPRESS Rack IDD. The load factors contained in this IDD are appropriate for payloads that are designed to be integrated into an EXPRESS Rack.
- F. SSP 52000-IDD-EPP, EXPRESS Pallet IDD. The load factors contained in this IDD are appropriate for payloads that are designed to be integrated into an EXPRESS Pallet.
- G. SSP 57003, Attached Payload Interface Requirements Document. The loads data contained in this IRD are appropriate for integrated payloads or facilities that attach directly to the US portion of the ISS External Truss. They apply only to on-orbit phases of the attached payload. Loads for lift-off/landing and on-orbit loads inside the Shuttle orbiter must be obtained from the IRD or IDD for the carrier used to get the attached payload to orbit. Loads for payloads mounted on platforms are attached to the ISS External Truss (e.g., payloads on the EXPRESS Pallet), are provided in a facility-specific IRD or IDD.

The loads criteria in these documents represent the best estimate of maximum loads as a function of flight condition and equipment location on the Orbiter or ISS.

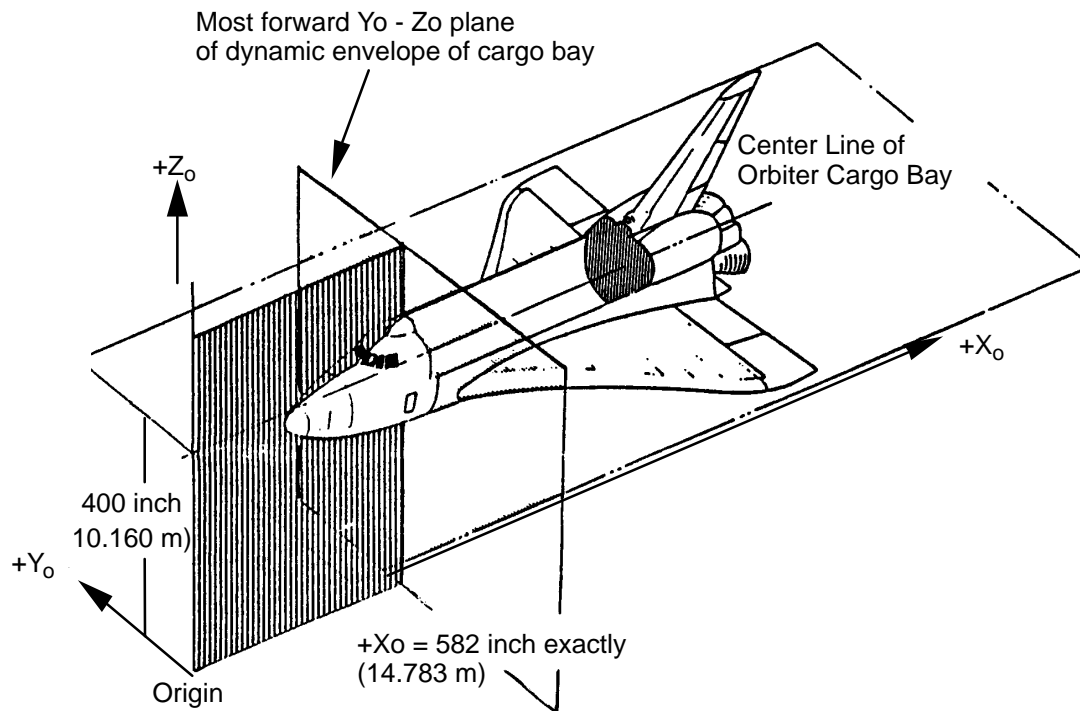
## 4.2 DESIGN LOADS AND LOAD FACTORS

For purposes of designing and verifying Space Station payload equipment hardware, design load factors shall be determined for the various equipment locations within the Orbiter/payload system for transportation/ground-handling, lift-off, descent, landing, and emergency landing events.

Design loads criteria for lift-off and landing is usually given in terms of accelerations or load factors (expressed in g's) pertaining to each phase of flight. For payloads, load factors represent the inertial force resulting from a given acceleration, and is therefore equal in magnitude and opposite in direction from that acceleration. Load factors provided by the Shuttle Program in the NSTS 21000-IDD-ISS, NSTS 21000-IDD-MDK, and NSTS 21000-IDD-SML documents are defined as the sum of the external forces acting on a payload divided by its weight. Thus, in the Shuttle case the load factor is in the same direction as the acceleration. Therefore, PDs need to be cognizant of how load factors are defined in the applicable IRD or IDD and use them accordingly to evaluate stresses with the correct directional sense.

Warpage loads are additional forces induced at the rack-to-module interface caused by redundancies in the rack/module connections. They are caused by the interaction of the rack with the flexible module (e.g., MPLM) structure. (The ISPR rack/MPLM interfaces are redundant by two degrees of freedom.) These loads induced by the relative displacements at the rack/MPLM interfaces can be significant, and must be combined with the inertial loads. The module-induced displacements are typically obtained from Coupled Loads Analyses (CLA). Guidelines and additional information are provided in the International Standard Payload Rack (ISPR) Structural Integrator's Handbook, SSP 57007, section 5.2.

Most accelerations or load factors are keyed to a given Degree of Freedom (DOF) using the Orbiter Coordinate System (figure 4.2-1) and may have positive and negative components with different magnitudes for each DOF. These accelerations are imposed on the payload equipment mass to generate reaction forces at the payload attach points. Accelerations may be given as linear accelerations in the  $\pm X$ ,  $\pm Y$  and  $\pm Z$  directions, or as linear and rotational accelerations in  $\pm X$ ,  $\pm Y$ ,  $\pm Z$ ,  $\pm \theta_x$ ,  $\pm \theta_y$ , and  $\pm \theta_z$ . The center of rotation for the rotational load factors is the payload center of gravity (cg) for the integrated rack or attached payload. All combinations of accelerations corresponding to a given phase shall be applied to obtain limit loads for that phase. The design loads are defined as the largest of the combined loads that apply during each phase. Specific rules for combination are given in the following subsections.



**FIGURE 4.2-1 ORBITER COORDINATE SYSTEM**

#### **4.2.1 DESIGN LOAD FACTORS FOR LIFT-OFF**

The design load factors for lift-off are derived by root-sum-squaring (rss) the random load factors with the low frequency transient load factors, one axis at a time as shown in Table 4.2.1-1. The transient load factors are applied simultaneously in the remaining two directions. Note that the transient and random load factors shall be in the same coordinate system before they are combined. An alternate loads combination approach, for rack-mounted payloads only, is provided in Appendix C and requires prior written approval of the Space Shuttle Program Structures Working Group.

The random load factors shall be calculated using the procedure described in paragraph 4.2.4.

There are 192 load factor cases for lift-off using all of the '+' and '-' value combinations. When there are no rotational load factors (or the effects of the rotational load factors are included in the translational load factors), there are 24 possible lift-off cases.

A static analysis of the rack constrained at the rack/module interface degrees of freedom shall be performed using the appropriate Quasistatic Load (QSL) factors from the Design Coupled Loads Analyses (DCLA) or Verification Loads Analysis (VLA). Warpage loads shall also be



developed using appropriate relative displacements from a DCLA or VLA. The calculated Margin of Safety (MS) will be computed based on the above load considerations.

**TABLE 4.2.1–1 LOAD COMBINATION CRITERIA FOR SPACE STATION COMPONENTS**

LOAD IN EACH AXIS ACTING SIMULTANEOUSLY						
LOAD SET	ORBITER X <sub>0</sub> AXIS	ORBITER Y <sub>0</sub> AXIS	ORBITER Z <sub>0</sub> AXIS	θ <sub>1</sub> (ABOUT X <sub>0</sub> )	θ <sub>2</sub> (ABOUT Y <sub>0</sub> )	θ <sub>3</sub> (ABOUT Z <sub>0</sub> )
<b>Lift-off</b>						
1	$1.5 \pm [(T_1 - 1.5)^2 + R_1^2]^{0.5}$	$\pm T_2$	$\pm T_3$	$\pm TRF_1$	$\pm TRF_2$	$\pm TRF_3$
2	$\pm T_1$	$\pm (T_2^2 + R_2^2)^{0.5}$	$\pm T_3$	$\pm TRF_1$	$\pm TRF_2$	$\pm TRF_3$
3	$\pm T_1$	$\pm T_2$	$\pm (T_3^2 + R_3^2)^{0.5}$	$\pm TRF_1$	$\pm TRF_2$	$\pm TRF_3$
<b>Landing</b>						
4	$\pm T_1$	$\pm T_2$	$\pm T_3$	$\pm TRF_1$	$\pm TRF_2$	$\pm TRF_3$

Where:

$T_i$  = Low frequency transient load factor in the *i*th direction (g's) (includes steady-state acceleration of 1.5 g's for x-direction during lift-off and 1.0 g's in z-direction during landing). The magnitude of  $T_i$  may be different, depending on the direction (+ or -) of the low frequency transient load.

$R_i$  = Random load factor in the *i*th direction (g's)

$TRF_i$  = Low frequency transient rotational load factor about the *i*th axis (rad/sec<sup>2</sup>)

*Note: The positive sign before the radical is used for a positive  $T_1$  and the negative sign is used for a negative  $T_1$  in the vector summation.*

#### 4.2.2 DESIGN LOAD FACTORS FOR LANDING

The design load factors for landing shall be obtained by combining the transient load factors in the X, Y, Z, θ<sub>x</sub>, θ<sub>y</sub>, and θ<sub>z</sub> directions simultaneously, as shown by table 4.2.1–1. Note that random load factors are not present at landing. There are 64 load factor cases for landing using all of the '+' and '-' value combinations. When there are no rotational load factors (or the effects of the rotational load factors are included in the translational load factors), there are eight possible landing cases.

#### 4.2.3 DESIGN LOAD FACTORS FOR EMERGENCY LANDING

The design load factors for emergency landing are applied one axis at a time against an ultimate factor of safety of 1.0. Note that the emergency landing case is essentially a "crash landing" of

the Orbiter and should not be confused with the contingency de-orbit landing case (in which the Orbiter must immediately return to Earth but the landing is nominal).

Since emergency landing load factors are considered ultimate conditions, they are usually below the design limit load factors multiplied by the factor of safety. Therefore, the design load factors for lift-off and for landing will usually govern the design. Under these conditions, detailed design calculations for emergency landing conditions are not necessary, and it is sufficient to show that load factors for normal flight phases are more severe. An exception to this is the emergency landing load factors for middeck-mounted equipment whose failure could result in injury to personnel or prevent egress from the vehicle. These load factors are given in table 4.2-1 of NSTS 21000-IDD-MDK and are applied independently.

#### **4.2.4 RANDOM VIBRATION LOAD FACTORS**

The Random Vibration Load Factors (RVLF) acting on payload flight equipment results from the resonant structural response of the equipment to random vibration environments (input from rocket engines mechanically and acoustically induced vibrations) during launch. Therefore, random load factors shall be combined with low frequency load factors and other loads which apply during the launch phase of flight operations. Also, the RVLFs do not apply to large mass items since they will not respond to random vibrations (at frequencies significantly above those included in the low frequency load factor range). RVLFs shall be calculated for lower mass items such as rack mounted payloads / components and cargo bay items under 1000 lb or 454 kg. (Items mounted in the middeck use load factors from the IDD-MDK which include random responses.) Specific RVLFs for payload flight equipment may be calculated using the following procedure.

- A. By calculation or test, determine the first (system) natural frequency, ( $f_n$ ), in each axis.
- B. Determine the resonant amplification factor, ( $Q$ ), (equal to  $1/2\xi$ , where  $\xi$  is the structural damping coefficient).
  - (1) from test data, if available
  - (2) use 10 if no data is available with the approval of the JSC-ES

- C. Using the natural frequency,  $f_n$  calculated in step A, and the applicable random vibration input criteria defined in the applicable IDD or payload-specific ICD (for the particular location of the equipment item), the applicable acceleration Power Spectral Density ( $PSD_n$  in  $g^2/Hz$ ) corresponding to the natural frequency  $f_n$  can be determined. If  $f_n$  falls on a sloped portion of the curve,  $PSD_n$  can be interpolated using the following relationship:

$$PSD_n = PSD_1(f_n/f_1)^{.3322s}$$

Where:

$PSD_n$  = PSD value which corresponds to  $f_n$

$PSD_1$  = PSD value corresponding to  $f_1$

$s$  = The slope of the PSD function (dB per octave)

$f_1$  = lowest frequency given for the portion of the PSD table being interpolated

$f_n$  = Natural frequency of system in the direction in which the load factor is being calculated.

- D. Determine the peak RVLF in each axis using the Miles' relationship:

$$RVLF = 3 \sqrt{\frac{\pi}{2} Q f_n PSD_n}$$

- E. For components resonant above 2000 Hz, the peak RVLF may be estimated from:

$$RVLF = 3 \times G_{rms}$$

Where:

$G_{rms}$  = the "composite" or "overall" level of the input acceleration PSD.

The factor of three in each of the above equations is a statistical factor applied because the load factors calculated from the power spectral density curves are one standard deviation amplitude for random vibrations, and design shall be based upon three standard deviations.

Alternate methods of RVLF derivation may be utilized in cases where relief is needed for systems or components in which the Miles' single DOF approximation is overly conservative. Several RVLF calculation techniques and their limitations are included in Appendix C.

#### **4.2.5 ACOUSTIC LOADING**

During the lift-off and ascent flight phases, significant acoustic energy will be imparted onto payload hardware. For payloads which are susceptible to acoustic impingement (those with large surface areas or low mass density), acoustic load factors shall be determined based on the acoustic environments defined in the applicable IRD or IDD (for the particular location of the equipment item). Examples of components which are susceptible to acoustic loading are antennas, solar arrays, large shields, large thin-walled nonstructural covers, and components with thin membranes. These acoustic load factors shall be combined with the RVLFs using the root-sum-square (rss) method. The resulting random load factor shall then be combined with the respective low frequency transient load factors by rss methods. The procedure for acoustic load factor calculation is provided in Appendix C. Acoustic loading is already included in the RVLF defined for rack mounted component payloads.

#### **4.2.6 THERMAL LOADING**

Thermal design environments are defined in the appropriate IRD or IDD. ISS payloads shall be designed to maintain positive MS when thermal effects are combined with static, dynamic, and pressure loads (as appropriate).

Payload hardware must also maintain positive structural MS with respect to ultimate FS under contingency deorbit thermal conditions (which do not include on-orbit thermal preconditioning prior to descent).

Minimum design FS for pressure vessels shall be maintained under conditions encountered at any continental United States or contingency landing site without postlanding services. Thermal analysis of postlanding conditions shall address the following: (a) worst-case, Orbiter-induced initial conditions due to an abort from orbit to a contingency landing site with the payload subjected to the most severe, on-orbit thermal attitude; (b) heat input from normal payload sources; (c) heat input from up to two payload failures (Orbiter power busses are de-energized at landing plus 30 min); and (d) the environments defined in NSTS 21000-IDD-ISS.

#### **4.3 PRESSURE LOADING**

Pressure environments are applicable to the lift-off, landing, and on-orbit flight/stage phases. Pressure design environments are defined in the appropriate IDD or IRD. ISS payloads shall be designed to maintain positive margins of safety when pressure effects (operational and pressurization/depressurization environments) are combined with dynamic and thermal loads (as appropriate). Payloads that have portable fire extinguisher (PFE) access ports shall maintain positive MS when exposed to the discharge given in figure 3.1.1.4-1 of SSP 57000.

The design loads for pressure vessels shall be the maximum combined loads resulting from the load factors defined in paragraphs 4.2 and 4.4 and the Maximum Design Pressure (MDP) (limit pressure) to which the vessel may be subjected, including thermal or other energy increasing effects.

#### **4.4 ON-ORBIT LOADING**

There are two phases of on-orbit loading. The first occurs when payloads are aboard the Orbiter. The second occurs when payloads are aboard the ISS. Table 4-1 defines the loading environments applicable for both the Orbiter and ISS (US elements only) on-orbit flight/stage phase. Loading environments can be conveniently grouped as acceleration, thermal, pressure, shock and crew loadings.

Section 4.4.1 provides the design loading environment for payloads aboard the Orbiter. Section 4.4.2 provides the loading environments for the US elements of the ISS. Crew-applied loads in Section 4.4.3 are applicable for payloads located in/on the Orbiter and ISS.

ISS payloads shall be designed to maintain positive MS during all on-orbit events.

##### **4.4.1 ORBITER ON-ORBIT DESIGN LOADS**

Except for the crew-applied loading defined in section 4.4.3, Orbiter on-orbit loading consists of low-level accelerations and impact microgravity disturbances that are substantially lower than lift-off/landing loads. Therefore unless a payload changes into an on-orbit structural configuration different from the lift-off or landing configuration, on-orbit acceleration environments can be omitted as a design condition.

Design load factors and random vibration environments associated with Orbiter on-orbit loads are defined in the appropriate IDD or IRD.

##### **4.4.2 ISS ON-ORBIT DESIGN LOADS**

ISS on-orbit design loads vary depending on whether the payload is inside a pressurized module or is attached to the US segment of the ISS Truss, the Columbus External Payload Facility (EPF), or the JEM Exposed Facility (EF). Payloads inside the pressurized US Lab module, the Columbus Module, or the JEM PM are referred to herein as “pressurized payloads”. Payloads attaching to the ISS Truss, the Columbus EPF, or the JEM EF will be broadly classified as “attached payloads” with further subclassification made in paragraph 4.4.2.2.

#### **4.4.2.1 PRESSURIZED-PAYLOADS ON-ORBIT DESIGN LOADS**

On-orbit design loads for pressurized payloads consist of low level acceleration loads defined in section 3.1.1.3 of SSP 57000, Pressurized Payloads IRD, as well as the pressure loads and crew applied loads discussed in paragraphs 4.3 and 4.4.3 herein. Since pressurized payloads normally attach to the ISS, ISPR, or rack facility using the same interfaces used for lift-off and landing, lift-off/landing loads discussed in paragraph 4.2 herein are usually the critical design loads. Payloads that include structural components that deploy on-orbit must verify the structural strength of the deployed item under the low-level on-orbit acceleration loads and crew-applied loads.

#### **4.4.2.2 ISS ATTACHED-PAYLOADS ON-ORBIT DESIGN LOADS**

Attached Payloads are divided into two subclassifications in this section: (1) Payloads and facilities that attach directly to the US segment of the ISS Truss and (2) payloads that attach to an EXPRESS Pallet facility.

##### **4.4.2.2.1 ON-ORBIT DESIGN LOADS FOR PAYLOADS ATTACHING TO ISS TRUSS**

Structural interfaces for payloads or facilities attaching directly to the US segment of the ISS Truss may not be the same as the payload-to-Orbiter interfaces during lift-off/landing. Thus, structural integrity analyses performed for lift-off and landing will not verify the on-orbit attachment interfaces and structural load paths. Design loads for payloads or facilities attaching directly to the US segment of the ISS Truss include acceleration vibration loads, design interface forces, thermal loads, pressure and shock loads. Crew applied loads are discussed in paragraph 4.4.3.

Acceleration vibration loads are defined in paragraph 3.1 of the Attached Payload IRD. This includes interface forces resulting from Orbiter RMS and SSRMS grapple, Payload Attach System (PAS) and Unpressurized Cargo Carrier Attach System (UCCAS) interface forces, PAS/UCCAS preload forces, payload generated operational loads (e.g., gimbaling equipment), berthing impact forces, and transportation/servicing via the Mobile Servicing System (MSS).

Thermal environments are defined in paragraph 3.1 of the Attached Payload IRD.

Shock impulse loads on payloads may result from the docking and grapple of a payload. These loads are defined in paragraph 3.1 of the Attached Payload IRD and in paragraph 14.4.1.6 of the ISS IDD (NSTS-210000-IDD-ISS).

#### **4.4.2.2 ON ORBIT DESIGN LOADS FOR EXPRESS PALLET PAYLOADS**

On-orbit design loads environments for EXPRESS Pallet payloads are defined in paragraph 4.6 of the EXPRESS Pallet Payloads IDD (SSP 52000-IDD-EPP). These loads include acceleration, random vibration, reboost, berthing, thermal, and plume-impingement pressure loads. Crew applied loads are discussed in paragraph 4.4.3.

#### **4.4.3 CREW-APPLIED LOADS**

Design load factors associated with crew-applied loads for payloads installed in habitable areas or payloads susceptible to crew-applied loads during planned Extravehicular Activity (EVA) are defined in the appropriate IRD or IDD.

Inadvertent kick and kick-off, push-off crew-applied loads do not apply to attached-payload hardware that is assembled or maintained using robotic systems. Contingency EVA activities associate with Attached Payloads will be performed by a crewmember restrained on the Space Station Remote Manipulator System (SSRMS) or Worksite Interface Fixture. Design loads associated with contingency EVA activities for Attached Payloads are defined in the Attached Payloads IRD and the EXPRESS Pallet IDD.

#### **4.5 GROUND HANDLING/TRANSPORTATION LOADS**

Typical design load factors associated with ground handling and transportation environments are defined in the appropriate IRD and IDDs for pressurized and EXPRESS payloads. Note: Equivalent load factors for ground handling and transportation are not provided in the middeck or sidewall IDDs.

#### **4.6 SPECIAL LOADING CONSIDERATIONS**

##### **4.6.1 SPECIAL LOADING CONSIDERATIONS FOR ORBITER-ATTACHED PAYLOADS**

Orbiter-attached payloads, which include sidewall adapter-mounted payloads and middeck-mounted payloads, have special requirements which must be met. These requirements depend on payload location and type of payload.

#### **4.6.1.1      SIDEWALL ADAPTER-MOUNTED PAYLOADS**

Payloads which attach to sidewall adapter carriers shall withstand the loading and meet the dynamic envelope requirements specified in NSTS 21000-IDD-SML and NSTS 21000-IDD-ISS. The load factors specified in NSTS 21000-IDD-SML are applicable to payloads with a minimum frequency of 35 Hz when constrained at the interface to the sidewall carrier. Payloads with fundamental frequencies below 35 Hz may experience higher loading, and unique design load factors from the Space Shuttle Program Structures Working Group (SSP-SWG) will be required.

#### **4.6.1.2      MIDDECK-MOUNTED PAYLOADS**

Middeck-mounted payloads shall be designed according to the load factors specified in NSTS 21000-IDD-MDK. The load factors are applicable to non-locker payloads with a minimum frequency of 30 Hz when constrained at the mounting plate. Payloads with fundamental frequencies below 30 Hz may experience higher loading, and unique design load factors from the SSP-SWG will be required.

#### **4.6.2      SPECIAL LOADING CONSIDERATION FOR SPACELAB PALLET**

Payloads which attach to the Spacelab pallet shall withstand the loading and dynamic model verification requirements specified in SLP/2104 and section 7 of this document.



## 5.0 DESIGN CRITERIA

All ISS experiments and hardware shall be designed to withstand the launch, on-orbit, and landing environments described in Section 4 of this document. All equipment shall withstand these environments (maintain positive MS) without any failure which could leak hazardous fluids or release any equipment, loose debris, or other particles that could damage the Space Station or Orbiter or cause injury to the crew.

Any hardware which fails to meet all of the requirements of this document shall be referred to the PSRP, and the JSC–ES for evaluation and resolution.

The PD shall design payload flight hardware such that the equipment integrity and load-carrying capability of structural mounting provisions fulfill the following requirements:

- A. Factors of Safety: The minimum Factor of Safety (FS) to be used with limit load conditions to establish design loads shall be as defined in paragraph 5.1.
- B. Margins of Safety: A positive MS as defined in paragraph 5.2 shall be maintained for every safety-critical structural element. All appropriate failure modes shall be evaluated (e.g., buckling, crippling, bearing, etc.).
- C. Fracture Control: The rigorous application of those branches of engineering, assurance management, manufacturing, and operations technology dealing with the analysis and prevention of crack propagation leading to catastrophic failure as defined in paragraph 5.3.
- D. Materials Selection: Materials selection shall be in accordance with paragraph 5.4 and applicable specifications.
- E. Welding: The use of weldments shall be in accordance with paragraph 5.5 and applicable specifications.
- F. Fastening: Selection of all fasteners and procedures shall be in accordance with paragraph 5.6 and applicable specifications.
- G. STS Interface Design Constraints: These include particular mounting provisions, load-carrying capability of payload equipment attach points, dynamic envelope requirements, crew-applied loads and interface requirements, and safety retention of moving parts.
- H. ISS Interface Design Constraints: These include particular mounting provisions, dynamic behavior, load-carrying capability, envelope requirements, mass and cg requirements, crew-applied loads, and retention of moving parts.

## **5.1 EQUIPMENT INTEGRITY AND FACTORS OF SAFETY**

Load factors given as design criteria are “limit” and envelope the maximum expected levels for the specified flight/stage phase (as defined in paragraph 4.0). These levels shall be amplified by a FS to account for uncertainties in the material properties, loads determination, manufacturing and assembly, and analysis procedures. By definition, structures shall not yield at limit load times the yield FS, nor shall they fail at limit load times the ultimate FS.

General guidelines for application of design safety factors are as follows:

- A. For components or systems subjected to multiple missions, static strength safety factor requirements shall apply to all missions.
- B. Consideration shall be given to transient loads and pressure, such as surge.
- C. Elongation criteria rather than the yield safety factors may be used with the following restrictions:
  - (1) The structural integrity of the component affected shall be demonstrated by adequate analysis and test.
  - (2) There shall be no deformations which adversely affect the function of the component or other adjacent payload items.
  - (3) The service life requirements of the fracture and fatigue sections shall be met.
- D. In circumstances where pressure loads have a relieving or stabilizing effect on structural load capability, the minimum expected value of such loads shall be used and shall not be multiplied by the FS in calculating the design yield or ultimate load.
- E. The drawing minimum thickness shall be used in stress calculations of pressure vessels, stability critical structure, and single load path structure. The drawing mean/average thickness may be used for stress calculations of all other structures. Actual as-built dimensions may be used in stress calculations when available.
- F. Thermal stresses/loads shall be combined with mechanical and pressure stresses/loads when they are additive, but shall not be combined when they are relieving.

### **5.1.1 SAFETY FACTORS FOR ORBITER-ATTACHED PAYLOADS**

Structural FS shall be in accordance with requirements levied by NSTS 14046 for Orbiter-attached payloads. There are no untested FS published for Orbiter-attached payloads. PDs with orbiter-attached facilities or payloads may use the “analysis only” structural verification approach with prior and written approval from the JSC-ES. Use of a higher FS alone is not sufficient to account for uncertainty and possible unconservatism in load factor

calculation and application. Justification for using untested FS shall accompany the request for “analysis only” verification. Possible justifications for the untested option which may be acceptable to the JSC-ES include:

- A. The structural design is simple with easily determined load paths.
- B. The structure is similar in overall configuration, design detail, and critical load conditions to a structure that has been test verified.
- C. Development and/or component tests have been successfully completed on critical elements of the structure which are difficult to analyze.
- D. Unpressured glass where the stresses are very low with respect to test verified allowables.

#### **5.1.2 SAFETY FACTORS FOR PAYLOADS ATTACHED TO PRIMARY AND/OR SECONDARY STRUCTURES**

Structural FS for payload flight equipment which attach to primary or secondary structure are provided in Table 5.1.2-1. Payloads in this category include those that attach to the USL, MPLM, ISPR, EXPRESS Rack, EXPRESS Pallet, Columbus and Spacelab Pallet. Note that only the payloads attached to the EXPRESS Pallet and Spacelab pallet are covered in this paragraph, not the actual integrated EXPRESS pallet and Spacelab pallet structures covered in paragraph 5.1.1.

Use of a higher FS alone is not sufficient to account for uncertainty and possible unconservatism in load factor calculation and application. The “analysis only” structural verification approach may be used only if all of the structural requirements of this document are satisfied, including the following:

- A. SCS will be made from metallic materials.
- B. All structural analyses for metallic materials shall be based on “A” Basis (or equivalent) (see Appendix B-1) material allowables.
- C. The drawing minimum thickness shall be used in stress calculations of pressure vessels, stability critical structure, and single load path structure. The drawing mean/average thickness may be used for stress calculations of all other structures. Actual as-built dimensions may be used in stress calculations when available.
- D. All loading conditions shall be thoroughly understood and analyzed.
- E. Dynamic testing shall be conducted to verify the analytical model if required (Section 7.1).
- F. Well-defined and conservative load factors shall be used in the structural analysis.

G. Boundary conditions shall be well understood and conservatively analyzed.

**TABLE 5.1.2-1 MINIMUM SAFETY FACTORS FOR PAYLOAD FLIGHT STRUCTURES  
MOUNTED TO PRIMARY AND SECONDARY STRUCTURE**

	YIELD	ULTIMATE	PROOF
<b>Metallic Structures</b>			
- Untested Shuttle (analysis only)	1.25	2.0	-
- Untested on orbit (analysis only)	1.25	2.0	-
- Tested Shuttle (analysis & test)	1.0	1.4	1.2
- Tested on orbit (analysis & test)	1.1	1.5	1.2
<b>Beryllium Structures</b>			
- Static test and analysis		2.0	1.4
<b>Composite Structures</b>			
- Non-discontinuity Shuttle	-	1.4	1.2
- Non-discontinuity on orbit	-	1.5	1.2
- Discontinuity	-	2.0	1.2
- Discontinuity on orbit	-	2.0	1.2
<b>Ceramics &amp; Glass</b>			
- Static test & analysis (non-pressurized)	-	3.0	(accept.) 1.2
- Static test & analysis (pressurized)	-	3.0	(accept.) 2.0 (see note 2)
- Analysis only (non-pressurized)	-	5.0	-
<b>Structural Bonds</b>			
- Bonded to glass (analysis & test)	-	2.0	(accept.) 1.2 (qual.) 1.4
- Other (analysis & test)	-	2.0	(accept.) 1.2

Note 1: "Shuttle" defines the transportation phases of the mission in the STS and "on orbit" defines operational activities in the ISS.

Note 2: The proof factor determined from fracture mechanics service life analysis must be used if it is greater than the minimum factor of 2.0.

Note 3: The "discontinuous structure" for Composite Structures applies to changes in structures such as occur at joints, changes in load paths, and abrupt changes in stress levels or materials. The JSC SWG will evaluate the proper application of the "discontinuity structure" safety factor requirement.

Some additional factors which may be used for justification of an "analysis-only" verification approach include (but are not limited to) the following:

- A. The structure is similar in overall configuration, design detail, and critical load conditions to a structure that has been test verified.
- B. Development and/or component tests have been successfully completed on critical elements of the structure which are difficult to analyze.
- C. The structure is statically determinate and/or has clearly defined load paths.
- D. The structural design is simple.
- E. Component mass and cg used in the analytical model and analysis are conservative (mass used  $\geq + 5\%$ , cg at worst-case location).

- F. All MS for SCS (excluding fasteners) are  $\geq 0.15$ . Note: Fastener MS must also be positive, but may be less than 0.15 due to the use of preload in the MS calculations.
- G. All hardware (including fasteners) is classified as non-fracture critical.

The responsible NASA center structures organization or approved partner/participant structures organization will review the payload verification approach to ensure that the requirements listed above are adequately satisfied (for PDs wishing to verify structural strength by analysis only). It is strongly recommended that PDs consult with the SSP-SWG or the responsible NASA center or approved partner/participant early in the design phase for any payloads which do not clearly satisfy these requirements. Early consultation will minimize the risk of the payload being disapproved for flight due to noncompliance with these requirements. Additional detailed requirements for nonmetallics, beryllium, ceramics, glass, composite materials, and structural bonds are included in Appendix F.

### **5.1.3 SAFETY FACTORS FOR PRESSURIZED SYSTEMS**

The MDP for a pressurized system shall be the highest pressure defined by maximum relief pressure, maximum regulator pressure, or maximum temperature. Transient pressures shall also be considered. Design FS shall apply to MDP. Where pressure regulators, relief devices, and/or a thermal control system (e.g., heaters) are used to control pressure, collectively they shall be two-fault tolerant to prevent the system pressure from exceeding the MDP of the system. Pressure integrity shall be verified at the system level by performing a leak check. The leak test will be performed at  $1.0 \times \text{MDP}$  or  $1.0 \times \text{Highest Operating Pressure}$  as a minimum. Additional testing and inspections at the component level may be required for fracture-critical pressurized systems (see Section 6.2.4). Safety factors for lines, fittings, and components are contained in NSTS 1700.7 ISS Addendum, paragraph 208.4c, and are summarized in paragraph 5.1.3.3.

#### **5.1.3.1 PRESSURE SYSTEM REQUIREMENTS**

Pressure system design data shall show that:

- A. The system provides the capability of maintaining all pressure levels in a safe condition in the event of interruption of any process or control sequence at any time.
- B. Redundant pressure relief devices shall have mutually independent pressure escape routes or shall meet the requirements of Section 5.1.3.6.

### **5.1.3.2 PRESSURE VESSELS**

The design burst factor for pressure vessels shall be a minimum of 2.0 times MDP with a proof-test factor equal to or greater than 1.5 x MDP or as required by MIL-STD-1522A.

The calculation must include any transient pressure caused by credible failures and environmental effects.

### **5.1.3.3 PRESSURIZED LINES, FITTINGS, AND COMPONENTS**

A. Lines and fittings with:

- (1) An outside diameter less than 1.5 in shall have an ultimate FS equal to or greater than 4.0 x MDP.
- (2) An outside diameter greater than or equal to 1.5 in shall have an ultimate FS equal to or greater than 2.0 x MDP.
- (3) Flex lines (flexible hard lines) shall have an ultimate FS equal to or greater than 4.0 x MDP and will have a proof-test factor equal to or greater than 2.0 x MDP.

B. All line-installed bellows and all heat pipes shall have an ultimate safety factor equal to or greater than 2.5 x MDP.

C. Other components (e.g., valves, filters, regulators, sensors, etc.) and their internal parts (e.g., bellows, diaphragms, etc.) which are exposed to system pressure shall have an ultimate FS equal to or greater than 2.5 (based on the system MDP).

### **5.1.3.4 DEWARS/CRYOSTAT SYSTEMS**

There is a special category of pressure vessels for dewars/cryostat systems because of unique structural design and performance requirements. Pressure containers in such systems shall meet the requirements for pressure vessels as supplemented per NSTS 1700.7 ISS Addendum, paragraph 208.4b.

### **5.1.3.5 BURST DISKS**

A properly designed and certified burst disk assembly may be considered equivalent to two relief devices. When burst disks are used as the second and final control of pressure, they shall be designed to the following requirements:

A. Burst discs shall incorporate a reversing membrane against a cutting edge to ensure rupture.

- B. Burst disc design shall not employ sliding parts or surfaces subject to friction and/or galling.
- C. Stress corrosion resistant materials shall be used for all parts under continuous load.
- D. The burst disc design shall be qualified for the intended application by testing at the intended use conditions including temperature and flow rate.
- E. Qualification shall be for the specific part number used, and it shall be verified that no design or material changes exist between flight assemblies and assemblies making up the qualification database.
- F. Each flight assembly shall be verified for membrane actuation pressure either by (1) use of special tooling or procedures to prevent cutting edge contact during the test or if (1) is not feasible, then (2) demonstration of a rigorous lot screening program approved by the PSRP.

#### **5.1.3.6 SECONDARY VOLUMES**

Secondary compartments or volumes that are integrally attached by design to the above parts and which can become pressurized as a result of a credible single barrier failure, shall be designed for safety consistent with structural requirements. These compartments shall have a minimum safety factor of 1.5 based on MDP. If external leakage would not present a catastrophic hazard to the Orbiter, ISS, or crew, the secondary volume shall either be vented or equipped with relief provisions in lieu of designing for system pressure.

#### **5.1.4 SAFETY FACTORS FOR HANDLING AND TRANSPORTATION OF FLIGHT STRUCTURES**

The handling and transportation FS for flight structures should be the same as those given in Table 5.1.2-1. Flight structure design should be based on flight loads and conditions, rather than on transportation and handling loads. Transportation and handling equipment design should ensure that flight structures are not subjected to loads more severe than 80 percent of flight loading conditions. Additionally, handling attachment points for flight hardware shall be designed to ensure positive MS during handling events defined in KHB 1700.7.

#### **5.1.5 METEOROID AND ORBITAL DEBRIS (M/OD) PROTECTION REQUIREMENT FOR EXTERNAL PAYLOADS**

An external payload that is a stored energy device, contains a stored energy device (examples: pressure vessels, cryogenic carriers), or contains any other hardware that could create a catastrophic hazard if impacted or penetrated by a meteoroid or orbital debris particle shall be designed to prevent such a potential hazard. This includes initial failure of the payload and secondary effects of the failure including creation of secondary ejecta.

The design shall provide a minimum Probability of No Penetration (PNP) defined by:

$PNP = 0.9999$  or  $PNP = 0.99999^{(A*Y)}$ , whichever is less.

Where: A = Payload total/hazardous impact surface area in square meters

Y = Exposure time in years

This PNP shall be calculated for the cumulative on-orbit exposure time of the payload beginning with the initial payload launch date. The meteoroid and orbital debris environments are specified in Section 8 of SSP 30425 with constraining parameters shown in Table 5.1.5–1.

Verification will be considered successful when an analysis is performed using Bumper-II (or approved equivalent) analysis code and shows compliance with the derived total probability of non penetration. A penetration is defined as complete perforation of the pressure vessel or casing, detached spall from the pressure vessel wall, damage to the pressure vessel that would allow unstable crack growth, or deformation of a casing of rotating machinery such that the deformation could intrude into the dynamic envelop of the rotating device.

**TABLE 5.1.5–1 PARAMETERS FOR M/OD ENVIRONMENTS DEFINITION**

Altitude	215 nautical miles (398.18 km)
Space Station attitude	Orbiter attached 10 percent of the time Orbiter not attached 90 percent of the time Flight attitude envelopes of $\pm 15$ degrees about all axes
Orbital inclination	51.6 degrees
Solar flux	$70 \times 10^4$ Jansky ( $F_{10.7} = 70$ )
Orbital debris density	$2.8 \text{ gm/cm}^3$
Maximum debris diameter	20 cm

### 5.1.6 SAFETY FACTORS FOR COMBINED LOADS

In cases where loads produced by different environments can occur simultaneously, these loads shall be combined in a rational manner to define the limit load for that flight event. Stresses due to mechanical loads shall be calculated when applicable (e.g. lift-off) with a combination of random (high frequency) and transient (low frequency) loads as described in Section 4.2. Mechanical stresses shall also consider aerodynamic, crew and redundancy induced loads when applicable. Pressure stresses shall be derived from the relevant pressure case consistent with the mechanical environment event. Equally, the pressure stresses due to the MDP of a pressure



system shall be combined with the consistent mechanical and thermal stresses corresponding to the event where the MDP might occur. The thermal stresses shall be calculated from the induced thermal gradients in the structure.

The minimum ultimate safety factor for stresses due to combined loads (e.g., mechanical, pressure and thermal) shall be determined in a rational manner using the equation given below with the variables defined in Table 5.1.5–1. Stresses induced into the structure by other loads (e.g., manufacturing, latching, torquing) shall be combined with appropriate factors of safety, but shall not be used as relieving stresses.

$$K_C = \frac{K_M S_M + K_P S_P + K_T S_T}{S_M + S_P + S_T}$$

The following restrictions shall apply:

1. This method of loads combination is only valid for stresses due to linear elastic material and linear geometric behaviors. This method of combination is not applicable to inelastic analysis and the approval of JSC–ES is needed on the specifics of the combination in such cases.
2. When the stresses are additive, the safety factor for mechanical stresses ( $K_M$ ) is defined in Table 5.1.2–1. The safety factor for thermal stresses ( $K_T$ ) shall be the same as the mechanical factors given in Table 5.1.2–1. Section 5.1.3. defines the safety factors associated with pressure stresses ( $K_P$ ) for several different types of pressurized items. A minimum of 1.5 shall be used for  $K_P$  when not specifically identified.
3. In circumstances where pressure stresses have a relieving or stabilizing effect on structural capability relative to other stresses, the minimum guaranteed relieving pressure shall be used to determine the stress relief. The stress relief safety factor shall be 1.0 (i.e.,  $K_P = 1.0$ ) when calculating  $K_C$ .
4. In circumstances where mechanical stresses have a relieving or stabilizing effect on structural capability relative to pressure stresses, the minimum guaranteed relieving mechanical stress shall be used to determine the stress relief. The stress relief safety factor shall be 1.0 (i.e.  $K_M = 1.0$ ) when calculating  $K_C$ .
5. Thermal stresses shall be combined with mechanical and pressure stresses when additive but shall not be used for stress relief (i.e. set both  $S_T$  and  $K_T = 0.0$ ).

**TABLE 5.1.6–1 VARIABLE DEFINITIONS FOR COMBINED LOADS SAFETY FACTOR**

Variable	Stresses		Description
	Additive	Relieving	
$K_M$	Table 5.1.2	1.0	Safety factor for mechanical stresses
$K_P$	Section 5.1.3	1.0	Safety factor for pressure stresses
$K_T$	Table 5.1.2	0.0	Safety factor for thermal stresses
$S_M$			Stresses due to mechanical externally applied loads (e.g. inertial, displacement, aerodynamic, crew)
$S_P$	Due to pressure loads	Due to minimum guaranteed pressure	Stresses due to pressure loads. Stresses due to MDP shall be verified considering the MDP consistent mechanical and thermal case event.
$S_T$			Stresses due to thermally induced loads (not included when relieving)
$K_C$			Safety factor for combined loads. Shall never be less than overall applicable safety factor.

The worst–case combined stresses depend upon the magnitude and direction of the component stresses. For case– and time–consistent conditions, both the maximum positive stress (e.g. tensile) and the maximum negative stress (e.g. compression) shall be evaluated based on the following six possibilities:

1.  $S_M$  = Primary Positive Mechanical Stresses with associated pressure and thermal stresses.
2.  $S_M$  = Primary Negative Mechanical Stresses with associated pressure and thermal stresses.
3.  $S_P$  – Primary Positive Pressure Stresses with associated mechanical and thermal stresses.
4.  $S_P$  = Primary Negative Pressure Stresses with associated mechanical and thermal stresses.
5.  $S_T$  = Primary Positive Thermal Stresses with associated pressure and mechanical stresses.
6.  $S_T$  = Primary Negative Thermal Stresses with associated pressure and mechanical stresses.

Alternatively, a max–on–max, non–case consistent, non–time consistent maximum positive and maximum negative stress conditions may be used to envelope all stress cases.

When stresses are derived from automated stress analysis systems (e.g., finite element models, post-processing programs), a method shall be available to demonstrate that proper signs and safety factors were used for each combined stress case.

## 5.2 MARGINS OF SAFETY

A MS is defined as the decimal fraction as defined in the example below:

(1) Example:

$$MS_u = \frac{P_u}{P_x FS_u} - 1 \quad \text{or} \quad MS_y = \frac{P_y}{P_x FS_y} - 1$$

Where:

$FS_u$  = Ultimate Factor of Safety

$FS_y$  = Yield Factor of Safety

$P$  = Limit Load (or stress) calculated in the analysis

$P_u$  = Load (or stress) at which material failure will occur

$P_y$  = Load (or stress) at which material yielding will occur

$MS_u$  = Margin of Safety against ultimate failure

$MS_y$  = Margin of Safety against material yielding

Margins of safety shall be positive for all structures in all combined loading conditions.

## 5.3 FRACTURE CONTROL

Fracture control is required on all safety-critical flight structures which must meet all of the requirements of NASA-STD-5003. The PD shall be responsible for identifying safety-critical and fracture-critical structures. All fracture-critical hardware should be designed using sound and established design practices. These practices should as a minimum include the following:

- A. Minimizing eccentricities and stress concentrations that could act as fatigue crack initiators.
- B. Providing access, conditions, and clearance to implement inspection, test, and maintenance.
- C. Selecting materials and their design operating stress levels so that the required life for a given component can be verified by analysis and available NDE techniques/proof-test.

- D. Selecting materials such that problems with stress corrosion per MSFC-SPEC-522, hydrogen embrittlement, environmental effects, temper embrittlement, creep, general and galvanic corrosion, radiation damage, and eutectic melting are prevented or minimized.
- E. Providing contained/restrained or fail-safe designs where practical. Any part of a redundant structure which may be loose after failure (such as a fastener) shall meet the requirements of paragraph 5.3.1.1.
- F. Fracture-critical parts shall be clearly identified in all design documents (engineering drawings, engineering orders, reports, etc.) to facilitate accumulation and retrieval of fracture control information by part, material, and process.

A fracture mechanics analysis shall be performed by the PD as described in paragraph 6.2. Results of the fracture mechanics analysis shall identify the remaining life for an assumed worst-case flaw, based on the NDE method used; or its Critical Initial Flaw Size (CIFS), that is, the flaw size which will grow to failure of the structure in four service lifetimes. NDE inspection shall be done by the equipment developer as described in paragraph 7.5 to detect cracks and flaws. These cracks and flaws shall be smaller than the CIFS determined by the fracture mechanics analysis based on life cycle stresses and material properties.

Fracture control shall be addressed in a fracture control plan establishing responsibilities, criteria, and procedures for the prevention of structural failures of fracture-critical parts associated with the initiation and propagation of crack-like flaws during fabrication, testing, handling and transportation, and operations life. This plan should be developed and submitted to the PSRP for review during the preliminary design phase of all applicable components and maintained throughout the program (see paragraph 6.2 for further discussion on fracture control requirements). Changes in design or process specifications, manufacturing discrepancies, repairs, and finished part modifications for all fracture-critical parts shall be reviewed by the designated fracture control individual or group and reported in the fracture control summary report.

Structural parts of a mechanical system whose failure would result in a catastrophic hazard are defined as fracture critical. These systems, or critical parts within a system, shall be assured against failure from flaws using fracture mechanics methodology.

The fracture control plan describes how the PD will meet the fracture control requirements, while the fracture control report verifies that each part of the payload structure falls into, and complies with, the requirements for at least one of the following classifications: low released mass, contained, fail-safe, low risk, or safe-life. Each of these classifications is discussed in the following paragraphs.

### **5.3.1 NON-FRACTURE-CRITICAL PARTS**

#### **5.3.1.1 LOW RELEASED MASS PART**

For a payload component to be classified as a low released mass part, it shall meet requirements A, B, C and D listed below:

- A. The part satisfies one of the following two conditions:
  - (1) Total mass of the part or any other released part is less than 0.25 lb (113 grams).
  - (2) Total mass in pounds (kilograms) supported by the part is not more than 14/h, where h is the part's travel distance in feet (or 1.94/h, where h is in meters) to the aft bulkhead of the Space Shuttle cargo bay. When the installation location of a potential released mass is not known, a documented maximum travel distance estimate may be used. Total mass of the released part shall not exceed 2 lb (0.9 kg).
- B. It can be shown that the release of this component will not cause a catastrophic hazard to the Space Shuttle or ISS because of subsequent damage to the payload from which it came.
- C. For parts which have low fracture toughness and are preloaded in tension, a fragment may be released at high velocity immediately following failure; therefore, the total released mass may not exceed 0.03 lb (14 grams). A part shall be considered to have low fracture toughness when its material property ratio  $K_{Ic}/F_{ty} < 0.33 \text{ in}^{1/2}$  ( $1.66 \text{ mm}^{1/2}$ ), where  $K_{Ic}$  is the plane strain fracture toughness and  $F_{ty}$  is the allowable yield tensile strength. If the part is a steel bolt and the  $K_{Ic}$  value is unknown, low fracture toughness shall be assumed when the specified minimum  $F_{tu} > 180 \text{ ksi}$  (1,240 mPa), where  $F_{tu}$  is the allowable ultimate tensile strength.
- D. On-Orbit: Structures, systems, tools, restraining and handling devices, etc., must be examined for consequences of single failure mass release on-orbit. If any single failure mass release would be a catastrophic hazard, appropriate fracture control must be applied to the hardware. If a single failure could release a mass (independent of size), and it would not result in a catastrophic occurrence or loss of a safety critical function, the part can be classified non-fracture critical. Where uncertainty exists as to consequences of a release, the criticality can be based on exceedence of 0.25 pounds at 35 ft./sec, or equivalently have released momentum of no more than 8.75 ft-lb/sec.

#### **5.3.1.2 CONTAINED PART**

For a payload component to be classified as a contained part, it shall be shown that all released pieces of the failed component that violate the low mass requirement (5.3.1.1) are completely contained in the payload and will not cause a catastrophic hazard to the Space Shuttle or carrier

as a result of subsequent damage to the payload in which it was installed. One of the following methods shall be used to verify containment:

- A. Engineering judgment supported by documented technical rationale may be used when it is obvious that an enclosure, a barrier, or a restraint exists that prevents the part from escaping into the Space Shuttle payload bay or loose in the ISS. Examples of such enclosures that have obvious containment capability include metallic boxes containing closely packed electronics, detectors, cameras, and electric motors; pumps and gearboxes having conventional housings; and shrouded or enclosed fans not exceeding 8 in (200 mm) in diameter and an 8,000 revolutions per minute (rpm) speed.
- B. Documented testing or analysis shall be used to show containment when the ability of the enclosure, barrier, or restraint to prevent the part from escaping is not obvious. For enclosures with holes, only internal parts that cannot pass through the holes shall be considered contained. When enclosures are designed to be opened, they must be closed again to establish containment for a later flight. Closure devices shall be single-failure tolerant, i.e. one fastener missing.

#### **5.3.1.3 FAIL-SAFE PART**

For a payload component to be classified as a fail-safe part, it must meet requirements A and C or requirements B and C below:

- A. It must be shown by analysis or test that, due to structural redundancy, the structure remaining after any single failure can withstand the redistributed limit loads with a safety factor of 1.0. In meeting these requirements, the effect of altered Space Shuttle/payload coupling shall be considered unless:
  - (1) Design loads are conservative with respect to Space Shuttle/payload dynamic coupling variations, or
  - (2) Failure of the component would not significantly alter payload dynamic response. Technical rationale to substantiate that there is no significant effect on payload dynamic response must be documented.
- B. Alternatively, engineering judgment supported by documented technical rationale may be used when it is obvious there is sufficient structural redundancy for fail-safe classification, or failure of the part clearly would not create a catastrophic hazard.
- C. Adequate quality control is implemented to ensure that generic or process defects are not introduced so that the remaining structure may be considered unflawed. For multi-flight payloads, it must be verified before reflight that the structural redundancy of a fail-safe part is still intact or sufficient fatigue life is available in the remaining structure to reach end-of-service life (e.g., 5.3.1.4.2.2). At a minimum, verification shall consist of a purposeful visual inspection for evidence of structural damage at the lowest level of planned

disassembly between missions. If there is evidence of damage, the affected structure shall be repaired or sufficiently examined to verify intact redundancy.

#### **5.3.1.4 LOW RISK FRACTURE PART**

A low risk fracture part shall comply with the requirements of 5.3.1.4.1 and 5.3.1.4.2 except for fasteners and shear pins, which need comply only with 5.3.1.4.3.

##### **5.3.1.4.1 LIMITATIONS ON APPLICABILITY**

The part shall be all metal. It shall not be the pressure shell of a human-tended module or personnel compartment, pressure vessel, pressurized component in a pressurized system containing a hazardous fluid, or high-energy rotating machinery. A part whose failure will directly result in a catastrophic hazard is also excluded, except when the total (unconcentrated) tensile stresses in the part at limit load are no greater than 30 percent of the ultimate tensile strength for the metal used and all other requirements for low risk classification are met. The intended use of low risk fracture classification shall be presented at the Phase I Safety Review to show an adequate understanding of the requirements. Identification of low risk fracture parts at Phase II, and compliance with these requirements shall be addressed in the Phase III Safety Review package and in the fracture control summary report.

##### **5.3.1.4.2 INHERENT ASSURANCE AGAINST CATASTROPHIC FAILURE FROM A FLAW**

The part shall possess inherent assurance against catastrophic failure due to a crack-like flaw by compliance with the requirements of the following paragraphs (5.3.1.4.2.1 through 5.3.1.4.2.3) as applicable.

###### **5.3.1.4.2.1 REMOTE POSSIBILITY OF SIGNIFICANT CRACK-LIKE DEFECT**

Assurance against the presence of a significant crack-like defect shall be achieved by compliance with the following criteria:

- A. The part shall be fabricated from a well-characterized metal which is not sensitive to stress corrosion cracking as defined in either MSFC-SPEC-522 or MSFC-HDBK-527/JSC 09604. If other than Table I or A-rated materials — as classified, respectively, in these documents — must be used, suitability for the specific application shall be documented by a Materials Usage Agreement (MUA). MUA forms contained in the cited documents, or equivalent, shall be used.

- B. The part shall not be fabricated using a process that has a recognized risk of causing significant crack-like defects, such as welding, forging, casting, or quenching heat treatment (for materials susceptible to cracking during heat treatment quenching) unless specific NDE or testing, which has been approved by the responsible fracture control authority, is applied to sufficiently screen for defects. It may be assumed that significant crack-like defects do not occur during machining of sheet, bar, extruded and plate products from materials that are known to have good machineability properties, do not have low fracture toughness (as defined in Appendix B), and are metals or alloys produced in accordance with applicable military specifications and standards or equivalent grade specifications.
- C. All parts classified as low risk fracture parts shall meet inspection standards consistent with aerospace practices to ensure aerospace-quality flight hardware. At a minimum, low risk fracture parts shall receive visual inspection. Inspection shall be made at the individual part level to assure maximum accessibility. Surface damage that could affect part life shall be cause for rejection.

#### **5.3.1.4.2.2 REMOTE POSSIBILITY OF SIGNIFICANT CRACK GROWTH**

Assurance against significant crack growth shall be achieved by compliance with any one of the following criteria:

- A. The part shall not be subjected to fatigue loading beyond acceptance and/or normal protoflight testing (if any), transportation, and one flight.
- B. The part shall be shown to possess a high safety margin on fatigue strength. This may be shown by either criteria 1 or 2 as follows:
  - (1) Limiting the local maximum cyclic tensile stress,  $S_{\max}$ , for a metal part to  $S_{\max} <$  endurance limit or, if data are not available, to
 
$$S_{\max} \leq F_{tu}/(4(1-0.5 R))$$
 where R is the ratio of minimum to maximum stress in a fatigue cycle, and  $S_{\max}$  is the local concentrated stress.
  - (2) A conventional fatigue analysis for crack initiation which conservatively accounts for the effects of notches and mean stress. The analysis must show a minimum of four complete service lifetimes with a safety factor of 1.5 on alternating stress.
- C. The part shall be shown to possess acceptable resistance to crack growth from potential initial defects caused by machining, assembly, and handling. Assumed initial surface cracks of 0.025 in (0.63 mm) depth and 0.05 in (1.25 mm) length and corner cracks of 0.025 in (0.63 mm) radius from holes shall not grow to failure in less than four complete service lifetimes.



#### 5.3.1.4.2.3 NONHAZARDOUS LEAK MODE OF FAILURE

Pressurized components or sealed containers that have a nonhazardous LBB mode of failure (i.e., critical length of through crack is at least 10 times wall thickness and fluid release would not create a catastrophic hazard) may be classified as low risk fracture parts if the component/container supports meet fracture control safe-life, fail-safe, or containment requirements and the component/container complies with the following requirements:

A. Requirements for sealed containers:

- (1) Compliant with the definition for sealed containers, as a single, independent (not part of a pressurized system) container, component, or housing that is sealed to maintain an internal nonhazardous environment and that has a stored energy of less than 14,240 ft-lb (19,310 Joules) and an internal pressure of less than 100 psia (689.5 kPa).
- (2) Container is made from metal alloys typically used for sealed containers (e.g., aluminum, stainless steel, or titanium sheet) and contains a fluid whose release is not a catastrophic hazard.
- (3) If compliant with criteria 1 and 2 and pressurized to 1.5 atmospheres or less, the containers are acceptable. If pressurized to more than 1.5 atmospheres, an analysis shall show that the safety factor is 2.5 or greater or that the container shall be proof-tested to a minimum of 1.5 times the MDP.
- (4) In special cases, containers with pressure or contained energy exceeding the limits defined in (1) above may be acceptable, but these containers shall be specifically approved by the responsible fracture control authority and by the PSRP. At a minimum, an analysis shall show the safety factor is 2.5 or greater and that the container is an LBB design. In addition, the container shall be proof-tested to a minimum of 1.5 times the MDP.

B. Requirements for pressurized components:

- (1) Components, lines, and fittings shall be in compliance with flight system safety factors as defined in NSTS 1700.7 ISS Addendum.
- (2) Components are made from metal alloys (e.g., stainless steel, aluminum, Inconel) typically used for pressurized systems.
- (3) Components that can sustain continued fatigue crack extension following leakage shall be shown by analysis to have safe-life-against-burst for the remaining possible cyclic pressurizations, or controls shall exist to detect leakage and prevent continued pressure cycles.

#### **5.3.1.4.3 FASTENERS AND SHEAR PINS**

Fasteners and shear pins may be classified as low-risk fracture parts when, though they are not shown to be compliant with 5.3.1.3, (a) fracture of the fastener does not result in a single-point direct catastrophic failure, and (b) they can meet the following requirements:

- A. Be high-quality military standard, national aircraft standard, or equivalent commercial fasteners or pins that are fabricated and inspected in accordance with aerospace-type specifications. Fasteners, which require specific tensile preload and which are used in joints that are loaded primarily in tension, shall have rolled threads meeting aerospace or equivalent rigorous standards.
- B. Be fabricated from well-characterized metal which is not sensitive to stress-corrosion cracking. Bolts in tension applications shall not be fabricated from low fracture toughness alloys (as defined in Appendix B) or specifically, Ti-6AL-4V STA titanium.
- C. Meet appropriate requirements for stress and fatigue analysis including torque/preload requirements for tension-load fasteners (i.e., sufficient preload to prevent gapping so that the cyclic loads are limited).
- D. Be of equal aerospace quality and meet all applicable criteria in A, B, and C above when reworked or custom-made fasteners.
- E. Have positive back-off prevention consistent with their criticality to assure the validity of fracture control of all fasteners.

#### **5.3.2 FRACTURE-CRITICAL PARTS**

Payload components which are identified as fracture critical shall be verified by analysis and/or test in accordance with the following paragraphs.

##### **5.3.2.1 SAFE-LIFE**

A fracture-critical component has acceptable safe-life if it can be shown by analysis or test that the largest undetected flaw that could exist in the component will not grow to failure when subjected to the cyclic and sustained loads and environments encountered in four complete service lifetimes. One complete service lifetime shall include all significant loadings occurring after flaw screening to establish maximum initial flaw size, and shall include testing, transportation, lift-off, ascent, on-orbit operations, descent, landing, and postlanding events, as applicable. Abort landing shall be considered for nonreturnable payloads. Since the service life factor of four accounts for the uncertainties in the observed measured material crack growth properties and fracture mechanics analysis, it shall be applied to all phases of the mission lifetime. This requires the determination of life cycle loads in accordance with Appendix E of this document.

For limited life parts (as defined in Appendix B), it shall be shown that at least four safe-lives remain before reflight. Renewed life predictions may be established by periodic inspection, proof-testing, or replacement; therefore, limited life parts shall be accessible for NDE inspection or replacement. Intervals between inspections, proof-tests, and/or replacement are to be established by safe-life analysis. Accessibility for inspection, testing, and/or replacement shall be addressed in the fracture control summary report.

A specific, detailed fracture mechanics analysis (or test) shall be performed to justify the use of any fracture-critical flight part with detected crack-like flaws. Approval by the responsible NASA center or approved partner/participant or sponsoring agency in conjunction with the PSRP shall be obtained prior to the use of any fracture-critical flight part containing detected cracks or crack-like defects. Incidences of detected crack-like flaws shall be included in the fracture control summary report along with the basis for acceptability.

Refer to paragraph 6.2.2 for guidance in safe-life analysis.

#### **5.3.2.2 PRESSURE VESSELS AND ROTATING MACHINERY**

Pressure vessels and rotating machinery (see definitions in Appendix B) are always fracture-critical structures and shall be analyzed and/or tested as required. Analysis methodologies for pressure vessels and rotating machinery are detailed in paragraphs 6.2.3 and 6.2.5, respectively (with results included in the fracture control summary report).

#### **5.3.2.3 OTHER SPECIFIC APPLICATIONS**

Compliance procedures for fracture-critical pressurized lines, fittings, and components; fracture-critical fasteners; fracture-critical composite/bonded structures; and fracture-critical glass components are given in paragraphs 6.2.4, 6.2.6, 6.2.7, and 6.2.8, respectively. Results of required analysis and testing shall be included in the fracture control summary report.

### **5.4 MATERIAL SELECTION**

#### **5.4.1 ALLOWABLE MECHANICAL PROPERTIES OF STRUCTURAL MATERIALS**

Materials used in the fabrication of payload hardware shall be selected by considering the operational requirements for the particular application and the engineering properties of the candidate materials.

Allowable mechanical properties of structural materials shall be obtained from authoritative sources, such as MIL-HDBK-5, "Metallic Materials and Elements for Aerospace Vehicle Structures" and MIL-HDBK-17, "Plastics for Flight Vehicles," or other sources which provide reliable and statistically valid data. Structural mechanical properties shall be determined by analytical methods described in MIL-HDBK-5.

Material "A" or equivalent allowable values shall be used for pressure vessels and for all applications where failure of a single load path could result in the loss of structural integrity in a fracture-critical structure. Material "B" or "S" or equivalent allowable values may be used in redundant structures in which the failure of a structural element would result in the safe redistribution of applied loads to other load-carrying structures.

#### **5.4.2 MATERIAL SAFETY CHARACTERISTICS**

Materials used in the construction of ISS payloads shall meet certain material safety characteristics as required by NSTS 1700.7 and NSTS 1700.7, ISS Addendum, paragraphs 208.3 and 209 in their entirety. The material safety characteristics which shall be addressed per NSTS 1700.7 ISS Addendum include Stress Corrosion Cracking, Materials Compatibility, Flammability, and Toxic Offgassing. In addition, galvanic corrosion and Thermal Vacuum Stability (if applicable) shall be addressed. Potential structural erosion (e.g., plasma environmental effects, atomic oxygen, etc.) shall be considered in the design and analysis of ISS payloads, as applicable.

#### **5.4.3 MATERIALS SAFETY CHARACTERISTICS SELECTION CRITERIA**

Whenever possible, materials shall be selected that meet the acceptance test criteria for a particular characteristic. Existing test data are compiled in NASA's Materials and Processes Technical Information System (MAPTIS) electronic database. This database contains an alpha "rating" indicating acceptability for the individual characteristics for each material.

A hardcopy version of the MAPTIS database is published periodically as a joint document between MSFC and Johnson Space Center (JSC), MSFC-HDBK-527/JSC 09604, Materials Selection List for Space Hardware Systems. The MAPTIS database is managed by the Materials and Processes Laboratory at MSFC.

#### **5.4.4 MATERIALS FOR PRESSURE VESSELS**

Material selection criteria for pressure vessels are contained in paragraph 6.2.3 of this document.

#### **5.5 WELDING REQUIREMENTS**

Welded structural components in payload flight equipment shall comply with the requirements for Class II or better welds in accordance with MSFC-SPEC-504 for aluminum alloys, MSFC-SPEC-560 for corrosion and heat resistant alloys, and other appropriate specifications for flight structures.

MSFC-SPEC-504 defines material and process requirements, inspection methods, and acceptance criteria applicable to gas-tungsten arc and gas-metal (shielded arc) welding of aluminum. MSFC-SPEC-560 gives the same information for steels, corrosion, and heat resistant steel alloys. Section 8.3 gives detailed generic requirements for process and quality control of flight equipment weldments based on these specifications.

Weldments on SCS should be avoided wherever possible because of the stringent requirements for space-qualified welds in terms of qualification of processes, weldment design, tests, and inspection. Braze metals and structural adhesive bonds also fall under the same scrutiny as weldments, and should be avoided wherever possible on SCS. If braze metals are used, the requirements of MIL-B-7883 and MSFC-STD-969 shall be satisfied.

#### **5.6 FASTENER REQUIREMENTS**

As specified in MSFC-STD-561, threaded fasteners connecting SCS shall use a means of positive locking. For non-fracture-critical fasteners which are not in habitable areas and do not require removal and/or replacement, cotter pins, safety wires, safety cable, locktite, locking nuts, locking inserts or equivalent, or vibration test results (which envelope the application and show that the non-secured fasteners/nuts did not back off during vibration testing to flight levels or higher) may be used to satisfy this requirement. For redundant fasteners (non-fracture critical) which are directly accessible by the crew, or which may require removal and/or replacement during the service life, safety-wiring is excluded as an acceptable method of securing threaded fasteners. These fasteners should be secured using self-locking nuts per MIL-N-25027, fastener systems such as those defined in MIL-STD-1515, or other approved methods. Fracture-critical fasteners and fasteners which retain a fracture critical rotating device shall be safety-wired, cotter-pinned per MS 33540, or safety-cabled per SAE AS4536. Fasteners internal to payload components, which are shown to be contained, are excluded from this requirement.

The principal concern is to ensure that threaded fasteners, when exposed to the ground and flight environments (i.e., acoustic, thermal, and vibration induced distortions), will not lose their preload by either the nut or bolt becoming loose from its secured position after torquing.

All safety-critical structural fasteners shall be torqued in accordance with MSFC-STD-486 and analyzed to the requirements defined in NSTS 08307. A bolt analysis procedure that meets the requirements of NSTS 08307, and sample bolt calculations can be provided on request. Guidance for the usage of threaded titanium alloy fasteners can be found in MSFC-STD-557.

Note: Fasteners less than  $\frac{3}{16}$  in. in diameter shall not be used in fracture-critical applications, except as noted in Section 6.2.6 of this document.

Use of nonstandard fasteners in SCS applications must receive prior and written approval of the responsible NASA center or approved partner/participant.

## **5.7 VIBRATION FREQUENCY REQUIREMENTS**

Vibration frequency requirements are levied for the STS lift-off and landing phases of a flight. Meeting the lift-off and landing frequency requirements allow the use of design load factors discussed in section 4.0. Additional frequency requirements are levied for some payloads during the ISS on-orbit phase to preclude dynamic coupling effects with the integrated ISS structure and with the STS and ISS remote manipulator systems.

### **5.7.1 STS LIFT-OFF/LANDING FREQUENCY REQUIREMENTS**

Payload flight equipment mounted directly to a primary structure (such as the USL, MPLM, and EXPRESS pallet) shall have a minimum natural frequency greater than or equal to 25 Hz when constrained at the boundary interface. Hardware mounted directly to secondary structure (e.g., ISPR, EXPRESS rack, and on adapter structure on EXPRESS pallet) shall have a minimum natural frequency greater than or equal to 35 Hz when constrained at the boundary interface. These generic frequency constraints have been placed on the payload flight equipment so that generic load factors (published in the Payload IDD or IRD) can be used by the PD. If the hardware cannot meet these frequency requirements, generic load factors cannot be used for design and analysis, and the JSC-ES center or appropriate partner/participant should be contacted.

The minimum natural frequency for US Facility Payload integrated racks, including US Facility Payload racks integrated by International Partners, is 25 Hz including the knee braces.

Middeck payloads which are not stowed in lockers are required to have a minimum fundamental frequency greater than 30 Hz (when constrained at the Orbiter attach points). Loads and deflections for these payloads shall be calculated using the load factors specified in NSTS 21000-IDD-MDK.

Sidewall-mounted payloads are required to have a minimum fundamental frequency greater than 35 Hz (when constrained at the adapter beam interface). Loads shall be calculated using load factors found in NSTS 21000-IDD-SML.

Payloads transported to or from the ISS via the SPACEHAB module are required to have a minimum frequency greater than 50 Hz (when constrained at the payload's SPACEHAB attach points). This requirement is imposed via paragraph 4.1 and the SPACEHAB/Experiment IDD (MDC91W5023C). If the hardware cannot meet this frequency requirement, generic load factors cannot be used for design analysis, and the SPACEHAB integrator must be contacted to obtain the appropriate load factors.

#### **5.7.2 ISS ON-ORBIT FREQUENCY REQUIREMENTS**

In addition to the STS lift-off/landing frequency requirements discussed in paragraph 5.7.1, attached payloads may have additional frequency or interface stiffness requirements. Payloads subject to the added frequency requirements are those that satisfy one of the following: attach directly to the ISS Truss Payload Attach System (PAS), require robotic manipulation via the Orbiter RMS or Space Station RMS (SSRMS), require robotic translation on the ISS, or require dexterous robotic support.

Payloads that attach directly to the ISS Truss PAS are required to meet minimum fundamental frequency requirements defined in paragraph 3.1.3.1.3 of the Attached Payloads IRD, SSP 57003 (when rigidly fixed at the PAS/UCCAS interface points).

Payloads requiring the use of the Orbiter RMS shall meet minimum fundamental frequency requirements defined in paragraph 14.4.5.2 of NSTS 21000-IDD-ISS (when held rigid at the grapple fixture). Similarly, payloads requiring SSRMS support shall meet minimum fundamental frequency requirements defined in paragraph 3.7.3 of the Attached Payloads IRD (when held rigid at the payload grapple fixture).

Attached payloads that require robotic translation support or temporary storage on the Mobile Servicing System (MSS) shall meet minimum fundamental frequency requirements defined in paragraph 3.7.5 of the Attached Payloads IRD (when held rigid at the grapple fixture).



Attached payloads that require dexterous robotic support shall meet minimum fundamental frequency requirements defined in paragraph 3.7.4 of the Attached Payloads IRD (when held rigid at the grasp point).

## **5.8 PRESSURIZED PAYLOADS (USL/MPLM-MOUNTED EQUIPMENT) SPECIFIC DESIGN REQUIREMENTS**

### **5.8.1 MASS AND VOLUME**

Payload flight equipment mounted within the module (e.g., facility class payloads) shall be compatible with the mass, interface force, and volume constraints levied by SSP 57000.

### **5.8.2 RACK EQUIPMENT MOUNTING AND INSTALLATION**

Rack-mounted payload flight equipment shall be designed to utilize the standard ISPR mechanical interfaces as defined in SSP 52000-PAH-PRP and SSP 57000.

A suitable number of attachments shall be used in the design to provide adequate distribution of loads, rigidity, and stability of the payload equipment within the acceptable range of applied loads to the rack structure.

The National Space Development Agency of Japan (NASDA) rack-to-payload interfaces are defined in SSP 52000-PAH-PRP, SSP 57000 and JCX-95006, JEM Payload Accommodations Handbook.

## **5.9 ISS ATTACHED PAYLOADS SPECIFIC DESIGN REQUIREMENTS**

ISS attached payloads involved in any of the following ISS activities are subject to specific design requirements: attach directly to the ISS Truss PAS, utilize the Space Station Extravehicular Robotics (EVR) capability, undergo robotic translation via the Mobile Servicing System (MSS), or require Extravehicular Activity (EVA).

Attached payloads connecting directly to the ISS Truss PAS shall be compatible with the general design requirements given in paragraph 3.1 of SSP 57003, Attached Payload IRD; including mass, volume, envelope, cg, natural frequency/stiffness, mechanical interface design, and interface preload. Specific design requirements for Extravehicular Robotics (EVR) and Extravehicular Activity (EVA) are given in paragraphs 3.7 and 3.8 of SSP 57003, respectively. Maintainability and maintenance requirements are given in paragraph 3.9 of SSP 57003.



Attached Payloads mounting to the EXPRESS Pallet shall meet the design requirements given in SSP 52000-IDD-EPP, EXPRESS Pallet Payloads IDD.

#### **5.10 ORBITER MIDDECK-MOUNTED EQUIPMENT SPECIFIC DESIGN REQUIREMENTS**

Payload flight equipment mounted within the Orbiter middeck shall be compatible with the mass, volume, cg, natural frequency, and mounting constraints in NSTS 21000-IDD-MDK, Shuttle/Payload Interface Definition Document for Middeck Accommodations.

#### **5.11 SPACELAB PALLET-MOUNTED EQUIPMENT SPECIFIC DESIGN REQUIREMENTS**

Payloads which attach to the Spacelab pallet shall meet the structural interface loads and mass, volume, natural frequency and cg constraints levied by SLP/2104, Spacelab Payload Accommodation Handbook.

#### **5.12 SIDEWALL ADAPTER-MOUNTED EQUIPMENT SPECIFIC DESIGN REQUIREMENTS**

Sidewall adapter-mounted payloads shall meet the interface loads requirements and weight/volume/cg constraints levied by NSTS 21000-IDD-SML. The overall configuration of the payload assembly shall be compatible with the load carrying capability defined in NSTS 21000-IDD-SML.

#### **5.13 SAFING OF MOVING STRUCTURES FOR LAUNCH AND LANDING**

Payload equipment developers should be particularly cognizant of the requirement for positive latching or safing of moving parts for launch and landing. These designs must be approved by the PSRP.

There are 2 ways to ensure the safing of such moving parts:

- A. Design for fail-safe braking with adequate margins of safety to withstand nominal landing load.
- B. Provide a two-failure tolerant relatch/lock mechanism for landing safing.

Braking, latching, and locking provisions shall withstand nominal translational and rotational loads experienced during the nominal launch and landing environment for the particular location

in the STS for the payload equipment. All latches should be designed for power-on release/power-off lock operation.

Redundant relatch provisions shall be provided in the event of main power interruption by some alternate means, such as the use of emergency power, or the equipment shall be designed to meet safety-critical structural requirements for nominal landing in the unlatched operating mode without power.

The structural design requirements shown in NSTS 1700.7 ISS Addendum, paragraph 208.1 and Mechanical System Safety letter MA2-00-057 (See paragraph 2.1.2) apply to all loading conditions including those that occur after credible mechanism failure(s). Mechanism failure(s) which result in limit load redistribution will require structural verification of the redistributed loads (if the PSRP determines the failed condition is credible). In order to minimize the number of structural configurations to be analyzed, payloads should provide two-failure tolerance against load redistribution caused by credible mechanism failures which could result in a hazard to the Orbiter, ISS, or crew. Structural verification of the redistributed load path is required and the 1.4 FS on limit loads must be maintained.

#### **5.14 FLIGHT EQUIPMENT DESIGN FOR MULTI-FLIGHT USE**

Payload developers shall define the usage spectrum of their equipment, including multi-flight operations. This may be an unscheduled reflight or scheduled reuse of the equipment. In any case, multi-flight use should be a factor in the initial design and development of payload flight equipment with safety-critical structural components to determine such things as design life for fracture control, selection of fasteners, selection of materials, and selection of design load factors for alternate mounting positions. The importance of this issue is emphasized here because pre-qualification for multi-flight use is much more cost effective than requalification for subsequent flights.

#### **5.15 STRUCTURAL ADHESIVE BONDS**

Structural adhesive bonds should be designed in accordance with MIL-HDBK-691 or aerospace industry standard, and shall meet the inspection requirements and test requirements levied by NSTS 14046 and listed in Appendix F of this document.

#### **5.16 JOINT FITTING FACTOR**

If required under the conditions outlined below, a fitting factor of 1.15 shall be used on yield and ultimate loads in the structural analysis of fittings.

- A. A fitting factor shall be used for joints which contain fittings whose strength is not proven by limit and ultimate load tests in which the actual stress conditions are simulated and measured in the fitting and surrounding structure.
- B. This factor shall apply to all portions of the fitting, the means of fastening, and the bearing on the members joined.
- C. In the case of integral fittings, the part shall be treated as a fitting up to the point where the section properties become typical of the member away from the joint.
- D. A fitting factor need not be used with limit and ultimate loads where the type of joint, such as continuous row of fasteners in sheet or plate, a welded or bonded joint, or a scarf joint in metal or plastic, etc., is strength-verified based on comprehensive limit and ultimate tests.

#### **5.17 BEARING FACTOR**

A bearing factor of 2.0 shall be used in conjunction with the yield and ultimate FS for the design of a joint subjected to shock or hammering action.

#### **5.18 CASTING FACTOR**

If metal casting is utilized as a fabrication process, an appropriate casting factor shall be developed by the design organization. The casting factor shall be applied in conjunction with the FS. Approval for the appropriate casting factor shall be obtained from the SWG and/or International Partner. If a casting is a fitting, then the fitting factor shall be applied in conjunction with the casting factors and applied with the respective yield and ultimate FS.

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## **6.0 STRUCTURAL ANALYSIS METHODOLOGY**

### **6.1 STRUCTURAL ANALYSIS REQUIREMENTS**

The procedure for verification of SCS that do not directly interface with the Orbiter is performed using the NASA Structural Analysis (NASTRAN) computer program. Cargo elements shall provide models in accordance with NSTS 37329. The element integrator combines all component and/or rack models up to the increment level. Therefore, NASTRAN (or NASTRAN-compatible) Finite Element Models (FEM) are required for use in the verification coupled loads analysis of the payload complement. This approach assures the compatibility of flight equipment assembly models with STS and ISS interface models for verification coupled loads. It also facilitates verification of the adequacy of Space Station payload analyses and flight structure. Use of any standard version of NASTRAN (COSMIC, MSC, CSA, etc.) or NASTRAN-compatible program (PATRAN, IDEAS, CAEDS, FEMAP, etc.) is acceptable, provided the guidelines regarding element usage in appendix D are followed. Guidelines in modeling with NASTRAN may be obtained from the following references:

- A. Computer Software Management Information Center (COSMIC) NASTRAN Manuals
- B. Computerized Structural Analysis Research (CSAR) NASTRAN Manuals
- C. MSC/NASTRAN Manuals
- D. MSC/NASTRAN Primer

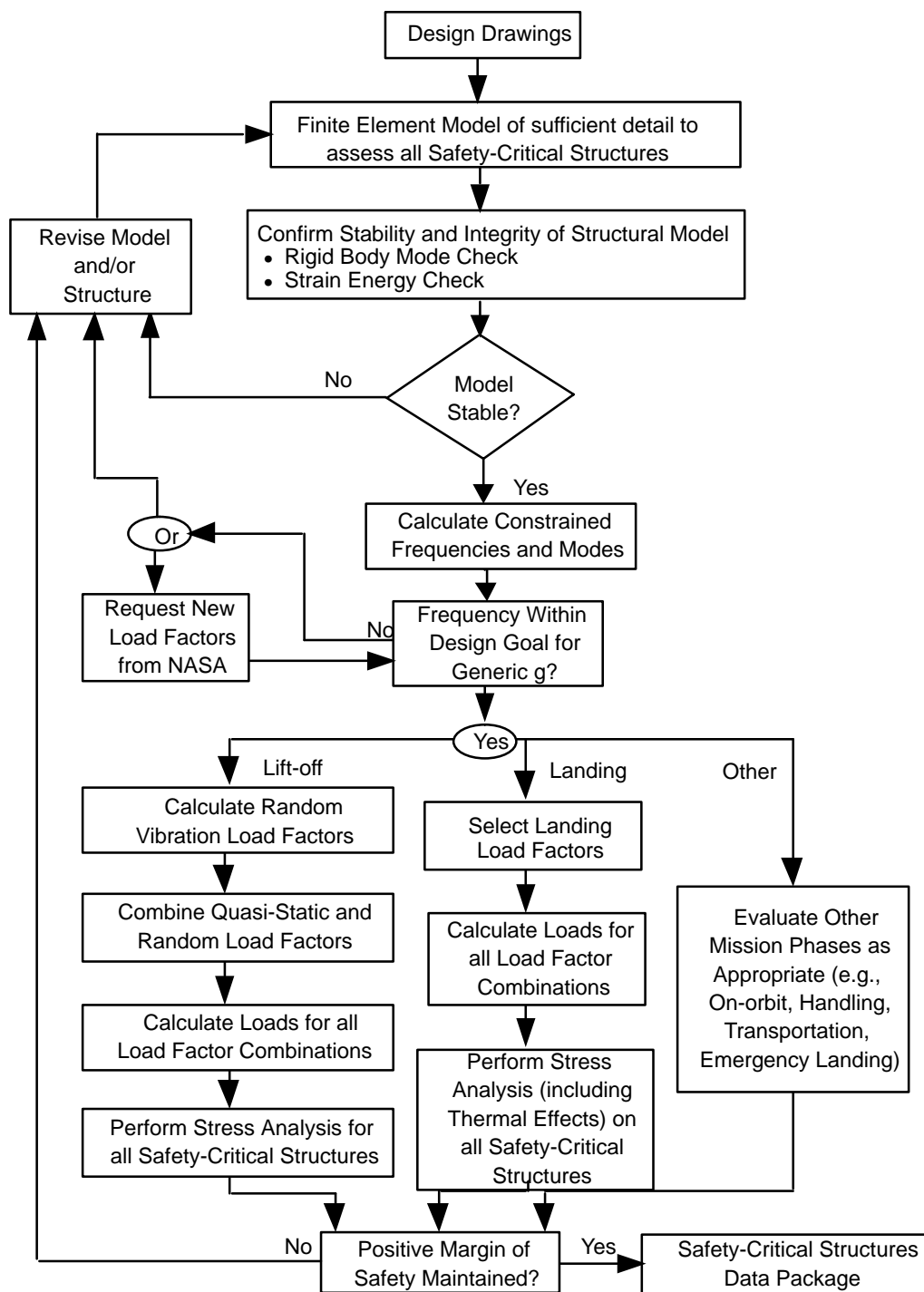
The following paragraphs describe the methods which shall be used to provide the required data for verification of SCS.

#### **6.1.1 STRUCTURAL ANALYSIS**

Structural analysis shall be performed for all payload flight equipment SCS to demonstrate compatibility with the STS and ISS. The analyses described herein are those which are required to provide the data necessary for verification of SCS. Note: All applicable failure modes must be evaluated (e.g., tension, torsion, buckling, crippling, bearing, etc.). The procedures may also be applicable to the detailed design and verification for functional integrity and survivability of payload flight equipment structures; however, requirements for this purpose are the prerogative of the PD.

The structural analysis shall fully substantiate the structural integrity of each safety-critical detailed part of each piece of payload flight equipment. A flow diagram is given in Figure 6.1.1-1 to demonstrate the structural analysis concept. Minimum data requirements for payload flight equipment include the following:

- A. Design drawings of the payload flight equipment final design configuration (especially SCS)
- B. Identification of SCS of the final design configuration
- C. Materials list for SCS
- D. Structural design loads (including rationale for their use)
- E. Structural models and model descriptions of the final design configuration
- F. Loads and dynamic analyses of the final design configuration
- G. Stress analysis of the final design configuration
- H. Fracture control/analysis
- I. Test results (from static, modal, random and acoustic tests, as applicable, per section 7.1)
- J. Other structural verification documentation



**FIGURE 6.1.1-1 STRUCTURAL ANALYSIS PROCEDURE FOR SAFETY CRITICAL STRUCTURES**

#### **6.1.1.1 DESIGN CONFIGURATION**

During initial design, the PD should consider the class of the payload and all possible locations for the equipment which would satisfy their objectives. The location will determine the load factors to be used in the structural analysis of the equipment. In cases where the manifest location has not been assigned, the PD should assume the locations (compatible with functional objectives) which are subjected to the greatest load factors. Load factors for various payload classes, and payload equipment attachment criteria (discussed in section 5), are given in the respective interface documents:

- A. SSP 57000, Pressurized Payloads Interface Requirement Documents
- B. NSTS 21000-IDD-MDK, Middeck IDD
- C. SSP 52000-IDD-ERP, EXPRESS Rack IDD
- D. SSP 52000-IDD-EPP, EXPRESS Pallet IDD
- E. NSTS 21000-IDD-SML, Shuttle/Payload IDD for Small Payload Accommodations (applicable for sidewall-mounted payloads)

The final structural analysis shall be based on the final design configuration, materials list, and environmental data and results from more refined structural loads analysis.

#### **6.1.1.2 STRUCTURAL MODELING**

The structural model shall be a NASTRAN or NASTRAN-compatible FEM of the payload flight equipment and attachment hardware. The model shall possess the sufficient detail to determine the dominant vibration natural frequencies, to adequately represent the primary load paths of the component, and verify structural integrity of all major structural elements of the system. Component support structure stresses are highly dependent on accurate representation of mass (M) and cg location. Safe design practice mandates the use of the control mass in combination with statistically valid dispersions on cg location.

Finite element structural models are required for all items, components, and assemblies with weight >40lb and  $f_1 < 50\text{HZ}$ . The FEM is to be provided in NASTRAN or NASTRAN-compatible format in agreement with the guidelines of appendix D. The model is to be documented to include description and/or references for: (a) assembly drawings and detailed structural drawings of the installation, (b) description of the FEM including mass, cg, grid points, constraints, elements, etc., (c) dynamic model bulk data input with control statements, and (d) analytical verification of FEM quality including geometrical plots, modal plots, checks of mass equilibrium, orthogonality of modes and dynamic properties (see appendix D), and correlation of test results (as required). Finite element structural models must be test verified in accordance with section 7.1. Section 7.1 assumes that the component is tested with flight-type boundary conditions.



Evidence that the minimum natural frequency is greater than or equal to 35 Hz may be verified by analysis and/or test, depending on the weight and class of the payload/component (see section 7.1).

The stability and integrity of the structural model shall be confirmed by performing a Rigid Body Modes (RBM) check on the unconstrained (not attached or fixed) and unsupported (do not use SUPPORT elements) model. This check should result in a "rigid body" mode shape with a characteristic frequency near zero ( $<10^{-2}$ ) for each DOF. For most typical payloads, this will result in six "rigid body modes," one for each DOF (X, Y, Z,  $\theta_x$ ,  $\theta_y$ , and  $\theta_z$ ). An example is provided in appendix D. Mechanistic interfaces may be constrained using rigid elements to mimic external constraints and avoid unwanted RBMs due to linkages and struts. The use of the RBM check on the model does not preclude the use of other methods to check the validity of a model. Other tests that can be performed include "strain energy checks".

Frequency and mode calculations may be made on a reduced version of the structural FEM, providing a standard reduction technique is used. The reduced model shall be compared to the "full up" model to ensure that the frequency and modal characteristics are not affected by the model reduction.

#### **6.1.1.3 DYNAMIC ANALYSIS**

A modal analysis shall be performed for the final design configuration using the model developed per paragraph 6.1.1.2. This analysis shall determine all modes up to 50 Hz and the first mode/frequency in each direction for the overall system and each major equipment component. A sufficient number of DOFs shall be retained in the model to produce the required number of modes and frequencies needed for assessing the payload during transient and random loading.

In the verification coupled loads analysis, the total payload system is modeled. All items in the payload system are either statically or dynamically represented, and verification of each structural model used in the cargo element is required. As a minimum, the static representation shall contain the mass, cg, coordinates, mass moments of inertia about the cg, boundary stiffness and constraints, and attachment interface location coordinates.

#### **6.1.1.4 LIFT-OFF/LAUNCH LOADS ANALYSIS**

Development of the loads to be used in the stress analysis shall consist of an assessment from the load conditions identified in section 4 and located in the IDD for each payload class. Total design loads shall be developed using the following subsections.

#### **6.1.1.4.1 MINIMUM NATURAL FREQUENCY**

Determine the minimum natural frequency of the overall structure/component in each axis. If separate components are included in the overall structure and are considered safety critical (see section 4), minimum natural frequencies (in each direction) shall also be calculated for these components.

#### **6.1.1.4.2 RANDOM VIBRATION LOAD FACTORS**

Calculate RVLFs using the frequencies found in paragraph 6.1.1.4.1 (lift-off configuration only) and the methodology provided in paragraph 4.2.4.

#### **6.1.1.4.3 LOW FREQUENCY LOAD FACTORS**

Determine the appropriate set of low frequency load factors for each structure/ component. The appropriate low frequency load factors depend on the location of payload equipment component. If a specific location has not been assigned, the PD shall use the highest accelerations consistent with the possible locations for their payload.

#### **6.1.1.4.4 COMBINED LOAD FACTORS**

Calculate the design (limit) load factors using the methodology provided in section 4. Note that the low frequency loads shall be applied simultaneously in all three translational directions (and all three rotational directions if applicable). For facility class payloads (e.g., integrated racks), the rotational (angular) loads may either be applied directly, or the equivalent translational load factors, which include the effects of the rotational loads, may be used. For sub-rack components, the three rotational load factors have already been incorporated into the component level translational load factors. The RVLFs are to be combined using the rss method with the low frequency load factors one direction at a time. Further explanation is provided in section 4.

#### **6.1.1.5 LANDING LOADS ANALYSIS**

Landing loads shall be the combination of loads generated by low frequency load factors combined with thermal effects.

##### **6.1.1.5.1 THERMAL EFFECTS ON MATERIAL PROPERTIES**

Hot case thermal effects for landing require that material properties be adjusted in the model to reflect any reduction in strength (e.g., tensile yield strength for aluminum (6061-T6) is reduced

by a factor of .95 to .97 when the reference temperature is modified to 150 °F from 70 °F). Material properties at the elevated temperature may be obtained from MIL-HDBK-5. Either the “degraded” material properties may be used for all load cases, or the reduced material property input shall be prepared by hand, since NASTRAN does not permit two sets of material properties to be used in the same calculation.

#### **6.1.1.5.2 LOW FREQUENCY LOADS WITH THERMAL EFFECTS**

The finite element math model can be executed using temperature inputs which reflect the change from temperature at hardware assembly to maximum or minimum service temperature as defined in the appropriate IDD or ICD. Thermally induced stresses should be calculated separately, i.e., flight loads should be excluded from this subcase. NASTRAN will calculate the loads due to the thermal environment as a subcase which can be combined with the appropriate flight load subcases in a total stress run.

Care should be taken to ensure that constraints and attachments are as realistic as possible when performing a thermal expansion loads analysis. Over-constrained boundaries (too many DOFs constrained or using conservative distances between rigidly coupled DOFs) can introduce unrealistically large thermal forces into a model with a modest temperature gradient. The indiscriminate use of rigid elements and offset section properties can induce large spurious thermal stresses. This may be avoided by executing a “hot” or “cold soak” case if dissimilar materials are not also present.

#### **6.1.1.6 STRESS ANALYSIS**

The stress analysis should be sufficiently detailed to assure the structural integrity of all structural safety-critical elements using the loads previously developed.

All load factor combinations shall be established and applied in all three axes simultaneously. Three-axis simultaneous load factors shall be applied for all “dynamic load” conditions. The loads analysis shall include an assessment of all loading conditions referred to in section 4 and the appropriate ICD or IDD, with a rationale of why these loads do/do not affect the design.

A minimum MS summary shall be included in the stress report for all SCS using the design loads. The report should have sufficient detail and sample calculations that the SSP-SWG or other responsible NASA center or approved partner/participant can verify loads development, FS, and analysis methodology.

The stress analysis should address the following points:

- A. A sketch of each area being analyzed should be given to describe the load path, pertinent dimensions, and structural details. Pertinent drawing numbers should be included.
- B. Examples of the types of analysis required include:
  - (1) Combined stress states
  - (2) Buckling and crippling
  - (3) Tension
  - (4) Shear
  - (5) Bending
  - (6) Bolt analysis
  - (7) Prying (heel and toe)
  - (8) Bearing
  - (9) Shear tear-out
  - (10) Lug analysis
- C. The source of the loads used in each section of the analysis should be noted (if it is not obvious). An example of this would be the output from a FEM (NASTRAN) or the results of hand analysis.
- D. Any unusual configurations or significant deviations between a FEM and actual structure should be fully documented (e.g., elastic FEM elements in the form of spring constraints that represent nonrigid interfaces).
- E. It should be noted that much of the final format of the analysis is the result of the analyst's good judgment. One should also keep in mind that this documented analysis will be used for safety verification and is the basis for a fracture mechanics assessment.

#### **6.1.1.7 BUCKLING AND CRIPPLING**

Buckling shall not cause structural members that are subject to instability to collapse when ultimate loads are applied, nor shall buckling deformation from limit loads produce unaccounted changes in loading.

Evaluation of buckling strength shall address the combined action of primary and secondary stresses and their effects on general instability, local or panel instability, and crippling.

All structural components that are subject to compressive and/or shear in-plane stresses under any combination of ground loads, flight loads, or loads resulting from temperature changes shall be considered for buckling failure modes. Design loads for collapse shall be ultimate loads, except that any load component that tends to alleviate buckling shall not be increased by the ultimate FS. Destabilizing external pressure or torsional limit loads shall be increased by the ultimate FS but stabilizing internal pressure loads shall not be increased unless they reduce structural capability. Diagonal tension designs are not precluded.

Analysis of buckling of thin-walled shells shall use appropriate “knockdown factors” (correlation coefficients) to account for the difference between classical theory and empirical instability loads.

### **6.1.2 STRUCTURAL DESIGN VERIFICATION**

The “as-built” hardware shall be assessed with respect to the structural design used in the structural analyses (“as-designed” stress, dynamic and fracture analyses).

The contents of the “as-built” data package shall include all structural changes (changes in the design, materials, loading, etc.) made to the “as-built” hardware. This data package shall document all structural modifications and model changes incorporated after the design drawings, Material Usage Agreements (MUAs), and analyses have been completed.

## **6.2 FRACTURE CONTROL ANALYSIS**

A list of safety-critical structural elements shall be identified by the PD, and this list shall be used to determine which structures/parts are fracture critical. SCS are not necessarily fracture critical, since they may be eliminated from the fracture-critical list if they are shown to be low released mass, contained, fail-safe, or low risk. Fracture mechanics evaluation shall be conducted based on the final design stress analysis (and such updates to that analysis as may be required because of changing loads criteria and designs). The procedures outlined below are for the guidance of PDs. Note that fracture-critical structures normally require NDE by the PDs. Fracture-critical equipment shall be designed to permit NDE (before assembly operations which may obscure critical flaw inspection sites). All payload fracture control shall be in accordance with the requirements stated in NASA-STD-5003.

The fracture control analyses shall be performed using the following guidelines:

## 6.2.1 CONTAINMENT/RESTRAINT ANALYSES

Containment/restraint analyses shall consider such factors as the velocity and energy of the part, worst-case sharpness/minimum area, elastic and/or plastic deformation, and the resulting stresses on the enclosure/tether.

### 6.2.1.1 CONTAINMENT ANALYSIS

For containment, it shall be verified by analysis that structures or parts will be contained in the event that they become detached from the payload because of structural failure of the part or attachment fasteners. Analysis shall be provided to show that no part or parts can attain sufficient kinetic energy to escape a container which completely encompasses the aggregate structures or parts (such that none of them or their fragments can escape the confines of their container to cause a hazard to the STS/ISS or crew). The equation to be used to show structural containment, commonly referred to as the "Punch" equation obtained from TN-ER-33-029-78, is as follows:

$$T_R = \left[ \frac{1}{2} \cdot V^2 \cdot \frac{W}{g} \cdot \frac{1}{\pi d Y_{S_w}} \right]^{1/2}$$

Where:

- $T_R$  = The minimum required wall thickness (inches) of the container to prevent escape of the component/part.
- $W$  = Weight (pound-force) of the detached piece or part to be contained.
- $g$  = Gravitational acceleration (in/sec<sup>2</sup>)
- $V$  = Velocity (inches per second) that may be attained by that piece or part (reference paragraph 6.2.1.1.3).
- $d$  = Minimum profile diameter (inches) of piece or part that will produce a shear load on the container wall before escape by any particular piece or part resulting from a structural failure.
- $Y_{S_w}$  = The yield strength (pounds per square inch) of the container wall material.

Consistent units shall be used in applying this equation. Extreme caution shall be used for evaluations of containment vessels if non-ductile materials are used.

#### 6.2.1.1.1 INHERENT SAFETY FACTORS

The Punch equation is in most cases conservative in that it is based on yield strength of the container wall (when the ultimate strength of the wall has to be exceeded to escape). This conservatism is minor, however, since the material strength appears as a square root function and

the square root ratio of yield strength to ultimate strength for most aerospace aluminum alloys is in the 0.85 to 0.95 range. The equation also ignores any yielding of the projectile.

#### 6.2.1.1.2 THE MINIMUM EFFECTIVE SHEAR DIAMETER

For objects which have no circular cross section, a diameter equivalent to a cylindrical projectile has to be calculated using the smallest possible projected perimeter for any angular orientation of the object. Examples follow:

- A.  $\pi D =$  Perimeter of the smallest face of a rectangular object.
- B.  $\pi D =$  Perimeter of the circular projection when looking at a conical end.
- C.  $\pi D =$  The base perimeter of a cone.
- D.  $\pi D =$  The perimeter of the projected flat edge of a disk (2 x (diameter + thickness)).

#### 6.2.1.1.3 PROJECTILE ENERGY LIMITS

The kinetic energy of the projectile(s) created as a result of a structural failure of contained structures or parts is limited by the mass of the detached part (M) and the velocity (V) it can attain within the confines of its container. There are two possible contributors to the projectile impact velocity which include velocity due to the low frequency transient acceleration of the projectile at separation and the steady state acceleration of the NSTS Orbiter at time of projectile separation and velocity induced by the sudden release of preload (e.g., failure of a preloaded fastener). For conservatism, the maximum velocity from each of the two contributors is superimposed into one velocity value to use in wall thickness calculations.

The projectile velocity attributed to the low frequency transient acceleration (in/sec<sup>2</sup>) is a function of the natural frequency of the attached part. It can be shown that the maximum projectile velocity prior to separation is given by the equation:  $V = \frac{A_{LF}}{2 \cdot \pi \cdot f_n}$  where  $A_{LF}$  is the low frequency transient acceleration and  $f_n$  is the minimum natural frequency in hertz. Since the velocity is inversely proportional to the natural frequency of the object, the minimum allowed natural frequency (in many cases 35 Hz) should be used for velocity calculations. The relative velocity due to the steady state acceleration of the NSTS Orbiter can be shown to be:  $V = \sqrt{2 \cdot a \cdot S_d}$  where "a" is the steady state acceleration ( $\approx 3.17g$ ) of the NSTS Orbiter and " $S_d$ " is the maximum travel distance of the projectile within the container (such as the longest diagonal in a rectangular box, minus the smallest dimension of the free part). The maximum limit load factors for NSTS Orbiter cargo bay are given in Table 6.2.1.1.3-1. If the failure is that of a preloaded fastener (having low fracture toughness per 5.3.1.1B), then the initial velocity,  $V_o$ , will be induced by the sudden conversion of stored energy (preload) to kinetic energy. The maximum projectile velocity is given by:

$$V_o = \sqrt{\frac{2U}{\left(\frac{W}{g}\right)}}$$

Where:

$$U = \frac{P^2 l}{2AE}$$

P = Preload

A = Fastener cross-sectional area

E = Modulus of Elasticity

l = Fastener length

W = 1/2 weight of fastener

The resultant of the listed accelerations for a given flight event shall be used to calculate the linear acceleration, “a,” from which the relative velocity due to steady state acceleration is determined. The sum of the two calculated velocities is then used in the containment equation.

**TABLE 6.2.1.1.3–1 CARGO LIMIT-LOAD FACTORS/ANGULAR ACCELERATIONS FOR PRELIMINARY DESIGN**

FLIGHT EVENT	LOAD FACTOR (g)			ACCELERATION (rad/sec <sup>2</sup> )			CARGO WEIGHT
	N <sub>X</sub>	N <sub>Y</sub>	N <sub>Z</sub>	$\ddot{\phi}$	$\ddot{\theta}$	$\ddot{\psi}$	
Lift-off	+3.1 -5.7	±1.5	±5.9	±3.7	±13.0	±6.0	Up to 5 klb (2,268 kg)
Landing	+5.0 -4.5	±2.7	+6.5 -3.0	±5.0	±13.0	±6.0	Up to 5 klb (2,268 kg) (returnable cargo)

Notes:

1. Reference NSTS–2100–IDD–ISS, TABLES 4.1.1.3.2.1–1, 4.1.1.3.2.2.1–1, and 4.1.1.3.2.2.2–1.
2. These loads are defined for preliminary design and may be replaced by a mission-specific coupled loads analysis with approval of the SSP-SWG.
3. Cargo load factor/angular accelerations are defined as the total externally applied force/moment on the cargo, or cargo component, divided by the corresponding total, or component, weight/mass moment of inertia and carries the sign of the externally applied force/moment in accordance with the Orbiter coordinate system (for clarification, see Figure 4.1.1.3-1 of NSTS 21000-IDD-ISS).

#### 6.2.1.1.4 CONTAINMENT EVALUATION APPROACH

The following is a simplified approach to the evaluation of container adequacy based on the “Punch” equation.



- A. Initial Calculations - To save time, it is recommended that the initial calculation be based on conservative assumptions of parameter values (even though these values may not be realistic). If the results indicate that the total mass of the container aggregate contents will not escape the container based on the container actual wall thickness ( $T_A$ ), impact velocity ( $V$ ) due to both low frequency acceleration and steady state acceleration, minimum effective profile diameter ( $D$ ) of the contents, and the Yield Strength ( $YS_w$ ) of the container wall, then the container is more than adequate. If not, a more detailed analysis will be necessary to demonstrate containment.
- B. Step Two - If the initial analysis fails to show adequate containment, choose one or more parts (or aggregation of parts) which represent the highest mass-distance products over the smallest diameter for evaluation. Although these parameters are still conservative, they are more realistic and may provide proof of containment.
- C. Detailed Analysis - If the second analysis described above fails to prove containment, a more detailed evaluation shall be required (unless the container can be easily redesigned to provide an adequate thickness or a higher yield strength wall material). This detailed analysis involves a prediction of contained parts and structures failure modes based on stress analysis of the parts most likely to separate based on the lowest margins of safety. This assessment would follow the procedure of Step Two on each possible detached part or piece.
- D. Analysis of the Container - Whether or not containment is adequately demonstrated, the container with its aggregate contents remains a SCS and shall demonstrate positive margins of safety when analyzed as one part (and is subject to the same fracture control provisions as any other component, except that contained parts and structures are not fracture critical).

#### **6.2.1.2 RESTRAINT ANALYSIS**

A part is considered restrained if it can be shown by analysis or test that failure of that part will not result in separation from the payload because of restraining wires, fasteners, or other elements structurally capable of preventing release into habitable areas or the Orbiter cargo bay. In addition, the failure of the part cannot result in any other hazard to STS/ISS or crew. As in the containment analysis, the PD shall show that the kinetic energy which can be achieved by the free part does not exceed the strength capability of the restraining device or tether. For parts which are closely held in restraint, the force ( $F$ ) applied to the restraining device is  $F = Ma$  where “ $M$ ” is the mass of the part and “ $a$ ” is the maximum resultant acceleration which can be achieved at its location in the Orbiter. Where the device is tethered, such tethers shall be capable of absorbing the maximum kinetic energy which can be attained by the part.

$$KE = M \cdot a \cdot S_d$$

Where:

$S_d$  = Tether slack; i.e., maximum distance the part may move before restraint by the tether becomes effective (assumes that the displacement during tether extension is small compared with  $S_d$ ).

$a$  = Maximum acceleration of the detached part.

This kinetic energy will be absorbed as strain energy in the tether as shown in the following relationship:

$$\frac{1}{2} * K * x^2 = M * a * S_d$$

From which,

$$x = \sqrt{\frac{2 \cdot M \cdot a \cdot S_d}{K}}$$

Then the force in the tether is:

$$F = K \cdot x$$

where the tether stiffness is given by:

$$K = \frac{A \cdot E}{L}$$

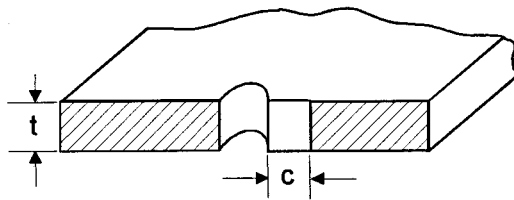
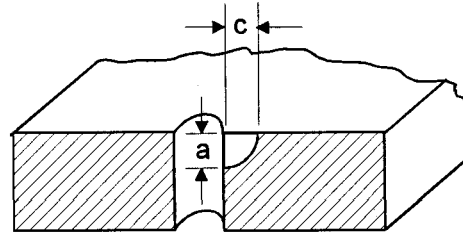
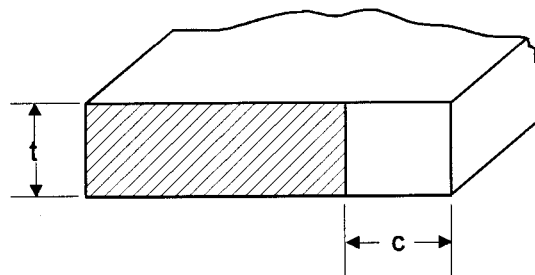
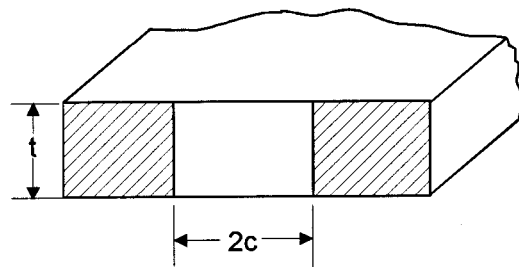
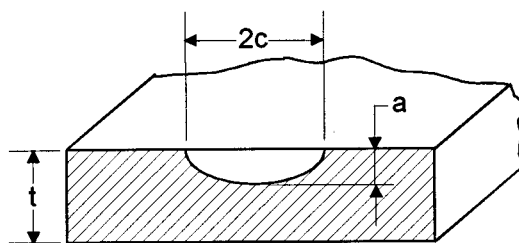
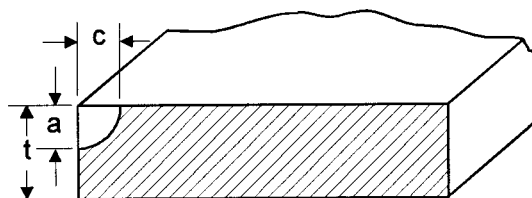
A safety factor of 1.4 is required.

## 6.2.2 SAFE-LIFE ANALYSIS

- A. When crack growth analysis is used to demonstrate safe-life design for a part, an undetected flaw shall be assumed to be in the most critical area and orientation for that part. The size of the flaw shall be based on either the appropriate NDE techniques (section 4.3 of NASA-STD-5003) or on proof-testing. Table I or II of NASA-STD-5003 lists flaw sizes representative of the capabilities of commonly used NDE techniques. Both the crack growth analysis and the proof-test flaw screening logic, if utilized, shall be based on state-of-the-art fracture mechanics methodology. Use of proof-testing as an alternative to NDE to support safe-life determination shall require prior approval of the responsible fracture control authority. Flaws screened by proof test shall have aspect ratio  $a/c$  from 0.2 to 1.0. For surface cracks in components, including pressure vessels, both sets of values for “a” and “c” from Figure 6.2.2–1 and Table 6.2.2–1 and Table 6.2.2–2 shall be considered.
- B. For components where it is necessary to consider the propagation of a crack into a hole, or from one hole into another hole, the analysis shall assume that the crack is not arrested or retarded by the hole, but continues on past the hole. In analyzing components or assemblies where drilling of numerous holes or the use of automatic hole preparation and fastener installation equipment at the assembly level makes NDE of holes impractical, an initial crack size can be assumed which is based on the maximum potential damage from hole preparation operations. With acceptable hole preparation (outlined in 6.2.2C, and in the

restrictions of 6.2.2D and 6.2.2E), the maximum initial crack size can be assumed to be smaller than those sizes specified in Table 6.2.2-1 and Table 6.2.2-2.

- C. Specifically, for drilled holes with driven rivets, the assumed defect (paragraph 6.2.2B) shall be a 0.005 in (0.13 mm) length crack through the thickness at one side of the hole. For fastener holes other than those for driven rivets, where the material thickness is equal to or less than 0.05 in (1.3 mm), the assumed fabrication defect shall be a 0.05 in (1.3 mm) length crack through the thickness at one side of the hole. Where the thickness is greater than 0.05 in (1.3 mm), the initial flaw size shall be a 0.05-in (1.3-mm) radius corner flaw at one side of the hole.
- D. The maximum fabrication defect sizes given in 6.2.2C, may be used for an analysis of holes only where (1) the holes are not punched, (2) the material is not prone to cracking during machining, (3) NDE is performed prior to machining of the holes, (4) no heat treatment or possible crack-forming fabrication processes are performed subsequent to NDE, (5) analysis is performed with separate and additional flaws assumed at the most critical locations away from the holes and with sizes that are consistent with the specified NDE method, and (6) prior approval is obtained from the responsible fracture control authority.
- E. Notwithstanding any of the options stated in 6.2.2D, NDE of holes shall always be required for fracture-critical components where the load is transmitted through a single hole, such as for a fitting.
- F. Either of two analysis approaches may be used to show that an NDE-inspected part meets safe-life requirements. The first or direct approach is to select the appropriate inspection technique and level indicated in Table I or II of NASA-STD-5003 and to use the listed minimum initial flaw sizes in analyses to show that the part will survive at least four lifetimes. The alternate or iterative approach is to calculate the critical (i.e., maximum) initial crack size for which the payload can survive four lifetimes and to verify by inspection that there are no cracks greater than or equal to this size. Where the iteratively derived crack size is smaller than the value given in Table I or II of NASA-STD-5003, use of the smaller size requires prior approval as per paragraph 7.5.2.
- G. Appropriate crack models and material properties, including all contributions to crack growth, such as environmental effects, shall be included in the analysis. For sustained stresses, it shall be shown that the maximum stress-intensity factor in the fatigue cycle,  $K_{\max}$ , is less than the stress corrosion or environmental cracking threshold,  $K_{\text{ISCC}}$ . Retardation effects on crack growth rates from variable amplitude loading shall not be considered without the approval of the responsible fracture control authority. The Fatigue Crack Growth Computer Program NASGRO (NASA/FLAGRO latest version) is an approved computer code for crack growth analysis of Space Shuttle / ISS payloads.

**GEOMETRIES FOR CRACKS AT HOLES \*****THROUGH CRACK****CORNER CRACK****GEOMETRIES FOR CRACKS NOT AT HOLES****THROUGH CRACKS****PARTIALLY THROUGH CRACKS****SURFACE CRACK****CORNER CRACK**

\* For more details, see the latest version of NASGRO

**FIGURE 6.2.2-1 STANDARD CRACK GEOMETRIES**

**TABLE 6.2.2-1 MINIMUM INITIAL CRACK SIZES FOR FRACTURE ANALYSIS BASED ON NDE METHOD – U.S. CUSTOMARY UNITS (IN.)\***

Crack Location	Part Thickness, t	Crack Type	Crack Dimension a	Crack Dimension c
<u>Eddy Current NDE</u>				
Open Surface	$t \leq 0.050$	Through	t	0.050
	$t > 0.050$	PTC <sup>1</sup>	$\begin{cases} 0.020 \\ 0.050 \end{cases}$	$\begin{cases} 0.100 \\ 0.050 \end{cases}$
Edge or Hole	$t \leq 0.075$	Through	t	0.100
	$t > 0.075$	Corner	0.075	0.075
<u>Penetrant NDE</u>				
Open Surface	$t \leq 0.050$	Through	t	0.100
	$.050 < t < .075$	Through	t	0.15-t
	$t > 0.075$	PTC	$\begin{cases} 0.025 \\ 0.075 \end{cases}$	$\begin{cases} 0.125 \\ 0.075 \end{cases}$
Edge or Hole	$t \leq 0.100$	Through	t	0.100
	$t > 0.100$	Corner	0.100	0.100
<u>Magnetic Particle NDE</u>				
Open Surface	$t \leq 0.075$	Through	t	0.125
	$t > 0.075$	PTC	$\begin{cases} 0.038 \\ 0.075 \end{cases}$	$\begin{cases} 0.188 \\ 0.125 \end{cases}$
Edge or Hole	$t \leq 0.075$	Through	t	0.250
	$t > 0.075$	Corner	0.075	0.250
<u>Radiographic NDE<sup>2</sup></u>				
Open Surface	$.025 \leq t \leq 0.107$	PTC	0.7t	0.075
	$t > 0.107$		0.7t	0.7t
<u>Ultrasonic NDE<sup>3</sup></u>				
Open Surface	$t \geq 0.100$	PTC	$\begin{cases} 0.030 \\ 0.065 \end{cases}$	$\begin{cases} 0.150 \\ 0.065 \end{cases}$

Notes:

1 - Partly through crack (PTC).

2 - Sizes not applicable to very tight flaws (e.g., forging flaws or lack of full penetration in butt welds).

3 - Comparable to Class A quality level (MIL-STD-410)

\* See latest version of NASGRO for any updates.

**TABLE 6.2.2-2 MINIMUM INITIAL CRACK SIZES FOR FRACTURE ANALYSIS BASED ON  
 NDE METHOD – SI UNITS (MM)\***

Crack Location	Part Thickness, t	Crack Type	Crack Dimension a	Crack Dimension c
<u>Eddy Current NDE</u>				
Open Surface	$t \leq 1.27$	Through	t	1.27
	$t > 1.27$	PTC <sup>1</sup>	{ 0.51	{ 2.54
			{ 1.27	{ 1.27
Edge or Hole	$t \leq 1.91$	Through	t	2.54
	$t > 1.91$	Corner	1.91	1.91
<u>Penetrant NDE</u>				
Open Surface	$t \leq 1.27$	Through	t	2.54
	$1.27 < t < 1.91$	Through	t	3.81-t
		PTC	{ 0.64	{ 3.18
	$t > 1.91$		{ 1.91	{ 1.91
Edge or Hole	$t \leq 2.54$	Through	t	2.54
	$t > 2.54$	Corner	2.54	2.54
<u>Magnetic Particle NDE</u>				
Open Surface	$t \leq 1.91$	Through	t	3.18
	$t > 1.91$	PTC	{ 0.97	{ 4.78
			{ 1.91	{ 3.18
Edge or Hole	$t \leq 1.91$	Through	t	6.35
	$t > 1.91$	Corner	1.91	6.35
<u>Radiographic NDE<sup>2</sup></u>				
Open Surface	$0.64 \leq t \leq 2.72$	PTC	0.7t	1.91
	$t > 2.72$		0.7t	0.7t
<u>Ultrasonic NDE<sup>3</sup></u>				
Open Surface	$t \geq 2.54$	PTC	{ 0.76	{ 3.81
			{ 1.65	{ 1.65

Notes:

1 - Partly through crack (PTC).

2 - Sizes not applicable to very tight flaws (e.g., forging flaws or lack of full penetration in butt welds).

3 - Comparable to Class A quality level (MIL-STD-410).

\* See latest version of NASGRO for any updates.

### 6.2.2.1 SAFE-LIFE TESTING

Testing is an acceptable alternative to safe-life analysis, but it is subject to prior approval of the test plan by the responsible program authority. Safe-life testing, which shall be performed in the appropriate environment on precracked specimens representative of the structural design of the part, shall demonstrate at least four lifetimes.

### 6.2.3 COMPLIANCE PROCEDURES FOR PRESSURE VESSELS

Pressure vessels are always classified as fracture critical and require the implementation of fracture-critical part tracking, control, and documentation procedures.

Bosses and local mechanical attachment areas of pressure vessels shall comply with either the fail-safe requirements of paragraph 5.3.1.3 or the safe-life requirements of paragraph 5.3.2.1.

To comply with the STS safety requirements of NSTS 1700.7 ISS Addendum and NASA-STD-5003, pressure vessels shall comply with sections 4 and 5 of MIL-STD-1522A, except as noted in paragraph 208.4 of NSTS 1700.7 ISS Addendum and paragraph 4.2.3.2.1 of NASA-STD-5003. These exceptions are repeated here for information purposes:

- A. Approach "B" of Figure 2 of MIL-STD-1522A is not acceptable.
- B. In addition to other required analyses, composite pressure vessels shall be assessed for adequate stress rupture life and damage tolerance.
- C. NDE of safe-life pressure vessels (i.e., safe-life against hazardous leak or burst) shall include inspection of welds after proof-testing to screen the initial NDE flaw size assumed for analysis.
- D. MDP as defined in the glossary and in paragraph 5.1.3 in this document shall be substituted for all references to Maximum Expected Operating Pressure (MEOP) in MIL-STD-1522A.
- E. For low cycle applications (<50 pressure cycles), a proof-test of each flight pressure vessel to a minimum of 1.5 times MDP, and a fatigue analysis showing the greater of 500 pressure cycles or 10 design lifetimes may be used in lieu of testing a certification vessel to qualify a vessel design that in all other respects meets the requirements of NSTS 1700.7 ISS Addendum and MIL-STD-1522A, Approach A.
- F. An acceptable approach to LBB is to show that a through the thickness crack of length 10 times the wall thickness is stable (i.e.,  $K_I < K_{IC}$ ) at MDP or other relevant maximum pressure. If fracture mechanics data are not available, or reliable conservative estimates of properties cannot be made, a vessel test shall be conducted to verify LBB capability. LBB pressure vessels which are fabricated to acceptable requirements, qualified for their application, and used where release of contained fluid would not be a catastrophic hazard are acceptable

without safe-life assurance. For the remote case where a pressure vessel may sustain continued fatigue crack extension subsequent to leakage, analysis shall show safe-life-against-burst for the remaining possible cyclic pressurizations, or controls shall exist to detect leakage and to prevent continued pressure cycles.

- G. For metal lined pressure vessels having an overwrap composite structure, the fracture control for safe-life and failure mode shall be applied to the liner. The overwrap shall satisfy paragraph 6.2.7 of this document.
- H. In the event of a conflict in requirements between MIL-STD-1522A and NASA-STD-5003, the requirements shown in NASA-STD-5003 shall take precedence. (Example: Burst factor for pressure vessels shall be a minimum of 2.0 times MDP with a proof-test factor equal to or greater than 1.5).

Particular attention shall be given to ensure compatibility of vessel materials with fluids used in cleaning, test, and operation. Data requirements for pressure vessels are listed in NSTS 13830.

#### **6.2.3.1 GENERAL REQUIREMENTS**

All pressure vessels shall comply with the requirements of section 4 of MIL-STD-1522A, NSTS 1700.7 (paragraphs 208 and 209), and NSTS 1700.7, ISS Addendum.

#### **6.2.3.2 ADDITIONAL REQUIREMENTS FOR NON-COMPOSITE PRESSURE VESSELS**

Non-composite pressure vessels shall comply with section 5.15. of MIL-STD-1522A except as noted above. Qualification test requirements are given in section 7.4.

#### **6.2.3.3 ADDITIONAL REQUIREMENTS FOR COMPOSITE PRESSURE VESSELS**

Composite pressure vessels shall comply with section 5.12 of MIL-STD-1522A except as noted above (see appendix G).

#### **6.2.4 PRESSURE SYSTEM AND COMPONENT REQUIREMENTS**

Pressure system components shall comply with the requirements of NSTS 1700.7 ISS Addendum. Lines, fittings, and other pressurized components (or equipment) including valves, filters, regulators, etc., are to be considered fracture critical if leakage or loss of pressurization would result in a catastrophic hazard. All fusion joints in fracture-critical systems shall be 100 percent inspected using a qualified NDE method; concurrence of the responsible NASA center



or approved partner/participant or sponsoring agency is required where full NDE is not considered practical. Cracks or any other type of flaw indication in the final product not meeting specification requirements shall be cause for rejection of these components. In addition to proof-testing of parts during individual acceptance, the complete pressure system shall also be proof-tested and leak-checked to demonstrate system integrity. The leak test will be performed at 1.0 x MDP or 1.0 x MEOP as a minimum. Safe-life analysis is not required for fracture-critical lines, fittings, and other pressurized components that are proof tested to a minimum of 1.5 times the MDP and meet the safety factor requirements of paragraph 5.1.3.3.

#### **6.2.4.1 HAZARDOUS FLUID CONTAINERS**

Hazardous fluid containers shall have safe-life against rupture or leakage when release of a fluid would cause a catastrophic hazard. Such containers shall be treated and certified the same as pressure vessels when the contained fluid has a delta pressure greater than one atmosphere. When approved by the responsible fracture control authority, an optional approach may be used for metallic or nonmetallic containers (including those with a differential pressure of less than one atmosphere). Containers using this optional approach shall have a minimum safety factor of 2.5 times MDP and shall meet the fracture control requirements for pressurized components given in 6.2.4. When a proof-test to a minimum factor of 1.5 is impractical, safe-life shall be assured by appropriate NDE applications and flaw growth analysis. Integrity against leakage shall be verified by test at a minimum pressure of 1.0 times MDP.

#### **6.2.5 COMPLIANCE PROCEDURES FOR ROTATING MACHINERY**

For the purpose of fracture control, a rotating mechanical assembly that has a kinetic energy of 14,240 ft-lb (19,307 Joules) or greater (based on  $\frac{1}{2}I\omega^2$ ) is, by definition, fracture critical. In addition to other requirements for fracture-critical components, rotating machinery shall be proof (spin) tested to screen for flaws and subjected to NDE before and after proof-testing or, if loss of function is not safety critical, shall be shown to be contained if failure occurs at maximum rpm. The proof-test level shall be greater than or equal to the level derived by fracture mechanics analysis. Rotating mechanisms with lower kinetic energy levels are to be classified by the same criteria as other structural components.

#### **6.2.6 COMPLIANCE PROCEDURES FOR FRACTURE-CRITICAL FASTENERS**

The use of fracture-critical tension fasteners should be avoided, whenever reasonable, through the use of multiple fastener types of designs where redundant load-carrying capability exists. Fasteners and shear pins shall be classified as fracture-critical parts when their fracture results in a single-point catastrophic failure. For this classification, all parts shall meet the requirements of paragraph 5.3.1.4.3 and the following requirements:

- A. They shall be highest quality aerospace fasteners fabricated from A286 steel, Inconel 718, MP35N alloy or similarly tough and environmentally compatible alloys, not sensitive to stress corrosion cracking. Bolts in tension applications shall not be fabricated from low fracture toughness alloys, particularly Ti-6AL-4V, STA titanium, or alloys of equal or less  $K_{Ic}/YS$  (yield strength) ratios. Fasteners requiring specific tensile preload that are used in joints that are loaded primarily in tension shall have rolled threads meeting aerospace quality requirements.
- B. Fasteners used to carry shear loading (shear bolts and pins) shall be designed or sized to carry shear in the shank area only. At a minimum, for the purpose of screening flaws, the shank area of these fasteners shall be NDE inspected by the eddy current method or an alternate method. Fasteners used to carry tension loading shall be similarly inspected in the shank, head fillet, and thread areas. If desired, this inspection may be performed by the fastener manufacturer or by one of the manufacturer's approved NDE houses. A safe-life analysis shall be conducted for shear loading (i.e., resulting bending stress) and for tension fasteners, with an assumed "thumbnail" type surface crack given in JSC 22267. For a fastener diameter,  $D$ , that is less than 0.50 in (12.7 mm), the initial crack length,  $2c$ , shall be equal to  $0.3D$ . For fastener diameter that is greater than 0.5 in (12.7 mm), the crack length shall be 0.15 in (3.8 mm). Analytical flaw location for shear fasteners and bolts shall be in the shank and shall be in the threads for tension fasteners. The depth,  $a$ , of the assumed crack may be calculated from the expression  $a = r(1 + \tan \frac{C}{r} - \sec \frac{C}{r})$  where  $r$  is the radius of the shank or one-half the minor diameter of the thread.
- C. Rationale for the use of fracture-critical fasteners smaller than 3/16 in (0.48 cm) in diameter (including the methods for flaw screening and preload control) shall be identified and specifically approved by the responsible NASA center or approved partner/participant or sponsoring agency.
- D. All fracture-critical fasteners shall be identified and stored separately following NDE or proof-testing. Installation of fracture-critical fasteners shall employ appropriate methods to accurately apply required preloads.

## **6.2.7 FRACTURE-CRITICAL COMPOSITE/BONDED STRUCTURES**

- A. For nonmetallic composite/bonded structures, analysis of damage tolerance by linear elastic fracture mechanics is generally agreed to be beyond the current state of the art. Therefore, fracture control of these structures shall rely on the techniques of containment, fail-safe assessment, use of threshold strain levels for damage tolerance, verification of structural integrity through analysis and testing, manufacturing process controls, and nondestructive inspection.
- B. All composite/bonded structures shall meet the structural requirements of paragraph 3.1.3. Furthermore, the payload designer/manufacturer shall use only manufacturing processes and controls (coupon tests, sampling techniques, etc.) that are demonstrated to be reliable and consistent with established aerospace industry practices for composite/bonded structures. Supporting data shall be available to verify that as-built flight articles satisfy design and

analysis assumptions, models, and all technical requirements. Test articles shall be designed and fabricated to the same requirements, drawings, and specifications as the flight article.

- C. Composite/bonded structures or components may be classified as non-fracture critical if it is shown that one of the following conditions is satisfied:
- (1) The structure or component in question meets the requirements of paragraph 5.3.1 for low released mass, contained or fail-safe components.
  - (2) The strain level at limit load is less than the composite/bonded structure's damage tolerance threshold strain level. The threshold strain level shall be determined by testing preflawed coupons or, if approved by the responsible NASA center or approved partner/participant or sponsoring agency, by using available data.
- D. All composite/bonded structures deemed fracture critical (i.e., which do not meet the fracture control screening criteria listed in paragraph 6.2.7C shall be shown to meet fracture control requirements by one of the two following methods:
- (1) A proof test (static or dynamic) to no less than 120 percent of the limit load. The proof test shall be conducted on the flight article. The test may be accomplished at the component or subassembly level if the loads on the test article duplicate those that would be seen in a fully assembled test article. Caution should be exercised when testing the flight article to 1.20 to prevent detrimental yielding to the metallic fittings and fasteners in the flight assembly and damage to the composite. Test loads on the composite should not exceed 80 percent of ultimate strength.
  - (2) A damage tolerance test program is conducted to establish that these structures possess at least four service lifetimes. These tests shall be conducted on full scale flight-like elements of critical components and samples with controlled flaws or damage. The size or shape of the flaws or damage shall correspond to the detection capability of the NDE to be imposed on the flight part. The type of flaws and damage considered shall be representative of those that could occur on the flight part.
- E. In particular cases where the requirements of paragraph 6.2.7D cannot be met, flight hardware may be approved for fracture control based on special considerations. These include a certified quality control program and demonstrated past experience. Specifically, it shall be shown that (1) the manufacturer of the composite article has a successful history of building a like design, (2) certified and controlled process specifications are used, (3) personnel are properly trained and certified, and (4) proposed nondestructive testing techniques are adequate to validate the quality and integrity of the hardware. This information must be provided to the Payload Safety Review Panel and shall be documented in the fracture control summary report. Use of this option shall be approved by the responsible NASA center or approved partner/participant or sponsoring agency.
- F. For all fracture-critical composite/bonded components, procedures for the prevention of damage resulting from handling or final assembly shall be addressed in the Fracture Control

Plan and approved by the responsible NASA center or approved partner/participant or sponsoring agency.

### **6.2.8 FRACTURE-CRITICAL GLASS COMPONENTS**

The design of all fracture-critical glass components shall include the evaluation of flaw growth under the conditions of limit stresses and actual environments. A fracture mechanics analysis for possible sustained stress crack growth shall be performed for each fracture-critical glass component using average flaw growth properties derived for 100 percent moisture. A proof-test or NDE of flight hardware shall be conducted to screen manufacturing flaws larger than those assumed in the fracture mechanics analysis, with the proof stress based on nominal  $K_{Ic}$  plus one sigma. A proof test shall be performed on all pressurized glass. All proof-testing shall be performed in a suitable environment to limit flaw growth during the proof-testing. Particular care must be taken to avoid crack growth in glass due to moisture or moist air. It shall be demonstrated that after four times the design life the part can sustain at least 1.4 times the design limit load without fracture, based on nominal  $K_{Ic}$  minus three sigma.

An alternative to the proof-tests required above is included for special cases. If a fracture mechanics analysis predicts critical flaws that are much greater than the constraints of the analysis, or if stresses are very low with respect to test-verified allowables and a FS of 5.0 or greater can be shown, a proof-test is not required.

If the component has only inertia loading during mission phases, including launch and landing, and does not meet either requirements of 5.3.1.1 and 5.3.1.2, a vibration test of the component, in excess of flight levels, followed by a rigorous visual inspection may satisfy fracture control requirements. Effects of humidity and/or cleanliness during the tests shall be considered. Use of this option shall be approved by the responsible fracture control authority.

For some payloads, a statistical analysis of flaw population in the glass components may be acceptable. The report ATR-93(3827)-1 may be helpful in these cases. Use of this option shall be approved by the responsible fracture control authority.

### **6.2.9 FATIGUE LIFE CONSIDERATIONS**

The fracture control requirements, which are based on the assumption that microscopic cracks exist whose growth to incipient failure shall not occur within the useful life cycle of the structural component, encompass and envelop fatigue life requirements. The data submittal for fracture control will satisfy fatigue life requirements for the parts analyzed. In any event, if the basic strength analysis shows that the magnitude of the combined limit stress is less than the endurance limit of the material, infinite fatigue life is assured. Note: If assurance of function is

required to control a payload hazard, then fatigue analyses must be performed on all parts which are critical to function.

If a fatigue life analysis is required by the PD to affirm payload equipment function and survivability, all concurrently occurring loadings shall be considered and rationally combined to represent a conservative appraisal of the loading during each successive design loading event. Analysis shall include the combined effects of static loading, low frequency loading, and random vibration loading.

The following life factors shall be used to take into consideration the interaction of low frequency and random vibration fatigue:

$$4 (\phi_{LF} + \phi_{RV}) \leq 1.0$$

Where:

$\phi_{LF}$  = low frequency fatigue damage

$\phi_{RV}$  = random vibration fatigue damage

Fatigue damage,  $\phi_f$ , may be evaluated by a linear damage accumulation,

$$\phi_f = \sum \frac{n_i}{N_{fi}}$$

Where:

$n_i$  is the actual number of cycles at a particular stress or strain amplitude, and

$N_{fi}$  is the cycles to failure at the same amplitude (Miner's Rule).

The maximum stress, either at the surface or internal, shall be used in all fatigue analyses. The two categories of stress to be considered in a fatigue analysis are:

- A. Alternating Stress - Any stress which changes as a function of time or flight event. Typical examples are stress results from low frequency and random loads, as described above.
- B. Mean Stress - Any constantly applied stress.

The fatigue analysis of components that are life-limited shall demonstrate a calculated life of four service lifetimes. This requires the determination of life cycle loads in accordance with appendix E of this document. Both the alternating and mean stresses shall include the effects of fatigue concentration factors.

Constant life fatigue data may be used with the combined mean and alternating stresses when available. When not available, the modified Goodman rule may be used, as represented by the formula:

$$\sigma_E = \frac{\sigma_A}{1 - \frac{\sigma_M}{X_{TU}}} \quad (1.15)$$

Where:

- $\sigma_E$  = Pure alternating stress (zero mean), which is equivalent to the combination of alternating and mean stresses
- $\sigma_A$  = Alternating stress =  $(\sigma_{\max} - \sigma_{\min}) / 2$
- $\sigma_M$  = Mean stress =  $(\sigma_{\max} + \sigma_{\min}) / 2$
- $X_{TU}$  = Ultimate tensile strength of the material

The Goodman rule may be used in calculating life when both alternating stress and mean stress are present.

Using the equivalent alternating stress,  $\sigma_E$ , the fatigue life of the structural element may be determined from a fatigue life, Stress versus Number of Cycles (S-N) curve, for the material being analyzed. The fatigue life thus determined is the  $N_{fi}$ , or “cycles to failure,” which was described earlier in the linear damage equation for  $\phi_f$ .

## 6.2.10 FRACTURE MECHANICS MATERIAL DATA

- A. Where environmental effects on crack growth must be considered, as in pressure vessel applications, the lower bound values of  $K_{ISCC}$  for the relevant fluid and material combinations shall be used in fracture mechanics analysis.
- B. When using assumed NDE initial flaw sizes for safe-life analysis of ordinary fracture-critical parts, the assumed fracture toughness values (the effective fracture toughness for a surface or elliptically shaped crack [ $K_{Ie}$ ],  $K_{Ic}$ , or the critical stress-intensity factor for fracture [ $K_{Ic}$ ]) as appropriate for predicting crack instability shall be average (i.e., typical) values. If conditions 1 and 2 are met, these average values may be obtained from data in literature, from actual testing, or from NASGRO as follows:
  - (1) The material is a standard mill product such as rolled sheet, plate, bar, extrusion, or forging.
  - (2) The material alloy composition, heat treatment, and environmental operating conditions are reliably known and correspond to those for which the literature or test data are available.
- C. For parts that are specifically considered high risk (e.g., failure will clearly result in catastrophic occurrence) and are fabricated from an alloy having a wide variety of fracture toughness for the particular fabrication and heat treatment process used, strength and

fracture toughness testing of actual representative material may be required. Testing for this case shall be explicitly required for low fatigue cycle applications (e.g., less than 1,000 cycles) when an assumed lower bound value of fracture toughness results in an inadequate safe-life. When these tests are not performed or when the conditions in 6.2.10B cannot be met, material properties which are clearly conservative with respect to expected properties shall be documented and approved by the responsible fracture control authority.

- D. If a proof-test is used for initial flaw screening, upper bound fracture toughness values shall be used to calculate the crack size determined by the proof-test. Upper bound values shall be determined by multiplying average properties by a factor of 1.2.
- E. Average fatigue crack growth rate properties shall be used for crack growth calculations for the NDE initial flaw size approach. Average fracture toughness values may be used in crack growth rate equations which model growth rate approaching instability; however, for flaw sizes determined by a proof-test, upper bound fracture toughness values used to determine the initial flaw size in condition D shall be used. Where the fatigue crack growth data sources are particularly sparse, conservative estimates of the growth rate shall be assumed and documented. All crack growth rate data shall correspond to the actual temperature and chemical environments expected or shall be conservative with respect to the actual environments. The crack growth rate data contained in NASGRO may be used if all the conditions in 6.2.10B are met.

## **6.2.11 SUMMARY DOCUMENTATION**

### **6.2.11.1 FRACTURE CONTROL SUMMARY REPORT**

To certify fracture control compliance of a payload, the organization with primary responsibility for the payload development shall prepare a fracture control summary report on the total system for review and approval by the responsible fracture control authority and the PSRP. As a minimum, this report shall include a listing of all fail-safe, fracture-critical (including limited-life), and low risk parts and shall be the basis for determining the acceptability of each part. This summary report shall be submitted to the responsible fracture control authority and the PSRP prior to the Phase III Payload Safety Review.

### **6.2.11.2 SUPPORTING DATA**

Documents supporting the fracture control summary report shall be kept by the sponsoring installation for the life of the payload where return or reflight is anticipated and shall be available for audit by the responsible fracture control authority and the PSRP. The documents required to support the acceptability of a fracture-critical part shall include a crack growth analysis (or safe-life test) report and an NDE inspection (or proof-test) report. A documented description of the load spectrum and material crack growth properties used in the analysis shall be included in the safe-life analysis report. The NDE inspection report shall include the date of



inspection, the serial or identification number of the part inspected, and the name of the inspector. If special NDE is used, additional data to ensure acceptability and traceability of the process shall be required in the inspection report.



## **7.0 STRUCTURAL TESTING METHODOLOGY**

Proof-testing (of pressure vessels and selected pressurized lines and fittings) and dynamic testing (for verification of analytical models) are required for all SCS. Structural strength testing is also required for all nonmetallic SCS and for metallic SCS which do not meet the criteria of paragraph 5.1.2. The dynamic test is used to verify the mass, stiffness, and primary load paths of the analytical math model. This test does not qualify as a structural strength (static) test, and therefore cannot be used as the sole justification for 'test only' structural verification, or be used to certify designs for lower FS. Other tests may be performed at the option of the PD, depending on the payload classification and specific design approaches selected.

For payloads/equipment which mount to unpressurized across-the-bay carriers or attach to sidewall adapter carriers, structural strength testing is required to prove the structure flightworthy, unless prior and written approval is obtained from the SSP-SWG. Piece-part static testing may also be used (with SSP-SWG approval) to provide proof that a "design configuration" can withstand flight loads. Proto-flight testing and associated test factors may be accepted in lieu of strength qualification testing with SSP-SWG approval. The test factors shall be limited to values which will not subject the proto-flight structure to detrimental deformation beyond the elastic limit. A separate qualification unit shall be used if strength qualification testing is performed. Further details concerning static testing of structures are available in the NSTS 14046 and NSTS 37329 documents.

Static testing is also required to certify that nonmetallic structures, beryllium structures, and structural adhesive bonds are capable of withstanding flight loads without failure. Several analysis and test options are available to the PD to qualify these types of hardware. Section 5 of this document details the requirements and verification options for nonmetallic, adhesively bonded, and beryllium structures.

Random vibration or acoustic testing is typically performed on instruments to verify that the equipment will operate after exposure to flight environments, but is not required for the verification of metallic SCS inside the MPLM unless the testing is required to demonstrate that fasteners will not back off, or to verify safety-critical mechanisms. Structural adhesive bonds that are in the primary load path or are used to secure SCS that cannot be adequately inspected using conventional NDE methods shall require random vibration qualification testing to verify joint design. Data obtained from random vibration testing can be used to verify the dynamic characteristics of the equipment, screen for workmanship flaws, and determine equipment response to expected random vibration environments. Resonant frequencies and amplification factors obtained from random vibration testing can be used in the development/verification of RVLFs (see paragraph 4.2.4).

Structural adhesive bonds shall be thermal cycle tested to verify structural strength and material characteristics after exposure to the temperature extremes which the component is expected to

see. Life testing shall also be performed for adhesive bonds in the primary load path to demonstrate adequate mission life.

## 7.1 VERIFICATION REQUIREMENTS FOR DYNAMIC STRUCTURAL MODELS

A FEM using NASTRAN (or NASTRAN-compatible code) is to be submitted to the cargo element integrator (see paragraph 6.1). The cargo element integrator will combine the various payload models, carrier models, etc., to develop the integrated cargo element model for use in Design Loads Assessment and the Verification Loads Analysis (VLA). All FEMs for equipment mounted in the cargo bay (e.g., pallet and sidewall adapter-mounted components) shall be verified by test, unless approval is obtained from the SSP-SWG. FEMs for module-mounted equipment weighing over 40 lb shall also be verified by test. Response at any location of the total Shuttle payload system is dependent on the mass, natural frequencies, and associated mode shapes represented in the FEMs. For relatively rigid components (whose flexibility is confined to mounting bracketry or frequency isolation hardware), a low level sinusoidal sweep test or an impact hammer resonant search test with limited instrumentation may be adequate for model verification. A modal survey test is required to verify the analytical models of relatively flexible hardware (whose flexibility is found throughout the component) since they lend themselves to coupling with the supporting structure. Note that the requirements on model verification vary depending on the component's weight, attachment configuration, and mounting location (e.g., mounted in a module, the middeck, the EXPRESS pallet, or to a sidewall adapter carrier). The model verification requirements for module (internal)-mounted components and external (pallet and sidewall adapter)-mounted components are provided in tables 7.1–1 and 7.1–2, respectively.

**TABLE 7.1–1 VERIFICATION REQUIREMENTS FOR COMPONENTS  
INTERNAL TO MODULES**

EQUIPMENT ITEM	VERIFICATION
Wt < 40 lb (pounds) and $f_{1i} < 35$ Hz	NASTRAN model with frequency identification up to 50 Hz in all directions by resonance search
Wt < 40 lb and $f_{1i} > 35$ Hz	Analytical Model Only
40 ≤ Wt < 70 lb and $f_{1i} < 35$ Hz 40 ≤ Wt < 70 lb and $f_{1i} \geq 35$ Hz	NASTRAN Model verified by Modal Survey up to 50 Hz NASTRAN model with frequency identification up to 50 Hz in all directions by resonance search
Wt ≥ 70 lb and $f_{1i} < 35$ Hz Wt ≥ 70 lb and $f_{1i} \geq 35$ Hz and $f_{2i} < 50$ Hz Wt ≥ 70 lb and $f_{1i} \geq 35$ Hz and $f_{2i} \geq 50$ Hz	NASTRAN Model verified by Modal Survey up to 50 Hz NASTRAN Model verified by Modal Survey up to 50 Hz NASTRAN model with frequency identification up to 50 Hz in all directions by resonance search

- $f_{1i}$  = the first (lowest) system eigen frequency in each direction  
 (where: i = X, Y, or Z direction)
- $f_{2i}$  = the second (or next highest) system eigen frequency in each  
 direction (where: i = X, Y, or Z directions)
- Wt = includes weight of support structure and all supported components.

**NOTES:**

- Frequency requirements include interface hardware.
- Use of the verification criteria specified above assumes that the component is tested with flight-type boundary conditions.
- Noncompliance with the model verification requirements specified herein and in NSTS 14046 without consultation and approval from the SSP-SWG is at the PD's risk.

**TABLE 7.1–2 VERIFICATION REQUIREMENTS FOR PALLET-MOUNTED AND SIDEWALL ADAPTER-MOUNTED COMPONENTS**

EQUIPMENT ITEM	VERIFICATION
$0 \leq Wt < 40 \text{ lb}$ and $f_{1i} < 35 \text{ Hz}$ $0 \leq Wt < 40 \text{ lb}$ and $f_{1i} \geq 35 \text{ Hz}$	NASTRAN Model verified by Modal Survey up to 50 Hz NASTRAN model with frequency identification up to 50 Hz in all directions by resonance search
$Wt \geq 40 \text{ lb}$ and $f_{1i} < 35 \text{ Hz}$ $Wt \geq 40 \text{ lb}$ and $f_{1i} \geq 35 \text{ Hz}$ and $f_{2i} < 50 \text{ Hz}$ $Wt \geq 40 \text{ lb}$ and $f_{1i} \geq 35 \text{ Hz}$ and $f_{2i} \geq 50 \text{ Hz}$	NASTRAN Model verified by Modal Survey up to 50 Hz NASTRAN Model verified by Modal Survey up to 50 Hz NASTRAN model with frequency identification up to 50 Hz in all directions by resonance search

$f_{1i}$  = the first (lowest) system eigen frequency in each direction (where:  $i = X, Y, \text{ or } Z$  direction)

$f_{2i}$  = the second (or next highest) system eigen frequency in each direction (where:  $i = X, Y, \text{ or } Z$  directions)

$Wt$  = includes weight of support structure and all supported components

**NOTES:**

1. Frequency requirements include interface hardware.
2. Use of the verification criteria specified above assumes that the component is tested with flight-type boundary conditions.
3. Noncompliance with the model verification requirements specified herein and in NSTS 14046 without consultation and approval from the SSP-SWG is at the PD's risk.

Components/assemblies that may be verified by resonance search shall be sufficiently instrumented to identify all system frequencies and their modal direction in the range of interest (zero to 50 Hz when constrained at the attachment interface). Detailed mode shapes are not required. The pre-test analytical model results shall be correlated with test results for verification of the structural model to be used in the verification coupled loads analysis. The correlation goal for the fundamental frequency in each axis is  $\pm 5$  percent, while the correlation goal for higher order frequencies is agreement within  $\pm 10$  percent.

Components/assemblies that require modal survey testing shall be sufficiently instrumented to identify all system mode shapes and associated frequencies in the range of interest (zero to 50 Hz when constrained at the attachment interface). The pre-test analytical model results shall be correlated with test results for verification of the structural model to be used in the verification coupled loads analysis. The correlation goal for the fundamental frequency in each axis is  $\pm 5$  percent, while the correlation goal for higher order frequencies is agreement within  $\pm 10$  percent. Evidence of modal correlation shall be provided. As a minimum, the modal plots should be correlated to the extent that there are no significant differences (when the analytical and test mode shapes are compared side-by-side, there should be no significant difference in the overall shape of the mode, and the deflection of all masses and boundaries should agree).

Additional evidence of modal correlation shall be provided using numerical comparison; such as the cross-orthogonality check, defined by:

$$[\phi]_A^T [M]_A [\phi]_T = [C_{ij}]$$

Where:

$[\phi]_A^T$  is the transpose of the analytical mode shape matrix

$[M]_A$  is the analytical consistent mass matrix (as defined in NASTRAN manuals)

$[\phi]_T$  is the test mode shape matrix

$[C_{ij}]$  is the correlation matrix.

The magnitude of matrix element  $[C_{ij}]$  represents the degree of correlation between the  $i$ th analytical mode and the  $j$ th test mode. For both analytical and test mode shapes normalized to generalized mass, a perfect correlation between the  $i$ th analytical mode and the  $j$ th test mode is unity (1.0 or -1.0), with zero for all other elements of the column of the matrix. The goals for acceptable correlation would be absolute values of diagonal terms greater than 0.9 with the absolute values for all off-diagonal terms being less than 0.1 for significant modes.

## 7.2 VIBRATION TESTING

Vibration tests are required for non-fracture-critical fasteners without positive locks (see paragraph 5.6), structural adhesive bonded joints, all components whose function is critical to safety, and high frequency items which cannot be analyzed. Vibration testing may be used for model verification in accordance with paragraph 7.1.

The test spectra shall be verified by narrow band spectral analysis using an analysis system that is independent from the analyzer/equalizer used to control the test. Tolerances considered acceptable are shown in table 7.2-1. Flight or flight-like bracketry shall be included in the test setup. The specified vibration criteria shall be controlled at the test fixture/component bracket interface.

**TABLE 7.2-1 VIBRATION TEST SPECTRA TOLERANCE GUIDELINES**

PARAMETER	TOLERANCE
Composite Root Mean Square Acceleration	±10%
Acceleration Spectral Density (Tolerances pertain to bandwidths of 25 Hz or less)	+100% / -30%
Sinusoidal Peak Acceleration	+20% / -10%
Sinusoidal Control Signal Maximum	±10%
Harmonic Distortion	
• Frequency	±5%
• Test Duration	+10% / -0%

## 7.2.1 RESONANCE SEARCH

Frequency identification by resonance search can be accomplished using either sinusoidal sweep testing or impact hammer resonance search testing. There are no technical advantages to one of these methods over the other. The PD should select the method of resonance search based on his equipment availability and how the test would fit into the overall plan of required tests. Linearity checks are required to be performed for all resonance search testing.

### 7.2.1.1 SINUSOIDAL RESONANCE SURVEY

Low level sinusoidal sweeps may be adequate for model verification of simple structures with relatively rigid components, whose flexibility is confined to mounting bracketry or frequency isolation hardware. Sinusoidal resonance surveys should be conducted in accordance with table 7.2.1.1-1.

**TABLE 7.2.1.1-1 SINUSOIDAL SWEEP VERIFICATION REQUIREMENTS**

PARAMETER	TOLERANCE
Axis	X, Y, Z
Frequency Range of Interest	5 - 2000 Hz*
Amplitude	0.5 g**
Sweep Rate	One oct/min
Sweep Direction	One sweep up

\* Upper frequency limit may be lowered provided flight configuration frequencies up to 50 Hz are identified and results are not needed for RVLf calculation.

\*\* Other amplitudes are acceptable, provided all structural modes can be excited.

### **7.2.1.2 IMPACT HAMMER RESONANCE SURVEY**

This method only requires a relatively stiff supporting structure or adapter plate and one of many modal analyzers currently on the market. A roving accelerometer is used to obtain response measurements on previously identified points in order to record all system frequencies in the range of interest. This data is also used to characterize the modal direction. It can then be used to verify and update the analytical math model, and to develop/update the random load factors. As a guideline, the supporting structure (or adapter plate) should weigh at least five times that of the test article and have a stiffness that is ten times that of the component to be tested.

### **7.2.2 RANDOM VIBRATION TESTING**

Random vibration testing is required for payloads that are required to function to prevent a safety hazard, for non-fracture-critical fasteners without positive locks, to verify high frequency items which cannot be analyzed, and to verify structural adhesive bonds which cannot be adequately inspected using traditional NDE techniques. Random vibration testing is recommended to verify function of electronic equipment, close tolerance moving devices, and optical equipment. The PD may also require random vibration testing to demonstrate functionality and survivability.

NOTE: Random vibration may be used instead of static test for small items or items where static test is not practical with approval from the SSP-SWG.

The approach to random vibration testing is provided below:

Random vibration testing falls into two categories, proto-type and proto-flight testing. Proto-type testing occurs when there is a dedicated test article. Proto-flight testing occurs when all vibration testing must be performed on flight hardware. The use of flight hardware for testing should be avoided whenever possible with the exception of Acceptance Vibration Testing.

#### **7.2.2.1 PROTO-TYPE/QUALIFICATION TEST**

Proto-type or qualification random vibration testing shall be conducted in the following manner. The test shall be performed on dedicated test hardware, (1) a Qualification for Vibration Test (QVT) and (2) a Qualification for Acceptance Vibration Test (QAVT). The level of the QVT shall be the maximum expected flight environment. The duration of the QVT is four times the expected life time exposure to flight vibration, but not less than 60 sec per axis.

The level of the QAVT shall be 2.3dB above the Acceptance Vibration Test (AVT) level defined in paragraph 7.2.2.2. Duration of the QAVT shall be the duration of the AVT times the number of AVTs being qualified for. (Hardware is usually qualified for 2 to 5 AVTs.)

### **7.2.2.2 ACCEPTANCE TESTING FLIGHT HARDWARE HAVING PERFORMED QUALIFICATION TEST ON A DEDICATED UNIT**

Each flight unit shall be subjected to an AVT. This test screens for workmanship flaws. The level of this test shall be an envelope of the QVT level minus 2.3dB and the minimum AVT level as defined in table 7.2.2.3–1. Duration of this test is 60 seconds per axis minimum.

### **7.2.2.3 PROTO–FLIGHT TESTING**

Proto–flight testing shall be conducted in the following manner. Only one test is performed on Proto–flight hardware. The level of the Proto–flight vibration test shall envelope the maximum expected flight environment and the minimum AVT test level given in table 7.2.2.3–1. Duration of the proto–flight test is 60 seconds per axis. (Proto–flight testing is not acceptable for hardware that will fly more than 3 missions.)

**TABLE 7.2.2.3–1 MINIMUM ACCEPTANCE VIBRATION TEST (AVT) LEVEL**

<b>FREQUENCY</b>	<b>LEVEL/SLOPE</b>
20 – 80 Hz	+3.0 dB/Oct
80 – 350 Hz	0.04 g <sup>2</sup> /Hz
350 – 2000Hz	–3.0 dB/Oct

For equipment weighing more than 50Kg or for equipment that is fragile or where Random Vibration Acceptance Testing is not appropriate, other methods for workmanship screening may be substituted with approval of the ISS Payload Control Board.

### **7.2.3 ACOUSTIC TESTING**

Acoustic testing is required to verify payloads that are required to function to prevent a safety hazard, the securing of non-fracture-critical fasteners which do not have positive locks, adhesive structural bonds which cannot be adequately inspected using traditional NDE inspection techniques, and other items which cannot be analyzed for high frequency or vibroacoustic environments. Otherwise, acoustic testing is an option to be selected by the PD. Acoustic tests do serve an important function in the checking of the survivability and workmanship of equipment with high surface area to mass ratios. Note: Acoustic testing should only be performed on hardware that is sensitive to the acoustic environment. Usually, random or acoustic testing is performed, but not both.



Acoustic testing simulates the Orbiter acoustic noise during launch. The application times for acoustic criteria are as follows:

The Qualification Test duration is 60 sec plus 30 sec per mission.

The Acceptance Test duration is 60 sec.

### **7.3 STRENGTH TESTING**

For payloads which attach to unpressurized across-the-bay carriers or to sidewall adapter carriers, structural strength testing is required unless prior and written approval is obtained from the SSP-SWG. Strength testing is also required for verification of structures which use strength testing as a basis for lower safety factors, for beryllium and composite structures, and for adhesively bonded joints.

If the structure/component to be tested is statically determinate, it may be tested as a stand-alone unit. If the structure/component to be tested is not statically determinate, the interfacing structure through which the loads and reactions are applied shall be simulated in the test. The interfacing structure used in the test shall simulate the stiffness and boundary conditions of the corresponding flight hardware.

### **7.4 PRESSURE VESSEL TEST REQUIREMENTS**

Pressure vessel test requirements shall be adhered to as discussed in paragraphs 5.1 and 5.2 of MIL-STD-1522 and as modified in paragraph 6.2.3 of this document for conformance to NSTS 1700.7 ISS Addendum.

### **7.5 NONDESTRUCTIVE EVALUATION TECHNIQUES**

#### **7.5.1 REQUIREMENTS AND ASSUMPTIONS**

The selection of NDE methods and level of inspection shall be based primarily on the safe-life acceptance requirements of the part. The NDE initial crack sizes used in safe-life analysis shall correspond to a 90-percent probability/95-percent confidence level of inspection reliability. Minimum detectable initial crack sizes for specific NDE methods are given in table 1 of NASA-STD-5003 for the geometries shown in figure 2 of NASA-STD-5003. Except for fasteners and shear pins, these are the minimum sizes to be used for safe-life analysis. Instructions for applying these NDE methods are given in MSFC-STD-1249, Standard NDE Guidelines and Requirements for Fracture Control Programs. Use of initial crack sizes for other geometries or NDE techniques (such as those given in JSC-22267) require the approval of the responsible NASA center or approved partner/participant or sponsoring agency. Where adequate



NDE inspection of finished parts cannot be accomplished, NDE may be required by the responsible NASA center or approved partner/participant or sponsoring agency on the raw material and/or on the part itself at the most suitable step of fabrication.

## **7.5.2 PERFORMANCE OF NDE INSPECTIONS**

All fracture-critical parts shall be NDE inspected or proof-tested. Prior approval of the responsible fracture control authority is required if flaws are to be screened by proof testing. NDE inspections shall be conducted according to standard aerospace quality control procedures. Personnel conducting standard NDE shall be certified in accordance with MIL-STD-410 or ASNT-CP-189. The use of special NDE techniques (e.g., to justify the use of initial crack sizes smaller than those shown in table 6.2.2-1) requires prior approval by the responsible NASA center or approved partner/participant or sponsoring agency. Etching of parts prior to penetrant inspection shall be required on mechanically disturbed metallic surfaces to remove smeared or masking materials. Etching shall be performed in accordance with an approved procedure that precludes contamination of the part. Where etching cannot be performed on the finished part, the part shall be etched and penetrant inspected at the latest practical stage of finishing (e.g., before final machining of parts with precision tolerances, or at the assembly level before holes are drilled). Previously etched and penetrant-inspected surfaces that are not subsequently mechanically disturbed require only chemical cleaning prior to re-inspection by the penetrant method. Unaided visual inspection and visual inspection aided only by magnification are not generally acceptable methods for screening cracks. For transparent optical elements such as windows and lenses, visual inspection with 10x or higher magnification is acceptable for detecting surface and embedded flaws of 0.100-in (2.54-mm) length or greater when proper lighting is applied at right angles to the actual flaw orientation.

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## **8.0 SAFETY-CRITICAL STRUCTURES QUALITY AND PROCESS CONTROL REQUIREMENTS**

This section addresses the requirements to control material processes such as welding, testing, and quality assurance requirements for SCS. It is not intended as a comprehensive listing of quality assurance provisions governing the adequacy of function and survivability of payload flight equipment (which is the responsibility of the PD).

### **8.1 PERSONNEL CERTIFICATION**

Any special qualification levels required to ensure that critical operations are performed and that skills match fracture control requirements shall be identified. Personnel engaged in nondestructive inspection of fracture control items shall be qualified in accordance with MIL-STD-410.

### **8.2 MATERIALS AND PROCESSES CONTROL**

Material selection for SCS shall meet the requirements of paragraph 5.4. Materials used in these structures shall be identified in the final design documentation and verified for the “as-built” hardware as specified in section 9 of this document.

Structural components, stress corrosion susceptible materials, stainless steel susceptible to hydrogen embrittlement, and precipitation hardening stainless steels should be chosen with caution. Titanium and titanium alloys should be used, cleaned, and processed with care. Caution should be exercised in selection of super alloys, elastomerics, reinforced plastics, adhesives, and epoxies. MSFC-STD-3029 should be consulted for information on stress corrosion cracking.

Traceability is required to assure that the materials used in the construction of hardware have properties equivalent to those used in the analysis or verification tests and to identify faulty hardware when a problem is discovered in a fabricated part. Traceability is required for all fracture-critical parts and shall include the following:

- A. Each item (part, subassembly, assembly) requires a unique serial number (S/N), marked directly on the item or in the accompanying data package.
- B. Engineering drawings and specifications shall include S/N and traceability requirements.
- C. Materials shall be certified by test or inspection to meet all the specified requirements. Traceability to manufacturer’s heat or lot number and to records of subsequent processing (e.g., heat treatment and mix records) shall be maintained at all stages of fabrication and assembly of each S/N item.

For each pressure vessel, a log shall be maintained to record all pressure cycles and associated environmental conditions occurring from the fabrication to the end of the service life of the vessel.

For some fracture-critical items, it may be more cost effective to remanufacture than to serialize and implement traceability for multiple flights (e.g., deintegrated fasteners are not reused, small piecepart items, etc.). For these single flight fracture-critical items, deintegration procedures that assure items are discarded following flight may be utilized rather than serialization. Note that material traceability must be maintained for all fracture-critical items.

### **8.3 WELD CONTROL**

The quality assurance provisions of the applicable welding specifications (given in paragraph 5.5) shall be adhered to in the control of critical structural weldment design and production. Typically, these specifications provide controls in the following areas.

#### **8.3.1 PRE-WELD AND WELD INSPECTION**

##### **8.3.1.1 DOCUMENTATION**

Documentation relative to the production weld shall be inspected for conformance to qualification of the welding process and personnel, including:

A. Schedule qualification pertaining to

- (1) Arc voltage, arc current, rate of travel, and filler wire feed rate for machine welds
- (2) Weld parameters and parameter ranges for manual welds
- (3) Visual and nondestructive inspection
- (4) Post-welding processes
- (5) Tensile tests
- (6) Shear tests of fillet welds
- (7) Metallographic sections

B. Operator qualification

C. Schedule departure

### **8.3.1.2 FILLER METAL**

Filler metal shall be examined for conformance to the applicable specification and the qualified welding schedule.

### **8.3.1.3 SHIELDING GAS**

Inert shielding gas (if applicable) shall be examined for conformance to specification and the qualified welding schedule.

### **8.3.1.4 JOINTS AND TOOLING**

The joints and tooling shall be inspected for conformance to the applicable specifications and shall not adversely affect the welding process or the quality of the weld.

### **8.3.1.5 EQUIPMENT SETTINGS**

Welding equipment shall be inspected for conformance of equipment settings to the qualified welding schedule.

### **8.3.1.6 OPERATIONS CERTIFICATION**

Quality control shall certify that each production weld was made within the range of operating parameters established for each qualification weld schedule. All departures shall be noted and referred to the responsible NASA center or approved partner/participant for disposition.

## **8.3.2 POST-WELD INSPECTION**

### **8.3.2.1 VISUAL INSPECTION**

The weld metal and adjacent base metal shall be visually inspected without the aid of optical magnification, to assure compliance with the general workmanship requirements. The weld shall be in the as-welded condition for initial weld inspection, except that surface smut and loose oxide shall have been removed.

### **8.3.2.2      DIMENSIONAL INSPECTION**

Dimensional inspection shall be performed on flight equipment welds to assure compliance with post-weld dimensional requirements.

### **8.3.2.3      INTERNAL QUALITY INSPECTION**

Nondestructive inspection shall be performed to assure compliance with the internal quality requirements including:

- A. Cracks
- B. Improper Fusion/Incomplete Penetration
- C. Close Spacing
- D. Maximum Discontinuity Size
- E. Scattered Discontinuities
- F. Linear Discontinuities
- G. Sharp Discontinuities
- H. Cluster Discontinuities

Radiographic technique is the preferred method; however, other techniques may be used with approval of the responsible NASA center or approved partner/participant. Nondestructive inspection procedures shall be documented in accordance with applicable specifications. When reliability of inspection and critical flaw detection so dictate, redundant and/or complementing inspection techniques and procedures shall be employed.

### **8.3.2.4      SURFACE QUALITY INSPECTION**

Nondestructive inspection shall be used to assure compliance with specifications for the same parameters listed in paragraph 8.3.2.3. Penetrant technique is the preferred inspection method; however, other techniques may be used with approval of the responsible NASA center or approved partner/participant. Nondestructive inspection procedures shall be documented in accordance with applicable specifications.

### **8.3.2.5 RECORDS**

A continuous audit of weldment production quality shall be maintained. Resulting records shall include the location of repairs, type of defects repaired, procedures used, and inches of repair per total inches of weld. These records shall be made available to the responsible NASA center or approved partner/participant upon request.

## **8.4 PROCEDURE CONTROL, CERTIFICATION, AND DOCUMENTATION**

Tests required for SCS shall be performed in accordance with section 6. A summary of pertinent procedures and results shall be provided for each test, and complete records of test conduction and results shall be maintained by the PD for the useful life of the flight articles to which they pertain.

A complete documentation set shall be prepared for all failures involving fracture-critical components during manufacture, qualification testing, and acceptance testing. Other parts that fail shall be assessed for fracture control. The cause of failure and any contributing factors shall be documented to the extent possible, and the document shall include recommendations for corrective actions required in the control of material procurement, fabrication processes, quality assurance methods, or operational procedures.

A report of failure evaluation results and recommended corrective action shall be prepared and provided to the responsible NASA center or approved partner/participant. Metallurgical failure analysis based on flaw topology, material microstructure, and other laboratory investigations shall be provided where necessary to identify the cause of failure.

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## **9.0 REPORTING REQUIREMENTS ON SAFETY-CRITICAL STRUCTURES**

This section defines the scope, schedule, format, and content requirements for payload flight equipment reports pertaining to SCS. These reports are the responsibility of the PD, and are included or referenced in the data package submitted to the PSRP and SSP-SWG, or their designated review organization.

### **9.1 SCOPE**

The reports described herein are limited to the minimum requirements for the assurance that all payload flight equipment meets STS and ISS structural safety requirements. These reporting requirements shall be met by the compilation of data generated in the course of payload flight equipment design, analysis, and test, but without the submittal of detailed reports except as specifically prescribed. The contents and format of each data requirement is described in paragraph 9.3.

### **9.2 SCHEDULE TEMPLATE**

Payloads flying aboard the ISS are required to provide data to support established ISS verification requirements and Payload Integration Manager (PIM) schedules. All payloads including pressurized and unpressurized payloads launched on an unpressurized across-the-bay carrier, on the Orbiter sidewalls, or in the Orbiter crew compartment may also be required to provide additional data to support established SSP verification requirements and schedules.

#### **9.2.1 ISS SCHEDULE TEMPLATE**

The PIM will establish the schedule for completion of data requirements to support ISS incremental milestones to include ISS phased safety reviews.

##### **9.2.1.1 ISS INCREMENT MILESTONES**

The ISS Cargo Integration Engineering Analysis generic template can be found in SSP 50200-03. It should be noted that each ISS Increment will define its own unique schedule and the generic template is intended as a guideline for model development milestones. Each cargo element integrator will be responsible for coordinating model deliveries with each PD for his cargo element.

## 9.2.1.2 ISS INCREMENTAL PHASED SAFETY REVIEWS

As with the ISS Increment milestones, the schedule for the phased safety reviews will be unique for each ISS increment. Table 9.2.1.2–1 describes each phased review, the purpose, and generic guidelines for supporting data needed. It is not uncommon to combine the phased safety reviews. Information needed to support combined reviews will be the combination of data identified for each review. All data submittals shall be in accordance with NSTS 13830.

The schedule for Phase 0, I, and II is flexible and typically based upon the payload development schedule. Phase 0 is held during the concept phase or at the start of payload design. Phase I is held as the hardware development is finishing preliminary design. Phase II is held at the completion of final design, prior to manufacture. The timing of the Phase III review is critical to the launch schedule. The Phase III (flight and ground) safety reviews must be completed 30 days prior to delivery of the payload to Kennedy Space Center (KSC). The ground safety certification shall be submitted 30 days prior to hardware delivery to KSC, and final flight safety certification shall be submitted at least 10 days prior to the Flight Readiness Review (FRR).

**TABLE 9.2.1.2–1 PHASED SAFETY REVIEW DATA SUBMITTAL GUIDELINES**  
 (Page 1 of 4)

Phased Safety Review	Hardware Status	Purpose of Review	Guidelines for Supporting Data
0	Payload conceptual design established	Identify potential hazards, hazard causes, and applicable safety requirements.	Conceptual payload descriptive including: hardware description, function, and identification of any pressure systems.
I		<p>Assess preliminary design against NSTS 1700.7 ISS Addendum.</p> <p>Evaluate preliminary hazard controls and safety verification methods.</p> <p>Prepare safety compliance data package.</p>	<p><b><u>Structures</u></b></p> <p>Proposed Structural Verification Plan in accordance with NSTS 14046, "Payload Verification Requirements" and/or SSP 52005 "ISS Payload Flight Equipment Requirements and Guidelines for Safety Critical Structures."</p> <p>Fracture Control Plan.</p> <p>Methodology for assurance of fastener integrity.</p> <p><b><u>Pressurized Systems (vessels, lines, fittings, components)</u></b></p> <p>Preliminary pressurized system schematic(s) and operating parameters (3e.g., temperature, pressure and other environmental conditions).</p> <p>Preliminary summary of the derivation of system MDP(s) per NSTS 1700.7 and NSTS 1700.7 ISS Addendum.</p> <p>Preliminary list of all system working fluids, amounts, potential hazards (e.g., flammability, explosion, corrosion, toxicity) and hazard category (e.g., catastrophic, critical, non-hazard).</p>

**TABLE 9.2.1.2-1 PHASED SAFETY REVIEW DATA SUBMITTAL GUIDELINES**  
 (Page 2 of 4)

Phased Safety Review	Hardware Status	Purpose of Review	Guidelines for Supporting Data
Cont'd			<p>Summary of pressure vessel(s) design and qualification approach.</p> <p>Fracture Control Plan.</p> <p>Proposed pressurized system(s) verification approach for controls to ensure pressure integrity.</p> <p>For fluids whose leakage is hazardous also include:</p> <p>Proposed pressurized system(s) verification approach including controls to prevent leakage (e.g. levels of containment, Design for DFMR). For the DFMR approach to protect against leakage that may cause a catastrophic hazard include: 1) identification of mechanical fitting and leakage certification approach for wetted areas. Consider all environments where leakage is hazardous (e.g. in the Shuttle payload bay) and 2) preliminary identification of fusion and bi-metallic joints within the system.</p> <p>Mechanisms in Critical Applications</p> <p>Identification of safety-critical mechanisms.</p> <p>Identification of area of applicability of holding or operating force or torque margin requirements and planned verification approach (test or analysis).</p> <p>Fracture control plan.</p>
II	Payload final design established	<p>Assess final design against NSTS 1700.7 ISS Addendum.</p> <p>Concur on hazard controls and safety verification methods. Finalize analysis procedures, test plans, and inspections for safety verification.</p> <p>Prepare safety compliance data package.</p>	<p><b><u>Structures</u></b></p> <p>Final structural verification plan, including: 1) summary of design loads derivation leading to critical load cases, and 2) math model verification plan.</p> <p>Fracture control status (including parts categorization).</p> <p>Identification of Material Usage Agreements (MUAs) on structural materials, the failure of which would cause a hazard (including, but not limited to, stress corrosion, hydrogen embrittlement, and materials compatibility).</p> <p><b><u>Pressurized Systems (vessels, lines, fittings, components)</u></b></p> <p>Complete and updated pressurized system schematic(s) and operating parameters, addressing all pressurized hardware.</p>

**TABLE 9.2.1.2-1 PHASED SAFETY REVIEW DATA SUBMITTAL GUIDELINES**  
 (Page 3 of 4)

Phased Safety Review	Hardware Status	Purpose of Review	Guidelines for Supporting Data
Cont'd			<p>Complete summary of the derivation of system MDP(s) per NSTS 1700.7 and NSTS 1700.7 ISS Addendum.</p> <p>Complete table of pressurized system hardware, MDP(s), proof pressure, ultimate pressure, resulting proof and ultimate safety factors and method of determining the safety factors (e.g. test, analysis, vendor data).</p> <p>Updated list of all system working fluids, amounts, identified hazards and hazard category.</p> <p>Status on pressure vessel(s) design and qualification.</p> <p>Fracture control status.</p> <p>Identification of MUAs on pressurized system materials the failure of which would cause a hazard (including, but not limited to, stress corrosion, hydrogen embrittlement, and materials compatibility [including working and cleaning fluids]).</p> <p>Final pressurized system(s) verification approach for controls to ensure pressure integrity including a summary of qualification and acceptance test plans and analyses.</p> <p>For fluids whose leakage is hazardous also include:</p> <p>Final pressurized system(s) verification approach including controls to prevent leakage (e.g. levels of containment, DFMR). Include a summary of qualification and acceptance test plans and analyses.</p> <p>For the DFMR approach to protect against leakage that may cause a catastrophic hazard include:</p> <p>1) summary of certification test plans and analyses to prevent leakage of wetted mechanical fittings, 2) identification of system fusion joints and their method of NDE. Identification of system bi-metallic joint(s), manufacturer and certification data, and 3) complete list of wetted materials and their compatibility rating with system and cleaning fluids. Define credible single barrier failures which may release fluid into a volume that is not normally wetted and provide a summary of maximum worst case temperatures which were considered.</p> <p><b>Mechanisms in Critical Applications</b></p> <p>Verification approach, including qualification and acceptance tests and analyses.</p> <p>List of MIPs.</p> <p>Fracture control status (including parts categorization).</p>

**TABLE 9.2.1.2-1 PHASED SAFETY REVIEW DATA SUBMITTAL GUIDELINES**  
 (Page 4 of 4)

Phased Safety Review	Hardware Status	Purpose of Review	Guidelines for Supporting Data
III	Payload fabrication and testing complete	<p>Complete safety analysis/assessment report.</p> <p>Complete all safety verification tests, analyses, and/or inspections.</p> <p>Prepare final safety compliance data package.</p>	<p><b><u>Structures</u></b></p> <p>Summary of verification tests/analyses/inspections results.</p> <p>Fracture control summary report.</p> <p>New/approved MUAs as defined in phase II.</p> <p>Documentation of compliance with fastener integrity program.</p> <p><b><u>Pressurized Systems (vessels, lines, fittings, components)</u></b></p> <p>Final pressurized system schematic(s) and operating parameters, addressing all pressurized hardware.</p> <p>Final MDP derivation summary and table of pressurized system hardware.</p> <p>Final list of all system working fluids, amounts, hazards and categories.</p> <p>Certification of pressure vessel(s) design, including qualification and acceptance test results.</p> <p>Fracture control summary report.</p> <p>New/approved MUAs as defined in phase II.</p> <p>For safe life and limited life pressure vessels, document existence of a Pressure Log, including log number.</p> <p>Summary of results from verification tests/analyses/inspections for controls to ensure pressure integrity.</p> <p>For fluids whose leakage is hazardous also include:</p> <p>Summary of results from verification tests/analyses/inspections for controls to prevent leakage.</p> <p>For the DFMR approach to protect against leakage that may cause a catastrophic hazard include: 1) summary of results from certification tests and analyses on wetted mechanical fittings, 2) final list of system fusion joints and results from NDE. Final list of system bi-metallic joint(s), manufacturer(s) and certification data, 3) final list of wetted materials and their compatibility rating with system and cleaning fluids.</p> <p><b><u>Mechanisms in Critical Applications</u></b></p> <p>Report of verification tests/analyses/inspection results.</p> <p>Fracture control summary report.</p>

## 9.2.2 SSP SCHEDULE TEMPLATE

The SSP Integration Engineering Office has established specific verification data requirements in the NSTS 14046 and NSTS 37329 documents, for payloads launched on an unpressurized across-the-bay carrier, on the Orbiter sidewalls, or in the Orbiter crew compartment. Table 9.2.2-1 describes the data requirements and schedule template for these payloads. Note that the schedule shown in table 9.2.2-1 provides the dates for delivery of items to the SSP Integration Engineering Office. Therefore, payloads flying on facility carriers, such as the EXPRESS Pallet, will likely be required to provide data to the Facility Integrator (at an earlier date than shown in the table) who will in turn submit a consolidated package to the SSP Integration Engineering Office by the dates shown. NSTS 14046 and NSTS 37329 provide further details about the data requirement, contents, and format.

**TABLE 9.2.2-1 SSP VERIFICATION DATA REQUIREMENT AND SUBMITTAL GUIDELINES**

Description of Data Requirement	Submittal Schedule
Payload Structural Verification Plan	At Phase 1 safety review or payload PDR (whichever is earlier)
Static/Strength Test Plan	2 months prior to testing
Dynamics Structural Test Plan	2 months prior to testing
Strength Test Results and Model Correlation Report	2 months prior to Cargo Integration Review (or as specified in PIM schedule)
Dynamics Test Results and Model Correlation Report	2 months prior to Cargo Integration Review (or as specified in PIM schedule)
Payload Design Loads Cycle Report	13 months prior to launch (or as specified in PIM schedule)
Summary of Stress Analysis and Test results	Per PIM schedule
Structural Life Assessment Summary	Per PIM schedule

\* Schedule shown is the dates for delivery of the items to the SSP Integration Engineering Office. Payloads manifested as part of an integrated carrier/facility likely will be required to meet an earlier schedule established by the carrier or facility integrator.

## 9.3 CONTENTS AND FORMATS

The PD shall be responsible for ensuring that the analysis and test requirements contained herein are satisfied and adequately documented. The PD shall prepare a comprehensive verification plan which specifies which data products will be delivered.

Analysis reports and data submissions shall be prepared in accordance with standard aerospace industry practice for flight hardware (discussed in the following paragraphs). Description of the format and contents acceptable for reports on SCS is contained in this section. The PSRP and

SSP-SWG, or their designated review organization, reserves the right to request supporting data from the PD, as needed, to ensure that all structural and safety requirements have been satisfied.

### **9.3.1 DRAWINGS OF PAYLOAD FLIGHT EQUIPMENT SAFETY-CRITICAL STRUCTURES FOR FINAL DESIGN CONFIGURATION**

Format: As prescribed by the PD.

Content: As-built drawings of all elements, components, or assemblies (including attachment hardware), which contain or are attached to SCS.

### **9.3.2 SAFETY-CRITICAL STRUCTURAL ANALYSIS REPORTS FOR FINAL DESIGN**

Structural analysis reports shall be developed and summarized for the final design configuration of each element, component, or assembly containing or attached to SCS. The reports may be documented separately or combined for each piece of payload flight equipment. Minimum content requirements for each document shall include:

- A. Introduction - a brief description of structures/components being analyzed and the load environments used for determining low frequency and random vibration loads.
- B. Reference list - includes all references used in the report or identified in the body of the report.
- C. Mass properties used in the report - weight, cg, mass moment of inertia shall be documented, including source and date (use control weights unless actual weights have been measured).
- D. Material properties used in the report - modulus of elasticity (E), modulus of rigidity (G), ultimate tensile strength of a material (allowable) ( $F_{tu}$ ), yield tensile strength of a material (allowable) ( $F_{ty}$ ), etc., include temperature effects if applicable.

#### **9.3.2.1 IDENTIFICATION OF SAFETY-CRITICAL STRUCTURES**

Format: As determined by the PD per the definitions in this document.

Content: List all safety-critical structural elements, components, and assemblies, including attachment hardware. Refer to design drawings or provide sketches which indicate load paths for all flight conditions. Present the rationale for identification of each safety-critical structural element using the provisions of sections 3 and 5 of this document. Also present proposed use of containment devices along with supporting rationale.

### 9.3.2.2 RESULTS OF FINAL DESIGN STRESS ANALYSIS

Format: To be determined by PD in conformance with good practice.

Content: The results of a stress analysis based on final (as-built) drawings and supporting test results shall be documented. The stress analysis should address the following points:

- A. A sketch of each area being analyzed should be given to describe the load path, pertinent dimensions, and structural details. Referenced drawing numbers should be included.
- B. Examples of the types of analysis required include (but are not limited to):
  - (1) Combined stress states
  - (2) Buckling and crippling
  - (3) Tension
  - (4) Shear
  - (5) Bending
  - (6) Bolt analysis
  - (7) Prying (heel and toe)
  - (8) Bearing
  - (9) Shear tear-out
  - (10) Lug analysis
- C. The source of the loads used in each section of the analysis should be noted if it is not obvious. An example of this would be the output from a FEM or the results of hand analysis.
- D. Any unusual configurations or significant deviations between an FEM and actual structure should be fully documented (i.e., elastic FEM elements in the form of spring constraints which represent non-rigid components).
- E. The stress levels determined in these analyses shall be used to calculate the appropriate MS. The MS shall then be summarized as indicated above.
- F. It should be noted that much of the final form of the analysis is the result of the analyst's good judgment. One should also keep in mind that this documented analysis will be used for safety verification and as a basis for a fracture mechanics assessment.



### **9.3.2.3 FINAL DESIGN STRUCTURAL MODELING DESCRIPTION**

Format: To be determined by the PD in conformance with good practice.

Content: In addition to the data above, this report should contain modeling details such as:

- A. Description of model boundary
- B. Mass representation
- C. 3-D views
- D. Plots of critical paths or locations
- E. Constraints and releases in the model
- F. Sample bulk data output
- G. RBM check
- H. Modeling philosophy

### **9.3.2.4 RESULTS OF FINAL DESIGN DYNAMIC ANALYSIS**

Format: To be determined by the PD in conformance with good practice.

Content: This analysis report shall contain the frequencies and mode shape plots of all system modes in the range of interest (equal to or less than 50 Hz). It shall also include FEM mass participation results or other analyses which support random vibration or acoustic load factor calculation.

### **9.3.2.5 RESULTS OF FINAL DESIGN LOADS ANALYSIS**

Format: To be determined by the PD in conformance with good practice.

Content: Describe the loads used in the model and how/why they were chosen (i.e., location in STS, data source, mission phase, structural attachment, and test data).

### **9.3.2.6 RESULTS OF FRACTURE CONTROL ANALYSIS OF SAFETY-CRITICAL STRUCTURES**

Format: As prescribed by NASA-STD-5003 (and described in this document in sections 3 and 5).

Content: The results of the fracture control analysis shall include the following:

A. Fracture control screening:

- (1) A description of all equipment considered in the analysis
- (2) The rationale for designating components and parts as fracture critical or non-fracture critical in accordance with the provisions of section 5.3.
- (3) Sketches or drawing references as required to support the above rationale
- (4) A list of fracture-critical components and parts

B. Fracture mechanics analysis:

- (1) Reference to screening analysis and the resulting list of fracture-critical components and parts
- (2) Technical approach used in the fracture mechanics analysis
- (3) Required life and cyclic loading calculations (see paragraph 6.2 and appendix E)
- (4) Critical initial flaw size calculations on each fracture-critical component or part (other approach is to use standard NDE and show that CIFS is greater than standard NDE resolution.)

C. NDE inspection requirements:

- (1) Component or part description
- (2) Sketches/drawings showing fracture-critical areas for inspection/analysis
- (3) Acceptable inspection methods (such as dye penetrant per MSFC-STD-366)
- (4) Detected flaw size

The PD shall perform NDE inspection for flaws and report the flaw sizes detected (whether or not the critical flaw size has been determined). The CIFS shall be used to evaluate the results of these inspections, and equipment having detected flaws larger than critical initial flaw size shall be disposed of by rework or rejection of the part.

### 9.3.3 VERIFICATION COUPLED LOADS ASSESSMENT

Format: As prescribed by PD

Content: The VLA is performed by the SSP, with the payload responses being provided to the PD for assessment. The developer is required to certify that his payload is safe for flight based on the results of the VLA.

### **9.3.4 FINITE ELEMENT MODEL**

#### **9.3.4.1 FEM - LIFT-OFF AND LANDING CONFIGURATIONS**

Format: NASTRAN compatible in English units

Content: FEM and associated test results as described in section 9.3.5.1 if applicable. Model description shall also be provided containing information as described in section 9.3.2.3. The model shall describe the lift-off and landing hardware configurations and will be used in support of the VLA.

#### **9.3.4.2 FEM ON-ORBIT CONFIGURATIONS**

Format: NASTRAN compatible in English units

Content: Rack level FEM having a frequency content up to 30 Hz. The model shall describe the on-orbit hardware configuration and will be used in support of on-orbit complement level analysis.

### **9.3.5 TEST RESULTS ON SAFETY-CRITICAL STRUCTURES**

Format: As prescribed by PD

Content: The results of any testing performed on SCS shall be reported so they may be evaluated for their contribution to verification of structural integrity and fracture mechanics life cycles. As a minimum, test reports shall be developed for each test to be included or referenced by the data package submitted to the PSRP and SSP-SWG or their designated review organization. Each test report should describe the item tested (including photographs or sketches of the test configuration), test fixtures, test setup, test conditions, instrumentation locations, as well as measurements and responses of the test article. The PD shall notify the responsible NASA center or approved partner/participant of all failures of the test articles to meet the prescribed test conditions (along with recommendations for corrective action).

#### **9.3.5.1 TEST-VERIFIED MODEL RESULTS**

Format: As prescribed by PD

Content: Reports of results of dynamic tests are required for certain payload flight equipment which contain or are attached to SCS, as determined by tables 7.1-1 and 7.1-2. The report shall contain a complete summary of the verification test and the model correlation analysis. Evidence that the model correlation has met the criteria contained in section 7 shall be presented. If the criteria cannot be met, then appropriate rationale must be provided for the acceptability of the model.

### **9.3.5.2 PRESSURE VESSEL AND OTHER PROOF-TESTING**

Format: As prescribed by PD

Content: Reports on results of proof-tests are required on pressure vessels, pressurized lines and fittings, and other items which require proof-testing for acceptance.

### **9.3.5.3 STATIC TEST RESULTS**

Format: As prescribed by PD

Content: Reports on results of static test are required for hardware in which static testing is required for verification of the design, or for static tests that are performed in support of analysis or lower safety factors.

### **9.3.6 QUALITY ASSURANCE AND INSPECTION REPORTS ON SAFETY-CRITICAL STRUCTURES**

Format: As prescribed by PD

Content: Quality assurance and inspection reports shall be prepared on all equipment involving SCS and any test activity required to certify SCS. Unsatisfactory equipment reports on SCS shall be forwarded to the responsible NASA center or approved partner/participant along with recommendations for corrective action.

The as-built structural characteristics of payload flight equipment shall be provided in a format designated by the PD. These as-built characteristics shall include the following data pertaining to or affecting SCS:

- A. Mass properties (mass, cg, mass moments of inertia, etc.)
- B. As-built dimensions
- C. As-built drawings
- D. Natural frequencies as determined by dynamic survey tests

### **9.3.7 MATERIALS LIST FOR SAFETY-CRITICAL STRUCTURES**

Format: As prescribed by the PD

Content: List of all materials designated for each SCS, including structural material properties, restrictions and limitations, and reference sources.

### **9.3.8 MATERIALS TRACEABILITY FOR FRACTURE-CRITICAL PARTS**

Format: As prescribed by the PD

Content: List of all fracture-critical items and their unique serial numbers. Traceability requirements and S/Ns shall be included on engineering drawings and specifications. Records providing traceability shall include actual chemical and physical material test results, certificates of compliance, and detailed process, inspection, and discrepancy records traceable to the material from which fabrication originated (heat and lot number). Traceability documentation shall be maintained at the PD site and shall be available upon request.

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## APPENDIX A ABBREVIATIONS AND ACRONYMS

a	Acceleration
A <sub>LF</sub>	Low Frequency acceleration
ASNT	American Society of Nondestructive Testing
AVT	Acceptance Vibration Test
BRL	Ballistic Research Laboratory
BW	Bandwidth
[C <sub>ij</sub> ]	Modal correlation matrix
CAEDS	Computer Aided Engineering Design System
cg	Center of Gravity
C.M.	Center of Mass
CIFS	Critical Initial Flaw Size
COSMIC	Computer Software Management Information Center
CSAR	Computerized Structural Analysis Research
D	Diameter of projectile
dB	Decibel
D <sub>f</sub>	Fastener diameter
DOF	Degree of Freedom
DR	Data Requirement
DRR	Document Release Record
E	Modulus of Elasticity
EO	Engineering Order
EXPRESS	EXpedite the PROcessing of Experiments to Space Station
EVA	Extravehicular Activity
F	Force
°F	Degrees Fahrenheit
f <sub>1</sub>	Lowest frequency associated with sloping portion of Power Spectral Density data
f <sub>1i</sub>	Fundamental (first system) eigen frequency in the ith direction
f <sub>2i</sub>	Second system eigen frequency in the ith direction
f <sub>n</sub>	Natural frequency
FEM	Finite Element Model
FEMAP	Finite Element Modeling and Post-processing
FLAGRO	Fatigue Crack Growth Analysis Program
FRR	Flight Readiness Review
FS	Factor(s) of Safety
FS <sub>u</sub>	Ultimate Factor of Safety
FS <sub>y</sub>	Yield Factor of Safety
ft-lb	Foot-Pound(s)
F <sub>tu</sub>	Ultimate tensile strength of a material (allowable)
F <sub>ty</sub>	Yield tensile strength of a material (allowable)

g	Gravitational acceleration
G	Modulus of rigidity
GHE	Ground Handling Equipment
G <sub>RMS</sub>	The “composite” or “overall” level of the input acceleration
h	Distance
HDBK	Handbook
Hz	Hertz (cycles per second)
I	Mass moment of inertia
ICD	Interface Control Document
IDD	Interface Definition Document
IDEAS	Integrated Design Engineering Analysis Software
in	Inch
IP	International Partners
IPT	Integrated Product Team
IRD	Interface Requirements Document
ISPR	International Standard Payload Rack
ISS	International Space Station
JEM	Japanese Experiment Module
JSC	Johnson Space Center
JSC–ES	Johnson Space Center – Structural Engineering Division
K	Stiffness
K <sub>c</sub>	Critical stress intensity factor for fracture
K <sub>I</sub>	Stress intensity
K <sub>Ic</sub>	Plane strain fracture toughness
K <sub>max</sub>	Maximum stress intensity factor
K <sub>Isc</sub>	Stress corrosion or environmental cracking threshold for no crack growth under sustained stress conditions
K <sub>t</sub>	Theoretical elastic stress concentration factor
KE	Kinetic Energy
kg	Kilogram
klb	Kilopound
kPa	Kilopascal
KSC	Kennedy Space Center
LBB	Leak-Before-Burst
lb	Pound(s)
M	Mass
m	Meter
[M] <sub>A</sub>	Analytical mass matrix
MAPTIS	Materials and Processes Technical Information System
MDK	Middeck



MDP	Maximum Design Pressure
MEOP	Maximum Expected Operating Pressure
MIL	Military
min	Minute
mm	Millimeter
M/OD	Meteoroid/Orbital Debris
MPLM	Mini-Purpose Logistics Module
MS	Margin(s) of Safety
MS <sub>u</sub>	Margin of Safety against ultimate failure
MS <sub>y</sub>	Margin of Safety against material yielding
MSC	MacNeal-Schwendler Corporation
MSFC	Marshall Space Flight Center
MSS	Mobile Servicing System
MUA	Material Usage Agreement
n <sub>i</sub>	Actual number of cycles at a particular stress or strain level
N <sub>fi</sub>	Number of cycles to failure at a particular stress or strain amplitude
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NASTRAN	NASA Structural Analysis (Computer program)
NDE	Nondestructive Evaluation
NHB	NASA Handbook
NSTS	National Space Transportation System
P	Applied (limit) Load
P <sub>u</sub>	Applied (limit) Load multiplied by the ultimate factor of safety
P <sub>y</sub>	Applied (limit) Load multiplied by the yield factor of safety
PAH	Payload Accommodations Handbook
PATRAN	NASTRAN-compatible pre- and post-processing computer program
PD	Payload Developer
PFE	Portable Fire Extinguisher
PIM	Payload Integration Manager
PNP	Probability of No Penetration
PSD <sub>n</sub>	Power Spectral Density taken at f <sub>n</sub>
psia	Pounds per Square Inch Absolute
PSRP	Payload Safety Review Panel
Q	Resonant amplification factor
QVT	Qualification Vibration Test
QAVT	Qualification for Acceptance Vibration Test
R	Random Load Factor
RBM	Rigid Body Modes
RCS	Reaction Control System
rpm	Revolutions per Minute
rss	Root Sum Square

RVLf	Random Vibration Load Factor
s	The slope of the PSD function (dB per octave)
S <sub>d</sub>	Travel distance of projectile
S <sub>max</sub>	Maximum cyclic tensile stress
SAE	Society of Automotive Engineers
SCS	Safety-Critical Structures
sec	Second
SPCs	NASTRAN Constraint Card
SPEC	Specification
SSP	Space Shuttle Program
SSP-SWG	Space Shuttle Program Structures Working Group
S-N	Stress vs. Number of Cycles
S/N	Serial Number
STD	Standard
STS	Space Transportation System (Shuttle Orbiter)
T <sub>A</sub>	Actual design wall thickness
TBD	To Be Determined
TNT	Trinitrotoluene
T <sub>R</sub>	Required wall thickness for projectile containment
TLF	Transient Load Factor
TRF	Transient Rotational load Factor
u	Ultimate (when used as a subscript)
ULC	Unpressurized Logistics Carrier
USL	United States Laboratory
V	Velocity
VAR	Verification Acceptance Review
VLA	Verification Loads Analysis
Wt	Weight
x	Distance
X,Y,Z	Coordinate axes with +X being toward the orbiter tail, +Y being toward the starboard side, and +Z being upward
X <sub>tu</sub>	Ultimate tensile strength of a material
y	Yield (when used as a subscript)
YS	Yield Strength of wall
YS <sub>w</sub>	Yield Strength of container wall
ξ	Structural damping

$\theta_x, \theta_y, \theta_z$	Coordinate rotational degrees-of-freedom using the right-hand rule, with $+\theta_x$ about the Orbiter X-axis, $+\theta_y$ about the Orbiter Y-axis, and $+\theta_z$ about the Orbiter Z-axis
$\emptyset$	Eigenvector or mode shape for a given natural frequency
$[\emptyset]_A$	Analytical mode shape matrix
$[\emptyset]_A^T$	Transpose of analytical mode shape matrix
$[\emptyset]_T$	Mode shape matrix derived from modal survey test
$\phi_f$	Fatigue damage
$\phi_{LF}$	Fatigue damage due to low frequency vibration
$\phi_{RV}$	Fatigue damage due to random vibration
$\sigma_A$	Alternating material stress
$\sigma_E$	Pure alternating stress which is equivalent to the combination of alternating and mean stresses
$\sigma_M$	Mean stress
$\omega$	Rotational frequency in radians per second

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## APPENDIX B GLOSSARY OF TERMS

**“A” Basis Allowables** - Minimum mechanical strength values guaranteed by the material supplier/suppliers such that at least 99 percent of the material they produce/supply will meet or exceed the specified properties with a 95 percent confidence level.

**Analysis** - A technical evaluation that relates equipment design and use parameters to prediction of actual design and operation.

**Brittle Fracture** - Brittle fracture is a type of catastrophic failure in structural materials that usually occurs without prior plastic deformation and at extremely high speed. The fracture is usually characterized by a flat fracture surface with little or no shear slips (slant fracture surface) and at average stress levels below those of general yielding.

**Burst Factor** - The burst factor is a multiplying factor applied to the Maximum Design Pressure (MDP) to obtain the design burst pressure. Burst factor is synonymous with ultimate pressure factor.

**Cargo Element** - A collection of payloads, support hardware, EVA hardware, etc., that are mounted on a carrier which is subsequently installed as an entity in the Orbiter cargo bay.

**Catastrophic Failure** - Failure that results in loss of the Space Shuttle, International Space Station, life of personnel, or major injury to personnel that results in incapacitation of flight crew.

**Catastrophic Hazard** - The presence of a potential risk situation caused by an unsafe condition that results in the potential for loss of the Space Shuttle, International Space Station, life of personnel, or major injury to personnel that results in incapacitation of flight crew.

**Component** - An experiment or portion of an experiment which attaches to primary or secondary structure (usually by bolts or rivets). Examples include electronics boxes, SIR drawers, middeck lockers, gloveboxes, etc.

**Containment** - A part is defined as contained if it can be shown by analysis or test that failure of the part will not result in separation from the payload and release into habitable areas or the Orbiter cargo bay. (Structures only)

**Critical Initial Flaw Size** - The largest crack that can exist at the beginning of the service life of a structure that has an analytical life equal to four lifetimes. A flaw that will grow to the extent of causing structural failure under flight loads.

**Damage Tolerant** - A composite or nonmetallic part other than glass is defined as damage tolerant if it is demonstrated by tests that the largest undetected flaw that could exist in the part will not grow to failure when subjected to the cyclic and sustained loads and environments in four complete mission lifetimes.

**Degree of Freedom** - The number of directions a point or rigid body can move. Six is the maximum for a single rigid body, three orthogonal translation and three orthogonal rotational directions.

**Design Load** - Largest of combined loads that apply during a mission phase.

**Emergency Landing Loads** - These are ultimate loads which must be met by all payload flight equipment to assure crew safety and crew egress after emergency landing.

**EXPRESS Pallet** - An attachment point platform with additional hardware for accommodating smaller attached payloads.

**EXPRESS Rack** - An ISPR with additional hardware for accommodating small sub-rack payloads, such as those in the Shuttle middeck lockers and Standard Interface Rack (SIR) drawers.

**F<sub>tu</sub>** – Allowable tensile ultimate stress

**F<sub>ty</sub>** – Allowable tensile yield stress

**Facility Class Payload** - A payload preinstalled with hardware subsystems for supporting a variety of experiments. Experiment-specific hardware is usually delivered to the ISS separately.

**Factor of Safety** - The factor by which the limit load is multiplied to obtain the ultimate or yield load. The limit load is the maximum anticipated load or combination of loads which a structure may be expected to experience. Ultimate and yield load is the load that a payload must be able to withstand without failure.

**Fail-Safe** - A redundant structure shown to be a non-fracture-critical component by meeting the requirements of NASA-STD-5003. A part is defined as fail-safe if it can be shown by analysis or test that, due to structural redundancy, the structure remaining after failure of the one part can sustain the new limit loads with an ultimate factor of safety equal to or greater than 1.0, the remaining structure has sufficient fatigue life to complete the mission, and the failure of the component will not result in the escape from the payload of any fragment.

**Fitting** - A structure element used to transfer load in defined load directions.

**Flaws or Crack-Like Defect** - Defect which behaves like a crack and which may be initiated during material production, fabrication, and testing, or which is developed during the service life of a component.

**Fracture Control** - The rigorous application of those branches of engineering, assurance management, manufacturing, and operations technology dealing with the analysis and prevention of crack propagation leading to catastrophic failure.

**Fracture-Critical Part** - A classification (of parts) which assumes that fracture or failure of the part resulting from the occurrence of a crack will result in a catastrophic hazard. A structural element which requires special analysis, inspection, tests, and quality and process controls to control the risk of a failure which would create a catastrophic hazard.

**Fracture Mechanics** - Fracture mechanics is an engineering discipline which describes the behavior of cracks or crack-like flaws in materials under stress.

**Fracture Toughness** - Fracture toughness is a material characteristic which reflects flaw tolerances and resistance to fracture and is equal to the value of the stress intensity factor at flaw instability. Fracture toughness is dependent on the environment, geometry, and loading rate.

**Habitable Area** – Any area that is or could be occupied by humans without Space Suits or protection.

**Hazardous Fluid** - Any liquid or gas which, if released, could result in the potential for personnel injury, loss of or damage to Orbiter/ISS, or loss of or damage to launch or ground facilities.

**$\frac{1}{2}(I\omega^2)$**  - The rotational energy of a rotating component where “I” is the mass moment of inertia and “ $\omega$ ” is the rotational frequency in radians per second.

**Increment** - The payload complement that is integrated into the MPLM, ISS, or the Orbiter.

**Inspection** - Inspection is a physical measurement or visual evaluation of equipment and associated documentation. Inspection may be used to verify construction features, drawing compliance, workmanship, and physical condition. It may include determination of physical dimensions.

**$K_c$**  – Critical stress–intensity factor for fracture

**$K_{Ic}$**  – Plane strain fracture toughness

**$K_{Ie}$**  – effective fracture toughness for surface or elliptically shaped cracks.

**$K_{Isc}$**  – Stress corrosion or environmental cracking threshold for no crack growth under sustained stress conditions.

**$K_{max}$**  – Maximum stress intensity in the fatigue cycle.

**Leak-Before-Burst** - A fracture mechanics design concept in which it is shown that any initial flaw will grow through the wall of a pressurized membrane or pressurized component and cause leakage rather than burst (catastrophic failure) at MDP. LBB describes the way in which a crack-like flaw in a pressurized membrane would grow and eventually fail in pressurized hardware at any pressure up to and including MDP. LBB is determined at MDP (less than yield strength of the membrane) and therefore is generally characterized by relatively slow leakage rather than fragmentary fracture or tearing rupture. LBB is determined analytically or by tests using fracture mechanics technology to show that a growing crack-like flaw will not become critical (unstable) before growing through the pressurized membrane thickness and leaking.

**Lifetime** - The total load history that a part will be exposed to, including load level and number of cycles. This history may include loadings due to fabrication, testing, transportation, lift-off, ascent, on-orbit, descent, landing, and postlanding events.

**Limited-Life Part** - A multi-mission part which has a predicted safe-life less than four times the service life required.

**Limit Load or Stress** - The maximum load or stress expected to act on a structure in the expected operating environments including fabrication, testing, transportation, ground handling, and flight.

**Loads Spectrum** - A representation of the cumulative static and dynamic loadings including load level and number of cycles anticipated for a structural component or assembly under all expected operating, transportation, testing, manufacturing, and flight environments.

**Low Fracture Toughness** - A material property characteristic for which the ratio of  $K_{Ic}/F_{ty} < 0.33 \text{ in}^{1/2} (1.66\text{mm}^{1/2})$ . For steel bolts with unknown  $K_{Ic}$ , low fracture toughness is assumed when  $F_{tu} > 180 \text{ ksi} (1,240 \text{ MPa})$ .

**Low Mass** - A part is defined as low mass if it can be shown that its mass is sufficiently low so that its release or functional loss due to structural failure will not cause a hazard to the STS/ISS or crew.

**Margin of Safety** - The decimal fraction by which the failure load or stress exceeds the limit load or stress that has been multiplied by the safety factor.



**Maximum Design Pressure** - MDP is the highest possible pressure occurring from maximum relief pressure, maximum regulator pressure, maximum temperature, or transient pressure excursions. Design factors of safety shall apply to MDP. Where pressure regulators, relief devices, and/or a thermal control system (e.g., heaters) are used to control pressure, collectively they must be two-fault tolerant from causing the pressure to exceed the MDP of the system.

**Maximum Expected Operating Pressure (MEOP)** – MDP shall be substituted for all references to MEOP in MIL-STD-1522A.

**Modal Analysis** - An analysis to determine the characteristic frequencies (eigenvalues) and mode shapes of a structural support system.

**Nondestructive Evaluation (NDE)** - Inspection techniques that do not cause physical or chemical changes to the part being inspected, or otherwise impair its adequacy for operational service, that are applied to materials and structures to verify required integrity and detect characteristic flaws. NDE method refers to the specific technique used, such as dye penetrant, x-ray, etc.

**Payload** - Integrated rack or attached payload composed of subsystem hardware and experiment hardware.

**Payload Developer** – Organization responsible for design, manufacture, analysis, and/or test of integrated racks or attached payloads.

**Payload organization** – NASA installation, sponsoring agency, or commercial customer that is responsible for a payload at the Space Shuttle Payloads Safety Reviews.

**Pressure Vessel** - A container designed primarily for pressurized storage of gases or liquids, which (1) contains stored energy of 14,240 ft-lb (0.01 lb trinitrotoluene (TNT) equivalent) or greater based on adiabatic expansion of a perfect gas; or (2) contains a gas or fluid at a pressure in excess of 15 psia which will create a hazard if released; or (3) will experience a design limit pressure greater than 100 psia.

**Primary Load Path** - Structural elements which transfer load from one part of a structure to another (and therefore experiences loading in excess of that created by its own mass).

**Proof-Test** - A load or pressure in excess of limit load or maximum operating pressure applied in order to verify the structural integrity of a part or screen initial flaws in a part.

**Random Vibration Loads** - The random vibration loads acting on payload flight equipment result from the resonant structural response of the equipment item to induced random disturbances from the rocket engine during launch. These disturbances result in both

mechanical and acoustic borne excitation. Random load factors are induced only during the launch phase of flight operations, and shall be combined with transient and other loads acting during the launch phase.

**Responsible fracture control authority** – The designated individual, panel, or group at the NASA Center or sponsoring institution responsible for fracture control methodology.

**Responsible NASA Center** – NASA Field Center acting as the sponsor or coordinator for the payload with the Space Shuttle Integration and Operations Office, JSC. For non-NASA payloads, JSC serves as the responsible NASA Center.

**Restrained** - A part is considered restrained if it can be shown by analysis or test that failure of that part will not result in separation from the payload because of restraining wires, fasteners, or other elements structurally capable of preventing release into habitable areas or the Orbiter cargo bay.

**Rotating Machinery** - For the purpose of fracture control, a rotating mechanical assembly that has a kinetic energy of 14,240 ft-lb (19,307 Joules) or greater (based on  $\frac{1}{2} I \omega^2$ ) is, by definition, fracture critical. Rotating machinery with lower kinetic energy shall be addressed as Safety-Critical Structures.

**Safe-Life** - A design criterion under which a flaw is assumed consistent with the inspection process specified, and it can be shown that the largest undetected flaw that could exist in the structure will not grow to failure in four service lifetimes when subjected to the cyclic and sustained loads in the environment encountered; also, the period of time for which the integrity of the structure can be ensured in the expected operating environments. All parts classified as safe-life require a fracture mechanics analysis and NDE to ensure that no flaws (cracks) exist which will grow to critical size in four lifetimes.

**Safe-life verification** – Analysis or test of a fracture-critical component which demonstrates safe-life.

**Safety-Critical Structure** - All structural elements (including interfaces, fasteners, and welds) in the primary load path including pressure systems, uncontained glass, composites, structural bonds/adhesives, beryllium, rotating/articulating machinery, and containment devices are safety critical.

**Sealed Containers** - Any single, independent (not part of a pressurized system) container, component, or housing that is sealed to maintain an internal non-hazardous environment and that has a stored energy of less than 14,240 foot-pounds (19,310 Joules) and an internal pressure of less than 100 psia (689.5 kPa).

**Service Life** - Service interval for a part beginning with the determination of initial crack size for analysis based on inspection or a flaw screening proof-test and extending through completion of its specified mission including testing, transportation, lift-off, ascent, on-orbit operations, descent, landing, and postlanding events.

**Single-point direct catastrophic failure** – Direct catastrophic failure resulting from fracture in a structural joint where the load path is transmitted through a single fastener or pin or other single structural element.

**Single-Point Failure** - Not redundant; a situation where a failure of one item or one structural element will cause the structure to become unstable and unable to carry design loads.

**Special NDE** – Formal crack-detection procedure using inspection techniques and/or equipment that exceeds common industrial standards, or where assumed detection capability exceeds that specified in Table 6.2.2-1 and Table 6.2.2-2.

**Standard NDE** – Formal crack-detection procedures that are consistent with common industrial inspection standards. Standard procedures include penetrant, magnetic particle, eddy current, ultrasonic and x-ray.

**Statically Determinate** - No redundant structural load path. A structure whose supports are the minimum for structural stability. A structure in which the number of equations of motion equals the number of unknowns.

**Static Fatigue** – In glass, flaws grow as a function of stress, flaw size, environment, and time. Strength degradation with time resulting from the flaw growth is also referred to as static fatigue.

**Threshold Strain** - Value of strain level below which catastrophic failure of the composite structure will not occur in the presence of flaws or damage under service load/environmental conditions.

**Transient Loads** - Slowly varying loads which are treated as steady-state loads in performing structural analysis. These loads result from the low frequency response to the Orbiter/ISS system to Orbiter forcing functions during lift-off and landing.

**Ultimate Load** - Maximum load (including ultimate factor of safety) used to calculate the maximum stress the material can withstand before rupture, collapse, or failure.

**Verification Coupled Loads** - These are mission-unique coupled loads derived after the integrated payload final design and used to verify the designed structural integrity of the as-built hardware.

**Yield Load** - Maximum load (including yield factor of safety) used to calculate the maximum stress the material can withstand before elongation increases with no increase in load (permanent deformation).

## **APPENDIX C LOAD DEVELOPMENT - ALTERNATE METHODS**

### **C.1 LOAD DEVELOPMENT FOR FLIGHT HARDWARE**

#### **C.1.1 REFERENCE COORDINATE SYSTEM**

Load factors and loading environments are given in terms of axes or directions in some referenced coordinate system. Lift-off and landing low frequency load factors usually reference the Orbiter coordinate system since they are based on STS flight events. The ISS element and rack coordinate systems are parallel to the Orbiter coordinate system, and are given in the applicable IDD or ICDs. On-orbit low frequency load factors for Space Station components and systems may reference the on-orbit element coordinate system or the basic on-orbit ISS coordinate system. For components whose coordinate system is not rectangular and parallel to the coordinate system of the load factor to be applied, load transformations must be done to apply the loads in their correct orientation.

Random vibration criteria are generally defined in the coordinate frame in which the vibroacoustic energy is transmitted. Consequently, random load factors (high frequency load factors) may be developed in coordinate systems which are not parallel to the basic coordinate systems. These random load factors must then be transformed to the same coordinate system as the low frequency load factors prior to application. Sometimes (as in the case of the USL and MPLM modules) random vibration criteria are given in cylindrical coordinates since the vibroacoustic energy is transmitted in a cylindrical coordinate frame. Random load factors developed from this type of criteria may require coordinate transformations to be consistent with the low frequency load factors. Since gravitational loads can only be applied into a rectangular coordinate system, the load factors referencing the cylindrical system either must be resolved into rectangular components or the loads must be applied as forces.

#### **C.1.2 LOW FREQUENCY TRANSIENT LOADS**

Low frequency transient loads are slowly varying loads which can be treated as steady-state loads (load factors) in performing structural analyses. Lift-off and landing transient loads result from the low frequency response of the payload structure to the Orbiter forcing functions during lift-off/ascent and descent/landing mission phases. On-orbit low frequency loads result from small dynamic events during ISS operations. Transient Load Factors (TLF) are an enveloping simplification of the maximum accelerations of several flight events and are generally derived from the results of coupled loads analyses. Design TLFs are generic load factors which are developed from loads data of similar payloads from previous missions or from up-front coupled loads parametric studies. They are frequently provided in terms of accelerations which must be reversed in sign to obtain load factors that can be applied to the payload center of gravity. These load factors are applicable only for payloads which meet minimum natural frequency requirements. For components that do not meet the minimum natural frequency requirements, the PD should contact the responsible NASA center or approved partner/participant or the

SSP-SWG (usually, the load factor is multiplied by an uncertainty factor until adequate coupled loads analyses results can be obtained). On-orbit loads are relatively small and are only consequential for microgravity, stability and pointing system analysis, or for payloads which have been reconfigured on orbit. Generally, lift-off loads envelope landing loads due to the addition of random loading for lift-off. The design TLFs for Space Station components in various mounting locations are given in the appropriate IDD. The TLFs are not uniform over the entire Orbiter and its payload because of the component frequency and boundary conditions' effect on load transmissibility and coupling. Note that the low frequency TLFs are applied in all three orthogonal axes simultaneously.

#### **C.1.2.1 COUPLED LOADS ANALYSES**

Coupled loads analyses are transient dynamic analyses of the integrated STS payload using a coupled model of the STS and cargo element where the dynamic characteristics of the payload elements are coupled with their supporting structure and subjected to standard forcing functions. A forcing function is a time-consistent history of forces which simulate a flight event over a prescribed time period.

The load factors derived from coupled loads analyses are generally neither time- nor case-consistent. They are based on maximum-minimum summaries of responses to all event forcing functions for the component or location. The most up to date and appropriate Shuttle math models and forcing functions will be utilized for coupled loads analysis. These forcing functions envelope all flight load measurements and main engine static firing data and have no frequency content above 35 Hz. There is a 2-sigma statistical distribution on these worst-on-worst load combinations. The lift-off forcing functions include such flight events as main engine firing, SRB ignition, and acceleration of the Shuttle away from the Earth. Included in landing forcing functions are the crosswind, sink rate, main gear touchdown, and nosegear slapdown flight events.

Early in the design cycle, generic design load factors are used. These may be updated during the design process, if required, by performing design coupled loads analyses. A verification coupled loads analysis is conducted for each flight configuration prior to flight for the final structural assessment of the flight configuration.

#### **C.1.2.2 MINIMUM NATURAL FREQUENCY REQUIREMENT**

Each structural component must meet the minimum natural frequency requirement to prevent inadvertent coupling with its supporting structure or with STS forcing functions and for design load factors to be applicable. If separate subassemblies in the overall structure are considered safety critical, minimum frequencies of each subassembly should be calculated.

Frequencies may be calculated using classical hand-analysis techniques, which can be found in “Formulas for Natural Frequency and Mode Shape,” by Robert D. Blevins (Krieger Pub., 1979) and “Vibration Analysis for Electronic Equipment,” by Dave S. Steinberg (John Wiley & Sons, 1988), or using a FEM analysis such as NASTRAN. Local structural modes, such as local panel modes, are not of global interest and are not required to meet minimum natural frequency requirements. Frequency requirements are applicable for the lowest structural system mode, regardless of the direction. Integrated assemblies should include all mass loading including freon lines and cable weights. Appropriate conservative weight estimates should be used in the design process to allow for reasonable weight growth as the design matures.

### C.1.3 RANDOM VIBRATION LOADS

The random vibration loads acting on payload flight equipment result from the structural response of the equipment component to induced random disturbances from the propulsion system during launch. These high frequency disturbances result in both mechanical and acoustic borne excitation, and occur during the launch phase only (lift-off and ascent) while the main engines are operating. Random vibration loads do not occur at regular intervals for a defined period of time; as the name implies, they are random in time of application and duration. Vibroacoustic data has been acquired from static firings, flight measurements, as well as acoustic tests and large-scale random vibration tests in many space programs. The random vibration design environments for Space Station equipment in several mounting locations are provided in the appropriate IDD or ICD.

In order to assess random vibration loads in hardware analysis, several simplifying assumptions must be made. Equivalent static load factors are generally calculated in each axis so that they may be combined with low frequency load factors and used in structural analysis. Random Vibration Load Factors (RVLF) are typically calculated from the applicable random vibration criteria using Miles’ Equation, which is based upon statistical analyses of induced acceleration spectra with a 3-sigma distribution. Miles’ Equation determines a load factor by assuming that the fundamental (first system) mode in each orthogonal direction will provide the primary response:

$$RVLF = 3 \bullet ((\pi/2) \bullet Q \bullet f_n \bullet PSD_n)^{1/2}$$

Where:

- Q = Amplification factor
- $f_n$  = System fundamental frequency (Hz)
- $PSD_n$  = Power Spectral Density at  $f_n$  ( $g^2/Hz$ )

The PSD values are determined from the component natural frequency,  $f_n$ , and the design random vibration environment, which envelopes the maximum input spectra for a particular mounting



location (e.g., rack-mounted components). If the frequency of interest ( $f_n$ ) falls on either a positive or negative slope of the input spectrum, the following equation is used to interpolate for the  $PSD_n$  value:

$$PSD_n = PSD_1 * (f_n/f_1)^{(0.3322s)}$$

Where:

$f_1$  = Reference frequency (at start of slope)

$f_n$  = Frequency of interest

$s$  = Slope of the PSD curve at frequencies above  $f_1$  (dB/octave)

$PSD_1$  = Power Spectral Density at  $f_1$

Component frequencies are determined either by analysis or sinusoidal sweep test.

Amplification factors ( $Q$ ) are chosen based on component mass, support structure flexibility, and method of attachment. For most components, a  $Q$  of 10 for all three directions should be used if no test data are available.

This method is reasonably accurate for systems with dominant fundamental system modes, considering it approximates a component's system response using only a single degree of freedom spring-mass system to represent loading over an entire frequency spectrum (usually 20 to 2000 Hz). Vibroacoustic test data for many types of hardware and many levels of random criteria indicate that the Miles' Equation is conservative at the low frequency end of the spectrum, and slightly unconservative at higher frequencies. For frequencies above 2000 Hz, an approximate RVLf may be obtained by multiplying the overall Grms value by 3 (for a 3-sigma statistical distribution).

A worst-case 'peak-of-the-curve' RVLf can be calculated when insufficient data are available to determine natural frequencies, or to simplify analysis of multiple configurations. The frequency and PSD value of the highest frequency on the plateau portion of the criteria provides the highest load factor for that environment.

For complex components in which a single dominant mode in each direction cannot be identified, the modal mass participation method (explained below) may be used to provide a more realistic, less conservative load factor. Essentially, this method allows the use of multiple modes in the calculation of the random load factor by multiplying the RVLf for each significant mode by a ratio of the effective mass participating in the mode to the total component mass. An example of a RVLf calculated in this manner is provided below.

Several alternative methods for establishing random load factors are discussed below.



A. Mass participation: This method is useful for complex components/systems that do not have a fundamental mode in each direction in which a majority of the mass is participating. Mass participation is ideal for calculating load factors for electronics boxes or experiments in which there are several independently supported masses, each of which has its own distinct resonant frequencies. A composite RVLf is calculated by taking all system modes with a significant amount of participating mass and calculating a load factor for each of these modes, multiplying it by the mass fraction, and root-sum-squaring it with the other system modes. The procedure for MSC/NASTRAN is presented below:

- (1) Run a normal modes solution on the finite element model with the boundary constrained in the flight configuration. Include the necessary commands to print out the mass participation of the model in each mode for each orthogonal direction. For example, a NASTRAN model should be run with Sol 103 (or Sol 3) with the flight boundary constrained (via SPCs), and with the executive control statement that calls to the mass participation alter (currently 'check.v68') and the 'Param, efwt, 2', 'Param, chkstif, 1', and 'Param chkmass1' added to provide the mass participation matrix.
- (2) Identify all modes that have significant mass participating in the direction of interest. The sum of the mass participating in all of the significant modes in each direction should add up to at least 80 percent of the total mass of the component.
- (3) Calculate the random load factor for each mode (in G's peak) using the following (Miles) relationship:

$$RVLf_i = 3 \cdot [(\pi/2) \cdot Q \cdot f_i \cdot PSD_i]^{1/2}$$

For modes above 2000 Hz, the random load factor may be estimated from:

$$\text{Random Load Factor} = 3 \times G_{rms}$$

Where:

$G_{rms}$  = the "composite" or "overall" level of the input acceleration PSD.

- (4) Multiply the equivalent random load factor for each mode,  $RVLf_i$ , by the effective weight for that mode,  $EFFW_i$  (obtained in step 1 from the finite element model). The result will be the  $RVLf_{(RMS)}$ .
- (5) Divide the  $RVLf_{(RMS)}$  for each mode by the total mass of the system. This will result in the mass-weighted RVLf for each mode,  $RVLf_{(MW)}$ .

- (6) Root-sum-square all of the mass-weighted RVLFs. The result is the composite RVLF for that orthogonal direction. This design load factor is then combined with the low frequency load factor and used in the analysis.

- B. Use actual test data derived from a random vibration test of the component in the flight configuration to the flight environment. For many components random vibration testing is desired by either the experimenter or the PD to ensure proper function of the hardware during or after exposure to the launch random environment. Resonant frequencies, amplification factors, power spectral densities, and bandwidth of the fundamental modes in each direction are easily obtained from this testing. These actual values can than be substituted into a modified equation for random load factor calculation:

$$1/2 \text{ Power RVLF} = 3 \bullet (BW \bullet \text{PSD}_{\text{peak}})^{1/2}$$

Where:

BW = Bandwidth ( $f_2 - f_1$ ) at  $\text{PSD}_{1/2 \text{ Power}}$  (Hz)

$\text{PSD}_{\text{Peak}}$  = Power Spectral Density at the peak value of the dominant resonant mode ( $\text{g}^2/\text{Hz}$ ).

For components resonant above 2,000 Hz, the random load factor may be estimated from:

$$\text{Random load factor} = 3 \times G_{\text{rms}}$$

Where:

$G_{\text{rms}}$  = the “composite” or “overall” level of the input.

- C. Random Response Analysis - This method requires the experimenter to have a detailed finite element model of the component. This method can be used to take the flexibility of the supporting structure into account. A dynamic response analysis is performed in NASTRAN or similar code using normal modes results. Detailed information may be found in one of the NASTRAN manuals. This method can be used to determine random load factors for use in subsequent static analyses, or in some cases, determine structural loads and stresses directly. One difficulty with using this approach is in combining the results due to random responses with those resulting from the transient loading.

Note that RVLFs are applied uniaxially and are root-sum-squared with the low frequency TLFs. See Table NO TAG.

#### **C.1.4 ACOUSTIC IMPINGEMENT LOADS**

The acoustic environment is defined as the maximum fluctuating pressure acting on the surface of the launch vehicle or payload structure. Acoustic loads are imposed on a structure due to the direct impingement of acoustic sound waves during launch. There are two primary sources of acoustic environment: engine-generated noise during static firing and lift-off, and aerodynamically generated acoustics during ascent and reentry flight.

The primary source of engine-generated acoustic field is the fluctuating turbulence in the mixing region of the rocket exhaust. The maximum acoustic environment impinging on the surface of the launch vehicle from rocket exhaust occurs during static firing or liftoff when the vehicle is still in close proximity to the deflected exhaust flow off of the ground plane. As the rocket lifts off, the exhaust stream trails the vehicle and the acoustic environment diminishes to a negligible level. Thus, the engine-generated acoustic noise is a function of exhaust flow parameters, launch stand configuration, and atmospheric conditions.

Aerodynamically generated acoustics are attributed to the fluctuating pressures occurring as the launch vehicle interacts with the atmosphere (accelerates) during ascent and reentry due to boundary layer turbulence. These pressures, called aerodynamic noise, are applied over the vehicle surface and generally are maximum during the transonic period.

##### **C.1.4.1 PAYLOAD COMPARTMENT ACOUSTIC LOADS**

The acoustic environment internal to the cargo bay (payload compartment) is the direct result of the external acoustic field impinging on the payload bay wall due to both sources. The payload compartment internal acoustic environment is a function of the external acoustics, noise reduction or attenuation through the cargo bay walls, and the volume of the unfilled compartment. The acoustic environments for the cargo bay and the module interior are given in the respective IDD. Acoustic load factors should be calculated for structural components with large surface areas. Acoustic loading is negligible for small, dense components, like electronics boxes and gloveboxes. Acoustic load factors are based on statistical analyses of the expected sound pressure level, and are calculated in a similar manner to RVLFs.

#### **Acoustic Force Calculation Procedure:**

The equations given below provide an approximate calculation of the acoustic pressure applied to structure exposed to the acoustic environment. Limited checks of these equations against more rigorous equations show reasonable correlation.

The resulting acoustic loads should be assessed for each axis. Two natural frequencies should be considered for each axis; one based on the overall system mode of the assembly in that axis (if

the assembly mode includes the items with large surface area to weight ratios), and one based on the panel/plate modes of the collecting surface. The frequencies resulting in the highest acoustic loading in each axis should be used in the structural assessment.

The equivalent static pressure caused by the acoustic environments is given by:

$$P_e = 3 \cdot [(\pi/2) \cdot Q \cdot f_n \cdot W_p]^{1/2}$$

$$W_p = (P_1)^2 / (Df)$$

$$Df = 0.233 \cdot f_n$$

$$P_1 = P_0 \cdot 10^{(dB/20)}$$

Where:

$$Q = \text{Resonant frequency amplification factor}$$

$$f_n = \text{Structure natural vibration frequency (Hz)}$$

$$W_p = \text{Pressure power spectral density}$$

$$P_0 = \text{Reference pressure } (P_0 = 2.9 \times 10^{-9} \text{ psi})$$

$$dB = \text{One-third octave band sound pressure level in dB relative to } P_0$$

An approximate acoustic load factor can then be calculated from the equivalent static pressure by:

$$F_a = A \cdot P_e$$

$$ALF = F_a / W$$

Where:

$$F_a = \text{Equivalent static force}$$

$$A = \text{Projected surface area with respect to axis}$$

$$ALF = \text{Equivalent acoustic load factor}$$

$$W = \text{Component weight}$$

The acoustic load factor may then be combined with the appropriate RVLF using the rss procedure. The resulting random load factor is then:

$$RLF = [ALF^2 + RVLF^2]^{1/2}$$

The resulting random load factor should then be combined with the low frequency loading using the methodology described in paragraph 4.2.1.

#### **C.1.5 TIME-DEPENDENT LOADS COMBINATION FOR RACK-MOUNTED PAYLOADS**

Integrated racks shall be designed in accordance with the requirements specified in SSP 52005; however, rack-mounted payloads may use the following time-dependent approach for combining random and quasi-static load factors in lieu of the method defined in SSP 52005 paragraph 4.2.1. Use of this alternate methodology requires prior, written approval of the SSP-SWG based on the requirements laid out in the following paragraphs.

The following alternate loads combination approach is to be used only if the loads combination method defined in SSP 52005 paragraph 4.2.1, along with the appropriate random vibration environment, results in negative margins which cannot be resolved by payload design modification. Rack-mounted payload random vibration criteria are defined in SSP 57000 Table 3.1.1.3-2 for payloads weighing less than 100 lbs, and 3.1.1.3-3 for payloads weighing more than 100 lbs. The PD shall identify the loads causing negative margins of safety. Structure showing positive margins of safety shall remain analyzed to those loads combined per SSP 52005 paragraph 4.2.1.

The time-dependent loads combination approach is detailed in Table C-1. Combined load factors are derived by root-sum-squaring the random load factors with the low-frequency transient load factors, one axis at a time. The PD must perform all load factor calculations as identified in Table C-1 (i.e., load sets 1a, 1b, 2a, 2b, 3a, 3b, and 4). For load sets 1-3, the high load factor between "a" and "b" shall be chosen individually for each axis. The peak transient loads  $T_{Ai}$  and  $T_{Bi}$  shall be calculated via coupled loads analysis, utilizing FEM's of the specific payload and rack. All appropriate uncertainty factors, based on the current level of design maturity and manifest uncertainty, shall be applied accordingly.

The PD shall confirm with coupled loads analysis results that the maximum transient loads occur within 3 seconds after SRB ignition for this approach to be applicable. All loads analyses shall be coordinated with the SSP-SWG, and results shall be provided in a timely manner. The mission specific Verification Loads Analysis (VLA) results will be used to confirm that the time-dependent loads combination approach remains valid. Per NSTS 37329, the PD will participate in the VLA to verify payload compatibility with the STS loads environment. The PD shall provide the proper payload math model data to the ISS Program to support the VLA and for review/assessment of VLA output.

**TABLE C-1 ALTERNATE LOADS COMBINATION CRITERIA**

LOAD SET	ORBITER X AXIS	ORBITER Y AXIS	ORBITER Z AXIS	$\theta_1$ (About $X_0$ )	$\theta_2$ (About $Y_0$ )	$\theta_3$ (About $Z_0$ )
higher of 1a or 1b	$1.5g_x \pm \sqrt{(T_{Ax} - 1.5g_x)^2 + \frac{(R_x)^2}{2}}$  $1.5g_x \pm \sqrt{R_x^2 + T_{Bx}^2}$	$\pm T_{Ay}$  $\pm \frac{R_y}{4}$	$\pm T_{Az}$  $\pm \frac{R_z}{4}$	$\pm TRF_1$	$\pm TRF_2$	$\pm TRF_3$
higher of 2a or 2b	$\pm T_{Ax}$  $1.5g_x \pm \frac{R_x}{4}$	$\pm \sqrt{(T_{Ay})^2 + \frac{(R_y)^2}{2}}$  $\pm \sqrt{R_y^2 + T_{By}^2}$	$\pm T_{Az}$  $\pm \frac{R_z}{4}$	$\pm TRF_1$	$\pm TRF_2$	$\pm TRF_3$
higher of 3a or 3b	$\pm T_{Ax}$  $1.5g_x \pm \frac{R_x}{4}$	$\pm T_{Ay}$  $\pm \frac{R_y}{4}$	$\pm \sqrt{(T_{Az})^2 + \frac{(R_z)^2}{2}}$  $\pm \sqrt{R_z^2 + T_{Bz}^2}$	$\pm TRF_1$	$\pm TRF_2$	$\pm TRF_3$
4	$\pm T_x$	$\pm T_y$	$\pm T_z$	$\pm TRF_1$	$\pm TRF_2$	$\pm TRF_3$

where  $T_{Ai}$  = Transient peak load in the range from 0 to 3 seconds in the  $i_{th}$  axis

$T_{Bi}$  = Transient peak load in the range above 3 seconds in the  $i_{th}$  axis

## **APPENDIX D GUIDELINES FOR ISS PAYLOAD EQUIPMENT STRUCTURAL MODEL DEVELOPMENT AND VERIFICATION**

### **D.1 INTRODUCTION**

The integrated STS structural dynamic model used for coupled loads analysis is made up of a large number of component/subsystem models. Consequently, compatibility between the individual models and proper understanding of each model is of utmost importance. With this in mind, a set of guidelines for model development and verification is presented for use by the PD to aid the system analysts in performance of coupled loads analyses.

### **D.2 MODELING REQUIREMENTS**

Dynamic structural models are used to perform coupled loads analyses. These models are to accurately represent structural modes with frequencies below 50 Hz. In some cases it is desirable to use the Finite Element Model (FEM) developed for stress assessment as a dynamic model. Oftentimes, however, these models include highly detailed representations of high frequency internal components (circuit boards, etc.) as well as high mesh densities throughout the structure to allow refined approximations of stress distributions. Such a level of detail is typically not required nor desired for coupled loads analysis. Construction of a relatively simple dynamic model is often in the best interest of both the PD and the Payload Integrator for several reasons:

- A. Assumptions required for stress and dynamic models often oppose each other in obtaining an accurate/conservative solution. Construction of a relatively small dynamic model allows the analyst to tailor assumptions to the type of analysis being performed (stress or dynamic).
- B. If dynamic testing is to be performed, a small-size dynamic model allows relatively quick solution time for pre-test analysis as well as post-test tuning. Additionally, tuning modifications become inherently simplified due to the reduced number of elements in the dynamic model.
- C. Allows for a manageable integrated rack model size for the payload integrator to prepare for coupled loads analysis as well as to perform integrated rack interface and overall stress analysis.

Additional uses of dynamic models could include assessing minimum natural frequency requirements and fundamental system mode shapes and frequencies for random load development. Techniques such as Guyan Reduction (using NASTRAN 'A-set') or Craig-Bampton reduction are available to achieve improved solution times in some cases.

Experiments and their internal components having no significant modes below 50 Hz (as verified by test, if appropriate) are candidates for lumped-mass representation in coupled loads analyses.



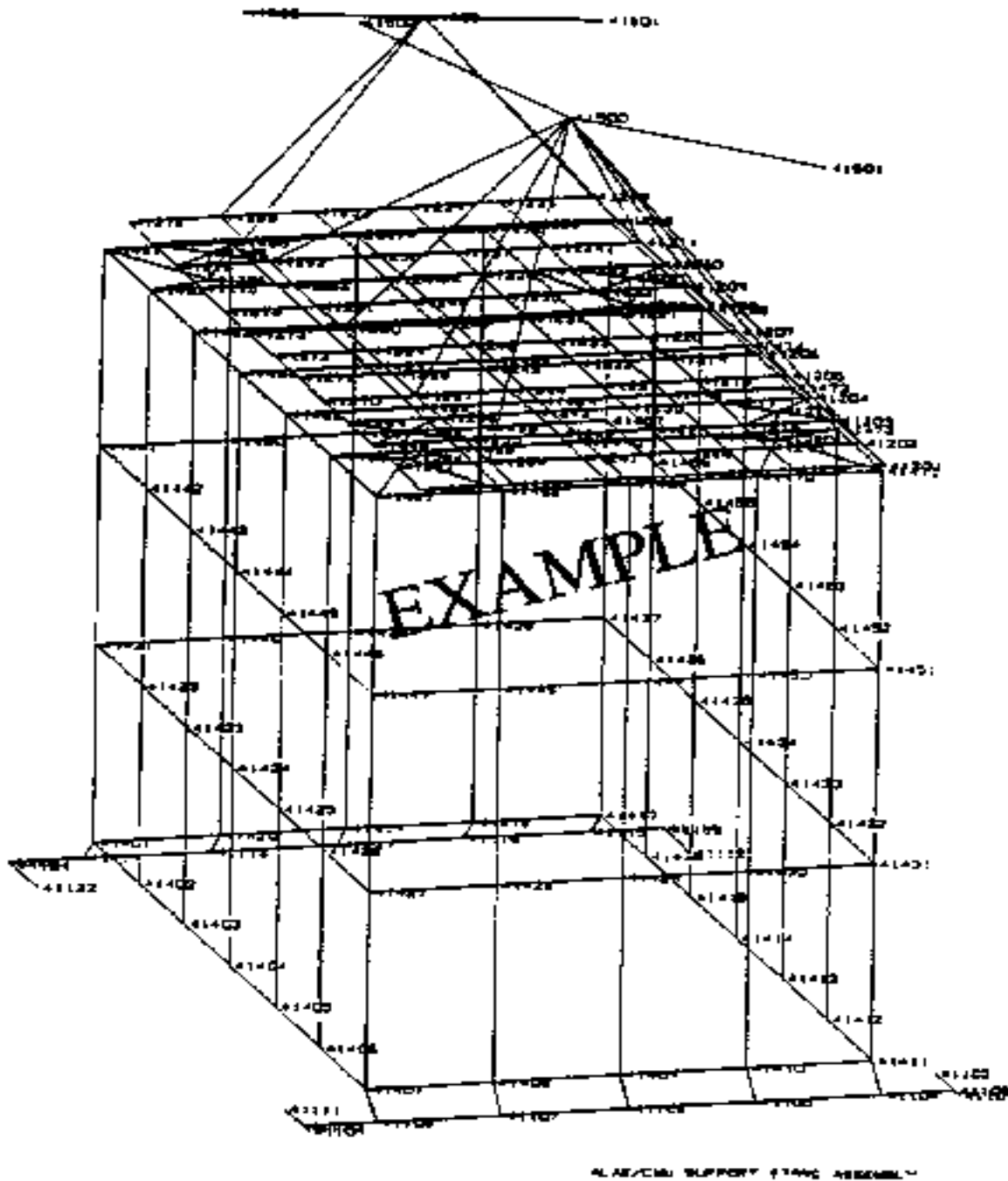
However, the interface stiffness must be accurately represented to the extent that it affects the structure to which the experiment is attached. For example, an experiment ( $>50$  Hz) cantilevered off a flat center-aisle plate would be well represented using tuned bar elements beamed up from the experiment footprint to a concentrated mass with appropriate inertias (the interface end of each bar element is typically released in all three rotations to prevent overstiffening the structure and to avoid unrealistic moment distributions at the interfaces). A rack-mounted experiment ( $>50$  Hz), however, would require accurate representation of mounting structural members whose stiffness affects overall rack behavior and load paths. Such a rack component model may still be somewhat small in size but with proper stiffness representation for the slides or other significant members.

The U.S. customary system of units is used for dynamic modeling of the integrated system and for the coupled load analyses. Distance is given in inches, mass is given in pounds-seconds-squared per inch, and force is given in pounds. Location, with accurate dimensions, of grid points at all structural interfaces is important in building the system model.

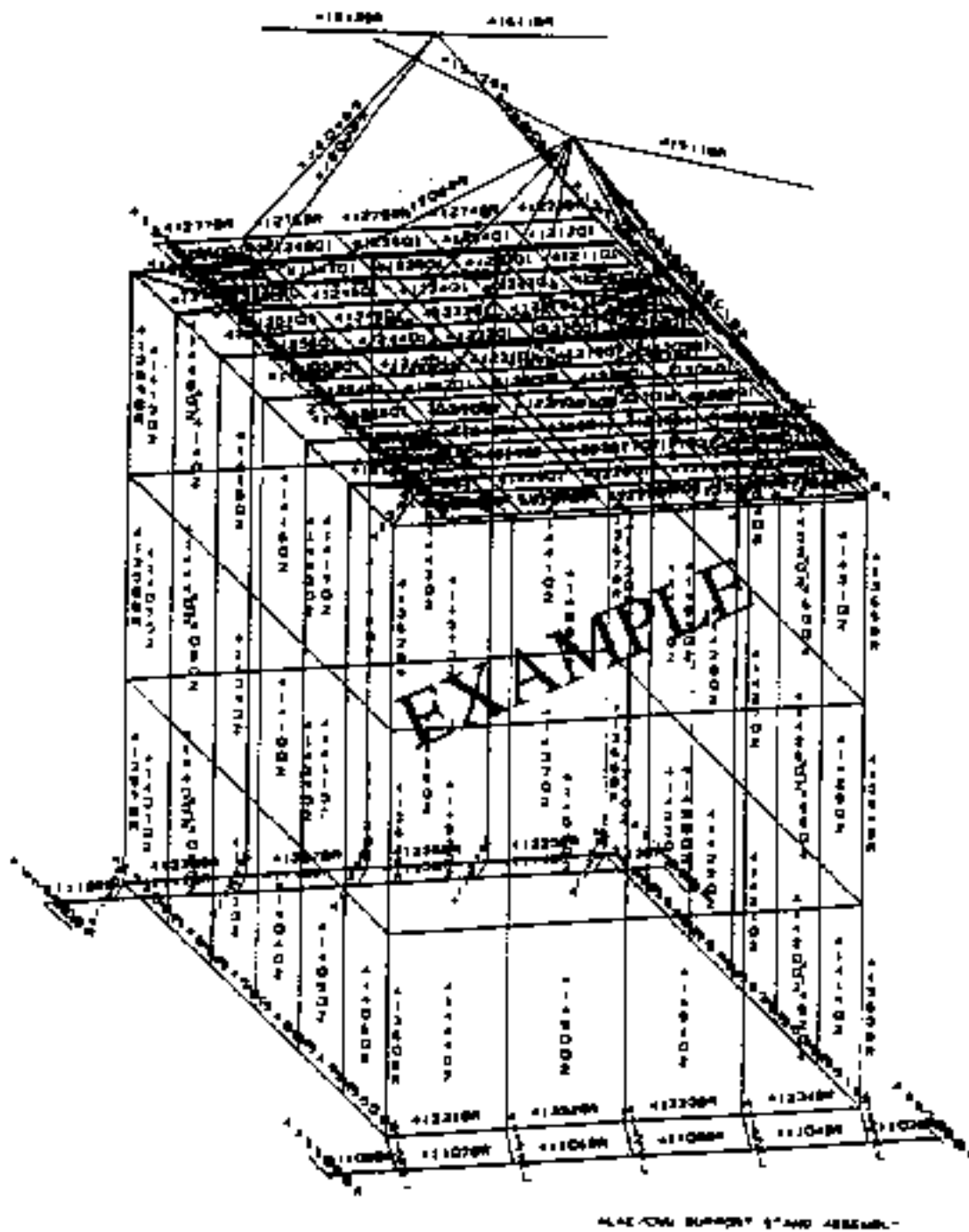
The integrated system models are developed using the NASTRAN finite element modeling code. Consequently, PD-provided component models should be provided in NASTRAN-compatible bulk data format. Explicit SPCs and SPC1s or permanent constraints on the GRID cards should be used instead of the PARAM AUTOSPC and K6ROT features. Rigid elements such as RBE1s and RBE2s are preferred over MPCs. RBE3s are not recommended due to potential rigid body modes incompatibilities. Use of any elements such as RBE3s, CELASs, or MPCs in a manner that precludes good rigid body modes will compromise the integrity of the coupled loads model and the accuracy of the results.

The model shall be documented to aid the mission integration analyst in model assessment and integration into the system model. The documentation should include drawings, NASTRAN-type bulk data listing, case control listing, and analysis results. The analysis results should include the NASTRAN-type generated mass summary table, geometric plots giving grid point numbers and element numbers, modal plots for modes of interest, and frequencies. Frequencies should be provided for the free-free configuration to show the model free of internal constraints and also for the component constrained at the attachment interface (constrained in directions that carry load). The free-free configuration frequencies should include all near-zero frequencies (rigid body mode) as well as the lowest elastic mode frequency. SUPPORT cards are not to be utilized in the free-free configuration analysis.





**FIGURE D-1 ALAE/CMU SUPPORT STAND ASSEMBLY (A TYPICAL EXPERIMENT PAYLOAD) UNDEFORMED SHAPE - GRID POINTS NUMBERED**



**FIGURE D-2 ALAE/CMU SUPPORT STAND ASSEMBLY UNDEFORMED  
SHAPE ELEMENTS NUMBERED**

1. 2. 3. 4. 5. 6. 7. 8. 9. 10. 11. 12. 13. 14. 15. 16. 17. 18. 19. 20. 21. 22. 23. 24. 25. 26. 27. 28. 29. 30. 31. 32. 33. 34. 35. 36. 37. 38. 39. 40. 41. 42. 43. 44. 45. 46. 47. 48. 49. 50. 51. 52. 53. 54. 55. 56. 57. 58. 59. 60. 61. 62. 63. 64. 65. 66. 67. 68. 69. 70. 71. 72. 73. 74. 75. 76. 77. 78. 79. 80. 81. 82. 83. 84. 85. 86. 87. 88. 89. 90. 91. 92. 93. 94. 95. 96. 97. 98. 99. 100. 101. 102. 103. 104. 105. 106. 107. 108. 109. 110. 111. 112. 113. 114. 115. 116. 117. 118. 119. 120. 121. 122. 123. 124. 125. 126. 127. 128. 129. 130. 131. 132. 133. 134. 135. 136. 137. 138. 139. 140. 141. 142. 143. 144. 145. 146. 147. 148. 149. 150. 151. 152. 153. 154. 155. 156. 157. 158. 159. 160. 161. 162. 163. 164. 165. 166. 167. 168. 169. 170. 171. 172. 173. 174. 175. 176. 177. 178. 179. 180. 181. 182. 183. 184. 185. 186. 187. 188. 189. 190. 191. 192. 193. 194. 195. 196. 197. 198. 199. 200. 201. 202. 203. 204. 205. 206. 207. 208. 209. 210. 211. 212. 213. 214. 215. 216. 217. 218. 219. 220. 221. 222. 223. 224. 225. 226. 227. 228. 229. 230. 231. 232. 233. 234. 235. 236. 237. 238. 239. 240. 241. 242. 243. 244. 245. 246. 247. 248. 249. 250. 251. 252. 253. 254. 255. 256. 257. 258. 259. 260. 261. 262. 263. 264. 265. 266. 267. 268. 269. 270. 271. 272. 273. 274. 275. 276. 277. 278. 279. 280. 281. 282. 283. 284. 285. 286. 287. 288. 289. 290. 291. 292. 293. 294. 295. 296. 297. 298. 299. 300. 301. 302. 303. 304. 305. 306. 307. 308. 309. 310. 311. 312. 313. 314. 315. 316. 317. 318. 319. 320. 321. 322. 323. 324. 325. 326. 327. 328. 329. 330. 331. 332. 333. 334. 335. 336. 337. 338. 339. 340. 341. 342. 343. 344. 345. 346. 347. 348. 349. 350. 351. 352. 353. 354. 355. 356. 357. 358. 359. 360. 361. 362. 363. 364. 365. 366. 367. 368. 369. 370. 371. 372. 373. 374. 375. 376. 377. 378. 379. 380. 381. 382. 383. 384. 385. 386. 387. 388. 389. 390. 391. 392. 393. 394. 395. 396. 397. 398. 399. 400. 401. 402. 403. 404. 405. 406. 407. 408. 409. 410. 411. 412. 413. 414. 415. 416. 417. 418. 419. 420. 421. 422. 423. 424. 425. 426. 427. 428. 429. 430. 431. 432. 433. 434. 435. 436. 437. 438. 439. 440. 441. 442. 443. 444. 445. 446. 447. 448. 449. 450. 451. 452. 453. 454. 455. 456. 457. 458. 459. 460. 461. 462. 463. 464. 465. 466. 467. 468. 469. 470. 471. 472. 473. 474. 475. 476. 477. 478. 479. 480. 481. 482. 483. 484. 485. 486. 487. 488. 489. 490. 491. 492. 493. 494. 495. 496. 497. 498. 499. 500. 501. 502. 503. 504. 505. 506. 507. 508. 509. 510. 511. 512. 513. 514. 515. 516. 517. 518. 519. 520. 521. 522. 523. 524. 525. 526. 527. 528. 529. 530. 531. 532. 533. 534. 535. 536. 537. 538. 539. 540. 541. 542. 543. 544. 545. 546. 547. 548. 549. 550. 551. 552. 553. 554. 555. 556. 557. 558. 559. 560. 561. 562. 563. 564. 565. 566. 567. 568. 569. 570. 571. 572. 573. 574. 575. 576. 577. 578. 579. 580. 581. 582. 583. 584. 585. 586. 587. 588. 589. 590. 591. 592. 593. 594. 595. 596. 597. 598. 599. 600. 601. 602. 603. 604. 605. 606. 607. 608. 609. 610. 611. 612. 613. 614. 615. 616. 617. 618. 619. 620. 621. 622. 623. 624. 625. 626. 627. 628. 629. 630. 631. 632. 633. 634. 635. 636. 637. 638. 639. 640. 641. 642. 643. 644. 645. 646. 647. 648. 649. 650. 651. 652. 653. 654. 655. 656. 657. 658. 659. 660. 661. 662. 663. 664. 665. 666. 667. 668. 669. 670. 671. 672. 673. 674. 675. 676. 677. 678. 679. 680. 681. 682. 683. 684. 685. 686. 687. 688. 689. 690. 691. 692. 693. 694. 695. 696. 697. 698. 699. 700. 701. 702. 703. 704. 705. 706. 707. 708. 709. 710. 711. 712. 713. 714. 715. 716. 717. 718. 719. 720. 721. 722. 723. 724. 725. 726. 727. 728. 729. 730. 731. 732. 733. 734. 735. 736. 737. 738. 739. 740. 741. 742. 743. 744. 745. 746. 747. 748. 749. 750. 751. 752. 753. 754. 755. 756. 757. 758. 759. 760. 761. 762. 763. 764. 765. 766. 767. 768. 769. 770. 771. 772. 773. 774. 775. 776. 777. 778. 779. 780. 781. 782. 783. 784. 785. 786. 787. 788. 789. 790. 791. 792. 793. 794. 795. 796. 797. 798. 799. 800. 801. 802. 803. 804. 805. 806. 807. 808. 809. 810. 811. 812. 813. 814. 815. 816. 817. 818. 819. 820. 821. 822. 823. 824. 825. 826. 827. 828. 829. 830. 831. 832. 833. 834. 835. 836. 837. 838. 839. 840.

由(1)(2) 7 (4) = 1, 故  $\mu_C(A) = \mu_C(B)$  故  $\mu_C(A) = \mu_C(B) = \mu_C(A \cup B)$

D - 5

TABLE D-1 ALAE/CMU SUPPORT STAND ASSEMBLY WEIGHT SUMMARY

```

OUTPUT FROM GRID POINT WEIGHT GENERATOR

REFERENCE POINT: 0

MU GRID BODY MASS MATRIX (IN GALS) COORDINATE SYSTEM
***
+ 1 497074710+02 0.00000000+00 0.00000000+00 0.00000000+00 1.638957080+03 -8.820667110+03 +
+ 0 00000000+00 1.497074710+02 0.00000000+00 -1.838957080+03 0.00000000+00 8.820667110+03 +
+ 0 00000000+00 0.00000000+00 1.497074710+02 8.520447110+03 -8.820667110+03 0.00000000+00 +
+ 0 00000000+00 -1.838957080+03 8.520447110+03 5.358983370+05 -5.596148190+05 -1.198885180+05 +
+ 1 638957080+03 0.00000000+00 -1.838957080+03 -5.596148190+05 7.012735090+05 -1.053335800+05 +
+ 8 520447110+03 8.520447110+03 0.00000000+00 -1.198885180+05 -1.053335800+05 1.153304590+04 +
***

S - TRANSFORMATION MATRIX FOR SCALAR MASS PARTITION
***
+ 1 00000000+00 0.00000000+00 0.00000000+00 +
+ 0.00000000+00 1.00000000+00 0.00000000+00 +
+ 0.00000000+00 0.00000000+00 1.00000000+00 +
+ 1 -4 ***

DIRECTION
MASS AXIS SYSTEM (S) MASS K-C.G. Y-C.G. Z-C.G.
X 1.497074710+02 0.00000000+00 5.6215443380+01 1.2290348840+01
Y 1.497074710+02 6.9681225140+01 0.00000000+00 1.2290348840+01
Z 1.497074710+02 6.5681225140+01 5.6215443380+01 0.00000000+00

I(S) - INERTIAS RELATIVE TO C.G.
***
+ 1.842567710+04 3.3035233570+01 -8.6201079020+02 +
+ -3.3035233570+01 3.2818289050+01 6.1160888180+02 +
+ 8.6201079020+01 6.1160888180+01 3.2487517680+04 +
***

I(C) - PRINCIPAL INERTIAS
***
+ 3.2854876490+04 +
+ 1.8750154080+04 +
+ 2.2636433370+04 +
***

Q - TRANSFORMATION MATRIX = I(C) * QT * I(S) * Q
***
+ 5.826488010+03 -8.7882810470+01 1.3975190380+01 +
+ -8.7882810470+01 4.1640279410+03 5.8401003180+02 +
+ 1.3975190380+01 5.8401003180+02 -8.7804330180+01 +
+ ***
  
```

**TABLE D-2 ALAE/CMU SUPPORT STAND ASSEMBLY MODAL FREQUENCIES  
 (FREE-FREE CONFIGURATION)**

**NOTE: THIS TABLE IS AN EXAMPLE**

**REAL EIGENVALUES**

| MODE<br>NO  | EXTRACTION<br>ORDER | EIGENVALUES      | RADIAN<br>FREQUENCY | CYCLIC<br>FREQUENCY | GENERALIZED<br>MASS | GENERALIZED<br>STIFFNESS |
|---|---------------------|------------------|---------------------|---------------------|---------------------|--------------------------|
| NASTRAN INFORMATION MESSAGE 3007, POTENTIALLY<br>1 EIGENVALUE(S) AT LOW FREQ. END NOT FOUND<br>(THIS MESSAGE CAN BE SUPPRESSED BY DIAG. 37) |                     |                  |                     |                     |                     |                          |
| 1   | 3                   | 5 . 780713E - 06 | 2 . 404311E - 03    | 3 . 826579E - 04    | 2 . 115337E - 01    | 1 . 222816E - 06         |
| 2   | 6                   | 9 . 585665E - 06 | 3 . 096072E - 03    | 4 . 927551E - 04    | 1 . 175708E - 01    | 1 . 126994E - 06         |
| 3   | 5                   | 9 . 914484E - 06 | 3 . 148727E - 03    | 5 . 927551E - 04    | 1 . 925741E - 01    | 1 . 909273E - 06         |
| 4   | 4                   | 1 . 378413E - 05 | 3 . 712698E - 03    | 5 . 908941E - 04    | 2 . 018037E - 01    | 2 . 781689E - 05         |
| 5   | 1                   | 1 . 598298E - 04 | 1 . 264258E - 02    | 2 . 012097E - 03    | 2 . 169539E - 01    | 3 . 467569E - 05         |
| 6   | 2                   | 2 . 521104E - 04 | 1 . 347798E - 02    | 2 . 527060E - 03    | 1 . 369437E - 01    | 3 . 452493E - 05         |
| 7   | 7                   | 2 . 297844E + 05 | 4 . 793684E + 02    | 7 . 629225E + 01    | 1 . 039016E - 02    | 2 . 387496E + 03         |

**TABLE D-3 ALAE/CMU SUPPORT STAND ASSEMBLY EIGENVALUE  
 ANALYSIS SUMMARY**

**EIGENVALUE ANALYSIS SUMMARY (INVERSE POWER METHOD)**

|   |          |
|---|----------|
| NUMBER OF EIGENVALUES EXTRACTED . . . . .                               | 7        |
| NUMBER OF STARTING POINTS USED . . . . .                                | 1        |
| NUMBER OF STARTING POINT MOVES . . . . .                                | 0        |
| NUMBER OF TRIANGULAR DECOMPOSITIONS . . . . .                           | 3        |
| TOTAL NUMBER OF VECTOR ITERATIONS . . . . .                             | 47       |
| REASON FOR TERMINATION . . . . .  | 7*       |
| LARGEST OFF-DIAGONAL MODAL MASS TERM . . . . .                          | 0.61E-05 |
| MODE PAIR . . . . .   | 3        |
| MODE PAIR . . . . .   | 2        |
| NUMBER OF OFF-DIAGONAL MODAL MASS<br>TERMS FAILING CRITERION . . . . .  | 0        |
| (* 1 OR MORE ROOT OUTSIDE FR. RANGE.<br>SEE NASTRAN U.M. SECTION 2.3.3) |          |

**TABLE D-4 ALAE/CMU SUPPORT STAND ASSEMBLY MODAL FREQUENCIES  
 (CONSTRAINED CONFIGURATION)**

| REAL EIGENVALUES  |                     |              |                     |                    |                     |                          |
|---|---------------------|--------------|---------------------|--------------------|---------------------|--------------------------|
| MODE<br>NO  | EXTRACTION<br>ORDER | EIGENVALUE   | RADIAN<br>FREQUENCY | CYCLE<br>FREQUENCY | GENERALIZED<br>MASS | GENERALIZED<br>STIFFNESS |
| *****<br>*<br>* NASTRAN INFORMATION MESSAGE 3304, LOWEST EIGENVALUE FOUND<br>* AS INDICATED BY THE STURM'S SEQUENCE OF THE DYNAMIC MATRIX<br>*<br>* (THIS MESSAGE CAN BE SUPPRESSED BY DIAG 27)<br>*<br>***** |                     |              |                     |                    |                     |                          |
| 1   | 2                   | 2.598277E+05 | 4.794028E+02        | 7.628944E+01       | 9.089312E-03        | 2.088924E+07             |
| 2   | 1                   | 2.502948E+05 | 4.718801E+02        | 7.637688E+01       | 9.078745E-03        | 2.090055E+07             |
| 3   | 3                   | 3.765080E+05 | 6.136003E+02        | 9.765788E+01       | 2.379190E-02        | 8.857711E+06             |
| 4   | 6                   | 4.957461E+05 | 7.010913E+02        | 1.120988E+02       | 8.316868E-03        | 4.123105E+06             |
| 5   | 9                   | 5.028585E+05 | 7.04814E+02         | 1.126384E+02       | 8.182228E-03        | 4.112871E+07             |
| 6   | 4                   | 5.722188E+05 | 7.19514E+02         | 1.203830E+02       | 8.377147E-02        | 4.793658E+07             |
| 7   | 7                   | 6.085735E+05 | 8.489207E+02        | 1.431133E+02       | 3.650812E-02        | 2.952058E+07             |
| 8   | 8                   | 6.213887E+05 | 8.063078E+02        | 1.442427E+02       | 5.028511E-02        | 4.131168E+07             |
| 9   | 5                   | 8.483442E+05 | 9.218990E+02        | 1.468772E+02       | 7.720001E-02        | 6.557637E+07             |
| 10  | 10                  | 1.051273E+06 | 1.025017E+03        | 1.631847E+02       | 3.473819E-02        | 3.651620E+07             |

### D.3 DYNAMIC TESTING FOR MODEL VERIFICATION

The purpose of the testing under consideration is for verification of the analytical model to be used in the verification coupled loads analysis. As discussed in Section 7 of this document, a sinusoidal sweep test is adequate in some instances, while a modal survey test is required in others. Each of the tests will be discussed.

#### D.3.1 SINUSOIDAL SWEEP TESTING

It is important that all PD-provided hardware be included in the test. When test fixtures are required for attaching the test article to the shaker table, care should be taken to ensure that the test fixture is rigid enough that modal coupling is not experienced in the frequency range of interest (0 to 50 Hz).

The test article should be flight hardware, or a hi-fidelity prototype, to the extent possible. Simulation of components should be limited to components that have frequencies above 50 Hz or are to be tested separately. Mass simulators should not overly stiffen the hardware to be verified.

The test article should be instrumented sufficiently to ensure that all component frequencies below 50 Hz are identified.

Sinusoidal sweep test for model verification is to be limited to components with only one structural frequency per axis below 50 Hz. Therefore, in the event that multiple frequencies from the sinusoidal sweep test results are identified below 50 Hz, a modal survey is required for model verification.

Results of the test are to be documented and provided as evidence of model verification.

### **D.3.2 MODAL TESTING**

Modal testing, by definition, results in the identification of natural frequency, modal displacement, and structural damping. Modal test results are to be used in correlation of both mode shapes and frequency of the analytical model for the component.

#### **D.3.2.1 TEST CONFIGURATION**

There are two well-accepted boundary conditions for performance of the modal survey, namely:

- A. Test article constrained to a seismic mass at all structural interface locations in the load-carrying directions.
- B. Attachment of test article to an appropriate test fixture and suspending the test fixture in a near free-free manner by use of bungee cords or air bags.

The method used by the PD should depend upon the component to be tested and the facilities available.

If the component to be tested is to be attached to a seismic mass, care should be taken to ensure that there is no significant motion of the seismic base. This should be shown by instrumenting both sides of the interface.

If a suspended test fixture is used, the fixture must first be modeled and verified by test. Then the test article is modeled and integrated into a single model with the fixture. This model is then test verified by only making model changes, if necessary, to the test article. The test article model is then extracted and is considered test verified. Note that the test frequency range may require adjustment to ensure that all hard-mounted modes of the component below 50 Hz are measured.



### **D.3.2.2 TEST ARTICLE**

The test article should be protoflight (flight) or prototype hardware to the maximum extent practical. Mass simulators must be used for any component omitted from the test. The simulators must be representative of the omitted component in mass and be designed not to overly stiffen the test article. Any component simulated becomes subject to separate model requirement and verification.

### **D.3.2.3 INSTRUMENTATION**

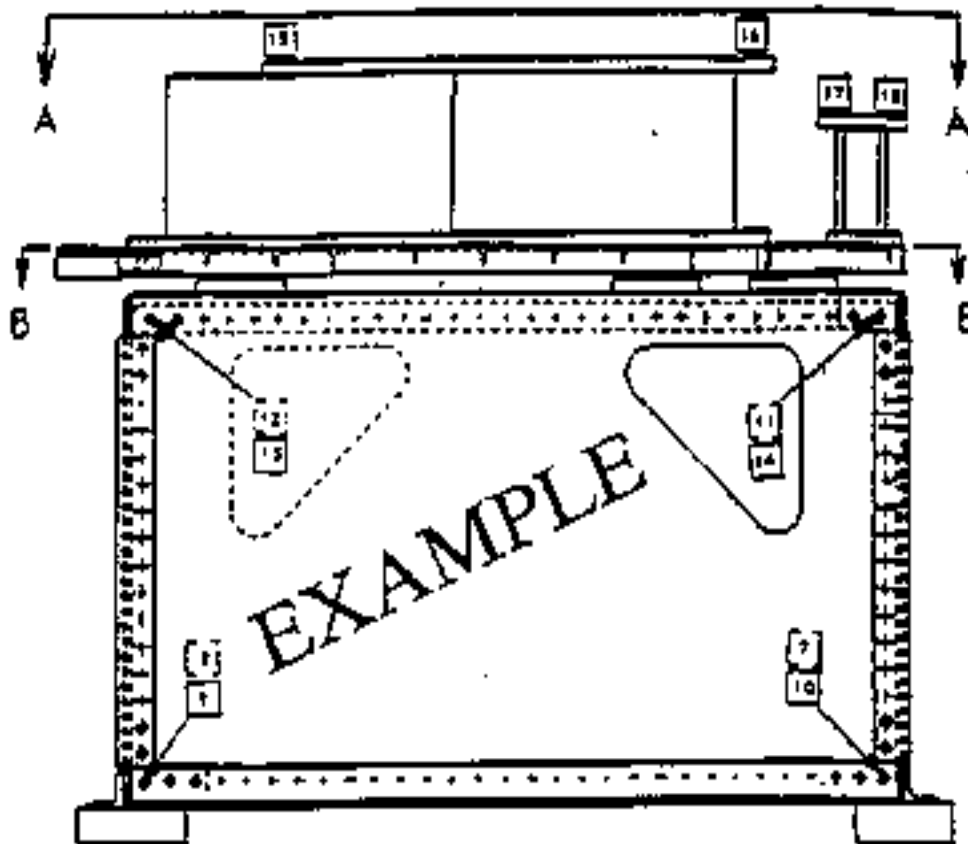
Instrumentation must be adequate to verify the analytical model for all structural modes in the range of interest. The object of the test is to provide data for realistic changes (if necessary) to the analytical model that result in correlated frequencies and mode shapes. Sparse instrumentation of the test article can only lead to difficulty when model correlation is attempted. The correlation is typically performed after the test configuration is disassembled, and obtaining more data becomes expensive in time, cost, and schedule.

### **D.3.2.4 STRUCTURAL LINEARITY CHECKS**

Checks for linearity of the structure should be performed by recording response at one or more locations on the test article to at least three input force levels. If nonlinear responses are identified, sufficient testing and/or assessments must be performed to determine the dynamic characteristics of the component under flight-type load environments. The correlated model must be representative of the component's characteristics under flight-type load environments.

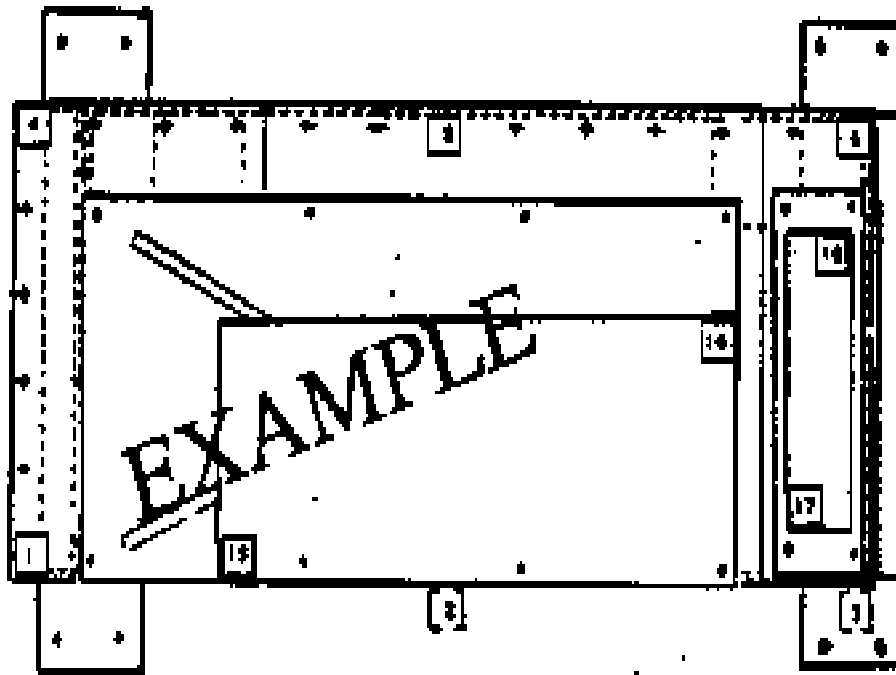
### **D.3.3 TEST PLAN**

A test plan is required at the experiment prior to testing. The following tables and figures are typical examples of what is expected in a test plan.



Accelerometers (7), (8), (11), and (12) are on the opposite side of the support stand.

FIGURE D-4 ACCELEROMETER LOCATIONS FOR ALAE/CMU SUPPORT  
STAND ASSEMBLY TEST (SHEET 1 OF 3)

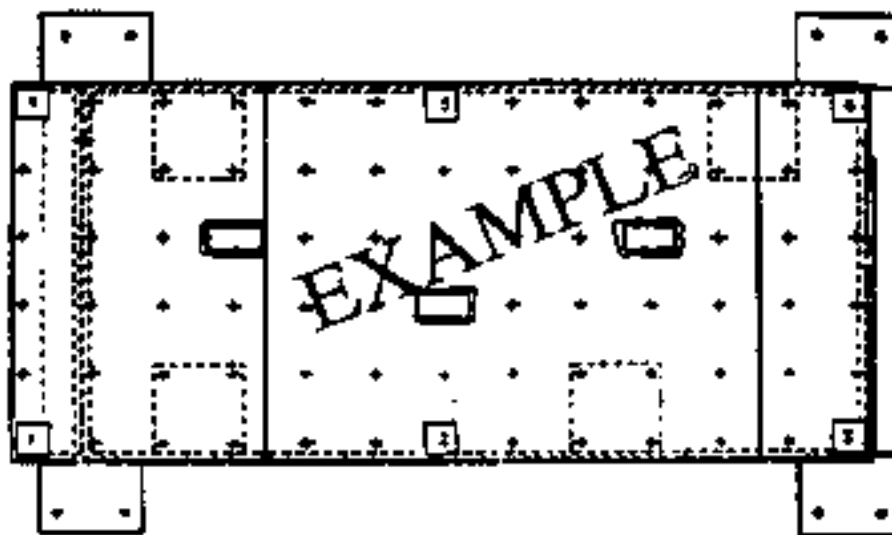


### SECTION A-A

Accelerometers (15) and (16) are located on on the top of the ALAE mass simulator.

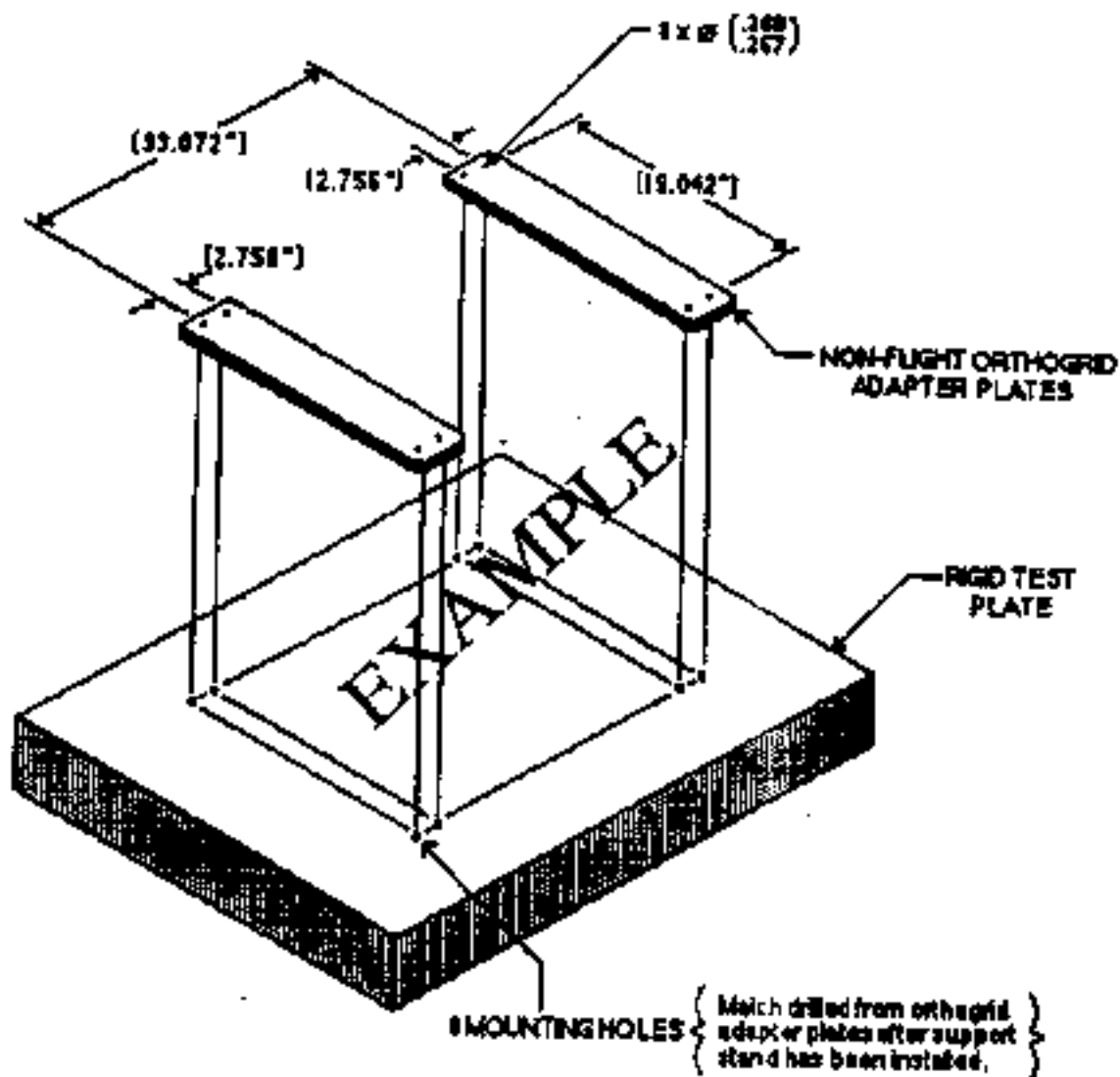
Accelerometers (17) and (18) are located on the top of the CMU mass simulator.

FIGURE D-4 ACCELEROMETER LOCATIONS FOR ALAE/CMU SUPPORT  
STAND ASSEMBLY TEST (SHEET 2 OF 3)

**SECTION B-B**

Accelerometers (1) thru (6) are located on the CPSS.

**FIGURE D-4 ACCELEROMETER LOCATIONS FOR ALAE/CMU SUPPORT  
STAND ASSEMBLY TEST (SHEET 3 OF 3)**



\* ALAE/CMU Support Stand not Shown for Clarity.

FIGURE D-5 ALAE/CMU SUPPORT STAND ASSEMBLY RIGID TEST PLATE  
 MOUNTING HOLE PATTERN

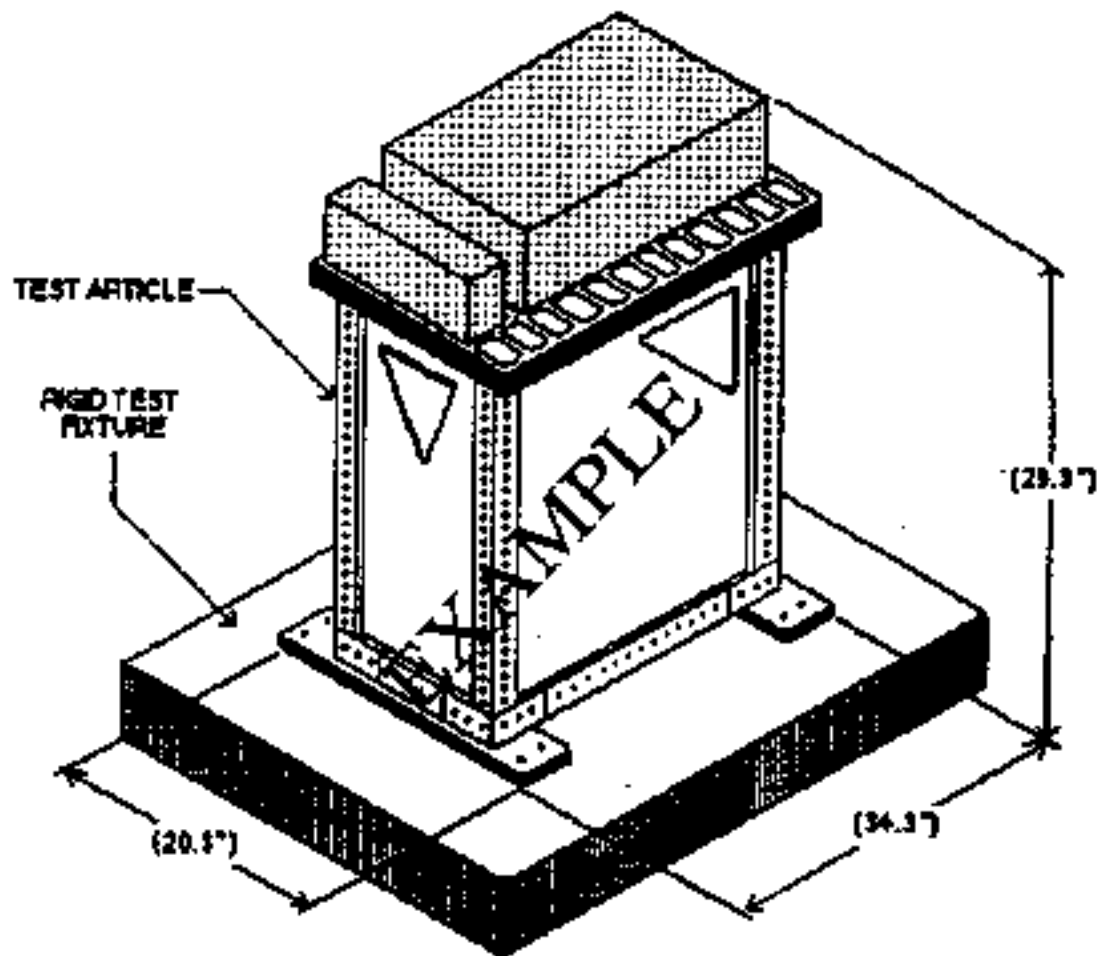


FIGURE D-6 ALAE/CMU SUPPORT STAND ASSEMBLY TEST SETUP

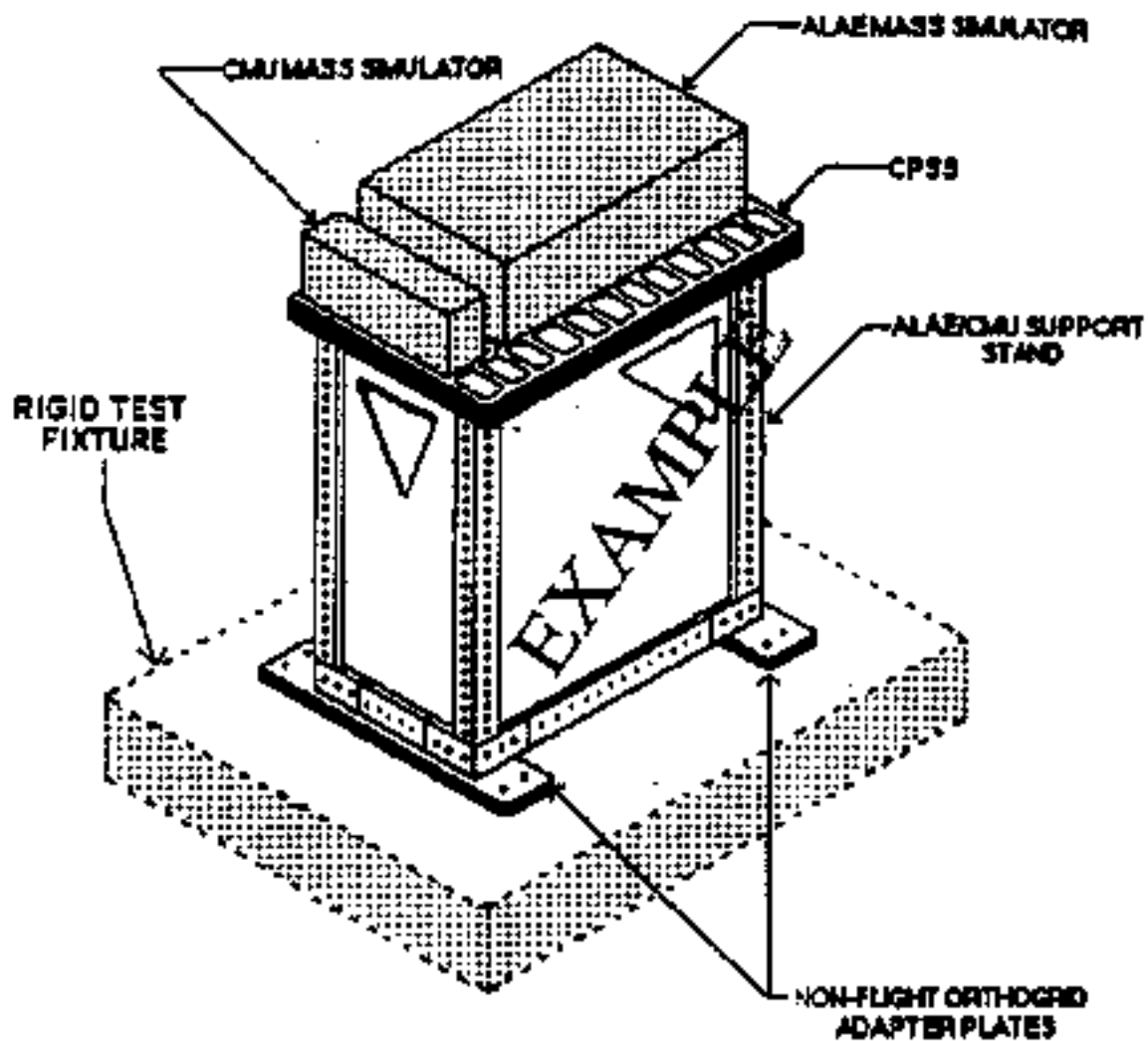


FIGURE D-7 ALAE/CMU SUPPORT STAND ASSEMBLY TEST ARTICLE

**TABLE D-5 ACCELEROMETER POSITION/NASTRAN MODEL GRID  
POINT CORRELATION**

| ACCEL.<br>NO. | GRID POINT<br>NO. | LOCATION                    |
|---------------|-------------------|-----------------------------|
| 1             | 41201             | Coldplate Support Structure |
| 2             | 41207             | Coldplate Support Structure |
| 3             | 41213             | Coldplate Support Structure |
| 4             | 41219             | Coldplate Support Structure |
| 5             | 41272             | Coldplate Support Structure |
| 6             | 41278             | Coldplate Support Structure |
| 7             | 41401             | Base of Support Stand       |
| 8             | 41407             | Base of Support Stand       |
| 9             | 41413             | Base of Support Stand       |
| 10            | 41419             | Base of Support Stand       |
| 11            | 41481             | Top of Support Stand        |
| 12            | 41487             | Top of Support Stand        |
| 13            | 41471             | Top of Support Stand        |
| 14            | 41477             | Top of Support Stand        |
| 15            | 41501             | Top of ALAN Mass Simulator  |
| 16            | 41502             | Top of ALAN Mass Simulator  |
| 17            | 41601             | Top of CMU Mass Simulator   |
| 18            | 41602             | Top of CMU Mass Simulator   |



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| 1.2        | Test Requirements.....                        | 1-1         |
| 1.3        | Objective.....                                | 1-4         |
| 1.4        | Responsibility.....                           | 1-4         |
|            | 1.4.1 MSFC Responsibility.....                | 1-4         |
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| <b>2.0</b> | <b>APPLICABLE DOCUMENTS</b> .....             | <b>2-1</b>  |
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| 2.2        | Drawings.....                                 | 2-1         |
| <b>3.0</b> | <b>TEST PROJECT DESCRIPTION</b> .....         | <b>3-1</b>  |
| 3.1        | Test Setup.....                               | 3-1         |
| 3.2        | Structural Test Article.....                  | 3-1         |
| 3.3        | Ground Handling/Ground Support Equipment..... | 3-1         |
| 3.4        | Instrumentation.....                          | 3-7         |
| <b>4.0</b> | <b>TEST FACILITY DESCRIPTION</b> .....        | <b>4-1</b>  |
| 4.1        | Method of Excitation.....                     | 4-1         |
| 4.2        | Data Acquisition System.....                  | 4-1         |
| 4.3        | Data Processing.....                          | 4-2         |

TABLE D-6 EXAMPLE TEST PLAN TABLE OF CONTENTS (SHEET 2 OF 2)

|   | <u>Page</u> |
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| 5.2 Test Operations.....                | 5-1         |
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## APPENDIX E LIFE CYCLE LOADS (FRACTURE)

### E.1 LIFE CYCLE LOADS FOR FRACTURE AND FATIGUE ANALYSIS

This section presents some guidelines to determine a loading spectrum for a part. The following three subsections cover: (1) a conservative, simplified launch and landing loading spectrum, based on an equivalent number of peak load cycles for each loading event, (2) methods for eliminating loading events that do not affect fatigue life, and (3) a detailed compilation of the loads and load combinations imposed upon the payload flight equipment during its life cycle.

#### E.1.1 SIMPLIFIED LOADING SPECTRUM FOR LAUNCH AND LANDING

A loading spectrum will be defined for each part that has fatigue damage equivalent to the loading spectrum expected during the life of the part. The following paragraph describes the conservative generic approach that will be used to define the loading spectrum for flight loads.

Note: The loading spectrum in NASA/FLAGRO may be substituted for the one described below.

For loads induced by the STS environment, the number of cycles to be applied to a particular component for one flight is determined using the criteria given in ED22-85-78, Criteria for Fatigue and Fracture Mechanics Assessments of Experiments/Components for Shuttle Payloads, September 18, 1985. The criteria are applied sequentially as follows:

- A. Apply  $R + LF_{LO}$  for 7.5 sec at  $F_n$  or 35 Hz, whichever is smaller.
- B. Apply  $R$  for 7.5 sec at  $F_n - 35$  Hz, if  $F_n > 35$  Hz.
- C. Apply  $LF_{LO}$  for 1.5 sec at  $F_n$  or 35 Hz, whichever is smaller.
- D. Apply  $LF_L$  for 10 sec at  $F_n$  or 35 Hz, whichever is smaller.

Where:

$R$  = Random load

$LF_{LO}$  = Low frequency load at lift-off

$LF_L$  = Low frequency load at landing

$F_n$  = Natural frequency of structure being analyzed.

Peak magnitudes are used for the various loads throughout the specified time intervals. Load cycles due to handling, transportation, and test are added as required.

For pressure vessels, loads induced by the STS environment are combined with pressure/thermal cycles to determine the life loading spectrum.

## **E.2 LOADING EVENT SELECTION**

The load spectrum given in paragraph E.3 is conservative enough to cover loads due to handling, transportation, and most tests. Special problems, such as a long truck ride with inadequate isolation, must be handled on a case-by-case basis. In any case, loads that are insufficient to cause crack growth at the minimum initial crack size determined by NDE can safely be assumed to be covered.

Let  $DK_i$  be the stress intensity range due to peak loads for the minimum initial flaw size, and let  $DK_{th}$  be threshold stress intensity range for crack growth. Define:  $r=DK_{th}/DK_i$ . Then if the applied load for a particular loading event, divided by the peak load, is less than  $r$ , that loading event can be ignored. Note that  $DK_i=(1-R)K_i$ , where  $K_i$  is the corresponding stress intensity and  $R$  is the ratio of minimum load to maximum load. Note also that,  $DK_{th}=DK_o(\frac{4}{p} \tan^{-1}(1-R))$ , where  $DK_o$  is obtained from the NASA/FLAGRO materials table. For fatigue life calculations,  $r$  is the endurance limit divided by the ultimate tensile strength.

## **E.3 DETAILED LOADING SPECTRUM**

The life cycles are separated into four phases which are shown in Figure E-1. Phase I occurs one time, and Phases II, III, and IV occur sequentially for each flight in the life cycle. Each phase shown in Figure E-1 is composed of a sequence of events or optional sequences of events, and each event imposes loads or combinations of loads on the payload flight equipment. Figures E-2 through E-5 list the sequence or optional sequences of events (shown in the boxes) that occur during each phase. Phases I, II, and IV events induce ground loads, and Phase III events induce flight loads.

The types of ground loads (handling, transportation, and testing) are listed for each event in Phases I, II, and IV. The types of Orbiter environmental loadings for the lift-off/ascent, on-orbit, and descent/landing events are listed for Phase III.

### **E.3.1 GROUND LOADS**

Ground loads for Phases I, II, and IV events are classified as transportation, hoisting, mating, and test loads and are described in the following paragraphs.

### E.3.1.1 TRANSPORTATION

The payload transportation modes are either aircraft, truck, forklift, or dolly. Example gravitational load factors are listed below (consult the respective IDD for current factors).

For this section,  $+X_o$  and  $-X_o$  are defined as the fore and aft directions respectively,  $+Z_o$  and  $-Z_o$  are defined as the up and down directions respectively, and  $Y_o$  is defined as the lateral direction in accordance with the right-hand rule.

#### A. Aircraft

| $X_o$     | $Y_o$     | $Z_o$        |
|-----------|-----------|--------------|
| $\pm 0.9$ | $\pm 0.8$ | $-1 \pm 0.7$ |

#### B. Truck (55 MPH/20 MPH)

| $X_o$     | $Y_o$     | $Z_o$     |
|-----------|-----------|-----------|
| $\pm 0.7$ | $\pm 1.7$ | $\pm 3.2$ |

#### C. Forklift

| $X_o$     | $Y_o$      | $Z_o$        |
|-----------|------------|--------------|
| $\pm 1.0$ | $\pm 0.75$ | $-1 \pm 0.5$ |

#### D. Dolly Towing (5 MPH)

| $X_o$      | $Y_o$     | $Z_o$        |
|------------|-----------|--------------|
| $\pm 0.75$ | $\pm 1.0$ | $-1 \pm 0.5$ |

The gravitational load factors for Orbiter transport and payload equipment transport are considered to be too low to consider as part of the load history.

### E.3.1.2 HOISTING

The payload hoisting modes are overhead crane and Orbiter mating. VPHD, payload canister, and PCR mating loads are the same as Orbiter mating loads. The overhead crane can be a vertical lift ( $Z_o$  vertical) or a horizontal lift ( $X_o$  vertical). The gravitational load factors and payload configuration are listed below.

#### A. Vertical Hoisting

+Z<sub>o</sub> and -Z<sub>o</sub> are defined as the up and down directions respectively, X<sub>o</sub> and Y<sub>o</sub> are defined as two horizontal directions, one parallel to the direction of travel and the second perpendicular to the direction of travel in accordance with the right-hand rule.

| X <sub>o</sub> | Y <sub>o</sub> | Z <sub>o</sub> |
|----------------|----------------|----------------|
| 0              | 0              | -1 ± 0.33      |

#### B. Horizontal Hoisting

+X<sub>o</sub> and -X<sub>o</sub> are defined as the up and down directions respectively, Y<sub>o</sub> and Z<sub>o</sub> are defined as two horizontal directions, one parallel to the direction of travel and the second perpendicular to the direction of travel in accordance with the right-hand rule.

| X <sub>o</sub> | Y <sub>o</sub> | Z <sub>o</sub> |
|----------------|----------------|----------------|
| -1 ± 0.33      | 0              | 0              |

#### C. Orbiter Horizontal Mating

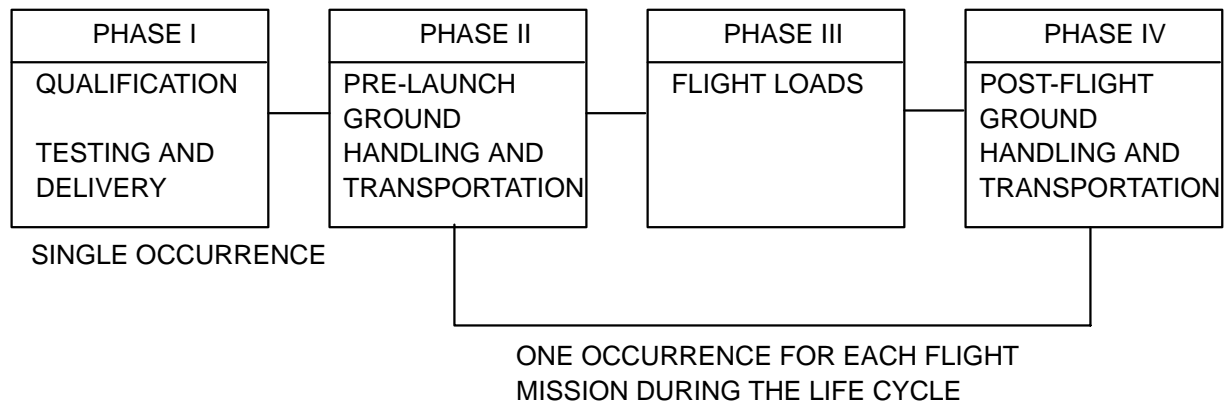
+Z<sub>o</sub> and -Z<sub>o</sub> are defined as the up and down directions respectively, X<sub>o</sub> and Y<sub>o</sub> are defined as two horizontal directions, one parallel to the direction of travel and the second perpendicular to the direction of travel in accordance with the right-hand rule.

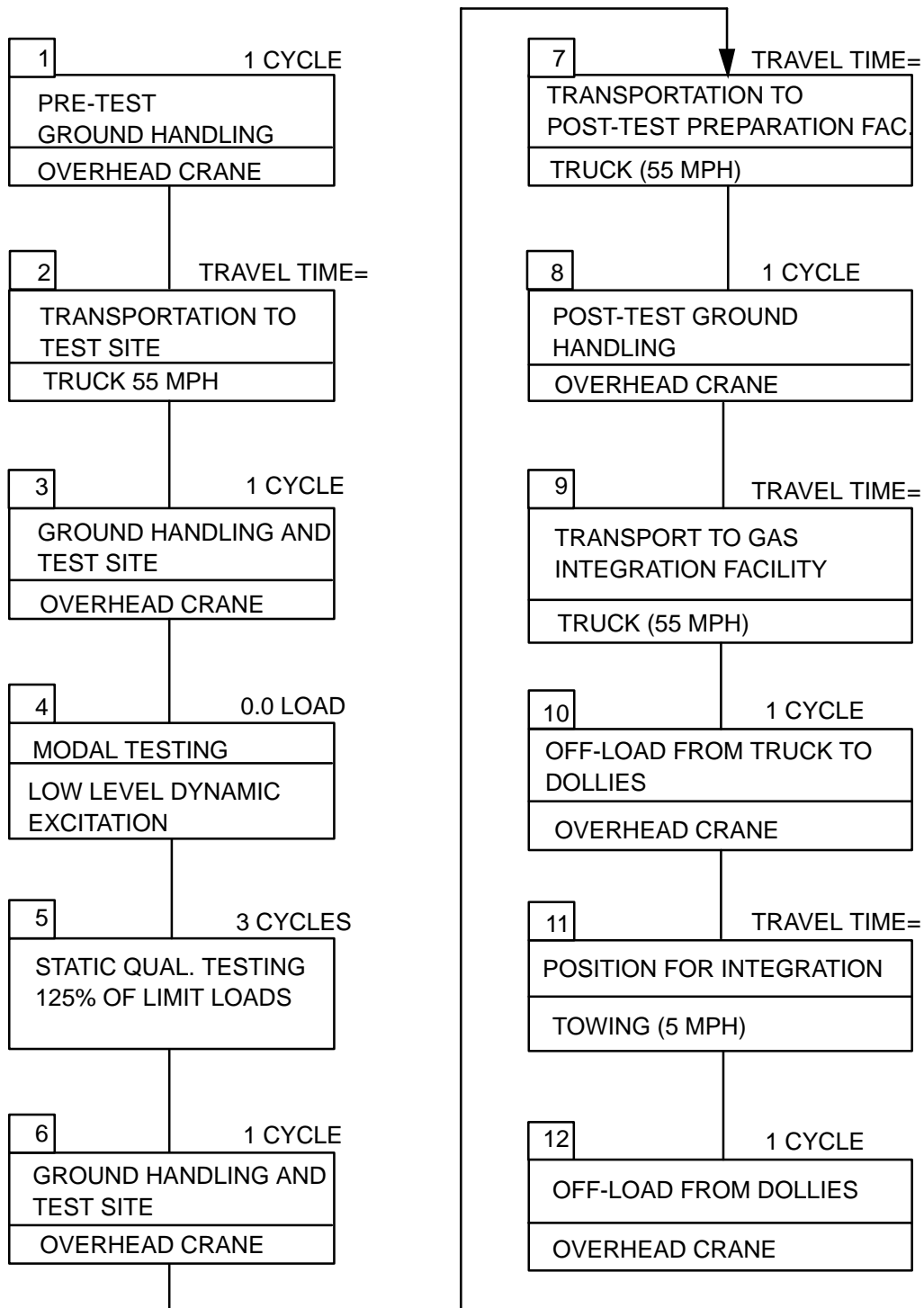
| X <sub>o</sub> | Y <sub>o</sub> | Z <sub>o</sub> |
|----------------|----------------|----------------|
| ± 0.5          | ± 0.5          | -1 ± 1.0       |

#### D. Orbiter Vertical Mating

+X<sub>o</sub> and -X<sub>o</sub> are defined as the up and down directions respectively, Y<sub>o</sub> and Z<sub>o</sub> are defined as two horizontal directions, one parallel to the direction of travel and the second perpendicular to the direction of travel in accordance with the right-hand rule.

| X <sub>o</sub> | Y <sub>o</sub> | Z <sub>o</sub> |
|----------------|----------------|----------------|
| -1 ± 1.0       | ± 0.5          | ± 0.5          |

**FIGURE E-1 PAYLOAD FLIGHT EQUIPMENT LIFE CYCLE PHASES**

**FIGURE E-2 PHASE I SEQUENCE OF EVENTS**



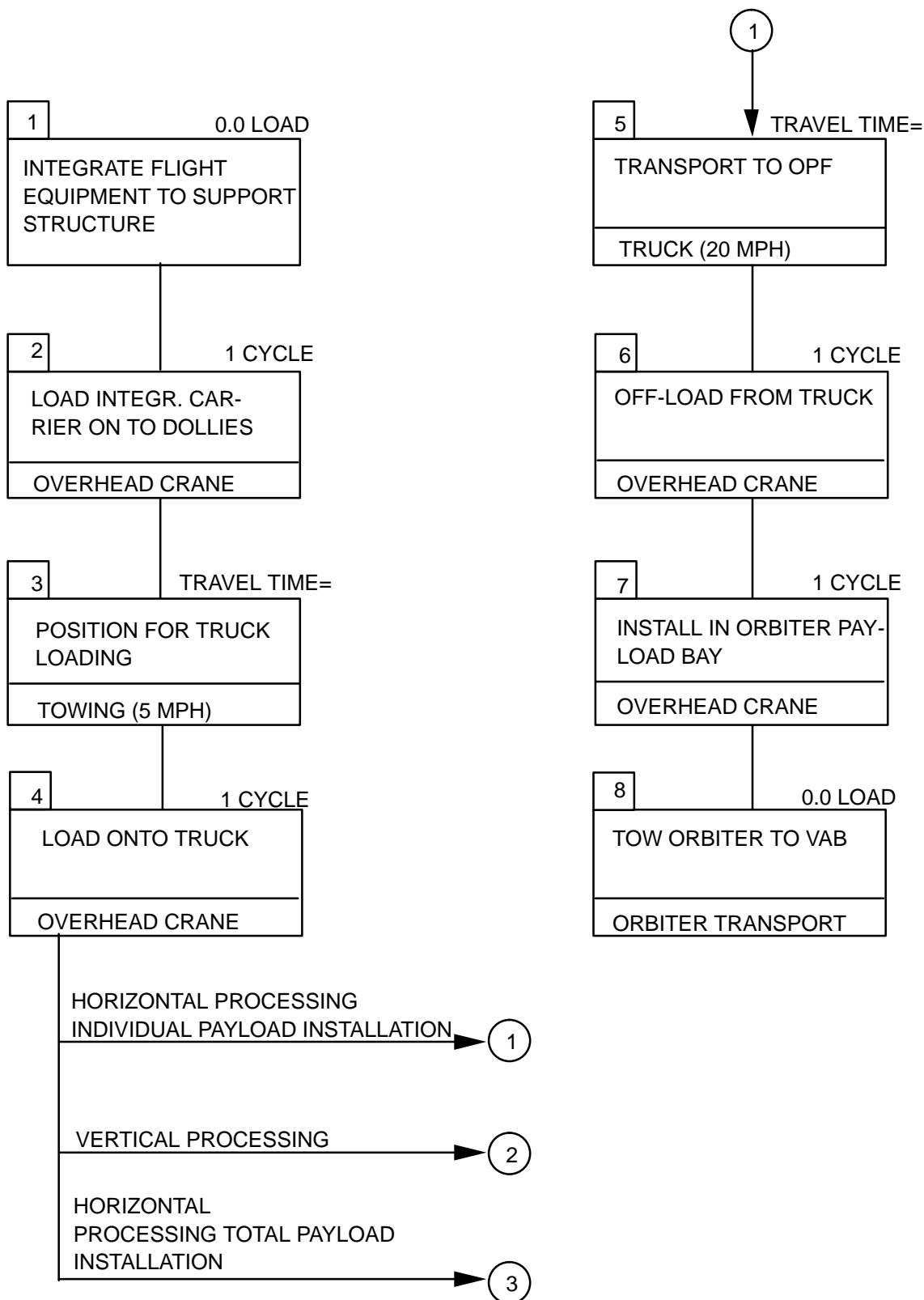


FIGURE E-3 PHASE II SEQUENCE OF EVENTS (SHEET 1 OF 4)

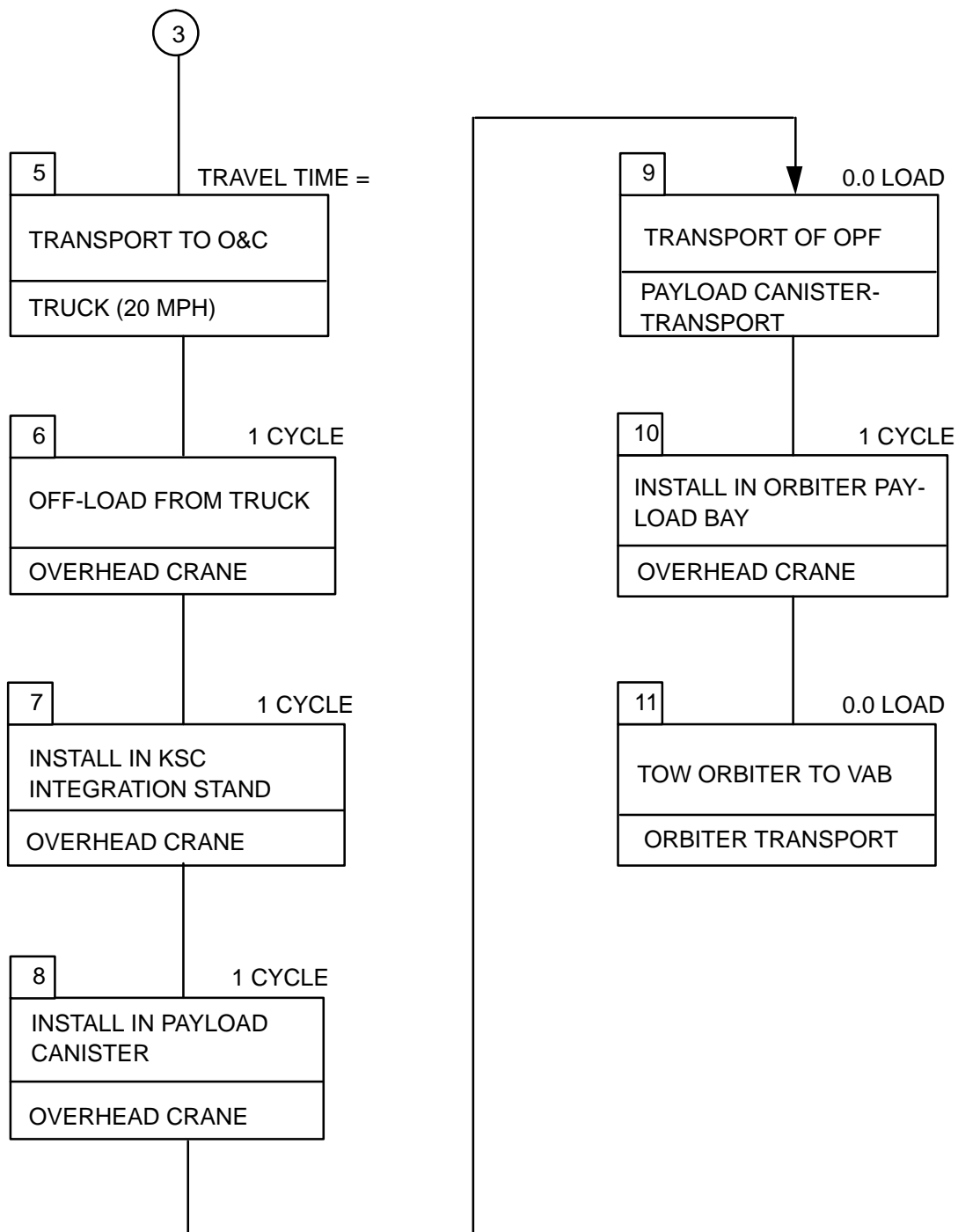


FIGURE E-3 PHASE II SEQUENCE OF EVENTS (SHEET 2 OF 4)

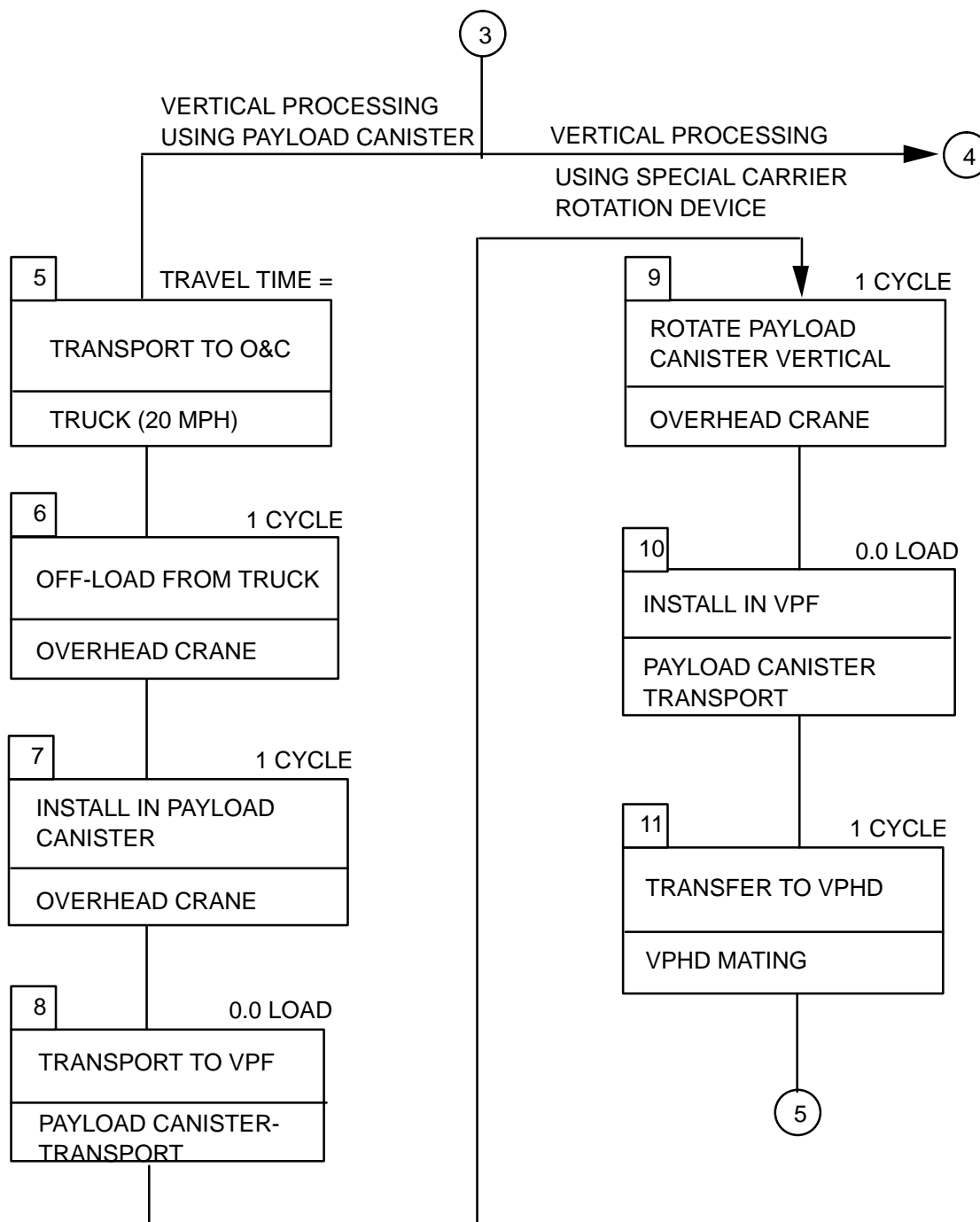


FIGURE E-3 PHASE II SEQUENCE OF EVENTS (SHEET 3 OF 4)

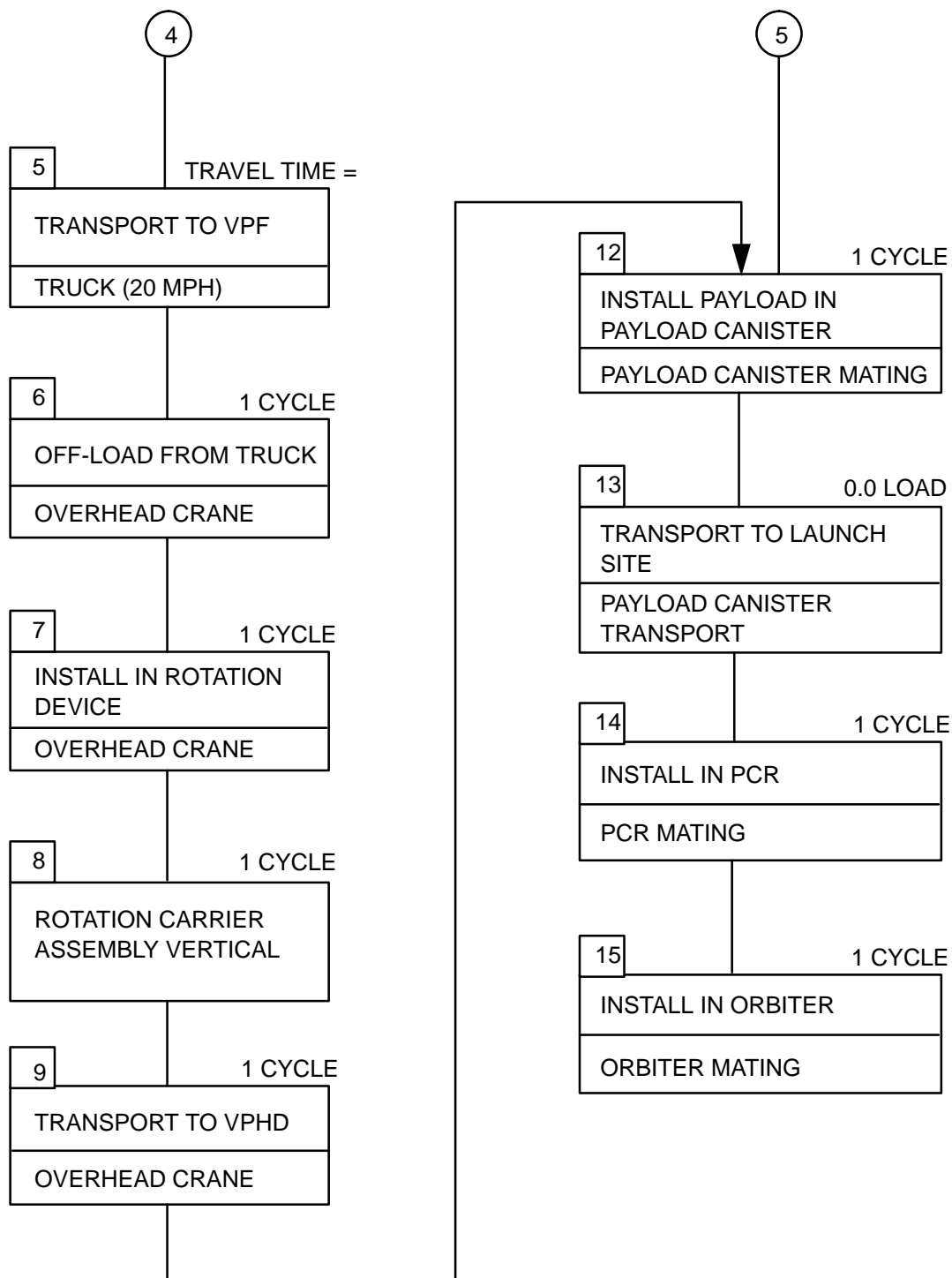
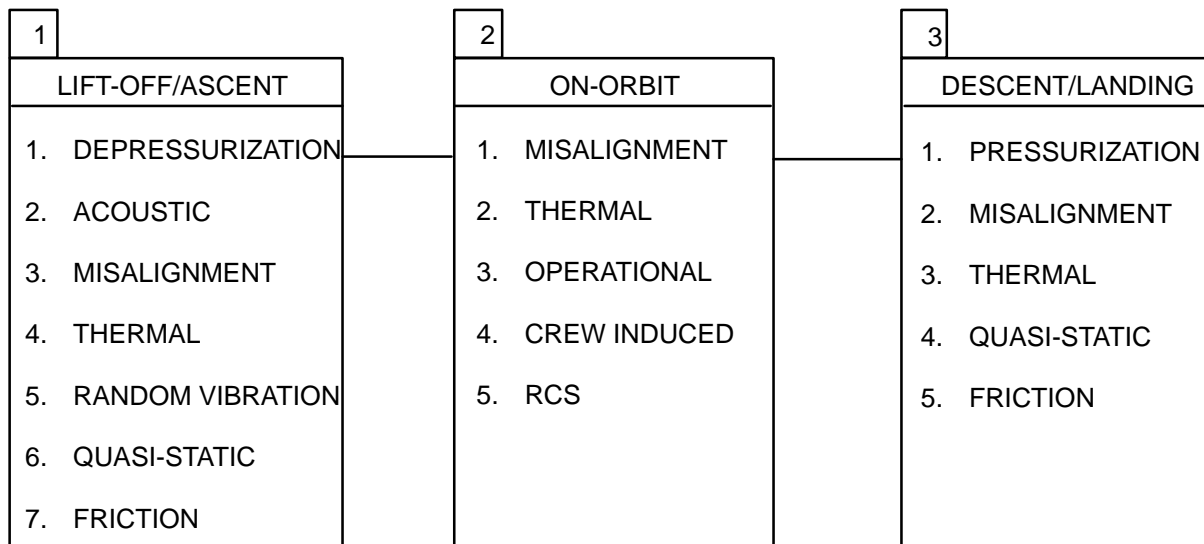
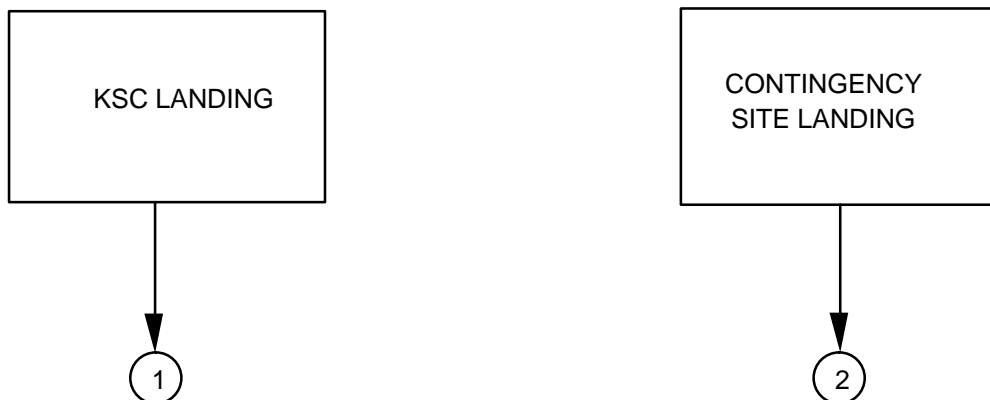


FIGURE E-3 PHASE II SEQUENCE OF EVENTS (SHEET 4 OF 4)



**FIGURE E-4 PHASE III SEQUENCE OF EVENTS**



**FIGURE E-5 PHASE IV SEQUENCE OF EVENTS (SHEET 1 OF 5)**

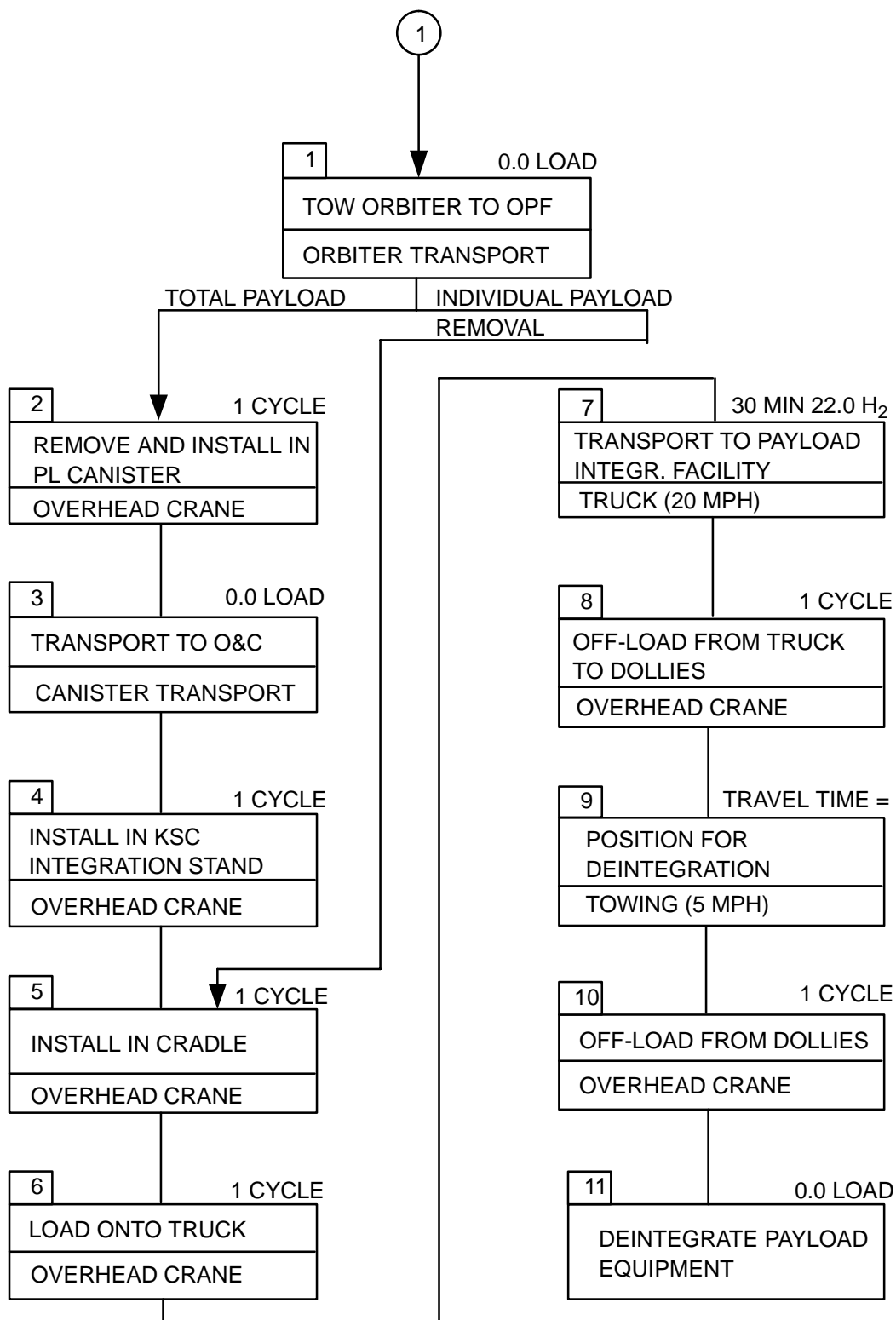


FIGURE E-5 PHASE IV SEQUENCE OF EVENTS (SHEET 2 OF 5)

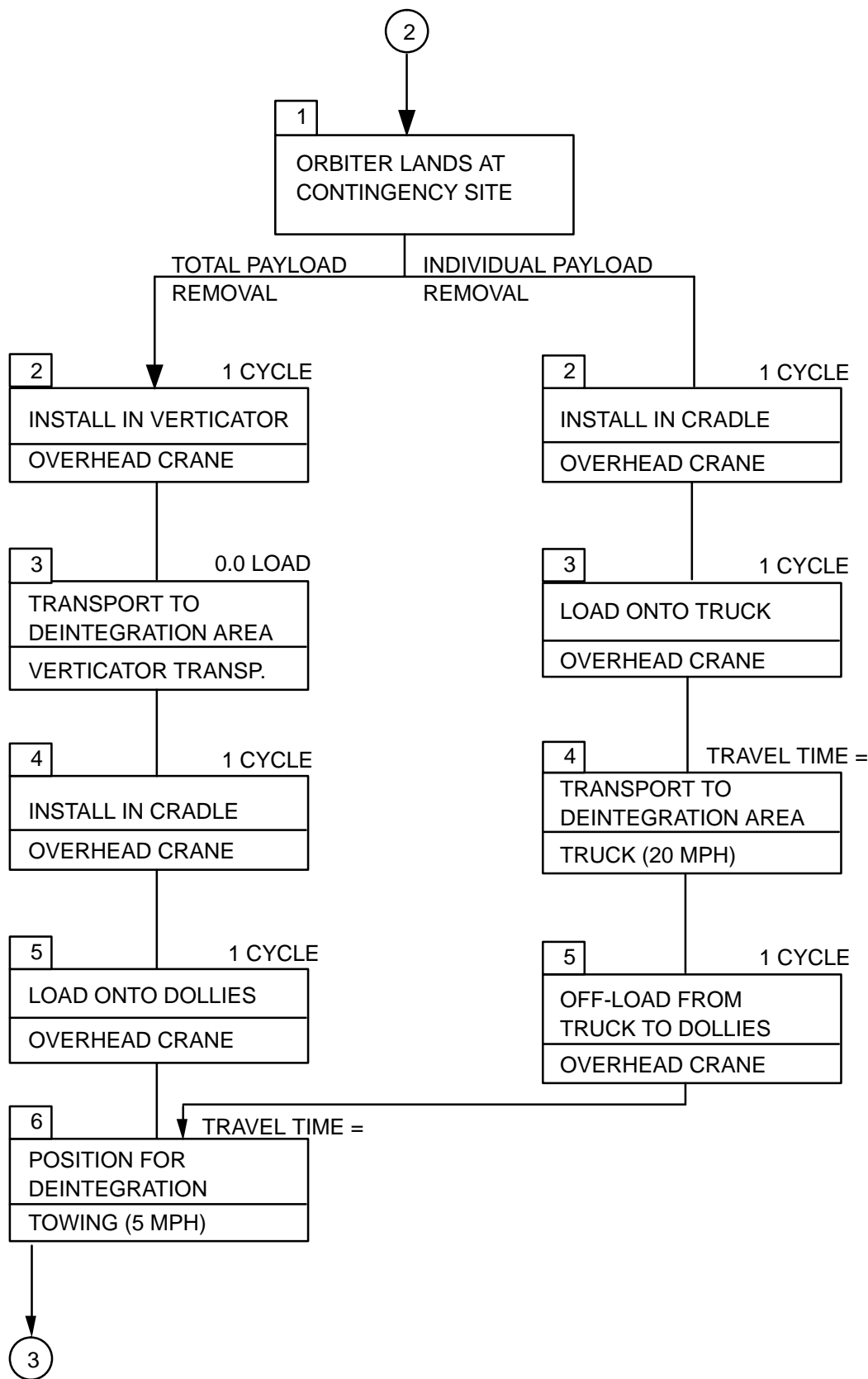


FIGURE E-5 PHASE IV SEQUENCE OF EVENTS (SHEET 3 OF 5)

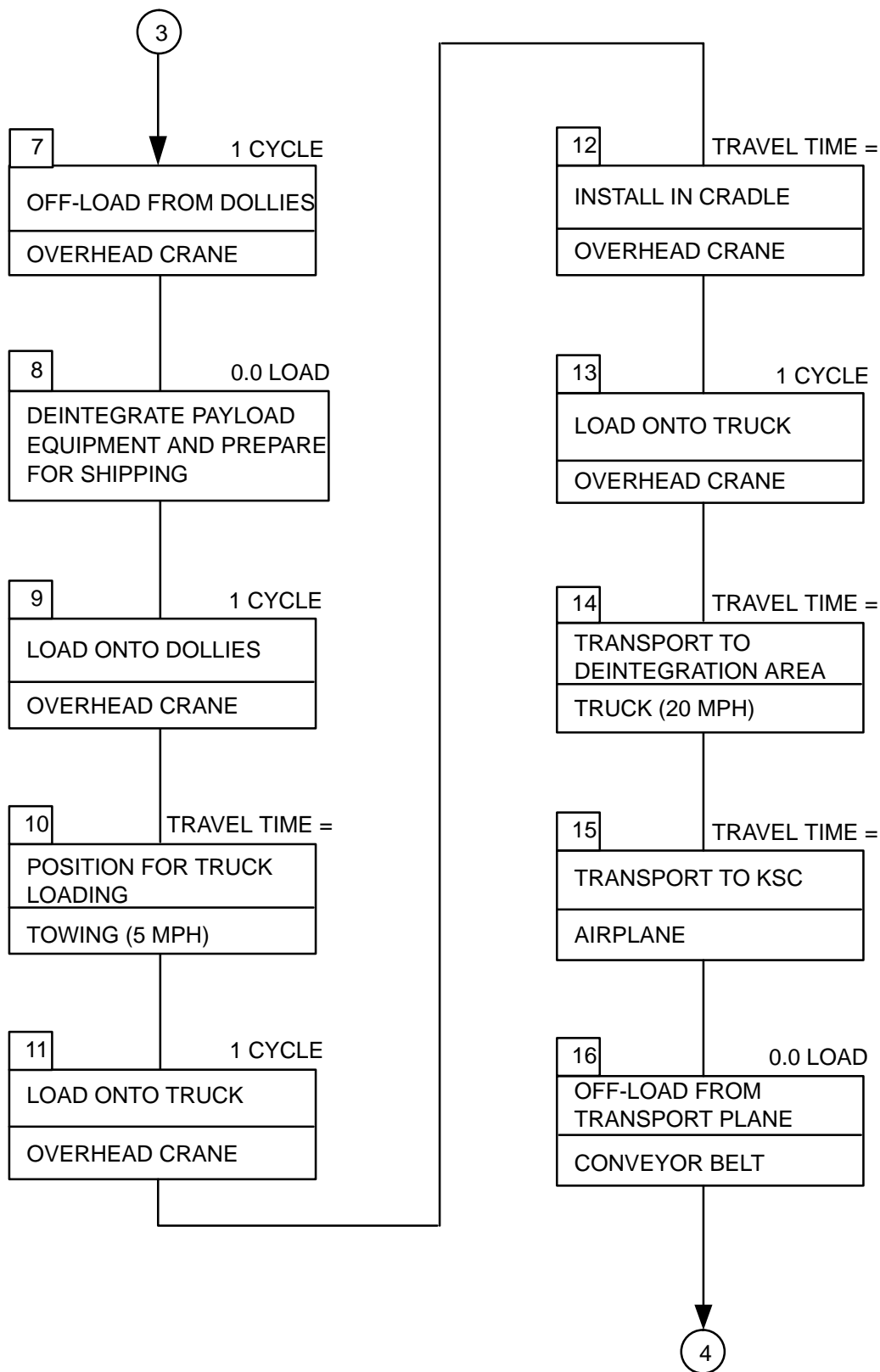
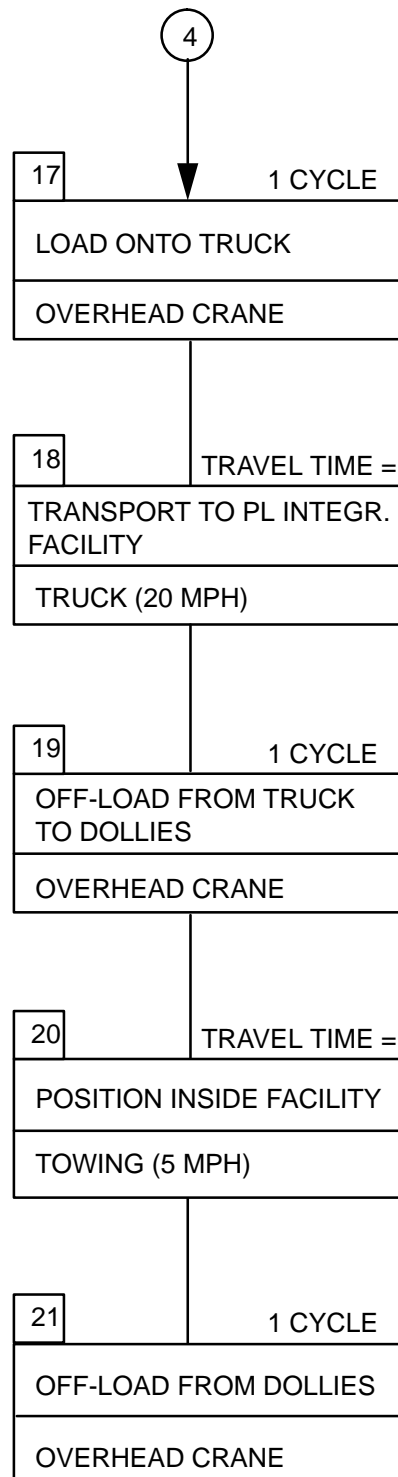


FIGURE E-5 PHASE IV SEQUENCE OF EVENTS (SHEET 4 OF 5)



**FIGURE E-5 PHASE IV SEQUENCE OF EVENTS (SHEET 5 OF 5)**

### **E.3.1.3 TEST**

The flight equipment test loads consist of four load cases which are identified below.

- A. Payload Static Qualification
- B. Payload Modal TESTING
- C. Payload Component Bracket System(s) Static Qualification
- D. Payload Component Bracket System(s) Modal Testing

### **E.3.1.4 GROUND LOADS SUMMARY**

The ground loads defined above do not control the design of the payload since the gravitational load factors are lower than the low frequency gravitational load factors for both the lift-off/ascent and descent/landing events. The ground loads control the design of the payload GHE (Ground Handling Equipment).

The ground loads occur once for each flight mission for the Phase II and Phase IV events. These loads can be significant based on their number of cycles when a life cycle requirement for a number of flights is coupled with the requirement that no fracture occurs within four life cycles.

Evaluation of the transportation loads in section E.3.1.1 shows that a gravitational load factor set of:

|           |           |           |
|-----------|-----------|-----------|
| $X_o$     | $Y_o$     | $Z_o$     |
| $\pm 1.0$ | $\pm 1.7$ | $\pm 3.2$ |

will envelop the four transportation modes. When the hoisting loads are evaluated, the vertical hoisting and Orbiter horizontal mating fall within the gravitational load factor set defined above.

To minimize the analyses required for incorporating ground loads into life cycle analysis, only two sets of ground load stresses will be determined.

#### **Set 1: Gravitational Load Factors**

|           |           |           |
|-----------|-----------|-----------|
| $X_o$     | $Y_o$     | $Z_o$     |
| $\pm 1.0$ | $\pm 1.7$ | $\pm 3.2$ |

Set 1 applies to a payload supported at its interfaces with the GHE. Set 1 applies to all transportation, vertical hoisting, and Orbiter horizontal mating modes.

Set 2: Gravitational Load Factors

| $X_o$ | $Y_o$ | $Z_o$ |
|-------|-------|-------|
| +0.67 | 0     | 0     |

Set 2 is applied to a payload supported at its interfaces with the GHE. Set 2 applies to the horizontal hoisting mode and Orbiter vertical mating.

### **E.3.2 FLIGHT LOADS**

Flight loads for Phase III are classified into the three events:

- A. Lift-off/Ascent
- B. On-orbit
- C. Descent/Landing

These events and the corresponding Orbiter environments that induce flight equipment loads were identified in Section 3 and were shown in Figure E-4.

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## **APPENDIX F ADDITIONAL REQUIREMENTS FOR BERYLLIUM, COMPOSITES, STRUCTURAL BONDS, CERAMICS, AND GLASS**

### **F.1 INTRODUCTION**

This appendix describes the design, analysis, test, and flight qualification requirements for beryllium, composite, adhesively bonded, ceramic and glass structures because they require different treatment and safety considerations than conventional metallic parts and structures. This is due to their inherent failure characteristics and/or manufacturing processes. Thus these materials must not only meet the payload verification requirements specified for metallic structures (as described in the main body of this document), but must also meet the material-specific verification requirements provided in this appendix. Note that the requirements contained herein summarize those levied by NSTS 14046. More detailed explanation of these requirements may be found in NSTS 14046, or by contacting the responsible NASA center or the SSP-SWG.

### **F.2 BERYLLIUM STRUCTURES**

The SSP-SWG must review and approve the Structural Verification Plan for any beryllium structure which is to be flown on the Space Shuttle or will reside on the ISS. Any deviation from the following criteria must be approved by the SSP-SWG:

- A. All beryllium structures must be reported to NASA by payload identification, part identification (drawing number), and beryllium alloy. Drawings of component as well as information regarding the Orbiter/ISS location and function of the beryllium component should be submitted. The only beryllium alloys exempt from this review are those where beryllium is a minor (less than 4 percent) constituent, such as copper-beryllium, nickel-beryllium alloys, and the beryllium oxide ceramics.
- B. A formal component internal loads analysis shall be submitted for review that includes the appropriate boundary conditions, external load applications, bounded static and dynamic loads used for the design, distortions and forces that affect the short transverse (through the thickness) direction stresses, and thermal loads.
- C. A formal stress analysis shall be submitted for review using the maximum design loads for the Shuttle flight environment. The formal stress analysis shall be in sufficient detail to address the effects of elastic stress concentrations, tolerances, and displacements that may occur in the short transverse direction of the beryllium material.
- D. For all beryllium structures, manufacturing and material processes are subject to SSP-SWG approval and must assure appropriate quality control and material processing to control residual stresses, surface imperfections, and mechanical properties. The following requirements must be included in the appropriate process specifications:

- (1) Machined/mechanically disturbed surfaces of a structural beryllium part must be chemically milled to ensure the removal of surface damage.
  - (2) All beryllium components must be penetrant inspected for crack-like flaws with high sensitivity fluorescent penetrant per MIL-STD-6866.
  - (3) All fracture-critical beryllium parts must meet the fracture control requirements detailed in the main body of this document, and levied by NSTS 1700.7 ISS Addendum.
- E. The Structural Verification Plan for beryllium structures should comply with one of the following options:
- (1) For two or more identical beryllium components, the ultimate load-carrying capability must be demonstrated by static testing one of the components (prototype or protoflight) to 1.4 times the maximum expected load (due to flight, assembly, and installation) or greater. A detailed inspection of protoflight articles after testing is required to verify structural integrity. The remaining flight articles shall be acceptance proof-tested to the limit load. Testing must also be used to demonstrate a minimum buckling margin of safety of 10 percent (above the 1.4) for beryllium structures subjected to buckling loads.
  - (2) For one-of-a-kind beryllium components, the flight article must be statically tested to 1.4 times the maximum expected load (due to flight, assembly, and installation) or greater, and inspected to ensure the structural integrity of the part prior to flight.
  - (3) If the beryllium component and all of its supported parts can be shown to be contained and the failed parts do not pose a safety threat to the Orbiter or other payloads, the special beryllium testing criteria in options 1 and 2 will not be required.
  - (4) Combinations of the criteria and/or testing listed above may be acceptable with prior approval of the SSP-SWG.

### **F.3 COMPOSITE PARTS AND STRUCTURES**

A composite structure is defined as a homogeneous material created by the synthetic assembly of two or more materials. Composite structures do not have the advantage that metallic structures enjoy; that is, the material characteristics and processes are not well defined and standardized. Therefore, such standard measures of strength as the modulus of elasticity, the modulus of rupture, and standard measures used with other materials are not available. Further, the strength of composite structures is a function of the composite layup (the configuration of the several layers of the materials which compose the composite) process, and these processes are not standardized. The existing composites whose strength has been determined by test do not have sufficient documentation on the layup processes used to enable determination of data applicable to similar structures using similar processes.

The SSP-SWG must review and approve the Structural Verification Plan for all safety-critical composite structures to be flown on the Space Shuttle or that will reside on the ISS. Any deviation from the following criteria must be approved by the SSP-SWG:

- A. All safety-critical composite structures shall be acceptance proof-tested to 1.2 times the maximum expected limit load. This testing must be performed on each and every flight article.
- B. A composite part may be exempt from acceptance testing if it can be shown that the manufacturer has extensive experience and a successful history of manufacturing a like design, has documented and proven quality control and NDE policies in place, and has certified personnel performing these tasks. This option requires prior and written approval of the SSP-SWG.
- C. Manufacturers of composite structures shall only use processes and controls that are consistent with established aerospace industry practices for composite structures. As a minimum, these manufacturing processes and controls shall provide adequate technical assurance that the flight articles satisfy design and analysis assumptions and are representative of the verification test article. Material properties must comply with MIL-HDBK-17 allowables, or must be developed using a statistically valid sample base with prior and written approval of the SSP-SWG.
- D. A plan for ensuring that the composite part is not damaged due to transportation or assembly shall be prepared and submitted to the responsible NASA center or the SSP-SWG for approval.
- E. All fracture-critical composite structures must meet the fracture control requirements levied by NASA-STD-5003 and contained within this document.

#### **F.4 STRUCTURAL ADHESIVE BONDS**

The SSP-SWG must review and approve the Structural Verification Plan for all safety-critical structural bonds to be flown on the Space Shuttle or will reside on the ISS. Structural bonds shall meet all of the requirements specified for safety-critical composite structures as well as the requirements of the following paragraph. Any deviation must be approved by the SSP-SWG.

The PD shall certify that the bonding materials and processes (e.g., chemical composition, processing, mechanical properties) used for the structural certification (qualification) hardware are the same as those of the flight hardware. Compliance of this requirement shall be submitted as a part of the verification package.

Thermal effects on bonds and bonding materials shall be considered. Thermal effects on the bonding material properties over time can affect the allowable stress on the bond, as well as the thermal effects on the bond at the time of load application (which is of primary importance since

bond strength may decrease sharply with elevated temperatures). Some bonding liquifies at temperatures encountered in space, or even at cargo bay temperatures during landing. Therefore, proof-tests are required to confirm load capacity at the temperature extremes corresponding to the maximum load conditions (temperatures occurring at the time the load is applied).

## **F.5 PARTS AND STRUCTURES MADE OF CERAMICS OR GLASS**

Uncontained ceramic and glass parts are always safety critical when located in a habitable area because of the inherent hazard to the crew. Therefore, glass in a habitable area must be shown safe from breakage or proven contained. Uncontained glass outside a habitable area is subject to the same scrutiny as other structural parts and shall be screened by the PD based on its hazard potential. All uncontained glass parts weighing 0.25 lb or more outside a habitable area will be safety critical and subject to fracture control.

The SSP-SWG shall review and approve the Structural Certification Plan for any safety-critical ceramic and/or glass structures to be flown on the STS and reside on the ISS. Any deviation from the following design and verification requirements must be approved by the SSP-SWG:

- A. All ceramic and glass parts which cannot demonstrate containment shall be designed to have an end of life factor of 1.4 or greater. Since moisture contributes to flaw growth in glass and many ceramics, flaw growth calculations shall be based on the total design life, with a life scatter factor of 4, and average flaw growth properties derived from 100-percent moisture.
- B. Accurate, confident predictions of the magnitude and location of the maximum tensile stress in the ceramic or glass structural component are essential in properly verifying the structure. Confidence can be assured by the use of detailed analyses and tests of the component. Tests to verify stress predictions may be waived if the stress predictions are historically accurate for a given configuration. This test exemption requires prior and written approval of the SSP-SWG.
- C. A fracture mechanics analysis will be completed which demonstrates that the component will have the required factor of safety and life. The fracture mechanics and stress analyses shall be available to the SSP-SWG, upon request.
- D. An acceptance proof-test of each flight article shall be conducted to screen for flaws larger than those assumed in the fracture mechanics analysis. Proof-test plans and results shall be available to the SSP-SWG, upon request.
- E. If the fracture mechanics analysis predicts critical flaws which are much greater than the constraints of the analysis, or if the stresses are very low with respect to test-verified allowables (including a factor of safety of 5.0 or greater), the proof-test described in item (D) above is not required. The appropriate analysis should be submitted to the SSP-SWG in lieu of test results.



## **F.6 DESIGN FEATURES OF GLASS**

BK7, ULE, and Fuse Silica are some of the candidate glass products to be used for space application. These glass products have been in use for years and have been exposed to many structural tests. The problem with glass is that the strength is a function of the surface finish and moisture content of the test specimen. If glass is not kept dry, micro crack growth will take place and reduce its strength. Therefore, much confusion exists on the actual allowables to use for strength assessment of glass.

Another inherent problem with glass is attachment provisions. Attaching glass to a support should be accomplished using any acceptable technique that will minimize the loads in the glass. Where high thermal expansions are expected, do not rigidly mount glass to material that has a high coefficient of thermal expansion. Mounting should be through a flexible seal (similar to the windshield of an automobile) when possible. Mounts bonded to the glass are subject to material characterization tests to establish an "A" Basis Allowable for the bond line. Sample size depends upon variability of the measurement using standard sampling techniques. All samples should duplicate the materials being bonded, and the test must be performed under the predicted worst-case environment in which the material(s) must withstand a load.

Optical and/or highly polished glass used in space application shall comply with the requirement stated in section 3.0 of SSP 30560. Verification requirement shall comply with section 4.0 of SSP 30560.

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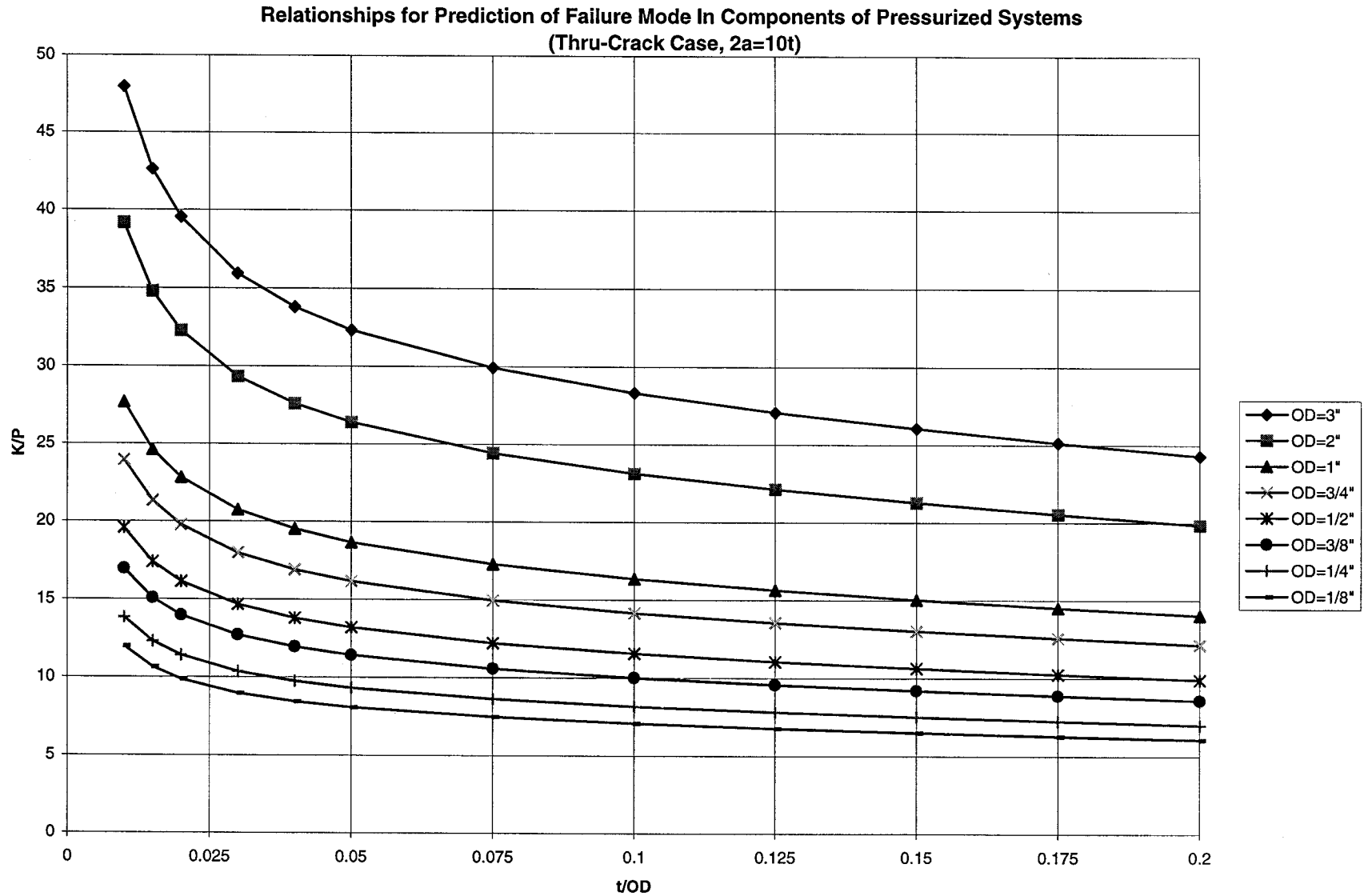
## APPENDIX G LEAK-BEFORE-BURST FAILURE MODE DETERMINATION

### G.1 INTRODUCTION

The design safety factor requirements applied to typical pressurized systems (exclusive of pressure vessels) and common materials of construction tend to ensure Leak-Before-Burst (LBB) characteristics under operating conditions. LBB failure, as determined by a fracture mechanics assessment, is characterized by relatively slow leakage as opposed to rapid tearing of fragmentary rupture. LBB failures are not safety critical so long as release of contained fluids does not result in a catastrophic hazard. If release of fluids would result in a catastrophic hazard, the system/component is fracture critical and must comply with the appropriate requirements.

LBB for pressure system lines, fittings and components can be verified by reference to Figure G-1. Any point above the curve for the OD (outer diameter) of interest indicates LBB mode of failure. An assumed flaw with a length ten times the membrane thickness ( $2c=10t$ ) has been incorporated into the curves as the basis for the LBB determination. The curves are plotted as the ratio of fracture toughness to internal pressure versus the ratio of membrane thickness to outer diameter. Fracture toughness ( $K_{IC}$ ) values and related membrane thicknesses to be used with Figure G-1 are presented in Table G-1. If a LBB failure mode is not indicated by Figure G-1, a specific fracture mechanics analysis may be conducted addressing actual component parameters and properties (if known) to establish failure mode. If evaluation shows that the component is not LBB its failure must be regarded as potentially catastrophic and the part classified and treated as fracture critical.

G-2



**FIGURE G-1 RELATIONSHIPS FOR PREDICTION OF FAILURE MODE IN COMPONENTS OF PRESSURIZED SYSTEMS (THRU-CRACK CASE)**

**TABLE G-1 FRACTURE TOUGHNESS FOR USE IN DETERMINATION OF FAILURE MODE  
IN COMPONENTS OF PRESSURIZED SYSTEMS**

| <b>MATERIAL</b>            | <b>TOUGHNESS<sup>(1)</sup><br/>K<sub>C</sub> (ksi in)</b> | <b>TOUGHNESS<sup>(2)</sup><br/>K<sub>E</sub> (ksi in)</b> |
|----------------------------|---|---|
| AISI 304 SS (ANN)          | 300   | 300   |
| AISI 316 SS (ANN)          | 225   | 225   |
| 2219-T62 Al                | 60  | 60  |
| 2219-T851 Al               | 65  | 60  |
| 2219-T87 Al                | 55  | 50  |
| 6061-T6 Al                 | 45  | 40  |
| 6061-T651 Al               | 50  | 50  |
| A356-T60 Cast Al           | 30  | 30  |
| Ti-6Al-4V STA              | 70  | 70  |
| Ti-6Al-4V BA               | 120   | 115   |
| Ti-6Al-4V ELI-BA           | 120   | 115   |
| Ti-3Al-2.5V (Extr)         | 70  | 65  |
| Inconel 718 (STA)          | 130   | 125   |
| Inconel 718 (STA) GTA Weld | 75  | 65  |
| 15-5PH Steel (H1025)       | 150   | 145   |
| 17-4PH Steel (H1025)       | 100   | 95  |
| PH13-8Mo Steel (H1000)     | 145   | 135   |

[Reference Memorandum TA-94-057]

NOTES:

1. Fracture toughness for components with thicknesses to 0.2 in.
2. Fracture toughness for components with thicknesses of 0.2 to 0.4 in.

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## APPENDIX H MATRIX OF TO BE DETERMINED (TBD) ITEMS

Table H–1 contains a matrix, listing all the specific items in the document that are not yet known. Each item is given a TBD number, using the section of the document that contains the items as the first digit, and a consecutive number for the second digit (i.e., TBD 3.1 is in Section 3, and is the first occurrence of this specific item in the document). The item is identified in detail, including the affected section and page number as well as a description of the TBD item. Each specific TBD item is listed once, with all of its associated affected Section numbers. As each TBD item is resolved, the correct text is inserted in place of the "TBD" in the document, and the entry is removed from this matrix.

**TABLE H–1 MATRIX OF TBD ITEMS**

| <b>TBD Number</b> | <b>Issue</b> | <b>Sections</b> |
|-------------------|--------------|-----------------|
|                   | NO TBD ITEMS |                 |
|                   |              |                 |

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