GENERAL FRACTURE CONTROL PLAN FOR PAYLOADS USING THE SPACE TRANSPORTATION SYSTEM (STS)

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ILLUSTRATIONS

TABLES

1.0 GENERAL POLICY

It is the general policy of the Goddard Space Flight Center (GSFC) that payloads intended for flight on the Space Transportation System (STS) possess adequate structural integrity to assure the safety of the STS and its crew. In particular, these assurances shall be maintained by measures which include, but are not limited to, the prevention of structural failure due to the initiation or propagation of flaws, cracks, or crack-like defects in payload flight structure. Furthermore, this policy should be implemented in such a way as to minimize the impact on payload weight, program cost, and schedule.

2.0 OBJECTIVE

The objective of this plan is to establish cost-effective criteria, procedures, and controls necessary to prevent payload structural failure due to the initiation or propagation of flaws, cracks, or crack-like defects in payload flight structure. The prevention of such failures is specifically intended to preclude subsequent catastrophic hazards to the STS or its crew. This plan is specifically intended to satisfy the requirements of NHB 8071.1, Fracture Control Requirements for Payloads Using the National Space Transportation System (NSTS), and paragraph 208 of NHB 1700.7B, Safety Policy and Requirements for Payloads Using the STS.

3.0 SCOPE

All activities that influence the integrity of payload flight structure with regard to the initiation or propagation of flaws, cracks, or crack-like defects shall be subject to the requirements of this plan. These activities include:

a. Structural design

b. Materials selection, procurement, and storage

c. Fabrication process control

d. Analysis and testing

e. Quality assurance and nondestructive examination (NDE)

f. Payload operations and maintenance

Payload flight structure comprises all parts of the payload to be flown in the STS crew compartment or cargo bay, including all instruments and subassemblies, which sustain loads or pressures, provide stiffness or stability, or provide support or containment.

This plan addresses all types of fracture phenomena including fatigue crack initiation, stress corrosion cracking (SCC), hydrogen embrittlement, and propagation of cracks due to cyclic or sustained loading.

4.0 APPLICABLE DOCUMENTS

The following documents form a part of this plan. Conflicts between these documents and the plan shall be submitted to the GSFC Project Manager or his designee for resolution.

- NASA
  - NHB 8071.1, Fracture Control Requirements for Payloads Using the NSTS
  - NHB 1700.7B, Safety Policy and Requirements for Payloads Using the STS
- Johnson Space Center
  - JSC 07700, Space Shuttle Systems Payload Accommodations, Volume XIV, Attachment 1 (ICD 2-19001) Shuttle Orbiter/Cargo Standard Interfaces
  - JSC 13830A, Implementation Procedure for NSTS Payloads System Safety Requirements
  - MSFC-HDBK-527/JSC 09604, Materials Selection List for Space Hardware Systems
  - NSTS 14046, Payload Verification Requirements
  - JSC 22267, Fatigue Crack Growth Computer Program "NASA/FLAGRO"
- Marshall Space Flight Center
  - MSFC-SPEC-522B, Design Criteria for Controlling Stress Corrosion Cracking
  - MSFC-HDBK-527/JSC 09604, Material Selection List for Space Hardware Systems
  - MSFC-STD-1249, Standard NDE Guidelines and Requirements For Fracture Control Programs

- o Goddard Space Flight Center
  - GMI 8040.1A, Configuration Management (CM)
  - SPAR-1, Guidelines for STS Payload Assurance Requirements (SPAR) for Free-Flyer Spacecraft and Instruments
  - Payload Assurance Requirements Document (PARD) (a project unique document based on SPAR-1)
  - MPD 313-005, Materials Processing Document, Etching of Aluminum Alloys Prior to Liquid Penetrant Inspection
  - MPD 313-009, Materials Processing Document, Fluorescent Penetrant Test Method Requirements and Guidelines
- o Department of Defense
  - MIL-STD-1522A, Standard General Requirement For Safe Design and Operation of Pressurized Missile and Space Systems (revisions as of Dec. 1984)
  - MIL-STD-410, Nondestructive Testing Personnel Qualification Certification
  - MS Fastener Standards
- o Other
  - NAS Fastener Standards, National Aerospace Standard Committee

5.0 ASSUMPTIONS AND PREREQUISITES

5.1 ASSUMPTIONS

The basic assumptions which underlie the requirements and provisions in this plan are the following:

a. All real structural elements contain crack-like defects or flaws located in the most critical area of the component in the most unfavorable orientation. The use of NDE techniques to detect such flaws does not negate this assumption but merely establishes an upper bound on their size. For conservatism, this crack size then becomes the smallest allowable size to be used in any analysis or assessment.

b. After a sufficient number of cycles of sufficiently high tensile stress, materials exhibit a tendency to initiate fatigue cracks even in nonaggressive environments. However, since the assumption of preexisting cracks in all structural elements imposes more severe requirements than that of crack initiation, the latter phenomenon does not affect the requirements or provisions in this plan. Therefore, the requirements for preventing failure due to fatigue crack initiation are completely enveloped and satisfied by the requirements in this plan.

The reasoning behind this statement is as follows. The plan requires all structural elements to be classified as either low-released mass, contained, fail-safe, or safe-life. The first classification includes elements whose failure poses an acceptable risk. The next two classifications confirm that the payload is safe even if the element has already failed. Safe-life elements are shown to possess adequate crack growth life starting with an assumed preexisting crack and analytically subjected to all of the cyclic loads, including testing, which the element is predicted to encounter. In order for fatigue crack initiation to cause a failure, the crack would have to initiate from nothing (or a microscopic dislocation or defect) and grow to failure under the cyclic loads. However, if the element has already been determined to be safe-life even with an assumed preexisting crack, then it is obviously safe from fatigue crack initiation and growth under the same cyclic loads.

c. Under sustained tensile stress in the presence of an aggressive environment, some materials exhibit a tendency to initiate and grow cracks. The circumstances under which this stress corrosion cracking (SCC) phenomenon occurs are sufficiently well documented to provide appropriate avoidance measures and criteria.

Crack initiation due to SCC, however, is not necessarily enveloped by the preexisting crack requirements. Under sustained tensile stress due to preloads, assembly or residual stresses, cracks initiated due to SCC may grow to sizes larger than assumed for preexisting cracks. This growth may occur after NDE inspection and assembly and prior to the imposition of cyclic loads, and its extent cannot be reliably predicted by fracture mechanics. Therefore, this plan prevents failures due to SCC by invoking the fracture control techniques of low-released mass, containment, fail-safe assessment and the selection of highly SCC resistant materials. In cases where low or moderately resistant materials have already been selected, this plan provides rational bases for Materials Usage Agreements (MUA's) or Payload Safety Noncompliance Reports (NCR's) as required by NHB 1700.7B.

d. Under cyclic and/or sustained tensile loading, the preexisting (or load initiated) crack or flaw may or may not propagate depending on the fracture toughness of the material, the initial size and geometry of the crack, the presence of an aggressive environment, the geometry of the part, and the magnitude and number of cycles of loading. The engineering discipline of linear elastic fracture mechanics provides analytical tools for the prediction of crack propagation and critical crack size.

e. Glass and glass-like materials exhibit growth of preexisting flaws predominately under sustained tensile loading in environments other than vacuum. Fracture control of these materials may use low-released mass, containment, fail-safe, or safe-life techniques. For transparent optical elements such as lenses and mirrors which have low stress, visual inspection with 10x or higher magnification may be assumed to detect surface and embedded flaws of 0.1 inch or larger in size when proper lighting is applied at right angles to the flaw orientations. However, for highly stressed glass parts, a proof test is usually required to detect flaws small enough to meet safe-life requirements.

f. For fiber-reinforced composites (both metal and polymer matrix), linear elastic fracture mechanics technology is generally agreed to be beyond the current state of the art. Fracture control of these materials, therefore, relies on the techniques of low-released mass, 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, as appropriate. Metallic honeycomb parts are not considered fiber-reinforced composite parts, and are therefore subject to the general fracture control requirements of this document.

g. High strength materials, particularly steels, may exhibit delayed failure due to hydrogen embrittlement when subjected to sustained tensile loads. The hydrogen often is introduced during processing of the component, typically during the electroplating or electroless plating of protective or wear-resistant coatings. Under a sustained load, the absorbed hydrogen diffuses to regions of high triaxial stresses and promotes cracking. Fracture control procedures, using an appropriate heat treatment, provide the required hydrogen embrittlement relief.

h. A scatter factor is required to account for the observed scatter in measured fracture mechanics material properties and analysis uncertainties. This requirement is satisfied by confirming analytically that no crack will propagate to failure in four mission lifetimes, including fabrication, testing, transportation, and service life, as applicable.

i. The failure and subsequent separation from the payload of any structural element, part, or fragment weighing more than 0.25 pound shall be assumed to constitute a catastrophic hazard, defined as damage to the STS or injury to the crew. For low fracture toughness metal parts preloaded in tension, however, failure may result in a high release velocity and therefore the total released mass may not exceed 0.03 pound. A part is considered to have low fracture toughness when its material property ratio $K_{Ic}/F_{ty} < 0.33 \sqrt{\text{inch}}$. If the part is a steel bolt and the K_{Ic} value is unknown, low fracture toughness is assumed when $F_{tu} > 180$ ksi. Also assumed to present catastrophic hazards shall be any structural failures which release hazardous substances into the STS cargo bay, failures which release any substance into the crew compartment which could affect the health or function of the crew, or failures which result in other hazardous structural or nonstructural failures.

j. The GSFC Project Manager may elect to apply the requirements of this plan to selected payload structural components whose failure could not cause a catastrophic hazard to the STS, but which could threaten payload performance or compromise mission success. It is understood that all such applications of this plan are optional, that is, they are not to be implemented unless specifically imposed by the Project Manager.

k. Wherever the term Project Manager is used in this plan, it is understood to refer to either the GSFC Project Manager or any other GSFC or contractor individual authorized by the GSFC Project Manager to act in his behalf on fracture control matters.

5.2 PREREQUISITES

5.2.1 Fracture Control Implementation Plan

The requirements and procedures of this plan should be implemented as an iterative process during the design phase of the payload using preliminary information about materials, loads, testing, etc. To assist in this process and to identify potential problems, a Fracture Control Implementation Plan (FCIP) shall be prepared as early as possible in the design phase of the payload and approved by the Project Manager. The FCIP, which shall be updated as needed, shall identify the intended methods for implementing the requirements of this plan and shall provide the following information to the extent that it is known or anticipated:

a. Fracture control classification of every part.

b. Initial flaw sizes established by the use of proof testing, special NDE, or other than the flaw sizes specified herein for standard NDE as described in paragraph 7.1.4.2.

c. Methods of NDE to be used on all fracture critical parts, including sensitivity levels, etching techniques, etc., as applicable.

d. Materials for which the absence of sufficient existing fracture mechanics data requires the assumption of conservative data or the establishment of new data through testing as described in paragraph 7.1.4.1.a.

e. The use of fracture mechanics crack growth analysis computer programs other than NASA/FLAGRO as described in paragraph 7.1.4.1.d.

f. The use of the fail-safe option for multi-mission parts, weldments, brazed parts, or castings as described in paragraph 7.2.4.

g. The anticipated use of or need for limited life parts as described in paragraph 7.1.4.1.e.

h. Materials which do not possess high resistance to SCC or for which the SCC resistance is unknown as described in paragraph 7.2.8.

i. The use of low fracture toughness fasteners or fasteners less than 3/16 inch in diameter in fracture critical applications as described in paragraph 7.2.6.

j. A description of all pressure vessels and pressurized systems and the intended verification programs as described in paragraph 7.2.7.

k. The use of glass or glass-like materials and the intended verification program as described in paragraph 7.2.9.

l. The use of fiber-reinforced composite materials and the intended verification program as described in paragraph 7.2.10.

m. A description of all fracture critical rotating mechanical assemblies and the intended verification program as described in paragraph 7.2.12.

n. A description of the procedures for configuration management and discrepancy resolution as described in paragraph 7.3.

o. The identities of the individuals, organizations, or subcontractors responsible for fracture control activities as described in paragraph 6.0.

5.2.2 Final Safety Verification

The basic prerequisites which must be fulfilled before the requirements of this plan can be implemented for final safety verification shall be the availability of the following data, as appropriate:

a. Reliable definition of all significant external loads, operating cycles, temperatures and environments. Reliable definition of all significant internal stresses due to residual and assembly stresses and preloads, if required.

b. Reliable identification of material composition, alloy, temper and material properties, including fracture mechanics properties.

c. Comprehensive structural analyses including detailed stress analyses.

d. Accurate knowledge of the design configuration through detail drawings and configuration management.

e. Complete and accurate assembly and test procedures, including test levels and environments.

f. Accurate knowledge of all fabrication processes used in manufacturing all structural components.

6.0 ORGANIZATION AND RESPONSIBILITIES

6.1 ORGANIZATION

The implementation of the fracture control requirements of this plan and associated design and safety reviews is the responsibility of the GSFC Project Manager. The Project Manager may appoint, or delegate authority to the implementing organization to appoint, a Fracture Control Coordinator (FCC). The FCC shall be supported by the normal GSFC or contractor discipline organizations responsible for:

a. Structural Design

b. Structural Analysis and Testing

c. Materials and Fabrication Processes

d. Quality Assurance

e. Systems Safety

6.2 RESPONSIBILITIES

The FCC and the discipline organizations which support the FCC shall have the responsibilities specified in the following paragraphs. Some implementing organizations may have different organizational units, or more than one unit, for these responsibilities.

However, all of the following responsibilities shall be assigned to an appropriate organization.

6.2.1 Fracture Control Coordinator

The FCC, appointed by the Project Manager or implementing organization, shall have the general responsibility for implementing the requirements of this plan and compliance with its objective. Specific responsibilities shall be:

a. Establishment of a single point of contact for technical consultation for all matters related to payload fracture control.

b. Preparation of the FCIP in collaboration with the discipline support organization for the approval of the Project Manager.

c. Review of all activities directed toward implementing the requirements of this plan and recommendation of approval/disapproval to the Project Manager.

d. Participation in Material Review Board (MRB) activities to determine the necessary corrective action for discrepant parts.

e. Coordination among the project, the discipline support organizations, and the Johnson Space Center (JSC) regarding design and safety reviews, Hazard Reports, MUA's, and NCR's involving fracture control.

6.2.2 Structural Design

The structural design organization(s) shall have the general responsibility to implement design practices which produce structural components that are safe and capable of proper function under all foreseeable conditions. Specific responsibilities shall be:

a. Reduction of stress concentrations due to manufacturing or design.

b. Elimination or reduction of undesirable residual and assembly stresses.

c. Selection of materials with adequate resistance to crack initiation and propagation, including stress corrosion cracking.

d. Specification of manufacturing methods which are compatible with the design.

e. Consideration of inspection requirements for flaw detection including access for reinspection of reusable hardware, when required.

f. Assurance that drawings for all parts carry a note which specifies the appropriate NDE requirements specified by the structural analysis organization. If no inspection is required, the drawing shall so state.

g. Assurance that drawings for all fracture critical parts carry a note which identifies the part as fracture critical.

6.2.3 Structural Analysis and Testing

The structural analysis and testing organization(s) shall have the general responsibility to perform all analyses and tests necessary to ensure the structural integrity of the payload and to implement the analytical requirements of this plan. Specific responsibilities shall be:

a. Performance of all coupled payload/STS transient response flight loads analyses and other dynamic analyses necessary to determine payload dynamic load responses during flight events.

b. Performance of all detailed stress analyses necessary to determine stress levels and strength margins of safety in all structural members.

c. Classification of all parts as fracture critical or nonfracture critical.

d. Performance of all analyses necessary to assure payload structural integrity by satisfying the containment or fail-safe requirements of this plan.

e. Performance of all fracture mechanics analyses necessary to assure that the safe-life requirements of this plan are satisfied.

f. Derivation and updating of all loading spectra due to all significant loading events which occur after the inspection for cracks or flaws including assembly, testing, transportation, flight and postflight, as appropriate.

g. Calculation or estimation of any significant residual stresses due to fabrication, assembly or testing, if required.

h. Specification and performance of all proof tests necessary for flaw detection.

i. Specification of NDE methods and levels used for all fracture critical components. If no inspection or NDE is required, that fact shall also be specified.

j. Assurance that all initial flaw sizes used in fracture mechanics analyses are consistent with the NDE techniques actually used.

6.2.4 Materials and Fabrication Processes

The materials and fabrication processes organization(s) shall have the general responsibility to ensure that materials utilized in payload structural components possess adequate resistance to both crack initiation and propagation while in the presence of stress concentrations, flaws or defects, or aggressive environments. Specific responsibilities shall be:

a. Review and approval of all material and procurement specifications used for all payload structural parts.

b. Review and approval of all fabrication and repair processes specified for structural components.

c. Verification, when necessary, of material identity, alloy or temper conditions.

d. Verification that storage conditions of structural materials are compatible with their intended use.

e. Review and approval of all material properties used in fracture mechanics, containment and fail-safe analyses and the compatibility of these properties with thermal and chemical environments.

f. Determination of stress corrosion cracking susceptibility for all structural materials and preparation of all MUA's in accordance with MSFC-SPEC-522B.

g. Review and approval of all NDE techniques specified and initial crack sizes assumed by the structural analysis organization.

6.2.5 Quality Assurance

The quality assurance organization(s) shall have the general responsibility to verify the implementation of all requirements, procedures, and specifications related to payload structure. Specific responsibilities shall be:

a. Verification that all structural materials and parts conform to the specifications under which they were procured.

b. Verification that specified fabrication and repair processes were used.

c. Performance or monitoring of all NDE inspections and verification of specified technique, equipment, and accessibility.

d. Verification that all specified NDE inspection techniques and procedures meet the requirements of MSFC-STD-1249, and that all special NDE inspectors and procedures have been certified by either the GSFC or Rockwell International, STS Division, Downey, CA.

e. Verification that specified assembly procedures were followed.

f. Verification that the as-built configuration of all payload structural components agrees with that specified on the design drawings.

g. Verification that specified test procedures, including those for proof tests, were followed.

h. Maintenance of logs documenting the environmental aspects of all storage conditions and all loading during testing and assembly of pressure vessels, fiber-reinforced composite parts, and limited life parts.

6.2.6 Systems Safety

The systems safety organization(s) shall have the general responsibility to coordinate and track fracture control activities and to prepare the Safety Compliance Data Package relating to such activities required by this plan. Specific responsibilities shall be:

a. Coordination of all fracture control implementation activities performed by the support organizations in paragraphs 6.2.2 through 6.2.5 and submittal of all analysis, testing, and inspection reports to the FCC for review.

b. Preparation and tracking of milestones relating to all fracture control activities and reporting progress to the FCC.

c. Preparation of the Safety Compliance Data Package and all Hazard Reports in accordance with JSC 13830A which document all hazards associated with fracture control including those nonstructural hazards which could result from failures of payload elements which otherwise comply with the low-released mass, containment, or fail-safe requirements of this plan. Such hazards shall be identified by the support organizations in paragraphs 6.2.2 through 6.2.5. Hazard Reports shall be coordinated with the FCC and approved by the Project Manager before submittal to the JSC for approval.

d. Preparation of all NCR's in accordance with JSC 13830A as soon as it is determined that any fracture control requirement in this plan cannot be met. Such NCR's shall be coordinated with the FCC and approved by the Project Manager before submittal to the JSC for approval.

e. Tracking, updating, and closure of all Hazard Reports, MUA's, and NCR's relating to the fracture control requirements of this plan.

7.0 REQUIREMENTS AND PROCEDURES

7.1 GENERAL REQUIREMENTS

The objective of this plan shall be met by applying the procedures of this section to demonstrate 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, or safe-life. Each of these classifications is discussed in the following paragraphs.

7.1.1 Low-Released Mass

For a payload component to be classified as a low-released mass part, it shall meet two requirements: (a) the component has a total mass of less than 0.25 pound; and (b) it can be shown that the release of this component will not cause any catastrophic hazard to the STS as a result of subsequent damage to the payload. For low fracture toughness metal parts preloaded in tension, however, failure may result in a high release velocity and therefore the total released mass may not exceed 0.03 pound. A part is considered to have low-fracture toughness when its material property ratio $K_{Ic}/F_{ty} < 0.33\sqrt{\text{inch}}$. If the part is a steel bolt and the K_{Ic} value is unknown, low-fracture toughness is assumed when $F_{tu} > 180$ ksi.

7.1.2 Contained

For a payload component to be classified as a contained part, it shall meet two requirements: (a) it can be shown that, if the part fails, all fragments of the part that violate the requirements of paragraph 7.1.1 are completely contained by the payload itself from being released into the STS cargo bay; and (b) it can be shown that the failure of this component will not cause a catastrophic hazard to the STS as a result of subsequent damage to the payload. The presence of enclosures, tethers, boxes, shrouds, other structure, or thermal blankets, if in compliance with the requirements of this paragraph, may be considered in assessing containment. However, containment analyses, which involve showing that a part will not penetrate a thin shell, shall consider such factors as the velocity or energy of the part as it strikes the shell, the worst-case sharpness (minimum area) of the part, and the elastic and/or plastic deformation and resulting stresses in the shell during impact. In cases where analysis is not feasible, penetration or containment tests shall be required. All containment test plans shall be submitted to the FCC for review before such tests are performed. Containment shall not be used to show compliance with the objective for pressure vessels.

7.1.3 Fail-Safe

For a payload component to be classified as a fail-safe part, it shall meet two requirements: (a) it can be shown by analysis or test that, due to structural redundancy, the structure remaining after any single failure can withstand the redistributed limit loads; and (b) the failure of the component will not result in the escape from the payload of any fragment that violates the requirements of paragraph 7.1.1. In meeting the fail-safe requirements, the effect of altered STS/payload coupling shall be considered unless (1) the design loads are conservative with respect to STS/payload dynamic coupling variations, or (2) failure of the component would not significantly alter payload dynamic response. When adequate quality control has been implemented to ensure that generic or process defects are not present, the remaining structure may be considered to be unflawed. However, if the remaining structure relies for its structural integrity on one or more redundant load paths composed of materials which are not highly resistant to SCC, the additional requirements of paragraph 7.2.8.1.c shall be satisfied. For multi-mission payloads, it shall be verified before reflight that the structural redundancy of a fail-safe part is still intact. Only one failure at a time need be considered; hazards caused by the failure of two or more parts in series need not be considered. The fail-safe criterion shall not be used to show compliance for pressure vessels.

7.1.4 Safe-Life

For a payload component to be classified as a safe-life part, it shall be shown 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 encountered in four complete mission lifetimes including fabrication, testing, transportation, lift-off, ascent, on-orbit, descent, landing, and postlanding events, as applicable. Abort landing shall be considered for nonreturnable payloads. Since the scatter factor of four accounts for the observed scatter in measured material crack growth properties and fracture mechanics analysis uncertainties, it shall be applied to all phases of the mission lifetime. Assessment methods for showing compliance with the safe-life requirements are given in the following paragraphs.

7.1.4.1 Fracture Mechanics Analysis--Linear elastic fracture mechanics analysis provides quantitative predictions of crack growth behavior when material, part geometry, initial crack size and geometry, chemical environment, and loading history are known. As the most general of the compliance procedures, it can be used for any structural component but must be used for all pressure vessels. The fracture mechanics analysis shall show that crack growth to failure or instability cannot occur within four mission lifetimes.

Fracture mechanics analyses shall be performed in accordance with all of the following requirements:

a. All material properties used to analytically predict crack growth behavior shall be valid for the actual temperature and chemical environments or shall be conservative with respect to the actual environments.

When using NDE to establish the initial flaw size, the fracture toughness value used in the fracture mechanics analysis (K_{Ie}, K_{Ic}, or K_c, as appropriate) shall be the average values obtained from literature or actual testing. If proof testing is used to establish the initial flaw size, an upper bound fracture toughness value shall be used in determining both the initial flaw size and the critical flaw size at fracture. The lower bound value of the available data for K_{Iscc}, the stress-corrosion or environmental cracking threshold stress intensity factor, shall be used when environmental effects or sustained loads are significant.

Average fatigue crack growth rate properties shall be used for crack growth calculation, regardless of whether NDE or proof test is used to establish the initial flaw size. When the data sources are particularly sparse, conservative estimates of the crack growth rate shall be assumed and documented in the FCIP.

When all of the following conditions are met, the material properties contained in NASA/FLAGRO may be used in fracture mechanics analysis:

(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 specified in NASA/FLAGRO.

(3) No material property test data is available for the specific material (or heat) being used which indicates that any property may be outside the expected range of scatter.

For materials which have been specially processed, such as special mill runs and custom forgings, test coupons should be used to establish yield strength and fracture toughness properties in accordance with ASTM specifications. When test coupons are not used, or when conditions (1) through (3) above cannot be met, material properties which are clearly conservative with respect to expected properties shall be documented in the FCIP, reviewed by the FCC, and approved by the Project Manager before use.

b. The loading spectrum used in the analysis shall be composed of the number of cycles of stress at levels representative of all significant loading events which occur after the inspection for cracks or flaws including assembly, testing, transportation, lift-off, ascent, on-orbit, deployment, descent, landing, and postlanding, as appropriate. Any significant residual stresses due to fabrication, assembly, or testing shall be considered. The lift-off, ascent, descent, and landing portions of the loading spectrum shall be equivalent to, or more conservative than, the spectra of Table A-5, Appendix A. Table A-5 gives the numbers of cycles at various percentages of the maximum or 100 percent load level. For lift-off, 100 percent load is defined as the maximum load derived by combining the low frequency lift-off transient loads with the vibroacoustic loads induced in the payload elements. For landing, 100 percent is defined as the maximum load derived by combining the low frequency landing transient loads with the thermal loads induced in the payload elements by the temperature distribution predicted to exist at normal or abort landing.

When using the loading spectrum of Table A-5, the stress ratio (R-ratio) appropriate for the part shall be used in the fracture mechanics analysis. For non-preloaded parts subjected primarily to flight-induced inertial loading, the loading is primarily fully-reversible and R = -1 may be assumed. However, when this is not the case, an R-ratio appropriate to the actual or expected loading shall be used. For example, for both fasteners and pressure vessels, initial preloading or pressurization occurs at R = 0 while subsequent flight-induced preload or pressure cycles (if any) occur at high R-ratios which depend on temperature and/or design details. However, in both cases, flight-induced loading shall use the numbers of cycles in Table A-5 in conjunction with the appropriate R-ratio, as illustrated in the example problem in paragraph A-7.0.

The complete loading spectrum shall be analytically imposed on the part four times in sequence, one after the other. This requirement specifically prohibits the use of one loading spectrum with four times the number of cycles in each of its constituent parts. Loading spectra may be simplified as long as the results are equivalent to, or more conservative than, the requirements of paragraph 7.1.4.1.b.

The loading spectrum shall be updated as necessary as the design matures and knowledge of loading events improves.

c. The fracture mechanics analysis shall consider, but not be limited to, the crack and part geometries given in Figure 7-5. Initial cracks shall be assumed to be located in the most critical area of the part in the worst possible orientation. The size of initial cracks used in the analysis shall be consistent with the inspection method and level actually performed on the part and in no case shall be smaller than those sizes given in Table 7-1 without demonstration of capability. The analysis shall consider the part-through (surface) crack aspect ratios (a/2c) indicated in Table 7-1 (where a is the crack depth and c or 2c is the surface crack length). In cases in which the most critical location or orientation of initial crack is not obvious, the analyst shall consider several such locations and orientations for the part.

d. The preferred fracture mechanics analysis approach is to perform a chronological cycle-by-cycle or finite incremental length integration of the growth rate equations for da/dN and dc/dN, the crack growth rates in depth and length directions, respectively. The analytical methodology used should be capable of accounting for the two-dimensional growth characteristics of cracks, variable-amplitude loading spectra, excursions between mean stress levels, and negative stress ratios, as required. The effects of intermittent overload on crack growth retardation shall not be considered in crack growth analyses. In some cases, a direct integration by hand calculation to obtain the total life of the part, using published da/dN versus Delta-K curves, may be sufficient. Many computer programs are available which perform crack growth predictions complying with the requirements of this paragraph. Any computer program, growth rate equation, or hand analysis technique may be used as long as the results are equivalent to, or more conservative than, the results given by the NASA/FLAGRO program. Programs other than NASA/FLAGRO shall be noted in the FCIP.

e. Limited life parts shall be shown to have at least four safe-lives remaining before reflight. Renewed life predictions for successive missions 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, or replacements shall be established by safe-life analysis.

f. For components where it is necessary to consider the propagation of a crack into a hole, or from one hole to another hole, the analysis shall assume that the crack is not arrested or retarded by the hole, but continues on past the hole. This means that when the crack tip reaches the edge of the hole, the analysis shall assume that the crack length immediately increases by an amount equal to the diameter of the hole. Then the crack growth analysis shall continue with this new crack length as the initial crack size using whatever crack/part geometry is appropriate. For example, if there are no additional holes between the crack tip and the free edge of the part, a geometry such as "through crack in center of plate" or "single edge through crack" (TC01 or TC02 in NASA/FLAGRO) should be used. However, if there are additional holes present, a geometry such as "through crack from hole in row of holes" (TC05 in NASA/FLAGRO) should be used.

7.1.4.2 Inspection for Cracks and Flaws--Compliance with safe-life requirements shall require inspection of the flight part in order to establish the largest undetected crack size which could exist in the part. The inspection methods in Table 7-1 shall be used singly or in combination to ensure that the safe-life assessment assumptions of an initial crack of size given in Table 7-1 and located in the most critical location and orientation are valid. Weldments, brazed joints, castings, and pressure vessels shall be 100 percent inspected for both surface and embedded flaws using the appropriate inspection methods of Table 7-1. Inspection levels are categorized as standard NDE and special NDE. Personnel conducting NDE shall be certified in accordance with MIL-STD-410. In addition, special NDE inspectors and their procedures shall pass a test administered by either the GSFC or Rockwell International, STS Division, Downey, CA in order to be certified to perform special NDE. Proof testing may also be used as an inspection technique.

The inspection requirements of this plan require the reporting of all detected cracks, crack-like indications, and significant flaws which behave like the analytical fracture mechanics model of an ideal crack. Examples of significant flaws are sharp gouges, deep scratches, inclusions, voids, pores with tails, and lack of fusion in welds. Examples of insignificant flaws are blunt gouges, shallow scratches or machining marks, shallow infoliations at the crests of fastener threads, and small amounts of pores without tails in welds. Unaided visual inspection and visual inspection aided only by magnification are not acceptable methods for screening cracks (except for transparent optical elements as noted in paragraph 7.2.9.2).

a. Standard NDE. This level of inspection comprises the use of one or more of the standard industrial NDE techniques such as dye penetrant, X-ray, ultrasonic, magnetic particle, or eddy current. Standard NDE shall be performed in accordance with MSFC-STD-1249. The initial crack sizes shall correspond to a 95 percent confidence/90 percent probability level of inspection reliability. Table 7-1 gives the largest crack sizes, for various NDE techniques and part geometries, which may remain undetected at these probability and confidence levels. No crack sizes smaller than these values shall be used in any safe-life assessment based on standard NDE unless it can be documented that detection of smaller sizes can be achieved at a 95 percent confidence and 90 percent probability level.

   MPD 313-009 may be used in addition to MSFC-STD-1249, as a guideline for dye penetrant inspection. Etching to remove surface material smeared by machining or grinding operations shall be required prior to dye penetrant inspection. The etching process shall result in the removal of 0.0004 to 0.0006 inch of material from all surfaces of the part and shall be performed in accordance with a specification or procedure that precludes contamination of the part. Etching of aluminum may be performed in accordance with MPD 313-005; all other etching specifications or procedures shall be reviewed by the FCC and approved by the Project Manager. Guidelines for effective use of etching and dye penetrant are given in the following:

(1) Etching is not required if the part consists almost entirely of the manufacturer's as-rolled surface (such as a part cut out of sheet or plate), or for fasteners or undisturbed welds.

(2) Parts which require precision dimensional tolerances may be rough machined to within 0.030 inch or less of final size, etched, dye penetrant inspected, and then finish machined. The finished part may be reinspected using dye penetrant without etching, or by another NDE technique, but there is no requirement to do so.

(3) For parts with drilled holes, if etching and dye penetrant inspection are performed prior to drilling, etching and inspection of the holes are not required after drilling. However, this does not apply when the load is transmitted through a single hole (such as in a lug). All such holes shall be either etched and dye penetrant inspected or inspected using another NDE technique.

(4) When penetrant inspection of drilled holes is required, etching of tapped threads should be avoided by the following sequence: drill tap holes, etch, tap threads, dye penetrant inspect, and install threaded inserts. Threaded holes smaller than 3/8 inch are uninspectable by penetrant and make the part more difficult to clean. In this case, the sequence should be: drill tap holes, etch, dye penetrant inspect, tap threads, and install threaded inserts.

(5) Threaded inserts and other areas likely to trap liquid should not be present during etching or dye penetrant inspection. Threaded holes are difficult to quickly and reliably seal.

(6) Application of coatings such as paint, anodize, chromate conversion, and dry film lube should follow etching and dye penetrant inspection.

b. Special NDE. The most sensitive level of inspection comprises the use of the same standard industrial NDE techniques as standard NDE, but employed by inspectors who have documented ability to detect smaller crack sizes at a 95 percent confidence/90 percent probability level of reliability. Special NDE inspectors and their procedures shall pass a test administered by either the GSFC or Rockwell International, STS Division, Downey, CA in order to be certified to perform special NDE. The use of special NDE techniques shall be noted in the FCIP, reviewed by the FCC, and approved by the Project Manager.

c. Proof Testing. Proof testing a flight part at a static stress level above limit stress but below the yield strength of the material may be used as a screening or inspection technique for cracks and flaws. Depending on the specific material, part geometry, and stress level used, proof tests which do not result in failure of the part may screen flaws smaller than those screened by NDE. The proof test approach may be selected for any structural component but this decision shall consider that, in order to screen sufficiently small flaw sizes, the proof test may require loads substantially in excess of those usually imposed on flight hardware. In addition, parts which are subjected to more than one stress distribution and which, therefore, require more than one proof test, may experience unacceptable crack growth with subsequent proof tests. The time duration of the proof test, including loading, hold at proof level, and unloading, should be as short as possible.

   In performing proof tests, test procedures and stress analysis predictions shall be sufficiently reliable and coordinated to ensure that the predicted stress level and distribution are actually achieved, and that lack of test failure assures that the flaw size to be screened was not present in the most critical location and orientation of the part. Linear elastic fracture mechanics theory shall be used with the actual test stress level achieved, the part geometry, and the upper bound value of critical stress intensity factor (K_{Ic}, K_{Ie} or K_c, as appropriate) to predict the screened initial flaw size, location, and orientation. The use of proof testing shall be documented in the FCIP, reviewed by the FCC, and approved by the Project Manager.

7.2 COMPLIANCE PROCEDURES AND PART DISPOSITION

7.2.1 Selection Criteria for Fracture Critical Parts

The logic of Figure 7-1 presents the basic criteria for selection of fracture critical and nonfracture critical parts following the objective of preventing damage to the STS or injury to the crew. A fracture critical part is defined as any of the following:

a. A part whose failure would cause a catastrophic hazard to the STS or its crew. All safe-life parts are therefore fracture critical.

b. Any pressure vessel defined in accordance with NHB 1700.7B.

c. Any pressure system component which contains hazardous fluids or which would cause a catastrophic hazard due to loss of pressurization.

d. All parts of a rotating mechanical assembly which have a kinetic energy of 14,240 ft-lbs or greater.

Nonfracture critical parts require only the normal GSFC (or GSFC approved contractor) quality control and configuration management procedures in addition to the fracture control documentation requirements of paragraph 7.3.1. Fracture critical parts, in addition to the normal GSFC (or GSFC-approved contractor) quality control and configuration management procedures, require the special tracking, control, and documentation procedures of paragraph 7.3.2.

7.2.2 Compliance Procedures for Low-Released Mass Parts

As shown by the logic of Figure 7-1, all parts meeting the requirements of paragraph 7.1.1 are classified as nonfracture critical and may be disposed of as acceptable parts by implementing the nonfracture critical part control and documentation procedures of paragraph 7.3.1. As the logic of Figure 7-1 shows, any part may be considered for compliance with the low-released mass requirements except pressure vessels.

7.2.3 Compliance Procedures for Contained Parts

As shown by the logic of Figure 7-1, all parts meeting the requirements of paragraph 7.1.2 are classified as nonfracture critical and may be disposed of as acceptable parts by implementing the nonfracture critical part control and documentation procedures of paragraph 7.3.1. As the logic of Figure 7-1 shows, any part may be considered for compliance with the containment requirements except pressure vessels.

7.2.4 Compliance Procedures for Fail-Safe Parts

As shown by the logic of Figure 7-1, all parts meeting the requirements of paragraph 7.1.3 are classified as nonfracture critical and may be disposed of as acceptable parts by implementing the nonfracture critical part control and documentation procedures of paragraph 7.3.1. As the logic of Figure 7-1 shows, any part may be considered for compliance with fail-safe requirements except pressure vessels. In addition, Figure 7-1 shows that, if the structure remaining after failure of the part relies for its structural integrity on one or more redundant load paths composed of materials which are not highly resistant to SCC, the additional requirements of paragraph 7.2.8.1.c shall be satisfied. For multi-mission payloads, it shall be verified before reflight that the structural redundancy of each fail-safe part is still intact. As a minimum, this shall require a visual inspection of each fail-safe part after every flight to ensure that the part has not failed. Such inspections need not require disassembly except as necessary to gain visual access to the part. Whether reusable or not, fail-safe weldments, brazed joints, and castings shall be 100 percent inspected for both surface and embedded flaws using the appropriate inspection methods of Table 7-1.

7.2.5 Compliance Procedures for Safe-Life Parts

As shown by the logic of Figure 7-1, all parts meeting the requirements of paragraph 7.1.4 are classified as fracture critical and may be disposed of as acceptable parts by all of the following procedures:

a. The fracture critical part tracking, control, and documentation procedures of paragraph 7.3.2 shall be implemented.

b. The appropriate method(s) of NDE shall be performed on the part.

c. If cracks or significant crack-like defects are detected, the procedures of the GSFC PARD for Control, Disposition and Reporting of Discrepancies shall be followed. This may result in MRB action to determine whether the part is acceptable, is able to be repaired, or shall be scrapped. As a minimum, acceptance of parts with crack-like defects shall require a detailed fracture mechanics analysis of the specific crack/part geometry in question, concurrence of the FCC, and approval of the Project Manager and the NSTS Payload Safety Review Panel.

7.2.6 Compliance Procedures for Fasteners

For the purposes of this plan, a fastener is defined as any metallic element which joins other structural elements and transfers loads from one to the other across a joint. This includes all bolts, nuts, shear pins, and rivets.

Since fasteners transmit loads, nonfracture critical fasteners are defined as those which are fail-safe. Fracture critical fasteners are defined as those which are safe-life. Therefore, fasteners use the same logic as other general parts, Figures 7-1, 7-2, and 7-4, as applicable. Note however, that fasteners of a size that would release an uncontained fastener fragment weighing greater than 0.25 pound if failed can never be classified as fail-safe, even if they are redundant. For low fracture toughness metal fasteners preloaded in tension, failure may result in a high release velocity and therefore the total released mass may not exceed 0.03 pound. A fastener is considered to have low fracture toughness when its material property ratio $K_{Ic}/F_{ty} < 0.33 \sqrt{\text{inch}}$. If the part is a steel bolt and the K_{Ic} value is unknown, low fracture toughness is assumed when $F_{tu} > 180$ ksi. Fasteners smaller than 3/16 inch diameter shall not be used in fracture critical applications, unless reviewed by the FCC and approved by the Project Manager. Approval factors include effectiveness of NDE methods and preload control.

7.2.6.1 Nonfracture Critical Fasteners--The logic of Figure 7-1 shows that fasteners which comply with the fail-safe requirements of paragraph 7.1.3 are classified as nonfracture critical. Such fasteners may be disposed of as acceptable parts if the following procedures are implemented:

a. They are procured under, and meet the requirements of, the applicable MS or NAS standard for fasteners, or equivalent specification.

b. The nonfracture critical part control and documentation procedures of paragraph 7.3.1 are implemented.

c. Quality assurance procedures are implemented to ensure that fasteners have never been over-preloaded so as to cause general yielding. Over-preloaded fasteners shall be scrapped.

d. It can be shown by analysis or test that all bolt heads and fastener fragments weighing more than 0.25 pound are contained.

7.2.6.2 Fracture Critical Fasteners--The logic of Figure 7-1 shows that fasteners which are not fail-safe are classified as fracture critical. These fasteners may be disposed of as acceptable parts by all of the following procedures:

a. They are procured under, and meet the requirements of, the applicable MS or NAS standard for fasteners, or equivalent specification.

b. The fracture critical part tracking, control, and documentation procedures of paragraph 7.3.2 are implemented.

c. The fasteners are shown by analysis to satisfy the safe-life requirements of paragraph 7.1.4. The assumed initial flaw size and geometry shall be that specified for fasteners in the NASA/FLAGRO computer program.

d. The fasteners are subjected to the appropriate method(s) of NDE. Dye penetrant inspection shall be performed in accordance with MPD 313-009 or equivalent. Fasteners with rolled threads shall not be etched, in order to preserve dimensional tolerances and beneficial residual stresses. For custom made fasteners, etching shall be performed prior to final machining, as described in paragraph 7.1.4.2.a, and prior to any thread rolling operations.

e. No significant cracks or flaws are detected. If significant cracks or flaws are detected, the fastener shall be scrapped.

f. Quality assurance procedures are implemented to ensure that fasteners have never been over-preloaded so as to cause general yielding. Over-preloaded fasteners shall be scrapped.

7.2.7 Compliance Procedures for Pressurized Systems

The Maximum Design Pressure (MDP) for a pressurized system shall be the highest pressure defined by maximum relief pressure, maximum regulator pressure, or maximum temperature. Transient pressures shall be considered. Design factors of safety shall apply to MDP. Where pressure regulators, relief devices, or a thermal control system are used to control pressure, collectively they shall be two-fault tolerant from causing the pressure to exceed the MDP of the system. Pressure integrity shall be verified at the system level.

7.2.7.1 Pressure Vessels--For the purpose of STS payload safety, a pressure vessel is defined in NHB 1700.7B as a container that stores pressurized fluids and:

a. Will experience a design limit pressure greater than 100 psi, or

b. Contains a gas or liquid at a pressure in excess of 14.7 psia which will create a hazard if released, or

c. Contains stored energy of 14,240 ft-lbs or greater based on adiabatic expansion of a perfect gas.

Pressure vessels so defined are always classified as fracture critical and require the implementation of the fracture critical part tracking, control, and documentation procedures of paragraph 7.3.2. To comply with the STS safety requirements of NHB 1700.7B, pressure vessels shall comply with MIL-STD-1522A. In addition, all pressure vessels shall comply with the general requirements of paragraph 7.2.7.1.1.

Bosses and local mechanical attachment areas of pressure vessels shall comply with either the fail-safe requirements of paragraph 7.2.4 or the safe-life requirements of paragraph 7.2.5. Heat pipes are classified as pressurized components, not pressure vessels, and are therefore subject to the requirements of paragraph 7.2.7.3.

7.2.7.1.1 General Requirements--All pressure vessels shall comply with the following requirements:

a. All material properties used in stress and fracture mechanics analyses shall be appropriate for the environmental conditions, including temperature and chemical, which the vessel experiences in each phase of the mission lifetime.

b. Care shall be taken that fluids used for cleaning, inspection, test, and operation of pressure vessels are chemically compatible with all vessel materials. Consideration shall be given to the acceptability of possible fluid contaminants such as chlorides in hydrazine.

c. Materials which show either low or moderate resistance to stress corrosion cracking, or appear in either Tables II or III of MSFC-SPEC-522B, or are rated either "B" or "C" in MSFC-HDBK-527/JSC 09604 should not be used for the construction of pressure vessels.

d. In addition to other required analyses, composite pressure vessels shall be assessed for adequate stress rupture life.

e. Pressure vessels shall be documented as required in JSC 13830A.

f. In addition to fracture control requirements, the structural integrity of pressure vessels for flight loading environments shall be demonstrated in accordance with NSTS 14046.

7.2.7.1.2 MIL-STD-1522A--In order for pressure vessels to comply with fracture control requirements using MIL-STD-1522A, the following tests and analyses shall be required. The use of paragraphs 5.1.3 and 5.2.3 of MIL-STD-1522A (approach "B" of Figure 2) is not acceptable. MDP shall be substituted for all references to Maximum Expected Operating Pressure (MEOP) in MIL-STD-1522A.

a. A complete stress analysis shall be performed showing that the minimum calculated burst pressure is at least 1.5 times the MDP.

b. A failure mode determination shall be performed by analysis to determine whether the vessel is leak-before-burst (LBB) nonhazardous, brittle, or LBB hazardous.

c. For vessels which are LBB nonhazardous, a conventional fatigue analysis shall be performed showing that the unflawed vessel has adequate fatigue life (4 times the required life) considering all loading.

d. For vessels which are brittle or LBB hazardous, a fracture mechanics safe-life demonstration shall be performed by analysis or test.

e. For all vessel types, a burst test on a qualification test (nonflight) unit vessel shall be performed showing that the actual burst pressure is at least 1.5 times the MDP. With the concurrence of the FCC and the approval of the Project Manager, a proof test to 1.5 times the MDP on a flight vessel may be substituted for this test.

f. For all vessel types, a cycle test on a second qualification test unit vessel shall be performed showing a life cycle capability of at least 4 times the maximum predicted number of operating cycles at the MDP. For LBB nonhazardous vessels, the test may be performed at 1.5 times the MDP for 2 times the maximum predicted number of operating cycles. In either case, the test shall be run for a minimum of 50 cycles. With the concurrence of the FCC and the approval of the Project Manager, a fatigue analysis showing that the unflawed vessel has 10 times the required life may be substituted for this test.

g. A pressure test on the second qualification test unit vessel (which was previously cycle tested) shall be performed showing no burst at 1.5 times the MDP. With the concurrence of the FCC and the approval of the Project Manager, this test may be deleted.

h. Complete 100% inspection for surface and embedded flaws by appropriate methods and levels of NDE shall be performed on every flight unit vessel before proof testing.

i. A proof test on every LBB nonhazardous flight unit vessel shall be performed at a pressure equal to (1 + Burst Factor) divided by 2 times the MDP, or to 1.5 times the MDP, whichever is lower. For every brittle or LBB hazardous flight unit vessel, a proof test shall be performed at a pressure defined by the fracture mechanics safe-life analysis or to a minimum of 1.25 times the MDP.

j. NDE of welds for embedded cracks shall be performed after proof testing of every flight vessel.

7.2.7.1.3 Inspection and Initial Crack Sizes--As the logic of Figure 7-3 shows, 100% inspection of pressure vessels for cracks and flaws shall be performed by NDE or proof test or both for surface and embedded flaws. When access to the inside of a finished vessel for the purposes of NDE inspection is not possible, dye penetrant inspection should be performed on both the inside and outside of the vessel pieces before welding or joining. After welding, the outside should be reinspected using dye penetrant, and the welds should be inspected using X-ray. The initial crack sizes given in Table 7-1 for the inspection level used shall be the smallest sizes used in the fracture mechanics analysis, unless special NDE has been approved by the Project Manager. The analysis shall consider the crack geometries in Figure 7-5, and crack aspect ratios (a/2c) in the range between 0.05 and 0.5 for equal area cracks. Inspection of pressure vessels may also be effectively carried out with a proof test at either room or cryogenic temperatures. In this case, the initial crack sizes used in the fracture mechanics analysis shall not be smaller than those screened by the proof test in accordance with paragraph 7.1.4.2. NDE of welds for embedded flaws shall be performed after proof testing of the pressure vessel.

7.2.7.1.4 Loading Spectrum--The loading spectrum used in fracture mechanics analysis of pressure vessels shall include all of the following loadings as appropriate:

a. All leak and proof test pressure cycles.

b. All mechanical test load cycles.

c. All temperature and pressure cycles associated with prelaunch and operation in the STS.

d. All temperature and pressure cycles associated with on-orbit operations with doors open.

e. All pressure and temperature cycles associated with abort landing.

f. All mechanically applied acceleration, vibroacoustic and thermal loads due to lift-off through landing. Appendix A, or equivalent, shall be used for lift-off, ascent, descent, and landing pressure cycles (with appropriate R-ratio), if any.

g. All postlanding temperature and pressure load cycles while in the cargo bay due to soak-back from the STS.

7.2.7.1.5 Acceptance Criteria--The fracture mechanics analysis shall ensure that no environmentally caused growth of preexisting cracks or flaws can occur under sustained loading by showing that $K_{sus} < K_{Iscc}$. In addition, pressure vessels shall satisfy one of the following acceptance criteria:

a. Leak But No Burst Criterion. If the vessel is LBB nonhazardous, then it is acceptable to allow the assumed initial crack to grow through the vessel wall and cause a leaking condition within four mission lifetimes. The fracture mechanics analysis shall assure, however, that the initial crack does not grow to a size which would cause unstable propagation and explosive failure of the vessel.

b. No Leak, No Burst Criterion. For all brittle or LBB hazardous vessels, the fracture mechanics analysis shall assure that neither leak nor burst of the vessel occurs within four mission lifetimes. This criterion shall require that the assumed initial crack neither grows through the thickness nor grows to a size which would cause unstable propagation and explosive failure of the vessel.

7.2.7.2 Dewars--Cryostats and dewars shall be subject to the criteria for pressure vessels specified in paragraph 7.2.7.1 as modified by the following requirements:

a. Pressure containers shall be LBB designs where possible as determined by a fracture mechanics analysis. Containers of hazardous fluids and all non-LBB designs shall employ a fracture mechanics safe-life approach to ensure safety of operation.

b. MDP of the pressure container shall be as defined in paragraph 7.2.7 or the pressure achieved under maximum venting conditions, whichever is higher. Relief devices shall be sized for full flow at MDP.

c. Outer shells (i.e., vacuum jackets) shall have pressure relief capability to preclude rupture in the event of pressure container leakage. If pressure containers do not vent external to the dewar but instead vent into the volume contained by the outer shell, the outer shell relief devices shall be capable of venting at a rate to release full flow without outer shell rupture. Relief devices shall be redundant and individually capable of full flow.

d. Pressure relief devices which limit MDP shall be certified to operate at the required conditions of use. Certification shall include testing of the same part number from the flight lot under the expected use conditions.

e. Non-hazardous fluids may be vented into the cargo bay if analysis shows that a worst case credible volume release will not affect the structural integrity or thermal capability of the STS.

f. The proof test factor for each flight pressure container shall be a minimum of 1.1 times the MDP. Qualification burst and pressure cycle testing is not required if all other requirements of paragraph 7.2.7.1 are met. The structural integrity for external load environments shall be demonstrated in accordance with NSTS 14046.

7.2.7.3 Lines, Fittings, and Components--Pressurized lines, fittings, and other pressure system components or equipment not defined as pressure vessels, including heat pipes, shall be classified as fracture critical if they contain hazardous fluids or if loss of pressurization would result in a catastrophic hazard.

7.2.7.3.1 Nonfracture Critical Lines, Fittings, and Components--Lines, fittings, and components which do not contain hazardous fluids or which would not cause a catastrophic hazard due to loss of pressurization are classified as nonfracture critical. Such parts may be disposed of as acceptable by the following procedures:

a. The safety factor requirements of NHB 1700.7B shall be demonstrated by stress analysis or manufacturer's certified test data.

b. Prior to assembly, individual flight parts or subassemblies shall be proof tested to a minimum of 2.0 times the MDP.

c. The completely assembled pressure system shall be proof tested to a minimum of 1.5 times the MDP and leak checked to demonstrate system integrity.

7.2.7.3.2 Fracture Critical Lines, Fittings, and Components--Lines, fittings, and components which contain hazardous fluids or which would cause a catastrophic hazard due to loss of pressurization are classified as fracture critical. Such parts may be disposed of as acceptable by the following procedures:

a. The safety factor requirements of NHB 1700.7B shall be demonstrated by stress analysis or manufacturer's certified test data.

b. Prior to assembly, individual flight parts shall be proof tested to a minimum of 2.0 times the MDP.

c. The completely assembled pressure system shall be proof tested and leak checked to demonstrate system integrity. Safe-life analysis is not required on fracture critical pressurized lines, fittings, and components which are proof tested at the system level to a minimum of 1.5 times the MDP and meet the safety factor requirements of NHB 1700.7B.

d. All welds and fusion joints shall be inspected for embedded flaws using appropriate NDE method(s) after system proof testing. If the assembled pressure system geometry precludes effective NDE, concurrence of the FCC and approval of the Project Manager is required to perform the NDE before proof testing or to omit it.

e. If cracks or significant crack-like defects are detected, the procedures of the GSFC PARD for Control, Disposition and Reporting of Discrepancies shall be followed. This may result in MRB action to determine whether the part is acceptable, is able to be repaired, or shall be scrapped. As a minimum, acceptance of parts with crack-like defects shall require a detailed fracture mechanics analysis of the specific crack/part geometry in question, concurrence of the FCC, and approval of the Project Manager and the NSTS Payload Safety Review Panel.

7.2.8 Compliance Procedures for Preventing Stress Corrosion Cracking (SCC)

Paragraph 208.3 of NHB 1700.7B specifies that materials selected for use in STS payloads shall be rated for resistance to stress corrosion cracking (SCC) in accordance with the tables in MSFC-SPEC-522B and/or MSFC-HDBK-527/JSC 09604. MSFC-HDBK-527/JSC 09604 may be used to supplement the tables of MSFC-SPEC-522B in that materials rated "A" for SCC may be used as Table I materials, "B" materials may be used as Table II, and "C" materials may be used as Table III.

Materials of Table I or rated "A" do not require safety approval and may be used without restriction, subject to satisfying all other fracture control requirements in this plan. Those on Tables II or III or rated "B" or "C" but which do not pose a hazard to the STS require this fact to be documented on the payload Hazard Report and approved by the STS Payload Safety Review Panel at the JSC. Table II, III, "B", or "C" materials which could cause a catastrophic hazard to the STS require GSFC approval of an MUA and JSC Safety Review Panel approval of the Hazard Report. Materials of unknown SCC resistance in a hazardous application shall be treated as Table III materials. Figure 7-4 presents the SCC requirements logic.

The Payload Safety Compliance Data Package including all Hazard Reports and required MUA's shall initially be submitted to the GSFC Project Manager. The FCC, with the support of the cognizant discipline organization(s), shall evaluate the package and recommend approval/disapproval to the Project Manager who may forward the package to the JSC, if appropriate.

7.2.8.1 Nonfracture Critical Parts--As shown by the logic of Figure 7-4, the use of parts made of materials which are not highly resistant to SCC (Table II or III of MSFC-SPEC-522B or "B" or "C" rating of MSFC-HDBK-527/JSC 09604) may be permitted if their failure cannot cause a hazard to the STS and a Hazard Report is approved by the STS Payload Safety Review Panel. Such parts are by definition nonfracture critical and may be disposed of as acceptable parts by any one of the following procedures:

a. The part meets all the requirements for low-released mass parts in paragraph 7.12.1.

b. The part meets all the requirements for contained parts in paragraph 7.1.2.

c. The part meets all the requirements for fail-safe parts in paragraph 7.1.3. However, if the structure remaining after failure of the part relies for its structural integrity on one or more elements made of materials which are not on Table I or rated "A", one of the following additional requirements shall be satisfied for those parts of the remaining structure. Note that these additional requirements depend only on the SCC resistance of the remaining structure and are required regardless of the SCC resistance of the fail-safe part.

(1) The material is protected at all times from aggressive environments by sealing, coating, maintenance of an inert atmosphere, or other measures which have documented ability to prevent SCC.

(2) The part is fabricated of aluminum alloy sheet of an original as-rolled thickness of less than 0.25 inch (or, for fasteners, an original as-formed diameter of less than 0.25 inch) and (a) no intermittent annealing, welding, or other heating operations occurred during forming or fabrication which might produce an equiaxed grain structure and (b) the surfaces of the part were not machined in such a way as to expose the short transverse grain of the material which can then be subjected to sustained tensile stresses.

(3) Stress analyses are performed which consider all sustained tensile stresses due to residual, assembly, and operational stresses. These analyses shall show that these stresses are below well-documented threshold stresses for SCC in all grain directions.

7.2.8.2 Fracture Critical Parts--As shown by the logic of Figure 7-4, the use of parts made of materials which are not highly resistant to SCC (Table II or III of MSFC-SPEC-522B or "B" or "C" rating of MSFC-HDBK-527/JSC 09604), even if their failure could cause a catastrophic hazard to the STS, may be permitted if an MUA is approved by the GSFC and a Hazard Report is approved by the STS Payload Safety Review Panel. These parts are by definition fracture critical and shall meet all the requirements for fracture critical parts in paragraphs 7.2.5, 7.2.6, 7.2.7, or 7.2.12, as appropriate, as well as the fracture critical part tracking, control and documentation procedures of paragraph 7.3.2. In addition, all fracture critical parts made of materials which are not highly resistant to SCC shall meet one of the following requirements:

a. The material is protected at all times from aggressive environments by sealing, coating, maintenance of an inert atmosphere, or other measures which have documented ability to prevent SCC.

b. The part is fabricated of aluminum alloy sheet of an original as-rolled thickness of less than 0.25 inch (or, for fasteners, an original as-formed diameter of less than 0.25 inch) and (1) no intermittent annealing, welding, or other heating operations occurred during forming or fabrication which might produce an equiaxed grain structure and (2) the surfaces of the part were not machined in such a way as to expose the short transverse grain of the material which can then be subjected to sustained tensile stresses.

c. Stress analyses are performed which consider all sustained tensile stresses due to residual, assembly, and operational stresses. These analyses shall show that (1) these stresses are below well-documented threshold stresses for SCC in all grain directions and (2) the stress intensity factors resulting from these stresses and initial crack sizes consistent with Table 7-1 for the inspection level used on the part are below the well-documented values of KI_{scc} for all grain directions. The latter requirement shall be satisfied after the four-mission-lifetime requirement for safe-life crack growth has been met.

7.2.9 Compliance Procedures for Glass and Glass-Like Materials

Parts made of glass and glass-like materials shall be classified as fracture critical or nonfracture critical using the same logic as used for other structural parts, Figure 7-1.

7.2.9.1 Nonfracture Critical Glass Parts--Parts made of glass and glass-like materials may be disposed of as acceptable parts by any one of the following procedures:

a. The part shall be shown to meet all the requirements for low-released mass parts in paragraph 7.1.1.

b. The part shall be shown to meet all the requirements for contained parts in paragraph 7.1.2.

c. The part shall be shown to meet all the requirements for fail-safe parts in paragraph 7.1.3.

7.2.9.2 Fracture Critical Glass Parts--As the logic of Figure 7-1 shows, parts made of glass or glass-like materials which do not satisfy the requirements in paragraph 7.2.9.1 are classified as fracture critical. These parts may be disposed of as acceptable by all of the following procedures.

a. The part shall be shown to be safe-life by performing NDE or a proof test at a stress level sufficiently high to detect flaws or cracks of a size which will not grow to failure or instability in four times the service lifetime during which the part is under sustained tensile stress. The maximum sustained tensile stress on the part shall then be limited throughout its lifetime to the level for which the part is safe-life for this proof test. In cases where sufficient crack growth rate data are not available for the material, testing shall be required to generate the data. NDE shall not be used to inspect for flaws or cracks in these materials unless it can be documented that the methods and levels used can reliably detect flaws small enough to meet safe-life requirements.

b. If NDE methods are used to establish initial crack sizes, it shall be demonstrated and documented that the NDE methods can reliably detect these crack sizes. 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 0.1 inch in length when proper lighting is applied at right angles to the actual flaw orientation.

c. Proof testing shall be performed on pressurized glass components such as windows or view ports.

7.2.10 Compliance Procedures for Fiber-Reinforced Composite Materials

Due to difficulties with NDE and/or fracture mechanics analysis, fracture control of fiber-reinforced composite materials (both metallic and non-metallic matrix), requires several considerations which are different than those for metallic materials. In particular, the use of these materials requires adherence to stringent quality control procedures. All parts made of any fiber-reinforced composite material, including bonded joints between these materials, shall meet the structural verification requirements of NSTS 14046. Furthermore, the payload designer or 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 and bonded structures. Supporting data shall be included in the FCIP to verify that as-built flight articles satisfy design and analysis assumptions, mathematical models, and all technical requirements. Test articles shall be demonstrated to be representative of the flight hardware by adequate process control and configuration management. Metallic honeycomb parts should not be treated as fiber-reinforced composite parts, but are subject to the general requirements of paragraphs 7.2.2 through 7.2.5.

7.2.10.1 <u>Nonfracture Critical Fiber-Reinforced Composite Parts</u>--Except as otherwise directed by hazard analyses, composite and bonded parts or components may be classified as nonfracture critical only if it is shown that one of the following conditions is satisfied:

a. The part meets all the requirements for low-released mass parts in paragraph 7.1.1.

b. The part meets all the requirements for contained parts in paragraph 7.1.2.

c. The part meets all the requirements for fail-safe parts in paragraph 7.1.3.

d. The strain level at design limit load is less than the composite or bonded part's damage tolerance threshold strain level. The threshold strain level shall be determined by testing appropriate preflawed coupons or, if reviewed by the FCC and approved by the Project Manager, by using available data.

7.2.10.2 <u>Fracture Critical Fiber-Reinforced Composite Parts</u>--All composite and bonded parts which do not meet the criteria of paragraph 7.2.10.1 are classified as fracture critical and shall be shown to meet fracture control requirements by one of the following methods:

a. A proof test (static or dynamic) shall be performed on the flight part to no less than 1.25 times the limit load. The test may be accomplished at the component or subassembly level if the loads on the part duplicate those that would be seen in a fully assembled structure.

b. A damage-tolerance test program shall be implemented to establish that these parts possess at least four service lifetimes. These tests shall be conducted on full scale flight-like parts and samples with controlled flaws or damages. The size and 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 that which could occur on the flight part.

For all fracture critical composite or bonded parts, procedures for the prevention of damage resulting from handling or final assembly shall be addressed in the FCIP and approved by the Project Manager.

7.2.11 Compliance Procedures for Hydrogen Embrittlement Relief

The fracture control procedures contained in this paragraph are required for fail-safe and safe-life parts which are made of electroplated or electroless plated metallic materials possessing an ultimate tensile strength greater than 150 ksi or a hardness greater than HRC 33 (titanium alloys excluded). The required hydrogen embrittlement relief procedure consists of baking parts within 4 hours, and preferably within 1 hour, after plating for a minimum of 23 hours at 375 ± 25 degrees Fahrenheit. Steps shall be taken to ensure that the hydrogen content of titanium alloys does not exceed 200 PPM as a result of etching and plating processes. The preceding bakeout is ineffective for titanium.

7.2.12 Compliance Procedures for Rotating Machinery

Rotating machinery and mechanical assemblies shall be classified as fracture critical or nonfracture critical using the same logic as used for other structural parts, Figure 7-1. However, assemblies having a rotational kinetic energy of 14,240 ft-lbs or greater (based on the quantity $\frac{1}{2}Iw^2$) shall always be classified as fracture critical.

7.2.12.1 Nonfracture Critical Rotating Machinery--Each part of a rotating assembly may be disposed of as acceptable by any one of the following procedures:

a. The part shall be shown to meet all the requirements for low-released mass parts in paragraph 7.1.1.

b. The part shall be shown to meet all the requirements for contained parts in paragraph 7.1.2.

c. The part shall be shown to meet all the requirements for fail-safe parts in paragraph 7.1.3.

7.2.12.2 Fracture Critical Rotating Machinery--Rotating machinery not meeting the requirements of paragraph 7.2.12.1, or having a kinetic energy of 14,240 ft-lbs or greater, is classified as fracture critical. These parts may be disposed of as acceptable by all of the following procedures:

a. The part shall be shown to meet all the requirements for safe-life parts of paragraph 7.1.4.

b. Initial crack sizes used in the safe-life assessment shall be based on proof testing. A proof (spin) test shall be performed at a sufficient level to detect the required flaws as described in paragraph 7.1.4.2.c, or to the level required for strength verification, whichever is higher.

c. NDE shall be performed before and after proof testing. If cracks or significant crack-like defects are detected, the procedures of the GSFC PARD for Control, Disposition and Reporting of Discrepancies shall be followed. This may result in MRB action to determine whether the part is acceptable, is able to be repaired, or shall be scrapped. As a minimum, acceptance of parts with crack-like defects shall require a detailed fracture mechanics analysis of the specific crack/part geometry in question, concurrence of the FCC, and approval of the Project Manager and the NSTS Payload Safety Review Panel.

7.3 TRACKING, CONTROL, AND DOCUMENTATION REQUIREMENTS

It is not the intent of this plan to require a single fracture control document containing all of the information required in the following paragraphs. Wherever possible, already existing documentation (e.g., drawings, test reports, stress analysis reports, etc.) may be used to satisfy the fracture control documentation requirements if, in the aggregate, all of the information required in the following paragraphs is available. In such cases, however, a chart or document shall be required which gives the identification and location of the separate documents which make up the fracture control documentation.

7.3.1 Nonfracture Critical Parts

Parts which are not fracture critical by the logic of Figure 7-1 require no special tracking procedures but do require the normal quality control procedures in the GSFC PARD and the normal GSFC CM procedures in GMI 8040.1A (or GSFC-approved contractor CM procedures). A summary listing giving the identification of each part, its fracture control classification (low-released mass, contained, or fail-safe) and its SCC resistance (high, moderate, or low) shall be deliverable. In addition, nonfracture critical parts shall be supported by the following fracture control documentation.

a. A description of the part with weight, identification of material, alloy and temper along with procurement specifications, as appropriate.

b. A report of the analysis or test by which the part was shown to comply with the containment or fail-safe requirements. (Test plans shall be available in advance of the tests.)

c. The reports of any MRB action on discrepant parts.

d. An assessment of the SCC resistance of the part material.

e. Any updates or revisions to the required data.

7.3.2 Fracture Critical Parts

Due to the necessity of controlling the risks imposed by fracture critical parts, the more stringent than normal control procedures contained in the following paragraphs shall be implemented in addition to the quality control procedures in the GSFC PARD and the GSFC CM procedures of GMI 8040.1A (or GSFC-approved contractor CM procedures). All logs and documentation shall be deliverable.

7.3.2.1 Tracking Requirements--Fracture critical parts shall be identified and accounted for by the following procedures:

a. Drawings for fracture critical parts shall contain notes which identify the part as fracture critical and specify the appropriate inspection procedures to be used on the part. Installation or assembly drawings may satisfy this requirement where appropriate.

b. Drawings and revisions for fracture critical parts shall be reviewed by the FCC.

c. For pressure vessels, fiber-reinforced composite parts, and limited life parts, a log or record shall be maintained which documents the environmental aspects of all storage conditions during the life of the part. Logs for identical parts which are stored as part of an assembly may be maintained at the assembly level.

d. A log or record shall be maintained which documents all loading of fracture critical parts due to testing and assembly, including torquing of fracture critical fasteners. The log shall devote particular attention to overloading and overtorquing (yielding), the occurrence of which shall be submitted to the FCC for review and recommendation. Logs for identical parts which are loaded as part of an assembly (e.g., fasteners) may be maintained at the assembly level.

e. A log shall be maintained, as required by NHB 1700.7B, for each pressure vessel/system documenting the complete pressurization history, all fluid exposures, and other pertinent data.

7.3.2.2 Documentation Requirements--Each fracture critical part shall be supported by a document that supplies the following data, as appropriate:

a. A description of the part with identification of material, alloy and temper, and a sketch showing the size, location, and direction of all assumed initial cracks.

b. The description and source of the loading spectrum used in the fracture mechanics analysis.

c. The detailed stress analysis which predicted the stress levels used in the loading spectrum.

d. The detailed fracture mechanics analysis by which the part was shown to be safe-life.

e. The reports of all inspections and NDE. The reports of any MRB action on discrepant parts.

f. Certification of special NDE inspectors and procedures.

g. An assessment of the SCC resistance of the part material.

h. A description of any special crack growth retarding features necessary to meet the requirements for safe-life, such as shot-peening, interference-fit fasteners, crack-stoppers, cold-worked holes, etc.

i. Final review by the FCC including date, acceptance method, and review findings.

j. Any updates or revisions to the required data.

8.0 ALTERNATIVES TO REDESIGN OF PARTS NOT MEETING SAFE-LIFE REQUIREMENTS

In the event that a particular requirement of this document cannot be met for a specific payload component, but an alternative or modified fracture control approach can be utilized to preclude the direct or indirect catastrophic hazard to the STS and its crew, a Hazard Report describing the alternate approach shall be prepared by the organization with the primary responsibility or the development of the payload. The Hazard Report shall be in accordance with JSC 13830A or alterations specified by JSC for NASA payloads. The report shall be approved by the Project Manager and the NSTS Payload Safety Review Panel at the earliest possible time but no later than the Phase III Safety Review. The following alternative procedures may be considered to show compliance with the objective of this plan:

a. Repeat the fracture mechanics analysis of paragraph 7.1.4.1 with more realistic, but never unconservative, loading spectra, crack growth rate equations, temperatures, environments, or material properties.

b. Where possible, reduce life requirements, loads, or pressures through redefinition of design requirements. Reanalyze to show compliance with safe-life requirements.

c. Introduce crack growth retarding design features which have documented effectiveness, such as shot-peening, crack-stoppers, cold-worked holes, or interference-fit fasteners. The use of such features shall require advance coordination with the FCC and approval by the Project Manager.

d. Repair a crack or flaw in the part using techniques which have been approved by the MRB. Repair techniques shall have demonstrated ability to rectify the deficiency in the part. After repair, the part shall be thoroughly reinspected using appropriate NDE methods and levels.

e. Perform full-scale cracked component testing under realistic conditions of loading, cycles, flaw size, and environment. If the component test shows that the safe-life requirements are satisfied, then the flight (untested) part is acceptable.

f. For payloads whose mission lifetime is more than one flight, establish reinspection, refurbishment, or proof tests at intervals equal to one-quarter of the number of flights (rounded down to the next lowest integer) which the fracture mechanics analysis shows would cause failure of the part. The part then becomes a limited life part.

g. Request approval from the Project Manager for any reasonable set of circumstances or factors by which the requirements of this plan can be shown to be satisfied. This should be done as soon as it is known that these requirements cannot be satisfied. The FCC, with the support of the cognizant discipline organization(s), shall evaluate the request and recommend approval/disapproval to the Project Manger who may forward it as an NCR to the JSC, per JSC 13830A, if appropriate.

9.0 DEFINITIONS

Aggressive Environment -- Any liquid or gaseous media and temperature combination which degrades static or fatigue crack growth characteristics from "normal" behavior associated with a dry laboratory air environment at ambient temperature.

Allowable Load -- The load that induces the allowable stress in a material.

Allowable Stress -- The maximum stress that can be permitted in a material for a given operating environment to prevent rupture or collapse, detrimental deformation, or unacceptable crack growth. Allowable stresses in these cases are ultimate (or buckling) stress, yield (or microyield) stress, and safe-life stress, respectively. The stress has units of force per unit area.

Assembly -- A subdivision of a component consisting of parts or subassemblies. (See Component, Part, Subassembly.)

Assembly Stress -- A stress produced and remaining in a structural element by deformations due to assembly procedures, misalignment, or tolerance build-up.

Brittle Fracture Failure Mode Pressure Vessel--A pressure vessel, so defined by the Failure Mode Determination appendix of MIL-STD-1522A.

Burst Factor -- A multiplying factor applied to maximum design pressure (MDP) to obtain burst pressure.

Burst Pressure -- The product of the maximum design pressure (MDP) and the burst factor. It is the minimum pressure which the vessel must withstand without rupture or collapse in the expected operating environments.

Catastrophic Hazard -- The presence of a potential risk situation which results in the potential for personnel injury, loss or damage to the STS, ground facilities, or STS equipment.

Component -- A functional subdivision of a subsystem and generally a self-contained combination of items. (See Subsystem.)

Containment -- An acceptable fracture control classification in which payload elements are prevented from separating from the payload and being released into the STS cargo bay or crew compartment. (See paragraph 7.1.2 for specific criteria.)

Crack or Crack-like Defect -- A significant defect which behaves like an analytical model of a crack that may be initiated during material production, fabrication, or testing or developed during the service life of a component.

Crack Arresting Feature -- A design device or attribute which has the inherent ability to stop the growth of cracks. Examples are the creation of a compressive residual stress field or physical barriers to crack growth such as crack stoppers or discontinuous structural members.

Crack Aspect Ratio -- For a part-through crack, the ratio of crack depth to crack length (a/2c).

Crack Growth Rate (da/dN or dc/dN) -- The rate of change of crack half-length c or depth a with respect to the number of cycles N.

Crack Growth Retardation -- The reduction of crack growth rate due to intermittent overloading of the cracked structural member.

Critical Flaw Size -- The size of a flaw which, for given applied stresses and environment, causes unstable propagation of the flaw.

Critical Stress Intensity Factor (K_{IC}, K_{Ie}, or K_C) -- The value of stress intensity factor at the tip of a crack at which unstable propagation of the crack occurs. (See Fracture Toughness, K_{IC}, K_{Ie}, K_C.)

Cyclic Loading (Operating Cycles) -- A fluctuating load (or pressure) characterized by relative degrees of loading and unloading of a structure. Examples are loads due to transient responses, vibroacoustic excitation, flutter, and oscillating or reciprocating mechanical equipment.

Element -- As used in this document, refers to component, assembly or part, depending on context.

Factor of Safety (F.S.) -- A multiplying factor applied to limit load or stress to obtain the required minimum design ultimate (or yield) load or stress. The factor of safety is used to account for design uncertainties that cannot be analyzed or accounted for in a rational manner. For example, a factor of safety would be used because of the designer's inability to predict complex stress distributions or because fabrication processes cannot be controlled to produce ideal or identical structures.

Fail-Safe -- An acceptable fracture control classification in which the structure is designed with sufficient redundancy so that the failure of one structural element does not cause general failure of the entire structure or hazard to the STS. (See paragraph 7.1.3 for specific criteria.)

Failure -- The rupture, collapse, seizure, excessive wear, or any other phenomenon resulting in an inability to sustain ultimate loads, pressures, and environments or perform designated function.

Fastener -- Any metallic element which joins other structural elements and transfers loads from one to the other across a joint.

Fatigue -- In materials and structures, the cumulative irreversible damage incurred by cyclic application of loads in given environments. Fatigue can initiate and extend cracks which degrade the strength of materials and structures.

Flaw or Flaw-like Defect -- A significant defect which behaves like an analytical model of a crack that may be initiated during material production, fabrication, or testing, or developed during the service life of a part.

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 structural part which requires special treatment to control the risk of a failure which would cause a catastrophic hazard. (See paragraph 7.2.1 for specific criteria.)

Fracture Mechanics -- An engineering discipline which describes the propagation behavior of cracks or crack-like defects in materials under stress.

Fracture Toughness -- An inherent property of a material which reflects the material's resistance to fracture. In fracture mechanics analysis, failure is assumed imminent when the applied stress intensity factor is equal to or exceeds the fracture toughness.

F_{tu} -- Ultimate tensile strength.

F_{ty} -- Tensile yield strength.

Initial Flaw or Crack -- A flaw or crack assumed to exist in a part before it is subjected to applied loads or environmental effects.

Initial Flaw or Crack Size -- The maximum flaw or crack size, as defined by proof test, or nondestructive examination which is assumed to exist for the purpose of performing a safe-life evaluation.

K (Stress Intensity Factor) -- A calculated quantity which is used in fracture mechanics analysis as a measure of the stress-field intensity near the tip of an idealized crack. Calculated for a specific crack size, applied stress level and part geometry.

K_{IC} (Plane Strain Fracture Toughness) -- The critical value of stress intensity factor at the crack tip under conditions of plane strain. The lower bound on critical stress intensity factor which is a material property independent of part size or geometry. Must be measured in accordance with the requirements of ASTM Specification E399-72. (See Critical Stress Intensity Factor.)

K_{Ie} (Effective Fracture Toughness) -- The critical value of stress intensity factor at the crack tip for surface or elliptically shaped cracks. Used instead of K_{IC} for surface and elliptical cracks.

K_{ISCC} (Threshold Stress Intensity Factor) -- The stress corrosion or environmental cracking threshold for no crack growth under sustained stress conditions.

K_C (Critical Stress Intensity Factor) -- The measured value of stress intensity factor at the tip of a crack at which unstable propagation of the crack will occur. Depends on part geometry, size and stress state and therefore is not a true material property.

K_{sus} -- The stress intensity factor at the tip of a crack due to sustained loading.

K_{TH} -- See K_{ISCC}.

K_o -- The measured stress intensity range below which crack growth will not occur for cyclic loading.

Leak-Before-Burst (LBB) Hazardous -- A pressure vessel is LBB hazardous if it contains a hazardous fluid. Safe-life analysis is required to show that neither leak nor burst will occur within four mission lifetimes.

LBB Nonhazardous -- A pressure vessel is LBB nonhazardous if it does not contain a hazardous fluid and it can be shown that any initial flaw will grow through the wall and cause leakage rather than burst.

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

Limit Load or Stress -- The maximum load or stress expected to act on a structure in the expected operating environments.

Limit Pressure -- The maximum differential pressure that can be expected to occur in service under the expected operating environments.

Linear Elastic Fracture Mechanics -- See Fracture Mechanics.

Loading Event -- A condition, phenomenon, environment, or mission phase to which the payload is exposed and which induces loads in the payload structure.

Loading Spectrum (History) -- A representation of the cumulative static and dynamic loadings anticipated for a structural element under all expected operating environments. May be expressed in terms of acceleration, force, or stress.

Low Frequency Transient Load -- A load induced in a payload structure by its dynamic response to a low frequency (less than about 50 Hz) loading event such as STS lift-off or landing. The duration, direction, magnitude and frequency content of a transient load are significant, and the payload response depends on the dynamic characteristics of the payload structure.

Margin of Safety -- The increment by which the allowable load or stress exceeds the limit load or stress (multiplied by the required safety factor) for a specific design condition, expressed as a fraction of the limit load or stress (multiplied by the required safety factor).

$$M.S. = \frac{\text{Allowable Load or Stress}}{\text{Limit Load or Stress X F.S.}} - 1$$

where: Allowable is the maximum permitted for yield, ultimate, microyield, etc.

Limit is the minimum expected under all operating conditions.

F.S. is factor of safety.

The margins so determined are used as final indicators of available strength after all other design characteristics, conditions, and factors have been accounted for in each service condition.

Maximum Design Pressure (MDP) -- For a pressure vessel, Maximum Design Pressure is the highest possible pressure occurring from maximum relief pressure, maximum regulator pressure, maximum temperature, or transient pressure excursions.

Mean Stress -- The steady-state or average value of stress about which the variable or cyclic stress oscillates.

Mission Lifetime -- The specified design conditions or loading events which define the duration and character of the payload mission. A typical mission lifetime for an STS payload includes fabrication, testing, transportation, some number of STS launches and landings, and some number of on-orbit environmental exposures or deployments.

Nondestructive Examination (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 and characterize flaws. NDE method refers to the specific technique used such as dye penetrant, X-ray, etc. NDE level refers to the degree of resolution of the technique such as standard or special. Also known as nondestructive evaluation (NDE) or nondestructive inspection (NDI).

Operational Load (Stress) -- A load or stress produced in a payload structure as a result of operational events such as launch, deployment or landing as distinct from such loading events as testing or transportation.

Part -- The lowest subdivision of a subassembly in which each part is a separate and distinct element not normally separated into further subdivisions without destruction or loss of the ability to perform its design functions.

Payload -- Any equipment or material carried by the STS that is not considered part of the basic STS itself. It therefore includes items such as free-flying automated spacecraft, individual experiments or instruments, subsystems and appendages, etc. The term payload also includes payload-provided GSE and systems, and flight ground systems software.

Pressure Vessel -- A container that stores pressurized fluids and:

a. Contains stored energy of 14,240 ft-lbs (19,310 joules) or greater based on adiabatic expansion of a perfect gas; or

b. Contains a gas or liquid at a pressure in excess of 14.7 psia which will create a hazard if released; or

c. Will experience a design limit pressure greater than 100 psi.

Proof Test -- The test of a flight structure at a proof load or pressure which will give evidence of satisfactory workmanship and material quality or will establish the initial flaw sizes in the structure.

Qualification Test -- A test conducted on flight-quality structures at load levels which are higher than flight levels and sufficient to demonstrate that structural design requirements have been achieved. Test factors and methods are specified by the responsible organization.

Residual Stress -- A stress that remains in the structure due to processing, fabrication, or prior loading.

Rotational Kinetic Energy--The kinetic energy of a rotating component equal to ½ Iw, where "I" is the moment of inertia and "w" is the rotational frequency.

Safe-Life -- An acceptable fracture control classification which requires 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 encountered in four complete mission lifetimes.

Service Life -- The interval beginning with manufacture of a payload and ending with completion of its specified mission.

Scatter Factor -- A multiplication factor applied to the required service life of the structure. The product of the scatter factor and required life is used as the predicted service life to allow for material property and fracture mechanics analysis uncertainties.

Short Transverse Grain Direction -- The direction perpendicular to the direction of rolling and parallel to the thickness of rolled plate metallic materials.

Special Nondestructive Examination (NDE) -- The formal inspection of parts using nondestructive procedures involving the use of techniques and/or equipment that exceed common industrial standards. Inspectors and their procedures shall be certified by the GSFC or Rockwell International, STS Division, Downey, CA for special NDE.

Standard Nondestructive Examination (NDE) -- The formal inspection of parts using nondestructive procedures consistent with common industrial standards. These standard procedures include dye-penetrant, eddy-current, magnetic particle, ultrasonic and X-ray.

Static Load (Stress) -- A load or stress of constant magnitude and direction with respect to the structure.

Stress Concentration -- The effective increase in stress level near a local discontinuity in a structural member when compared to the stress level at locations remote from the discontinuity.

Stress Corrosion Cracking (SCC) -- The initiation and/or propagation of cracks due to the combined action of applied tensile stresses and aggressive environmental effects.

SCC Threshold Stress -- The applied tensile stress level below which SCC is not expected to occur.

SCC Susceptible Material -- Any metallic material not listed in Table I of MSFC-SPEC-522B, not rated "A" in MSFC-HDBK-527/JSC 09604, or otherwise documented to possess low or moderate resistance to SCC.

Stress Intensity Factor (K) -- A calculated quantity which is used in fracture mechanics analysis as a measure of the stress-field intensity near the tip of an idealized crack. Calculated for a specific crack size, applied stress level, and part geometry.

Stress Ratio -- The ratio of the minimum (lowest algebraic value) stress to maximum (highest algebraic value) stress with stresses positive when tensile.

Stress Rupture Life (Composite) -- Analytical ability of the composite to maintain structural integrity during the required service life considering the combined efforts of stress level(s), time at stress level(s), and associated temperatures.

Structural Redundancy -- A characteristic of a structure which provides more than the minimum number of load paths required to prevent kinematic motion of the structural members. Also called an indeterminate structure because the number of unknown internal member forces exceeds the number of equations of equilibrium of the structure.

Structure -- All parts of all components, assemblies, and subassemblies which sustain loads or pressures, provide stiffness and stability, or provide support or containment.

Subassembly -- A subdivision of an assembly consisting of two or more parts.

Subsystem -- A functional subdivision of a payload consisting of two or more components.

Thermal Load (Stress) -- The structural load or stress arising from temperature gradients and differential thermal expansion between structural components, assemblies, subassemblies, or parts.

Threshold Stress Intensity Factor (K_{ISCC} or K_{TH}) -- The maximum value of stress intensity factor for a given material at which no environmentally induced crack growth will occur for the specified environment.

Threshold Strain Level -- The value of strain level, below which catastrophic failure of the composite structure will not occur in the presence of flaws/damages under service load/environmental conditions.

Ultimate Strength -- Corresponds to the maximum load or stress that an unflawed structure or material can withstand without incurring rupture or collapse.

Variable Amplitude Loading Spectrum -- A loading spectrum or history whose peak amplitudes vary with time.

Vibroacoustic Load -- A structural load induced by high-intensity acoustic noise associated with various segments of STS flight profile. The load may be the result of separately applied, or the combination of, directly transmitted acoustic excitation and structure-borne random vibration excitation.

Yield Strength -- Corresponds to the maximum load or stress that an unflawed structure or material can withstand without incurring detrimental deformation, usually stated as the stress corresponding to a permanent offset strain of 0.2 percent.

10.0 REFERENCES

The following documents contributed significantly to the development of the technical requirements of this plan:

a. Fracture Control of Metallic Pressure Vessels, NASA SP-8040, National Aeronautics and Space Administration, May 1970.

b. Space Shuttle Orbiter Fracture Control Plan, SD73-SH-0082A, J. R. King, P. Julian, and K. R. Johnson, Rockwell International, September 1974.

c. Damage Tolerant Design Handbook, MCIC HB-01, Battelle Memorial Laboratory, January 1975.

d. Materials and Processes for Corrosion Prevention and Control in Aerospace Weapons Systems, MIL-STD-1568A, U.S. Air Force, November 1975.

e. Stress Corrosion Cracking Control Measures, B. F. Brown, American University and National Bureau of Standards, June 1977.

f. Fracture Control Plan for Payloads Using the STS, Technical Report 101, M. I. Basci and T. Wilson, Swales and Associates, Inc., May 1981.

g. Galileo Orbiter Fracture Control Plan, PD 625-227, J. A. Hendrickson, Jet Propulsion Laboratory, November 1981.

h. Gamma Ray Observatory Fracture Control Plan, DO4336, G. A. Vroman and L. A. Barney, TRW Defense and Space Systems Group, January 1982.

i. Galileo Orbiter Stress Corrosion Cracking Control Plan, PD625-230, S. A. D'Agostino, Jet Propulsion Laboratory, April 1982.

j. JSC letter NS2/86-L124 of June 2, 1986, Arnold D. Aldrich, Manager National Space Transportation System to Lt. Col. Ben Lucas, Director of Mission Readiness, STS Program Office, USAF Space Division.

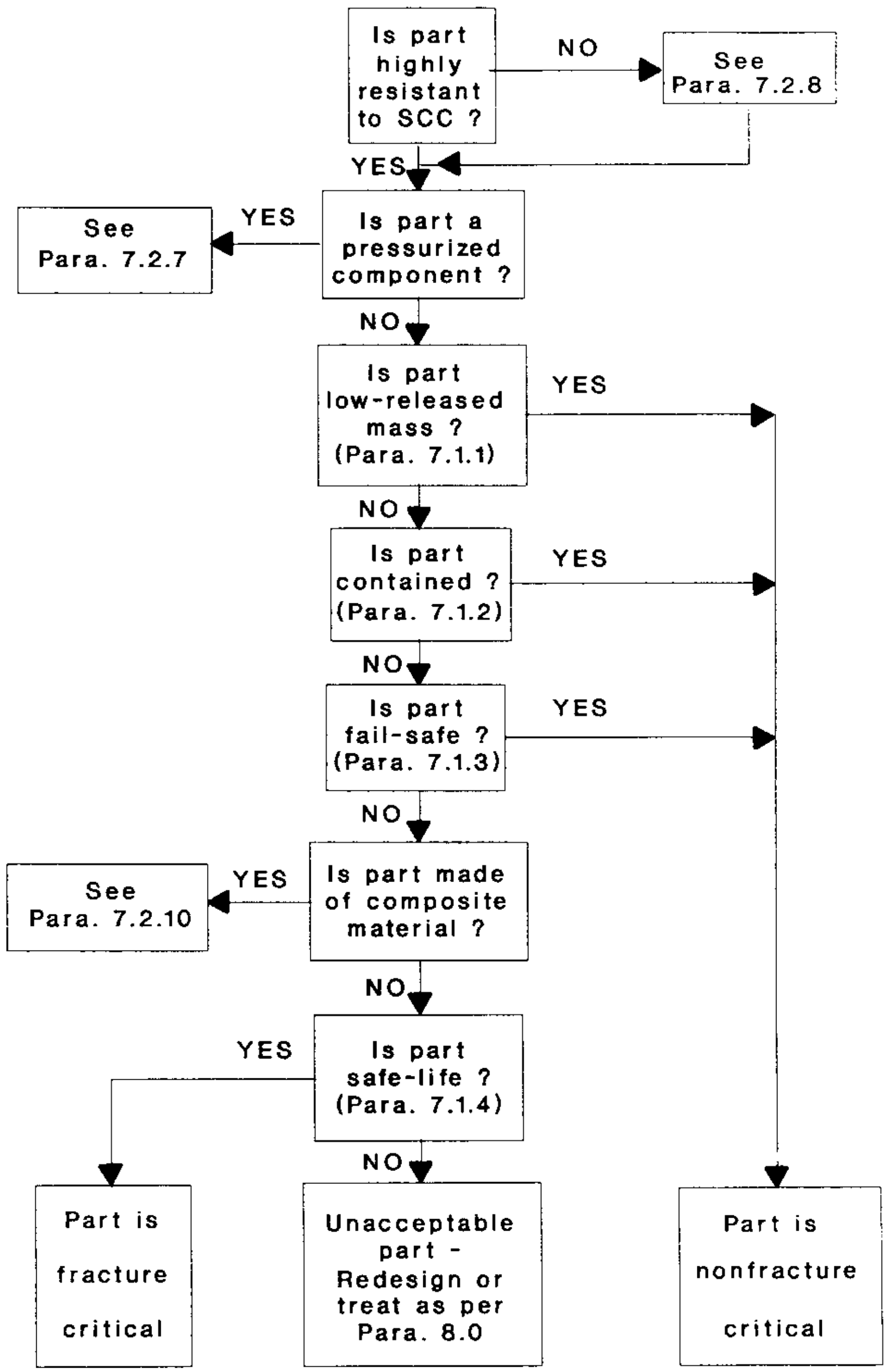


FIGURE 7-1: FRACTURE CRITICAL PART SELECTION LOGIC

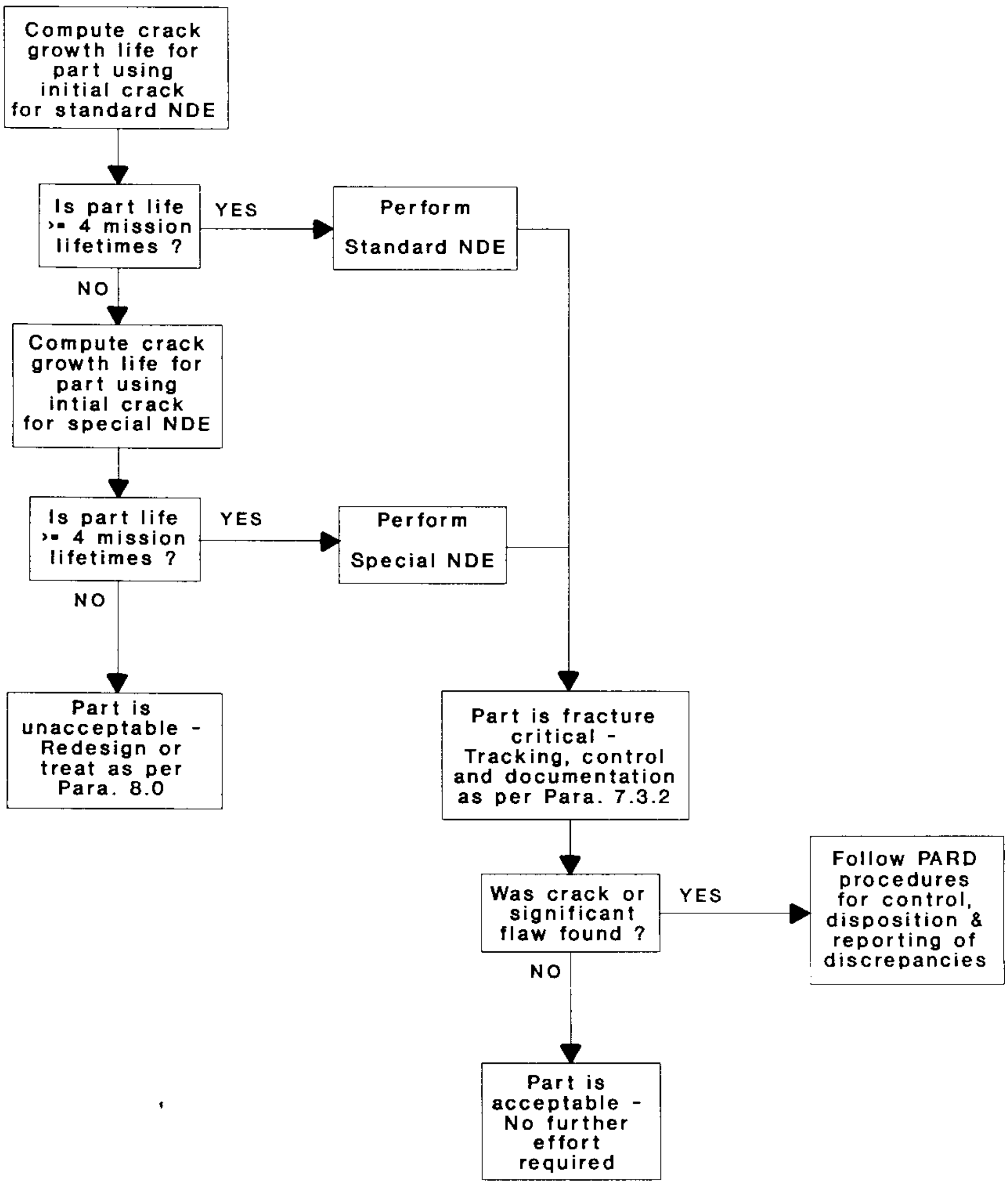


FIGURE 7-2: FRACTURE MECHANICS ANALYSIS REQUIREMENTS LOGIC FOR FRACTURE CRITICAL PARTS

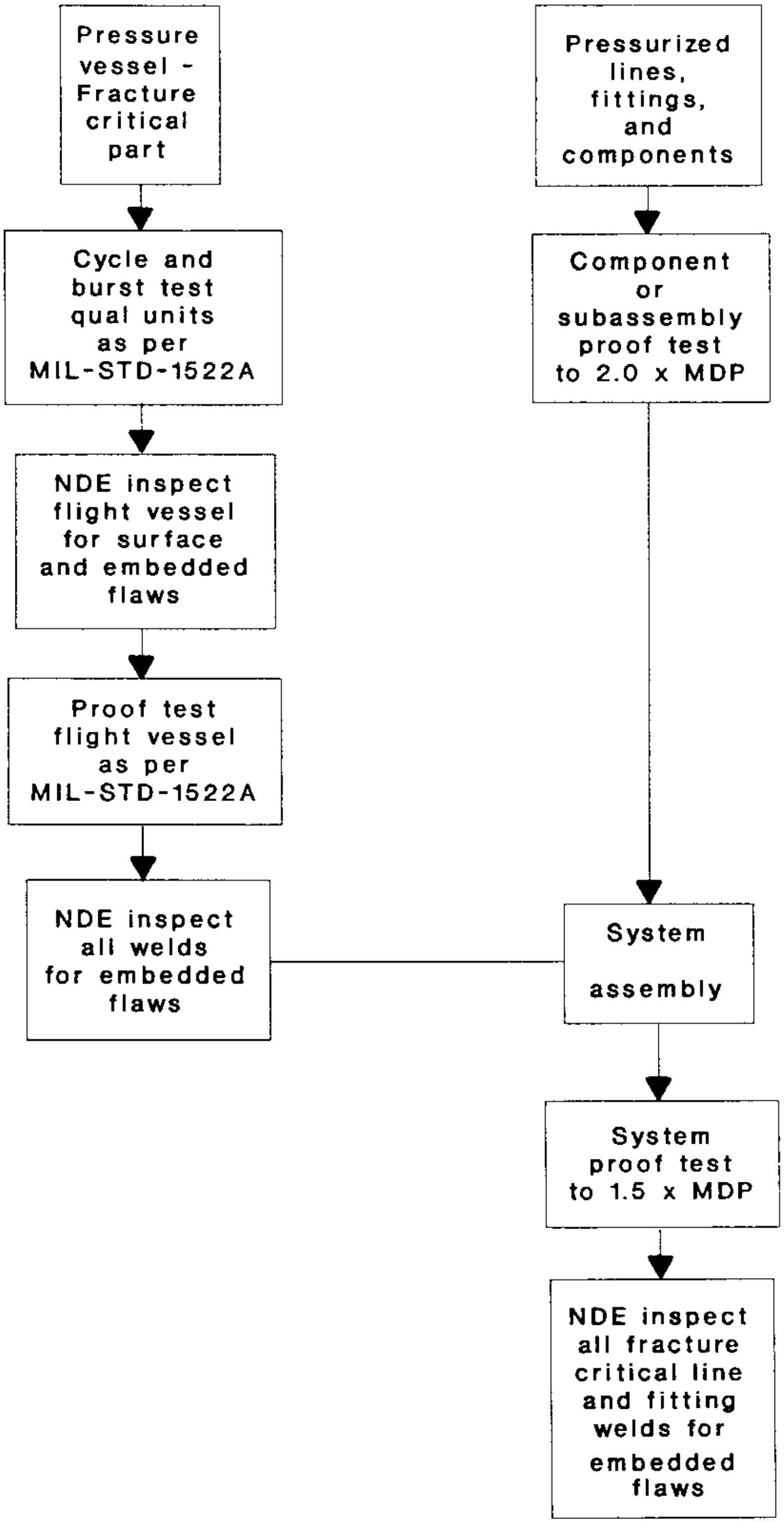
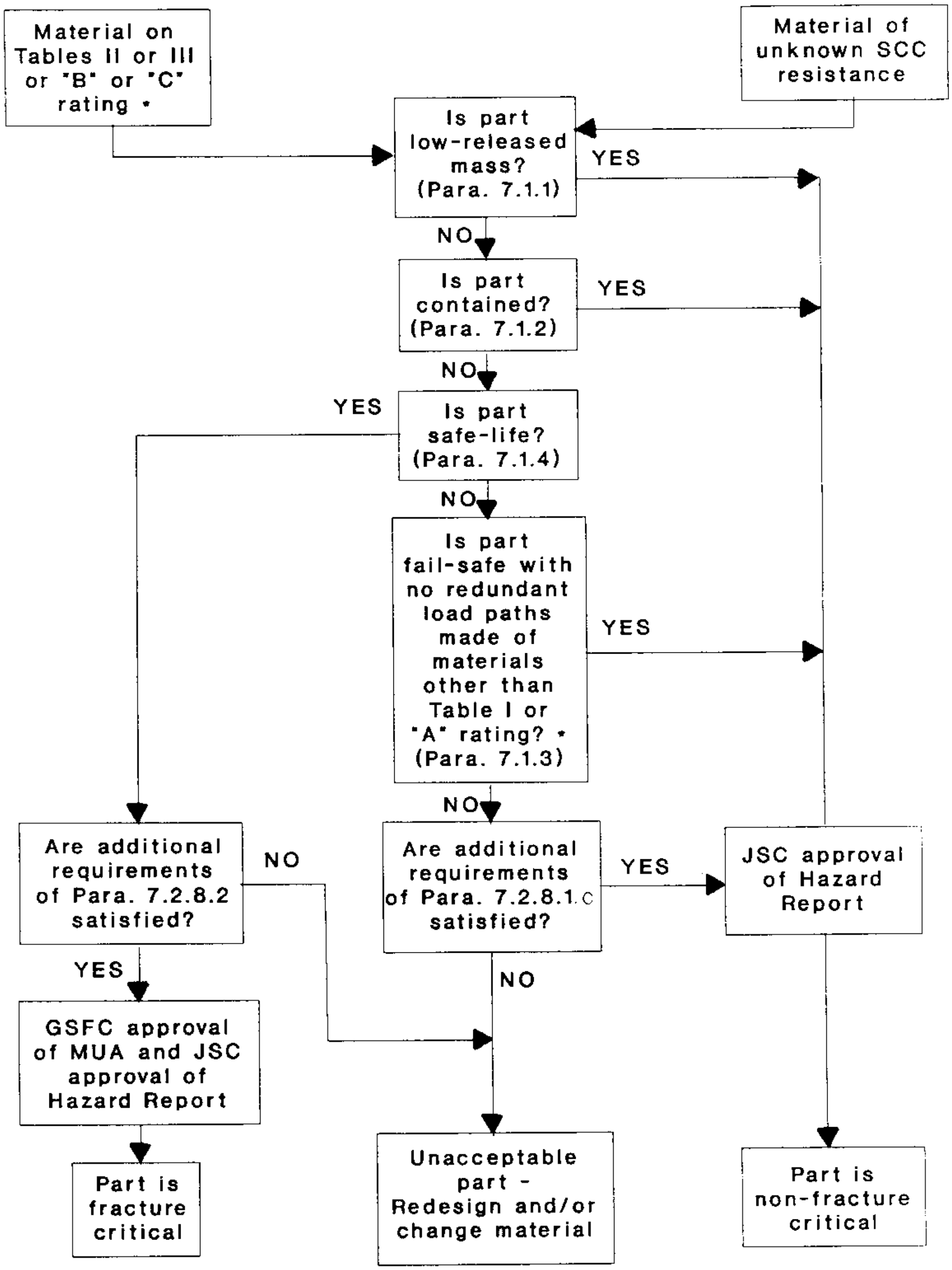


FIGURE 7-3: PRESSURE SYSTEM FRACTURE CONTROL REQUIREMENTS LOGIC



* Table II or III, per MSFC-SPEC-522B
"B" or "C" rating per MSFC-HDBK-527/JSC 09604

FIGURE 7-4: STRESS CORROSION CRACKING REQUIREMENTS LOGIC

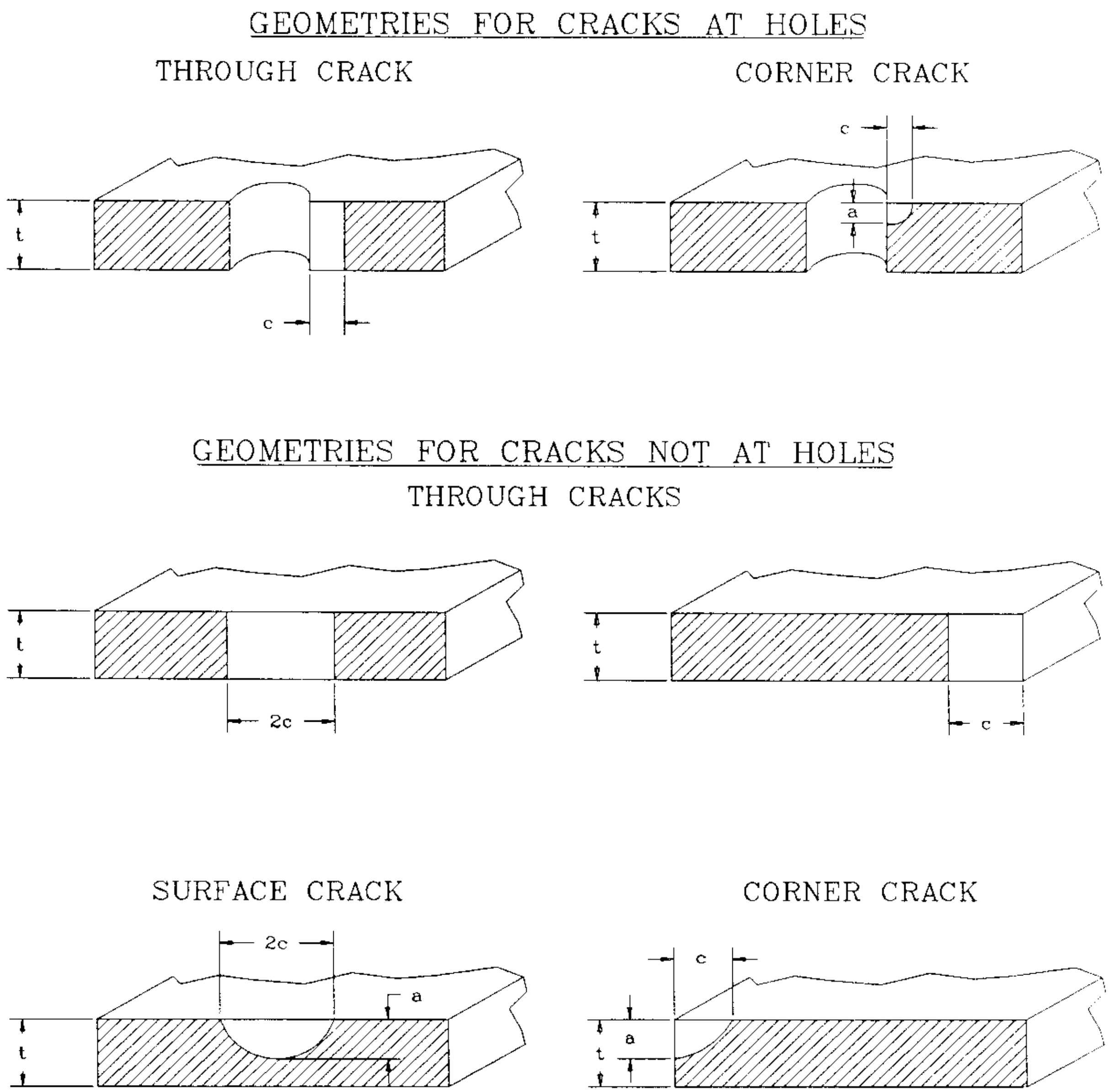


FIGURE 7-5: STANDARD CRACK/PART GEOMETRIES

TABLE 7-1 : MINIMUM INITIAL CRACK SIZES FOR FRACTURE ANALYSIS BASED ON STANDARD NDE METHOD

U. S. CUSTOMARY UNITS (inches)

Crack Location	Part Thickness, t (inches)	Crack Type	Crack Dimension a (inches)	Crack Dimension c (inches)	Crack Dimension 2c (inches)
		Eddy Current NDE			
Open Surface	$t \le 0.050$	Through	t	-	0.100
	$t > 0.050$	Surface	0.020	-	0.200
			0.050	-	0.100
Edge or Hole	$t \le 0.075$	Through	t	0.100	-
	$t > 0.075$	Corner	0.075	0.075	-
		Penetrant NDE			
Open Surface	$t \le 0.050$	Through	t	-	0.200
	$.050 < t \le .075$	Through	t	-	0.30 - $2t$
	$t > 0.075$	Surface	0.025	-	0.250
			0.075	-	0.150
Edge or Hole	$t \le 0.100$	Through	t	0.100	-
	$t > 0.100$	Corner	0.100	0.100	-
		Magnetic Particle NDE			
Open Surface	$t \le 0.075$	Through	t	-	0.250
	$t > 0.075$	Surface	0.038	-	0.376
			0.075	-	0.250
Edge or Hole	$t \le 0.075$	Through	t	0.250	-
	$t > 0.075$	Corner	0.075	0.250	-
		Radiographic NDE			
Open Surface	$.025 \le t \le .107$	Surface	$0.7t$	-	0.150
	$t > 0.107$		$0.7t$	-	$1.4t$
		Ultrasonic NDE			
Open Surface	$t \ge 0.100$	Surface	0.030	-	0.300
			0.065	-	0.130

APPENDIX A

LOADING SPECTRA FOR
TESTING, LIFT-OFF/ASCENT AND
DESCENT/LANDING

ACKNOWLEDGMENT

The development of the loading spectra in this appendix was carried out under the direction of Stephen J. Brodeur of the Mechanical Engineering Branch, Applied Engineering Division, Goddard Space Flight Center (GSFC). Mehmet I. Basci of Swales and Associates, Inc., was primarily responsible for the detailed technical development. Data analysis was performed by Margaret W. Latimer also of Swales and Associates. Support for analog to digital conversion of flight data was provided by William F. Bangs, Chairman, Dynamics, Acoustic and Thermal Environment (DATE) Working Group, GSFC, and performed under the direction of Donald J. Hershfeld of the Environmental Test and Integration Branch, Engineering Services Division, GSFC. The development of the testing spectra was based on an approach by Matthew Creager, Applied Engineering, Inc., Reference A-3.

APPENDIX A
CONTENTS

ILLUSTRATIONS

TABLES

A-1.0 INTRODUCTION

This appendix presents the detailed data for the loading spectrum to be used in the fracture mechanics analysis of paragraph 7.1.4.1. Procedures are developed to define loading spectra for lift-off, ascent, descent, landing and structural testing using sinusoidal, random or acoustic excitation.

The loading spectra due to testing, lift-off/ascent and descent/landing are usually the most significant cyclic loading events on the payload structure. These spectra are developed in generalized form for a typical Space Transportation System (STS) payload. For a specific payload, transportation, on-orbit, and postlanding loading spectra, if significant, may be derived and combined with the spectra of this appendix. For conciseness, lengthy derivations have been omitted and only the assumptions, technical methodology, and results are presented.

A-2.0 LOADING SPECTRUM FOR SINUSOIDAL SWEEP VIBRATION TEST

A-2.1 ASSUMPTIONS

The cyclic loading imposed on payload structure during a sine sweep vibration test may be determined using the following assumptions:

a. The frequency response of a payload structural element to the sine input is equivalent to its response to a steady state input as a function of frequency.

b. The sine sweep test may be notched or un-notched but, if notched, the notch factor, α, the ratio of un-notched to notched response, is known.

c. The shape of the frequency response curve and the maximum response of the structural element is known (or can be calculated) in terms of displacement or stress. These quantities are assumed to be proportional so that the number of cycles of loading is the same regardless of the measure of the loading. The response is assumed to be fully reversible.

d. The response of the structural element may be narrowband or wideband. Narrowband response is the same as that of a single degree-of-freedom (DOF) system with a single resonant frequency, f_n. Wideband response is the same as that of a multi-DOF system with several closely spaced resonant frequencies over a known frequency range, Δf. Both of these types of response are treated in the following paragraphs. It is assumed that the analyst will determine whether the response is narrowband or wideband for a specific element.

e. The cyclic loading spectrum for the sine sweep test is that equivalent number of constant-amplitude cycles at the maximum stress level that would produce the same crack growth damage as the true variable-amplitude sine sweep spectrum.

A-2.2 METHODOLOGY--NARROWBAND RESPONSE

Figure A-1 shows the frequency response of a single DOF system of resonant frequency, f_n, due to both notched and un-notched sinusoidal inputs. The un-notched response is treated as a special case of the notched response by setting the notch factor, α, equal to unity. The maximum response, σ_{max}, corresponds to the maximum stress induced in the structural element during the sine sweep. Other parameters are defined as follows:

λ = Sweep rate (octaves/minute)

Δt = Time duration of test (seconds)

Q = Amplification factor

f_n = Resonant frequency (Hz)

α = Notch factor

C,n = Paris crack growth rate equation constant and exponent, respectively, for a specific material

a = Crack size (inch)

da/dN = Crack growth rate (inch/cycle)

K = Stress intensity factor (ksi $\sqrt{in}$)

The variation of stress response with respect to frequency during a notched sine sweep test is given by:

$$\sigma(f) = \frac{\alpha\sigma_{max}}{Q}\left[(1-\beta^2)^2 + \left(\frac{\beta}{Q}\right)^2\right]^{-1/2} \tag{1}$$

where: $\beta = \frac{f}{f_n}$

This response function is used to prescribe the stress range, σ, in the Paris crack growth rate equation:

$$\frac{da}{dN} = C\,(\Delta K)^n = C\,[\,g\,(a)\,\sigma\,(f)\,]^n \qquad (2)$$

Since dN = f dt, this expression can be integrated over the frequency range from zero to infinity. Comparing the results with a crack growth rate expression for constant stress range, the equivalent number of fully reversible, constant-amplitude stress cycles at σ_{max} is determined. This equivalent number of constant-amplitude cycles, N_{eq}, is given in Table A-1 as a function of various parameters.

A-2.3 RESULTS--NARROWBAND RESPONSE

Table A-1 gives the number of equivalent constant-amplitude cycles, N_{eq}, due to a sine sweep test, both notched and un-notched. For the notched sine sweep test, the coefficient A_o (σ, n) may be calculated as a function of σ and n or it may be found in the tabulation of Table A-2 for discrete values of σ between 1.1 and 2.0 and n between 2 and 6. For the un-notched sine sweep test, the value of the coefficient A_o (1, n) for σ = 1 is given in Table A-1 for various values of n between 2 and 6. These ranges of σ and n cover all cases of practical interest.

It must be noted that the value of N_{eq} calculated from Table A-1 corresponds to one sweep only. If both up and down sweeps are performed, N_{eq} must be doubled. N_{eq} as calculated here must be multiplied by the scatter factor of 4 as discussed in paragraphs 5.1.h and 7.1.4.1.b.

A-2.4 METHODOLOGY--WIDEBAND RESPONSE

Figure A-2 shows an approximate (or enveloped) frequency response for a multi-DOF system with several closely spaced resonant frequencies between f_1 and f_2. The response may be notched or un-notched. The maximum response, σ_{max}, corresponds to the maximum stress induced in the structural element during the sine sweep and is independent of frequency in the range between f_1 and f_2. The variation of number of cycles, N, with frequency, f, is:

$$dN = \frac{60}{\lambda \ln 2}\,df \qquad (3)$$

where: λ = Sweep rate (octaves/minute)

Integrating this equation between f_1 and f_2 (Δf) gives the expression for the equivalent number of cycles:

$$N_{eq} = \frac{60 \Delta f}{\lambda \ln 2} \qquad (4)$$

A-2.5 RESULTS--WIDEBAND RESPONSE

Equation (4) gives the number of constant-amplitude cycles, N_{eq}, due to a sine sweep test, both notched and un-notched. It must be noted that this value of N_{eq} corresponds to one sweep only. If both up and down sweeps are performed, N_{eq} must be doubled. N_{eq} must also be multiplied by the scatter factor of 4 as discussed in paragraphs 5.1.h and 7.1.4.1.b.

A-3.0 <u>LOADING SPECTRUM FOR SINUSOIDAL DWELL VIBRATION TEST</u>

A-3.1 ASSUMPTION

The cyclic loading imposed on payload structure during a sine dwell vibration test is dependent only on the constant frequency and time duration of the test.

A-3.2 RESULTS

The number of cycles of loading, N_{eq}, which in the case of the sine dwell test are truly constant-amplitude and fully reversible, is given as:

$$N_{eq} = f \Delta t \qquad (5)$$

where:

f = Frequency of sine dwell test (Hz)

Δt = Time duration of test (seconds)

A-4.0 LOADING SPECTRUM FOR RANDOM VIBRATION TEST

A-4.1 ASSUMPTIONS

The cyclic loading imposed on payload structure during a random vibration test may be determined using the following assumptions:

a. The response of a payload structural element to the random input is the same as the narrowband response of a single DOF system.

b. The response is Gaussian with zero mean and, therefore, it may be characterized by its standard deviation.

c. The probability density function for the probability of attaining a given peak stress is given by a Rayleigh distribution.

d. The peak stress level is given by the 3-sigma, or 3 times the root-mean-square, stress level.

A-4.2 METHODOLOGY

The expected crack growth rate due to the random vibration test is determined by substituting the peak stress distribution:

$$P = \frac{\sigma}{\bar{\sigma}^2} e^{\left(\frac{-\sigma^2}{2\bar{\sigma}^2}\right)} \qquad (6)$$

where:

P = Probability density function for the probability of attaining a given peak stress

σ = Stress at any instant of time (psi)

$\bar{\sigma}$ = Standard deviation of response probability distribution into the Paris crack growth rate equation:

$$\frac{da}{dN} = C\,(\Delta K)^n \qquad (7)$$

By integrating the result over the time interval Δt of the test and comparing with the crack growth rate under a constant-amplitude, fully reversible stress σ_{max}, the equivalent number of constant amplitude cycles, N_{eq}, is found to be:

$$N_{eq} = f_n \Delta t \left[\left(\frac{\sqrt{2}}{3} \right)^n \Gamma \left(\frac{n+2}{2} \right) \right] \qquad (8)$$

where:

N_{eq} = Equivalent number of constant-amplitude cycles at σ_{max}

σ_{max} = Maximum stress induced in structural element (3-sigma) (psi)

Δt = Time duration of test (seconds)

f_n = Dominant resonant frequency (Hz)

$\Gamma\left(\frac{n+2}{2}\right)$ = Gamma function $= \int_0^{\infty} x^{n/2} e^{-x} \, dx$

n = Paris crack growth rate equation exponent for the specific material

A-4.3 RESULTS

Table A-3 gives the number of equivalent constant-amplitude cycles, N_{eq}, for the random vibration test for various values of n. N_{eq} must be multiplied by the scatter factor of 4 as discussed in paragraphs 5.1.h and 7.1.4.1.b.

A-5.0 <u>LOADING SPECTRUM FOR ACOUSTIC TEST</u>

A-5.1 ASSUMPTION

The cyclic loading imposed on a payload structural element during an acoustic test may be determined using the same assumption as was used in paragraph A-3.1 for the random vibration test.

A-5.2 METHODOLOGY

The equivalent number of constant-amplitude cycles at the maximum stress level σ_{max} is determined using the same procedure as was used in paragraph A-3.2 for the random vibration test.

A-5.3 RESULTS

Table A-3 gives the number of equivalent constant-amplitude cycles, N_{eq}, for the acoustic test for various values of n. N_{eq} must be multiplied by the scatter factor of 4 as discussed in paragraphs 5.1.h and 7.1.4.1.b.

A-6.0 LOADING SPECTRA FOR LIFT-OFF/ASCENT AND DESCENT/LANDING

A-6.1 ASSUMPTIONS

The cyclic loading on payload structure during STS lift-off/ascent and descent/landing is determined using measured flight payload response data and the following assumptions:

a. An approximation to the shape of the loading spectrum for a typical STS payload may be determined by measuring the acceleration response time-histories of a sufficient number of representative locations on a specific STS payload. By normalizing each measured time-history to its respective maximum, counting the number of cycles in each of several normalized load ranges, and enveloping the number of counts in each load range, a typical loading spectrum may be approximated.

b. The shape of the stress spectrum is equivalent to the shape of the measured acceleration spectrum if the acceleration time-histories are filtered at 200 Hz. Accelerations beyond 200 Hz produce small displacements which result in insignificant stresses.

A-6.2 METHODOLOGY

Measured flight acceleration data were taken from several accelerometers mounted on the Office of Space Science-1 (OSS-1) payload which was flown on STS-3, Orbiter No. 102, between March 22 and 30, 1982. The accelerometers, part of the DATE complement of flight instrumentation, were selected as representative of typical instrument responses in both high- and low-frequency ranges. Data reduction was provided by the DATE Program at the GSFC, and a complete description of all data can be found in Reference A-2. The specific accelerometer channels used are identified and described in Table A-4 and a complete description of the methodology for development of the loading spectra is given in Reference A-5.

Lift-off and ascent acceleration data were recorded for 600 seconds from SSME ignition to MECO. Descent and landing data were recorded for only the 360 seconds prior to wheel-stop, but the descent portion of the data was extrapolated backward to 600 seconds to provide a more realistic representation of the descent loading spectrum. In order to limit the frequency content of the high frequency data to the range that is significant for structural element stresses, the data were filtered using a fifth-order Butterworth low-pass filter. This filtering process also removed unwanted high-frequency noise from the data. Low-frequency data were used in the as-recorded condition.

The amplitude of each data channel was normalized to the maximum response of that data channel, resulting in a time-history with the same shape as the original but a peak value of 1.0 or 100 percent acceleration. Each data channel was reduced to a loading spectrum using the "rainflow" cycle counting method, Reference A-4. This method, shown graphically in Figure A-3, records the numbers of cycles of load in certain ranges rather than counting the load peaks. Since the rate of crack growth is a function of stress range, the rainflow counting method is considered the most appropriate counting method for crack growth loading spectra.

A brief explanation of the rainflow counting method is given as follows. In Figure A-3, the stress time-history is turned with the time axis vertical so that the time-history forms a series of "roofs." "Rain" is considered to flow from the highest roof down to lower ones and then off the roofs, with rain never flowing on a roof that is already "wet." The range of these rainflows is considered to be the range of the stress. In Figure A-3, for example, the stress ranges would be given by the flows AB, CD, EF, GH, KL, MN and PQ.

Since the shape of the stress time-history was assumed to be equivalent to the shape of the filtered acceleration time-history and both were assumed to be fully reversible, each acceleration range determined by the rainflow counting process was divided by 2 to obtain the "peak" acceleration for that "cycle." The ratio of this peak acceleration to the overall maximum acceleration for the channel under consideration determined the percentage of maximum response for that cycle. Percentages between 90 and 100 percent were recorded as 100 percent; those between 80 and 90 percent as 90 percent, and so on, with the total number of cycle "counts" at each percentage level being recorded for each channel.

The number of cycles at each percentage level was enveloped over the six data channels in Table A-4 used for lift-off and landing. This enveloping procedure provides confidence that the final spectrum is sufficiently conservative to apply to any other typical payload. The resulting enveloped spectra in Table A-5 give the number of cycles of load or stress at each of several percentages of maximum load or stress for both lift-off through ascent and descent through landing.

A-6.3 RESULTS

The loading spectra developed by the techniques described are given in Table A-5. Since these spectra represent one mission profile only, they must be used four times in succession in the crack growth analysis to provide a scatter factor of four as discussed in paragraphs 5.1.h and 7.1.4.1.b.

A-7.0 EXAMPLE PROBLEM

To illustrate the development of loading spectra for parts with different mean stress levels, let us calculate the loading spectra for two different parts in a spacecraft assembly, a bracket make of 2024-T851 aluminum alloy and a fastener made of A-286 steel alloy. The bracket is primarily subject to flight-induced inertial loading which produces fully-reversible stresses which oscillate about zero giving a stress ratio (R-ratio) R = -1. The fastener has a high tensile preload and a stiffness analysis of the joint indicates that the additional flight-induced tensile force is ± 10% of the externally applied force on the joint, giving a variable R-ratio. The assembly is subjected to sine sweep and random vibration tests, an acoustic test, and one STS mission profile consisting of lift-off through landing. The fabrication, assembly, transportation, on-orbit, and post-landing phases of the assembly's lifetime are assumed to produce negligible stresses.

A-7.1 SINE SWEEP TEST LOADING SPECTRUM

Let us assume a notched sine sweep test with notch factor α = 1.8. The other parameters for a typical case are assumed to be:

Sweep rate: λ = 2 octaves/minute
Response amplification factor: Q = 20
Dominant resonant frequency: f_n = 30 Hz
Maximum/Minimum stress in the bracket during test: ± 25 ksi
Maximum/Minimum stress in the fastener during test: 100 ± 12.5 ksi

Then, from Table A-1 with an assumed n = 3 for 2024-T851 aluminum:

$$(N_{eq})_1 = \frac{60\, f_n}{\lambda Q \ln 2} \cdot A_o(\alpha, n) = \frac{60(30)}{2(20)\ln 2} \cdot A_o(1.8,3)$$

From Table A-2, A_o (1.8,3) is obtained as:

$$A_o(1.8,3) = 2.479$$

and $(N_{eq})_1$ = 161 cycles

Again, from Table A-2 with an assumed n = 2.5 for A-286 steel, A_o is obtained by interpolation as:

$$A_o\,(1.8,2.5) = 3.405 - \left(\frac{3.405 - 2.479}{1.00}\,.\,0.5\right) = 2.942$$

and $(N_{eq})_1 = 191$ cycles

Thus,

$(N_{eq})_1 = 161$ cycles for the bracket
$(N_{eq})_1 = 191$ cycles for the fastener

Note that only an up-sweep was assumed. For an additional down-sweep, the above number of cycles would be doubled.

A-7.2 RANDOM VIBRATION TEST LOADING SPECTRUM

Let us assume that the time duration of the random vibration test is 60 seconds per axis so that $\Delta t = 180$ seconds for the three axis test. In addition,

Maximum/Minimum stress in the bracket during the test: ± 10 ksi
Maximum/Minimum stress in the fastener during the test: 100 ± 5 ksi

Then, from Table A-3, with n = 3 for 2024-T851:

$$(N_{eq})_2 = (30)\,(180)\,(0.139) = 751$$

$$(N_{eq})_2 = 751 \text{ cycles}$$

Again, from Table A-3 with n = 2.5 for A-286 steel:

$$(N_{eq})_2 = (30)\,(180)\left[0.222 - \left(\frac{0.222 - 0.139}{1.00}\,.\,0.5\right)\right] = 975$$

$$(N_{eq})_2 = 975 \text{ cycles}$$

Thus,

$(N_{eq})_2 = 751$ cycles for bracket
$(N_{eq})_2 = 975$ cycles for fastener

A-7.3 ACOUSTIC TEST LOADING SPECTRUM

Let us assume that the time duration of the acoustic test is 60 seconds. In addition,

Maximum/Minimum stress in the bracket during the test: ± 5 ksi
Maximum/Minimum stress in the fastener during the test: 100 ± 2.5 ksi

Then, from Table A-3 with n = 3 for 2024-T851:

$$(N_{eq})_3 = (30)\ (60)\ (0.139) = 250$$

$$(N_{eq})_3 = 250 \text{ cycles}$$

Again, from Table A-3 with n = 2.5 for A-286 steel:

$$(N_{eq})_2 = (30)\ (60) \left[0.222 - \left(\frac{0.222 - 0.139}{1.00}\ .\ 0.5 \right) \right] = 325$$

$$(N_{eq})_3 = 325 \text{ cycles}$$

Thus,

$(N_{eq})_3$ = 250 cycles for the bracket
$(N_{eq})_3$ = 325 cycles for the fastener

A-7.4 LIFT-OFF/ASCENT AND DESCENT/LANDING LOADING SPECTRA

Let us assume that the maximum stresses in the parts are the same for both lift-off and landing, ± 20 ksi in the bracket and 100 ± 10 ksi in the fastener. Then, applying the numbers of cycles and percentages of limit stress in Table A-5 to the flight-induced portion of the part stresses, we get the lift-off/ascent and descent/landing segments of the complete load spectra shown on pages A-12 and A-13.

A-7.5 COMBINED LOADING SPECTRA

The results of paragraphs A-7.1 through A-7.4 are combined to produce the total loading spectra for the parts and are repeated on pages A-12 and A-13 for convenience. The scatter factor of four must be applied by repeating these total loading spectra four times in succession.

EXAMPLE PROBLEM - COMBINED LOADING SPECTRUM FOR BRACKET

Event	Number of Cycles	Stress (ksi) Maximum	Minimum	R-ratio
Sine Sweep Test	161	25.0	-25.0	-1.00
Random Vibration Test	751	10.0	-10.0	-1.00
Acoustic Test	250	5.0	-5.0	-1.00
Lift-off/Ascent	1	20.0	-20.0	-1.00
	3	18.0	-18.0	-1.00
	5	16.0	-16.0	-1.00
	12	14.0	-14.0	-1.00
	46	12.0	-12.0	-1.00
	78	10.0	-10.0	-1.00
	165	8.0	-8.0	-1.00
	493	6.0	-6.0	-1.00
	2229	4.0	-4.0	-1.00
	2132	2.0	-2.0	-1.00
	2920	1.4	-1.4	-1.00
	22272	1.0	-1.0	-1.00
	82954	0.6	-0.6	-1.00
Descent/Landing	1	20.0	-20.0	-1.00
	1	18.0	-18.0	-1.00
	3	16.0	-16.0	-1.00
	3	14.0	-14.0	-1.00
	3	12.0	-12.0	-1.00
	3	10.0	-10.0	-1.00
	13	8.0	-8.0	-1.00
	148	6.0	-6.0	-1.00
	891	4.0	-4.0	-1.00
	1273	2.0	-2.0	-1.00
	2099	1.4	-1.4	-1.00
	6581	1.0	-1.0	-1.00
	8701	0.6	-0.6	-1.00

EXAMPLE PROBLEM - COMBINED LOADING SPECTRUM FOR FASTENER

Event	Number of Cycles	Stress (ksi) Maximum	Stress (ksi) Minimum	R-ratio
Sine Sweep Test	191	112.5	87.5	0.778
Random Vibration Test	975	105.0	95.0	0.905
Acoustic Test	325	102.5	97.5	0.951
Lift-off/Ascent	1	110.0	90.0	0.818
	3	109.0	91.0	0.835
	5	108.0	92.0	0.852
	12	107.0	93.0	0.869
	46	106.0	94.0	0.887
	78	105.0	95.0	0.905
	165	104.0	96.0	0.923
	493	103.0	97.0	0.942
	2229	102.0	98.0	0.961
	2132	101.0	99.0	0.980
	2920	100.7	99.3	0.986
	22272	100.5	99.5	0.990
	82954	100.3	99.7	0.994
Descent/Landing	1	110.0	90.0	0.818
	1	109.0	91.0	0.835
	3	108.0	92.0	0.852
	3	107.0	93.0	0.869
	3	106.0	94.0	0.887
	3	105.0	95.0	0.905
	13	104.0	96.0	0.923
	148	103.0	97.0	0.942
	891	102.0	98.0	0.961
	1273	101.0	99.0	0.980
	2099	100.7	99.3	0.986
	6581	100.5	99.5	0.990
	8701	100.3	99.7	0.994

A-8.0 REFERENCES

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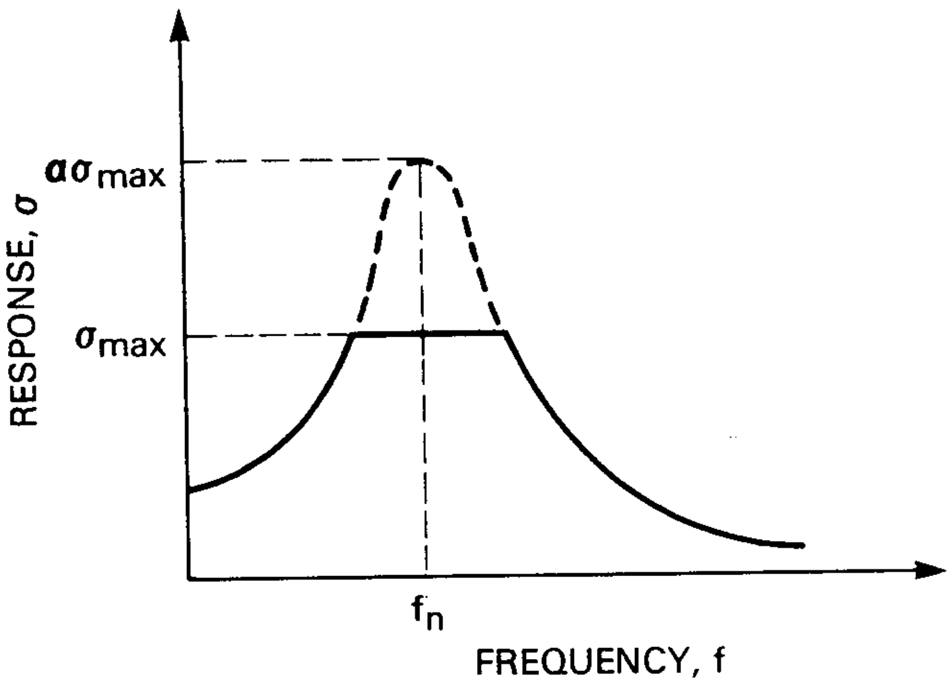

Figure A-1: Frequency Response for Sine Sweep Vibration Test - Narrow Band Response

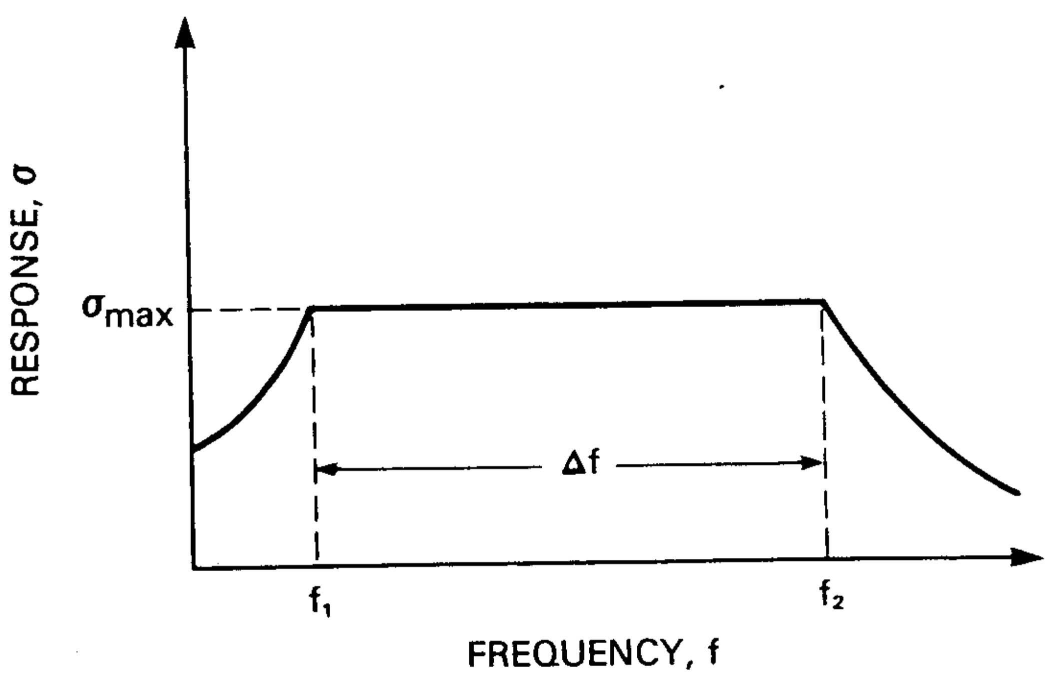

Figure A-2: Frequency Response for Sine Sweep Vibration Test - Wide Band Response

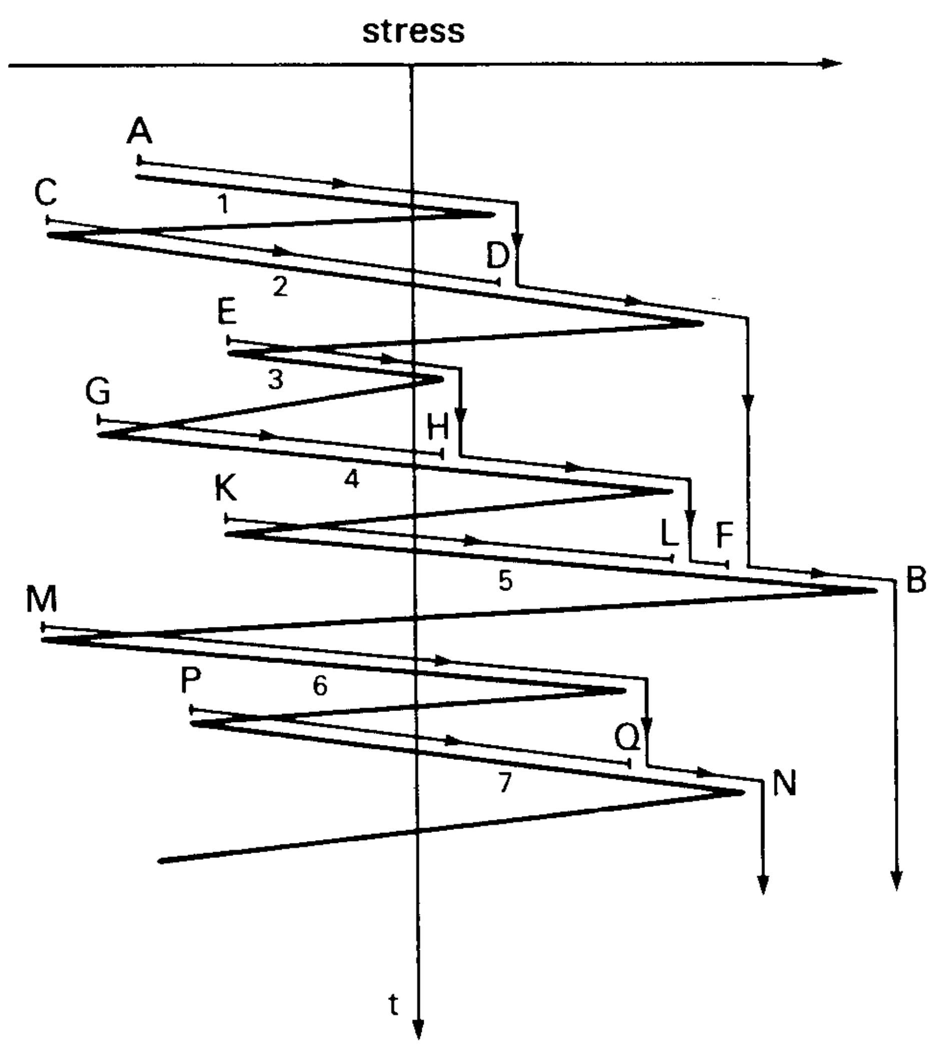

Figure A-3: Rainflow Counting Method Example

Table A-1
Equivalent Number of Constant - Amplitude Cycles, N_{eq}, at Maximum Stress Level for Sine Sweep Vibration Test - Narrow Band Response

n	NOTCHED SINE SWEEP TEST NARROW BAND RESPONSE. $N_{eq} = \frac{60 f_n}{\lambda Q \ln 2} A_o(\alpha,n)$ $A_o(\alpha,n)$ IS GIVEN BELOW	UNNOTCHED SINE SWEEP NARROW BAND RESPONSE $N_{eq} = \frac{60 f_n}{\lambda Q \ln 2} A_o(1,n)$ $A_o(1,n)$ IS GIVEN BELOW
2	$\left[\frac{\pi}{2} + \frac{\sqrt{\alpha^2-1}}{\alpha^2} - \tan^{-1}\sqrt{\alpha^2-1}\right]\alpha^2$	$\frac{\pi}{2}$
3	$\left[1 - \sqrt{\alpha^2-1} \cdot \frac{\alpha^2-1}{\alpha^3}\right]\alpha^3$	1
4	$\left[\frac{\pi}{4} + \sqrt{\alpha^2-1} \cdot \frac{2-\alpha^2}{2\alpha^4} - \frac{\tan^{-1}\sqrt{\alpha^2-1}}{2}\right]\alpha^4$	$\frac{\pi}{4}$
5	$\left[\frac{2}{3} + \sqrt{\alpha^2-1} \cdot \frac{3-2\alpha^4-\alpha^2}{3\alpha^5}\right]\alpha^5$	$\frac{2}{3}$
6	$\left[\frac{3\pi}{16} + \sqrt{\alpha^2-1} \cdot \frac{8-3\alpha^4-2\alpha^2}{8\alpha^6} - \frac{3}{8}\tan^{-1}\sqrt{\alpha^2-1}\right]\alpha^6$	$\frac{3\pi}{16}$

Table A-2
Values of $A_o(\sigma,n)$ for Various Values of σ and n

n \ α	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
2	1.839	2.082	2.314	2.539	2.760	2.977	3.192	3.405	3.616	3.826
3	1.235	1.436	1.624	1.803	1.977	2.148	2.315	2.479	2.642	2.804
4	1.016	1.207	1.382	1.548	1.707	1.863	2.014	2.164	2.311	2.457
5	0.900	1.087	1.256	1.416	1.569	1.717	1.861	2.003	2.143	2.281
6	0.826	1.012	1.179	1.335	1.484	1.628	1.768	1.905	2.041	2.174

Table A-3
Equivalent Number of Constant-Amplitude Cycles, N_{eq}, at Maximum Stress Level for Random Vibration and Acoustic Tests

n	N_{eq}
2	$f_n \cdot \Delta t \cdot (0.222)$
3	$f_n \cdot \Delta t \cdot (0.139)$
4	$f_n \cdot \Delta t \cdot (0.099)$
5	$f_n \cdot \Delta t \cdot (0.077)$
6	$f_n \cdot \Delta t \cdot (0.066)$

Table A-4
STS-3 Date Measurement Information From OSS-1 Used in Loading Spectra

Measurement No.	Type	Measurement Description	Axis	Amplitude Range	Frequency Response	Events
V08D9282A	LFA	THERM CAN X AXIS FWD INBD COR	X	± 8 G	1.5-50 Hz	LO,LA
V08D9283A	LFA	THERM CAN Y AXIS FWD INBD COR	Y	± 8 G	1.5-50 Hz	LO,LA
V08D9284A	LFA	THERM CAN Z AXIS FWD INBD COR	Z	± 8 G	1.5-50 Hz	LA
V08D9285A	LFA	SUNYA INSTR PED X AXIS FACING AFT	+X	± 8 G	1.5-50 Hz	LO
V08D9286A	LFA	SUNYA INSTR PED Y AXIS	-Y	± 8 G	1.5-50 Hz	LA
V08D9287A	LFA	SUNYA INSTR PED Z AXIS	-Z	± 8 G	1.5-50 Hz	LA
V08D9288A	LFA	INTERSECT STIFF FWD SIDE VERT PLANE	-X	± 8 G	1.5-50 Hz	LO,LA
V08D9298A	HFA	INSD THERM CAN FWD INBD COR	X	± 20 G	5-2 KHz	LO
V08D9299A	HFA	AFT INSIDE THERM CAN	Y	± 40 G	5-2 KHz	LO
V08D9302A	HFA	AFT SIDE VERT PLATFORM	X	± 20 G	5-2 KHz	LO

LO = Lift-off/Ascent
LA = Descent/Landing
LFA = Low Frequency Accelerometer
HFA = High Frequency Accelerometer

Table A-5

Lift-off/Ascent and Descent/Landing Loading Spectra

Stress Level % of Maximum	Number of Cycles Lift-off/Ascent	Descent/Landing
100	1	1
90	3	1
80	5	3
70	12	3
60	46	3
50	78	3
40	165	13
30	493	148
20	2,229	891
10	2,132	1,273
7	2,920	2,099
5	22,272	6,581
3	82,954	8,701