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FRACTURE CONTROL REQUIREMENTS

FOR SPACEFLIGHT HARDWARE

**MEASUREMENT SYSTEM IDENTIFICATION:
METRIC (INCH-POUND)**

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FOREWORD

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

This standard is approved for use by NASA Headquarters and NASA Centers, including Component Facilities.

Fracture control is mandatory for all human-rated spaceflight systems, payloads, propulsion systems, orbital support equipment, and planetary habitats. This document establishes fracture control requirements and methodologies (replacing NASA-STD-5007). It was developed by a NASA-wide Fracture Control Working Group to provide a common framework for fracture control practices on NASA programs.

Requests for information, corrections, or additions to this document should be submitted via "Feedback" in the NASA Technical Standards System at http://standards.nasa.gov.

Original Signed By

January 7, 2008

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1. SCOPE

1.1 Introduction

NASA's policy is to produce flight systems with a high degree of reliability and safety. This is accomplished through sound engineering practices in the design, analyses, inspections, testing, fabrication, maintenance, and operation of flight structures. In keeping with this policy, fracture control shall be required on all human-rated space systems to preclude catastrophic failure. Fracture control provides a specialized methodology to address the consequences of naturally occurring and service-induced flaws, damage, or cracks in a part or structure. This document establishes the fracture control requirements for all human-rated spaceflight systems including payloads, propulsion systems, orbital support equipment, and planetary habitats.

A viable fracture control program relies on design, analysis, testing, nondestructive evaluation (NDE), and tracking of fracture-critical hardware. It is expected that all spaceflight hardware will be manufactured consistent with industrial standards, practices, and quality. It is beyond the scope, or intent, of this document to address technical or quality disciplines that should already exist and be in place regardless of fracture control. Fracture control is imposed and required to enhance the safety and mission reliability of systems by reducing the risk of catastrophic failure.

It is recommended that the fracture control practitioners become familiar with all portions of this standard. The requirements are contained in section 4. Section 1.4 addresses responsibilities in fracture control. Applicable fracture control requirements documents are provided in section 2. Reference documents are provided in section 5. Section 4.1 addresses non-fracture-critical and fracture-critical hardware for generic and specific hardware items. The methodology for assessing fracture-critical parts is provided in section 4.2, and tracking for these parts is provided in section 4.3. Section 4.4 provides documentation descriptions, section 4.5 provides verification requirements, and section 4.6 provides alternative methods for fracture control. Section 4.7 provides other requirements. An acronym list and definitions are given in section 3. NASA-HDBK-5010, Fracture Control Implementation Handbook for Payloads, Experiments, and Similar Hardware, provides useful guidance and examples for meeting the fracture control requirements contained in this document.

1.2 Purpose

Fracture control is implemented to reduce the risk of a catastrophic failure from a defect or damage. The intent of this standard is to provide fracture control requirements for spaceflight hardware. A variety of fracture control considerations and options are addressed, some of which may not be applicable to a given design. Information is provided to assist the user in the development of an effective Fracture Control Plan and other fracture control documentation.

1.3 Applicability

These requirements are not imposed on systems other than human-rated spaceflight but may be tailored for use in specific cases where it is prudent to do so, such as when national assets are at risk. This standard may be cited in contract, program, and other Agency documents as a technical requirement. Mandatory requirements are indicated by the word “shall”; explanatory/guidance text is indicated in italics in sections 4 and 5. Tailoring of this standard for application to a specific program or project shall be approved by Technical Authority through the Responsible Fracture Control Board (RFCB) for that program or project.

1.4 Responsibilities

The NASA Center responsible for the manned spaceflight system shall be responsible for designating fracture control authorities and for assuring compliance with the requirements of this document. Within a project, the lines of responsibility for fracture control activities can be complex. Responsibilities may involve both the line and project organizations. Definitions for the various organizations involved are given in section 3.2. Generally, the line organization is responsible for overseeing the technical adequacy of a given program/project; and the project organization is responsible for implementing a technically adequate fracture control program on its hardware.

The Fracture Control Coordinator (FCC) and the System Safety and Mission Assurance (SSMA) representative shall assure that the fracture control activity is properly implemented and expedite the generation of the required documentation according to section 4.4 of this standard. Fracture control implementation shall be done with the oversight, advice, and approval of the RFCB. Fracture control program responsibilities shall be identified at Project Formulation or Project/System Requirements Review (P/SRR). For effective fracture control implementation, the group, organization, or person(s) need to be identified who have the following responsibilities:

a. Fracture classification of parts.

b. Identification and specification of required NDE or any other special requirements on fracture-critical parts.

c. Implementation of traceability and documentation showing adherence of hardware to approved drawings, specifications, plans, and procedures.

d. Fracture mechanics and structural analyses.

e. Assessment of anomalies on fracture-critical parts and for decisions regarding questions or issues relating to fracture control.

f. Compilation and configuration control of the fracture control and related structural documentation for the lifetime of the hardware.

Designers and analysts should become familiar with fracture control requirements and conduct a hardware assessment as delineated by the requirements in this document to establish the fracture criticality of structural parts and components. After a final list of fracture-critical parts is determined, the required analyses, inspections, and other fracture control activities need to be implemented and monitored to assure timely and proper completion.

Most of this standard is written for the personnel responsible for assembling the Fracture Control Plan, analysis, and much of the final documentation. The designers who design the hardware and produce the drawings from which hardware is made also have an important responsibility in fracture control. In addition to good design practices, the following are encouraged:

a. Design parts with redundancy. Avoid single-point catastrophic failures in joints and structures when it is reasonable to do so.

b. Design parts for inspectability. Avoid welds that are not inspectable on all sides.

c. Avoid processes that tend to be crack prone such as welding, custom forging, and casting.

d. Use well-characterized, standard aerospace materials for which the strength, fatigue, and fracture properties are known, or provide for adequate material testing. Material testing may also be warranted for standard materials if they are to be used in unique applications.

2. APPLICABLE DOCUMENTS

2.1 General

The documents listed in this section contain provisions that constitute requirements of this standard as cited in the text of section 4. The RFCB, as defined in this document, shall replace all definitions of a fracture control board in all applicable documents. The applicable documents are accessible via the NASA Technical Standards System at http://standards.nasa.gov, directly from the Standards Developing Organizations, or from other document distributors.

2.2 Government Documents

NASA

NASA-STD-(I)-5009, September 11, 2006	Nondestructive Evaluation Requirements for Fracture Critical Metallic Components
NASA-STD-(I)-6008, September 12, 2006	NASA Fastener Management and Control Practices

NASA-STD-(I)-6016, September 11, 2006	Standard Materials and Processes Requirements for Spacecraft
JSC 20793, April 2006	Crewed Space Vehicle Battery Safety Requirements
JSC 62550, August 30, 2005	Strength Design and Verification Criteria for Glass, Ceramics and Windows in Human Space Flight Applications
MSFC-RQMT-3479, June 29, 2006	Fracture Control Requirements for Composite and Bonded Vehicle and Payload Structures

Department of Defense

MIL-HDBK-6870A, August 28, 2001	Inspection Program Requirements, Nondestructive for Aircraft and Missile Materials and Parts

Department of Transportation

DoT Title 49, October 1, 2000	United States Code, Transportation

2.3 Non-Government Documents

ANSI/AIAA S-080-1998, September 1999	Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components
ANSI/AIAA S-081A-2006, July 2006	Space Systems - Composite Overwrapped Pressure Vessels (COPVs)
ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 or 2, September 2004	Rules for Construction of Pressure Vessels, Section VIII, Division 1 or Division 2, Alternative Rules

2.4 Order of Precedence

When this standard is applied as a requirement or imposed by contract on a program or project, the technical requirements of this standard take precedence, in the case of conflict, over the technical requirements cited in applicable documents or referenced guidance documents.

3. ACRONYMS AND DEFINITIONS

3.1 Acronyms

The acronyms used in this standard are listed here to assist the reader in understanding this document.

AIAA	American Institute of Aeronautics and Astronautics
ANSI	American National Standards Institute
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
CM	Configuration Management
COPV	Composite Overwrapped Pressure Vessel
DoT	Department of Transportation
ECF	Environmental Correction Factor
EVA	Extra Vehicular Activity
FCC	Fracture Control Coordinator
FCSR	Fracture Control Summary Report
HCF	High-Cycle Fatigue
HD	Hardware Developer
HDBK	Handbook
JSC	Johnson Space Center
MDP	Maximum Design Pressure
MEOP	Maximum Expected Operating Pressure
MIL-HDBK	Military Handbook
MIL-STD	Military Standard
MMOD	Micrometeoroid and Orbital Debris
MSFC	Marshall Space Flight Center
MUA	Materials Usage Agreement
NASA	National Aeronautics and Space Administration
NASGRO®	NASA Crack Growth Computer Program
NDE	Nondestructive Evaluation
NHLBB	Non-Hazardous Leak Before Burst
PDR	Preliminary Design Review
PRR	Preliminary Requirements Review
P/SRR	Project/System Requirements Review
RFCB	Responsible Fracture Control Board
RQMT	Requirements
SSMA	System Safety and Mission Assurance
STD	Standard

3.2 Definitions

The definitions in this section may be used in conjunction with the fracture-control requirements presented in this document to aid in understanding and implementation of effective fracture control.

A Basis: A statistically calculated number for which at least 99 percent of the population of values is expected to equal or exceed with a confidence of 95 percent.

Assembly/Assemblage: An integral arrangement of parts that make up an individual unit and which act as a whole.

Catastrophic Event: Loss of life, disabling injury, or loss of a major national asset such as the Space Shuttle, Crew Exploration Vehicle, Crew Launch Vehicle, or International Space Station.

Catastrophic Failure: A failure that directly results in a catastrophic event.

Catastrophic Hazard: Presence of a risk situation that could directly result in a catastrophic event.

Component: Hardware item considered a single entity for the purpose of fracture control. The terms "component" and "part" are interchangeable in this document.

Composite/Bonded Structure: Structure (excluding overwrapped pressure vessels or pressurized components) of fiber/matrix configuration and structure with load-carrying non-metallurgical bonds, such as sandwich structure or bonded structural fittings.

Composite Overwrapped Pressure Vessel (COPV): A pressure vessel with a composite structure fully or partially encapsulating a metallic liner. The liner serves as a fluid (gas or liquid) permeation barrier and may carry substantial pressure loads. The composite generally carries pressure and environmental loads.

Contained: A condition in which a suitable housing, container, barrier, restraint, etc. prevents a part or pieces thereof from becoming free bodies if the part or its supports fail.

Crack or Crack-like Defect: Defect assumed to behave like a crack for fracture control purposes.

Custom Forging: A near net-shape forging with a unique geometry special ordered from a forging vendor. A non-standard forging.

Damage Tolerant: Fracture control design concept under which an undetected crack or damage (consistent in size with the sensitivity of the NDE applied) is assumed to exist and is demonstrated by fracture mechanics analysis or test that it will not grow to failure (leak or instability) during the period equal to the service life factor times the service life. "Damage Tolerant" has replaced the term "Safe Life" in this document and other NASA Standards to avoid confusion with other technical documents.

Environmental Correction Factor (ECF): An adjustment factor used to account for differences between the environment (thermal and chemical) in which a part is used and the environment in which it is proof tested.

Experiment: For fracture control, an arrangement or assemblage of hardware that is intended to investigate phenomena on a provisional, often human-tended, basis.

Fail Safe: For fracture control, a condition where, after failure of a single individual structural member, the remaining structure (considered unflawed) can withstand the redistributed loads, and the failure will not release a potentially catastrophic free body.

Fastener: For fracture control, any single part which joins other structural elements and transfers loads from one element to another across a joint.

Flight Hardware: Any structure, payload, experiment, system, or part that will be built to flight structural requirements.

Fracture Control Coordinator (FCC): A designated individual experienced with fracture control who is responsible for implementing fracture control and ensuring its effectiveness in meeting all requirements by monitoring, reviewing, and approving all related activities performed both internally and by subcontractors that affect the fracture control aspects of the hardware. Designation may be in the form of specific duties assigned within an existing function.

Fracture Critical: Classification that identifies a part whose individual failure is a catastrophic hazard, and which requires damage tolerant analysis or other fracture control assessment to be shown acceptable for flight.

F_{tu}: Material A basis ultimate strength.

F_{ty}: Material A basis yield strength.

Habitable Modules: Flight containers/chambers designed for supporting life.

Hardware Developer (HD): Organization directly responsible for doing the design, manufacture, analysis, test, and safety compliance documentation, including fracture control, of the hardware.

Hazardous Fluid: For fracture control, a fluid whose release would create a catastrophic hazard. Hazardous fluids include liquid chemical propellants, liquid metals, and highly toxic liquids or gases. A fluid is also hazardous if its release would create a hazardous environment such as a danger of fire or explosion, unacceptable dilution of breathing oxygen, an increase of oxygen above flammability limits, over-pressurization of a compartment, or loss of a safety-critical system.

Hazardous Fluid Container: Any single, independent (not part of a pressurized system) container or housing that contains a fluid whose release would cause a catastrophic hazard and that is not classified as a pressure vessel.

High-Cycle Fatigue (HCF): A high-frequency, low-amplitude loading condition created by structural, acoustic, or aerodynamic vibrations that can propagate flaws to failure. An example of an HCF loading condition is the vibrational loading of a turbine blade due to structural resonance.

Initial Crack Size: The crack size that is assumed to exist at the beginning of a damage tolerant analysis, as determined by NDE or proof testing.

K_c: Critical stress intensity factor for fracture.

K_{eac}: Stress intensity factor threshold for environment-assisted cracking. Highest value of stress intensity factor at which crack growth is not observed for a specified combination of material and environment.

K_{Ic}: Plane strain fracture toughness.

K_{Ie}: Effective fracture toughness for a surface or elliptically shaped crack.

K_{Iscc}: K_{eac} is often denoted K_{Iscc} in the literature. K_{eac} is interchangeable with K_{Iscc}.

K_{th}: Threshold stress intensity for crack growth to occur under dynamic (cyclic) loading conditions.

Life Factor: See Service Life Factor.

Lifetime: See Service Life.

Limit Load: The maximum expected external load or worst-case combination of loads that a structure may experience during the performance of specified missions in specified environments.

Limited Life Part: Multi-mission part which has a predicted damage tolerant life that is less than four (4) times the complete multi-mission service life.

Low-Cycle Loads: A low-frequency, high-amplitude loading condition created by thermal, pressure, or structural loads that can propagate flaws to failure. An example of a low-cycle loading condition is the aerothermal loading of a turbine blade during launch.

Low-Fracture Toughness: Material property characteristic, in the applicable environment, for which the ratio is $K_{Ic}/F_{ty} < 1.66 \text{ mm}^{1/2}$ ($0.33 \text{ in}^{1/2}$). For steel bolts with unknown K_{Ic}, low-fracture toughness is assumed when $F_{tu} > 1240$ MPa (180 ksi).

Materials Usage Agreement (MUA): A formal document showing that a non-compliant material is acceptable for the specific application identified.

Maximum Design Pressure (MDP): For a pressurized system, the highest pressure defined by the maximum relief pressure, maximum regulator pressure, maximum temperature, and transient pressure excursions based on two credible system failures.

Mechanism: A system of moveable and stationary parts that work together as a unit to perform a mechanical function, such as latches, actuators, drive trains, and gimbals.

Nondestructive Evaluation (NDE): Examination of parts for flaws using established and standardized inspection techniques that are harmless to hardware, such as radiography, penetrant, ultrasonic, magnetic particle, and eddy current.

Non-Hazardous Leak Before Burst (NHLBB): Characteristic of pressurized hardware whose only credible failure mode is development of a non-hazardous leak, as opposed to catastrophic fragmentation or abrupt rupture.

Part: See Component.

Pressure Vessel: A container designed primarily for pressurized storage of gases or liquids and the following:

a. Contains stored energy of 19,307 joules (14,240 foot-pounds) or greater based on adiabatic expansion of a perfect gas; or

b. Contains a gas or liquid in excess of 103.4 kPa (15 psia) that will create a hazard if released; or

c. Stores a gas that will experience an MDP greater than 689.5 kPa (100 psia).

Pressurized Component: A line, fitting, valve, regulator, etc. that is part of a pressurized system and intended primarily to sustain a fluid pressure. Any piece of hardware that is not a pressure vessel but is pressurized via a pressurization system.

Pressurized Structure: A hardware item designed to carry both internal pressure and vehicle structural load.

Pressurized System: An interrelated configuration of pressurized components under positive internal pressure. The system may also include pressure vessels.

Proof Test: A load or pressure in excess of limit load or the MDP by a defined factor applied to a structure or pressurized hardware to verify structural acceptability or to screen flaws.

R Ratio: The ratio of minimum stress to maximum stress.

Responsible Fracture Control Board (RFCB): The designated board at the NASA Center or sponsoring institution responsible for fracture control methodology that can interpret fracture control requirements. Designation may be in the form of specific duties assigned within an existing function.

Responsible NASA Center: The NASA Center acting as the sponsor and/or coordinator for the payload/hardware. For non-NASA payloads, the Johnson Space Center (JSC) serves as the responsible NASA Center.

Rotating Machinery: Devices with spinning parts such as fans, centrifuges, motors, pumps, gyros, and flywheels.

Rotational Energy: The energy of a rotating component is expressed as $\frac{1}{2} I\omega^2$, where I is the mass moment of inertia and ω is the rotational speed in radians per second.

Safe Life: See Damage Tolerant.

Safety Critical: For fracture control, a part, component, or system whose failure or loss would be a catastrophic hazard.

Sealed Container: Any single, independent (not part of a pressurized system) container, component, or housing that is sealed to maintain an internal non-hazardous environment.

Service Life: Service interval for a part beginning with manufacture and extending through its planned and specified usage. The service life includes all loadings and environments encountered during this period that will affect crack growth and all manufacturing, testing, transportation, launch, on-orbit, descent, landing, and post-landing events. A "service life" is sometimes referred to as a "lifetime." In this sense, "lifetime" means a specified life as opposed to an analytically predicted life.

Service Life Factor: The factor on service life required in damage tolerant analysis or testing. A minimum service life factor of four (4) is required. The "service life factor" is often referred to as the "life factor."

Shatterable Materials: Any material that is prone to brittle failures during operation which could release many small pieces into the surrounding environment.

Standard Forging: Common, commercially available parts that include billets, or rings with channel, angle, tee, or other common cross sections that are regularly produced in quantity by forging vendors.

Standard NDE: Formal crack-detection procedures that are consistent with common industrial inspection standards.

Static Fatigue: Strength degradation with time resulting from flaw growth is referred to as static fatigue. For instance, in glass, flaws grow as a function of stress, flaw size, environment, and time.

System Safety and Mission Assurance (SSMA) Representative: A designated individual from the SSMA organization who is responsible for ensuring SSMA requirements are met including the fracture control requirements of traceability and documentation. The SSMA representative is also responsible for ensuring that the flight hardware complies with approved drawings, specifications, plans, and procedures by providing an independent assessment of established safety, reliability, maintainability, and quality requirements.

Tools: Devices that are manually employed by a crew member to perform work or serve a structural function.

Yield Strength: The stress that corresponds to a plastic axial strain of 0.002 mm/mm (0.002 in/in).

4. REQUIREMENTS

4.1 Fracture Control Classification of Parts

a. Fracture control shall be initiated by a structure/system screening review to identify fracture-critical parts based on failure modes, consequences of failure, applicable requirements, and experience.

b. All spaceflight hardware shall be examined to determine its fracture control classification.

c. In the event previously flown hardware exists that was certified to fracture control requirements levied under prior programs, the hardware shall be re-assessed using the fracture control requirements specified here.

d. Additionally, all hardware that deviates from the certified design configuration, either through off-nominal conditions or degradation during service, shall require a complete update to the existing fracture control classification and analyses.

Hardware may be classified as exempt, non-fracture critical, or fracture critical. These three categories are broken down further to assist in the classification of parts.

Exempt hardware typically includes non-structural items such as flexible insulation blankets, enclosed electrical circuit components/boards, electrical connectors (including locking devices), wire bundles, and seals. Small mechanical parts, such as bearings and valve seats, that have been developed and qualified through required test programs and rigorous process control to demonstrate their reliability, and whose failure does not directly lead to a catastrophic hazard, may be exempt from fracture control with the approval of the RFCB.

Non-fracture-critical hardware can include low-released or contained mass, fail safe, NHLBB pressurized components, low-speed and low-momentum rotating machinery, and protected glass. Section 4.1.1 gives a detailed description of all of the non-fracture-critical classifications and requirements for classifying specific hardware items.

Fracture-critical hardware includes pressure vessels, high-energy or high-momentum rotating equipment, hazardous fluid containers, habitable modules, and any remaining hardware that does not fit the categories of exempt or non-fracture critical.

e. All fracture-critical hardware shall be shown to meet fracture control requirements through analysis and/or test as defined in section 4.2.

Section 4.1.2 provides requirements for classifying and assessing specific types of fracture-critical hardware.

f. Assessment of hardware criticality shall examine the different phases of application including transportation, launch, on-orbit, interplanetary, or lunar travel including surface operations and return-to-ground (including contingencies) to determine the applicability and extent of fracture control.

For example, a part may not be fracture critical during the launch phase, but could be fracture critical for on-orbit service. In this case, the fracture control assessments will address the on-orbit phase as well as other phases and their potential effects on the on-orbit performance.

g. Fracture-critical parts shall be identified as such on the engineering drawings to alert all who use the drawing as to the criticality of the part.

Designers and analysts need to work together to assure that required notations, including NDE and/or proof-test requirements, are provided on the drawing for any fracture-critical part.

4.1.1 Non-Fracture-Critical Parts

This section gives a detailed explanation of each of the non-fracture-critical classifications and requirements for classifying specific hardware items as such.

Those parts that are identified as non-fracture critical shall be designated as complying with the requirements of fracture control without further activity beyond conventional aerospace verification and quality assurance procedures.

4.1.1.1 Low-Released Mass

All parts of any size in this category whose release would not be a catastrophic hazard either to the source of the mass or to any other structures, systems, or crew that could be impacted by the mass during any phase of launch or flight can be classified non-fracture critical.

a. Where uncertainty exists as to consequences of a released mass inside a structure, the released mass shall not be able to achieve (for example, via contact with crew or release during launch) a velocity of more than 10.7 m/sec (35 ft/sec) or a momentum of more than 1.24 kg-m/sec (8.75 ft-lb/sec).

b. Released mass external to a vehicle shall be shown to present acceptable risk (section 4.1.1.8.1) after impact upon all potential impact surfaces if applicable.

c. Fasteners preloaded in tension that have low-fracture toughness, $K_{Ic}/F_{ty} < 1.66\ mm^{1/2}$ ($0.33\ in^{1/2}$), shall be limited to 14 gm (0.03 pound) potential free mass.

d. Parts with a single-point failure that would exceed low-released mass limits shall be contained (section 4.1.1.2) or meet the low-risk criteria (section 4.1.1.12) to be classified non-fracture critical.

4.1.1.2 Contained Parts

A failed part confined in a container or housing or otherwise positively restrained from free release that does not result in a catastrophic hazard can be classified as non-fracture critical.

a. Pressurized components or rotating devices within stowed or contained hardware shall be assessed independently, as provided in this standard, to ensure safe application against catastrophic failure of the container/compartment.

b. Containment of rotating devices shall consider the combined effect of rotational speed and potential for mass release to determine classification (see section 4.1.1.5).

Guidance for calculating containment of high-energy rotating devices is given in NASA-HDBK-5010.

c. Contained hardware shall also be examined for potential damage effects of single-point mass releases inside the confinement itself.

d. Release of masses (of any size) within a container that could credibly defeat an internal safety-critical function shall be precluded by appropriate technical measures, which can include compliance with requirements for low-risk part classification (see 4.1.1.12), or other techniques approved by the RFCB.

e. Enclosures with openings shall only be assessed for containment of parts larger than accessible openings.

f. When containment is furnished by a compartment with doors or other hardware designed to open, the closure design shall be one failure tolerant of accidentally opening; i.e., hinges, latches, and other mechanisms shall be redundant for keeping a door closed in the event one device fails.

Typical electronic boxes and related equipment such as radios, cameras, recorders, personal computers, and similar close-packed and enclosed hardware can be regarded as acceptable containers of internal parts without further assessment.

Release of a free mass from a fastener that is mechanically constrained (e.g., safety wired) can be assumed to be contained. All constrained fasteners can be classified non-fracture critical if failure does not result in a catastrophic hazard due to loss of structural integrity of the fastener or loss of a safety-critical function.

4.1.1.3 Fail Safe

a. A part, or any load-carrying element such as a fastener, latch, or weld, can be identified as "fail safe" and classified as non-fracture critical when it meets the following criteria:

(1) Due to structural redundancy, the structure remaining (assumed unflawed) after complete part failure (all load paths severed) shall withstand all redistributed loads with a minimum ultimate safety factor of 1.0 on limit load.
(2) Composite, non-ductile metallic parts and bonds shall have an appropriate safety factor coordinated with the RFCB.
(3) The structural failure shall not release a potentially catastrophic mass in violation of sections 4.1.1.1 and 4.1.1.2.

b. In doing a fail-safe analysis of an assembly of several similar parts with a common function, such as fasteners in a bolted joint or struts in a truss, the part with the highest load and the part with the lowest margin (these may not be the same) shall be removed separately to assess fail-safe capability.

c. In doing a fail-safe analysis where the parts in the assembly are distinct, each part shall be removed to assess fail-safe capability.

d. In highly redundant complex structures, the rationale for part selection shall be documented by the analyst and presented to the RFCB for approval.

e. When determining redundancy, the effect of altered dynamic coupling on loading shall be considered unless

(1) the design loads are shown to be conservative with respect to dynamic coupling variations, or
(2) failure of the part does not significantly alter dynamic response of the hardware.

f. Redundancy against catastrophic failure shall be re-verified between missions for a fail-safe structure that is re-flown and for on-orbit structures subject to significant fatigue loading at program prescribed intervals.

Re-verification may be accomplished by a close visual inspection (aided by cameras, boroscopes, or other assistance if necessary) of the hardware for signs of damage. If damage is indicated, a more rigorous inspection can be made to establish fail-safe structural integrity with the approval of the RFCB. An alternative to re-verification of structural redundancy is to show the remaining structure has sufficient fatigue capability, demonstrated by a fatigue or damage tolerance analysis or test, to reach end of service using concentrated stresses and a service life factor of 4.0 on total cycles.

4.1.1.4 NHLBB Pressurized Components

a. Pressurized components whose only credible failure mode is development of a non-hazardous leak (as opposed to catastrophic fragmentation or abrupt rupture) and that meet items b(1) through b(4) in this section can be classified as NHLBB, provided that release of the contents is not a catastrophic hazard.

(1) NHLBB shall not be applied to habitable structures and enclosures.
(2) To be classified NHLBB, the components shall not have coatings, barriers, liners, or other means that prevent or inhibit leakage through a flaw.

Catastrophic hazards to be considered in this assessment include unacceptable dilution or toxicity of breathing environment, increases in oxygen or flammable fluids beyond flammability limits, or loss of a safety-critical function.

b. Pressurized lines, fittings, and other system components such as regulators, valves, filters, and bellows can be classified as NHLBB and non-fracture critical provided items (1) through (4) below shall be met:

(1) A leak is not a catastrophic hazard.
(2) System supports and brackets meet fracture control.
(3) The crack opening of the critical flaw size at typical operating pressures is large enough to allow a stable leak that reduces the internal pressure.

The methodology given in API-RP-579, Fitness-for-Service can be used for guidance in meeting the leakage requirement.

(4) The leak is automatically detected and further pressure cycling is prevented, or there is no re-pressurization.

4.1.1.5 Non-Fracture-Critical Rotating Machinery

Rotating machinery that has kinetic energy less than 19,307 joules (14,240 foot-pounds) and angular momentum less than 136 Newton-meter-seconds (100 pound-foot-seconds) and does not present a catastrophic hazard risk can be classified as non-fracture critical.

a. In the event of failure, low-energy and low-momentum rotating equipment shall be examined for protection against a catastrophic occurrence resulting from released masses.

b. Rotating equipment whose failure could be catastrophic shall be shown to be contained (section 4.1.1.2).

c. Where containment cannot be assured or failure directly results in a catastrophic hazard, the device shall be treated in accordance with applicable criteria in section 4.1.2.2 for fracture-critical rotating machinery.

d. The mounts for rotating machinery shall be addressed as standard structure and assessed for fracture criticality.

Shrouded or enclosed fans (8000 rpm and 20.4-cm (8-in) diameter maximum), electric motors, shafts, gearboxes, recorders, conventional pumps (including roughing pumps), and similar devices can be classified non-fracture critical unless failure would lead to a catastrophic hazard.

4.1.1.6 Fasteners and Shear Pins

A fastener or pin whose individual single-point structural failure would clearly not be a catastrophic hazard, or a group of fasteners or pins where loss of any one fastener or pin would clearly not result in a catastrophic hazard, can be classified non-fracture critical by meeting the requirements of sections 4.1.1.1, 4.1.1.2, and/or 4.1.1.3, as applicable.

a. All rivet applications shall meet fail-safe requirements (section 4.1.1.3).

Locking devices to prevent fastener or connector back out, including wires, tangs, or other methods are non-fracture critical by exemption.

b. Fasteners and shear pins can also be classified as low risk if the following are met:

(1) Fastener shall be in a local pattern of two or more similar fasteners.
(2) Fastener and joint shall be within the Shuttle or International Space Station experience base.
(3) Fastener shall be fabricated and inspected in accordance with military standard, national aircraft standard, or equivalent commercial aerospace specifications.
(4) Fasteners shall be procured and have positive back-off prevention consistent with their criticality using NASA-STD-(I)-6008, NASA Fastener Management and Control Practices.
(5) Fasteners used in multi-cycle applications shall have rolled threads and be fatigue rated.
(6) Fastener shall be fabricated from a metal not sensitive to stress corrosion cracking as defined in NASA-STD-(I)-6016, Standard Materials and Processes Requirements for Spacecraft.
(7) If used in tension applications, the fastener shall not be made from a low fracture-toughness alloy as defined in section 3.2 or, specifically, Ti-6Al-4V STA titanium.
(8) Fasteners shall meet appropriate preloads and stress requirements with no joint gapping (gapping is allowed under fail-safe and/or emergency conditions).
(9) Reworked or custom-made fasteners shall require RFCB approval.

4.1.1.7 Non-Fracture-Critical Composite/Bonded Structures

Polymer matrix composite/bonded structures that meet the non-fracture-critical requirements as specified in MSFC-RQMT-3479, Fracture Control Requirements for Composite and Bonded Vehicle and Payload Structures, and meet the intent of MIL-HDBK-6870A, Inspection Program Requirements, Nondestructive for Aircraft and Missile Materials and Parts, can be classified non-fracture critical.

4.1.1.8 Shatterable Components and Structures

External and internal components manufactured from a material that is prone to brittle failures can be classified as non-fracture critical if the requirements of section 4.1.1.8.1 or 4.1.1.8.2 are met.

4.1.1.8.1 Low-Risk External Components and Structures

Any components or structures that are on the external surface of a spacecraft, including thermal protection systems, which are manufactured from a material that has limited ductility such that it is prone to brittle failures when cracked and/or subjected to impact, can be classified as non-fracture critical by meeting a, b, and c, below.

a. Process controls verified by lot testing of components or structures shall provide A Basis static and dynamic strength properties.

Structural testing may be substituted, with prior approval of the RFCB, for component level lot testing when process controls and coupon testing have been shown to reliably establish component strengths.

b. Multi-mission components or structures shall be assessed for integrity between flights via inspection or test.

c. Components or structure shall meet either of the following two requirements throughout the mission life while presuming a worst-case mission environment, including but not limited to credible impacts from vehicle loss of external surface mass, micrometeoroid and orbital debris (MMOD), extra vehicular activity (EVA) inadvertent contacts, and EVA tool impact hazards:

(1) The component or structure shall have a factor of 4 on life and 1.4 on strength while reliably accounting for the effects of manufacturing and/or service-induced flaws.
(2) The design shall be redundant in function and strength such that loss of a primary member does not result in catastrophic loss of function or required strength that prevents the spacecraft from safely completing the mission.

4.1.1.8.2 Shatterable Components and Structures Inside Volumes

Non-fracture critical shatterable components in volumes shall meet the requirements contained in JSC 62550, Strength Design and Verification Criteria for Glass, Ceramics and Windows in Human Space Flight Applications.

If approved by the RFCB, small shatterable parts can be accepted for use based on vibration environmental testing, inspection, and functional tests that verify the integrity. Camera lenses and similar pieces that are recessed or protected during non-use periods are considered protected and can be classified non-fracture critical.

4.1.1.9 Sealed Containers

Sealed containers (e.g., a sealed electronics box) can be classified as non-fracture critical if failure does not result in a catastrophic hazard, the container supports meet fracture control requirements, and the container complies with the following:

a. The container shall be made from materials typically used for commercially available sealed containers procured to an aerospace standard or equivalent.

b. The container shall be pressurized to 1.5 atmospheres or less.

(1) If the container is pressurized to more than 1.5 atmospheres, an analysis shall show that the container has a positive margin against burst when a factor of 2.5 on MDP is used, or
(2) The container shall be proof tested to a minimum of 1.5 times the MDP.

The container portion of a non-fracture critical sealed container does not require NDE to screen for flaws. The container supports may require NDE depending on their individual fracture control classification.

4.1.1.10 Tools/Mechanisms

All tools and mechanisms that are not classified as fracture critical according to section 4.1.2.6 can be classified non-fracture critical if the requirements of sections 4.1.1.1 or 4.1.1.2 are met.

4.1.1.11 Batteries

Batteries and battery systems that meet the requirements of JSC 20793, Crewed Space Vehicle Battery Requirements, can be classified non-fracture critical. Battery cells/cases that meet either the NHLBB requirements in section 4.1.1.4 or the sealed container requirements in section 4.1.1.9 can be classified non-fracture critical. Small batteries in common use, such as button cells of 200 milliamp-hours or less and carbon-zinc or zinc-air batteries of size "F" or smaller are exempt from fracture control.

4.1.1.12 Low-Risk Part

This section addresses parts that can be classified non-fracture critical because of large structural margins and other considerations that make failure from a pre-existing flaw extremely unlikely.

a. For a part to be classified low risk, it shall be constructed from a commercially available material procured to an aerospace standard or equivalent.

b. Aluminum parts shall not be loaded in the short transverse direction if this dimension is greater than 7.62 cm (3 in).

c. A part whose failure directly results in a catastrophic hazard shall be excluded from being classified low risk, except when the total (unconcentrated) stresses in the part at limit load are less than 30 percent of the ultimate strength for the material used and requirements (1) through (3) and either (4) or (5) are met.

d. If there is a change in loads, parts classified as low risk shall be re-evaluated to ensure that net section stresses remain below 30 percent of ultimate strength.

(1) If the part contains metallic materials, it shall be fabricated from a well-characterized metal that is not sensitive to stress corrosion cracking as defined in NASA-STD-(I)-6016.

A. Metallic parts shall have a material property ratio of $K_{Ic}/F_{ty} > 1.66 \text{ mm}^{1/2}$ (0.33 $\text{in}^{1/2}$).

B. *With the approval of the RFCB, the effect of material thickness on K_{Ic} value may be considered, and the K_{Ie} value may be used in lieu of K_I, if it is known for a specific application.*

(2) The part shall not be fabricated using a process that has a significant probability of introducing flaws unless specific NDE or testing, which has been approved by the RFCB, is applied to sufficiently screen for flaws.

(3) At a minimum, the parts shall receive an inspection for surface defects prior to assembly.

A. Defects that could affect part life shall be cause for rejection of the low-risk classification.

(4) A maximum stress that does not exceed the endurance limit or $S_{max} < F_{tu}/(4\{1\text{-}0.5 R\})$, where S_{max} is the local concentrated stress, and R is the ratio of minimum stress to maximum stress in a fatigue cycle.

(5) A damage tolerance analysis from a 0.127 mm (0.005 in) initial crack that conservatively accounts for the effects of notches and mean stress and shows a minimum of four (4) complete service lives with a factor of 1.5 on alternating stress.

4.1.2 Fracture-Critical Parts

This section provides criteria for classifying and assessing specific types of fracture-critical hardware.

In addition to the requirements in this section, fracture-critical parts shall meet the damage tolerance requirements in section 4.2 unless specifically stated otherwise.

4.1.2.1 Pressurized Hardware

a. All pressurized hardware, including pressure vessels (see definition in section 3.2) and pressurized structure, that contains hazardous fluids shall be classified fracture critical.

b. A pressurization history log shall be maintained for pressure vessels to ensure that allowable numbers of pressurizations and time at pressure are not exceeded and to document that required conditions for pressurization (such as temperature and rate) are adhered to.

c. If fracture mechanics analyses are used to meet the damage tolerance requirements in section 4.2, the approach shall be approved by the RFCB.

4.1.2.1.1 Metallic Pressure Vessels

a. Metal pressure vessels shall comply with the latest revision of ANSI/AIAA Standard S-080, Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components, with the following tailoring:

(1) MDP shall be substituted for all references to maximum expected operating pressure (MEOP).

(2) Pressure vessels designed and manufactured in accordance with the rules of the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 or 2, or DoT Title 49, that also meet the NHLBB requirements of section 4.1.1.4, shall not be required to meet the damage tolerance requirements of section 4.2.

A. All other pressure vessels shall meet the damage tolerance requirements of section 4.2, in accordance with the requirements of 4.1.2, and therefore not be designed to the Leak Before Burst requirements of ANSI/AIAA S-080.

4.1.2.1.2 Unlined Composite Pressure Vessels

Unlined composite pressure vessels shall require the prior approval of the RFCB.

4.1.2.1.3 COPVs

COPVs shall comply with the latest revision of ANSI/AIAA Standard S-081, Space Systems-Composite Overwrapped Pressure Vessels (COPVs), with the following tailoring:

a. MDP shall be substituted for all references to MEOP.

b. Mechanical damage control shall include protective covers and damage indicators as a minimum unless otherwise approved by the RFCB.

c. If damage indicators are utilized, the indicator shall be inspected between missions.

4.1.2.1.4 Lines, Fittings, and Other Pressurized Components

a. Lines, fittings, and other pressurized components (hardware items that are part of a pressurized system including valves, filters, regulators, heat pipes, and heat exchangers) shall be considered fracture critical if they contain hazardous fluids or if loss of pressurization would result in a catastrophic hazard.

b. All fusion joints in fracture-critical pressure components shall be 100 percent inspected using a qualified NDE method to determine the presence of unacceptable lack of penetration or other unacceptable conditions both on the surface and within the fusion joint.

c. Inspection of fracture-critical fusion joints shall be made after proof testing, and for lines and fittings, after proof test of the final assembly.

d. Concurrence of the RFCB shall be required where full NDE is required but not considered practical.

e. Any type of flaw indication in the final product that does not meet specification requirements shall be cause for rejection.

f. In addition to proof testing of parts during individual acceptance, the complete pressure system shall also be proof tested and leak checked to demonstrate system integrity.

If the lines, fittings, and other pressurized components are proof tested to a minimum of 1.5 times the MDP, then the damage tolerance requirements of section 4.2 are not required.

4.1.2.2 Rotating Machinery

a. A rotating mechanical assembly shall be fracture critical if it has a kinetic energy exceeding 19,307 joules (14,240 foot-pounds) or an angular momentum exceeding 136 Newton-meter-seconds (100 pound-foot-seconds).

b. In addition to other requirements for fracture-critical components, fracture-critical rotating machinery shall be proof tested (spin tested) to a minimum factor of 1.05 and subjected to NDE before and after proof testing.

c. If NDE after proof testing is not practical, then the rotating part shall be contained (see section 4.1.1.2), and

(1) loss of function shall not be safety critical, or
(2) it shall be shown that the proof test adequately screens for flaws (see section 4.2.4.4.2) with RFCB approval.

NASA-HDBK-5010 contains guidance on classifying fracture-critical rotating hardware.

4.1.2.3 Fasteners

Fasteners that do not comply with the various non-fracture-critical criteria applicable to fasteners in section 4.1.1 are classified fracture critical.

a. Fracture-critical fasteners shall meet items (3) through (9) of the criteria in section 4.1.1.6.

b. Use of fracture-critical fasteners less than 0.48 cm (3/16 in) diameter shall require prior approval by the RFCB.

c. Preload and its effect on flaws and cyclic stresses shall be considered in the damage tolerance assessment.

d. All fracture-critical fasteners shall be inspected by the eddy current NDE technique or be proof tested to screen for flaws.

e. Damage tolerance analysis shall assume a flaw in the thread root of a size consistent with NDE sensitivity or proof-test level.

NDE flaw sizes are given in NASA-STD-(I)-5009, Nondestructive Evaluation Requirements for Fracture Critical Metallic Components.

Pins, tangs, and lock wire used for assurance against fastener back-off are exempt from fracture control.

f. Inserts used in conjunction with fracture-critical fasteners shall be proof-load tested to a minimum factor of 1.2 after installation.

This would include, for example, inserts bonded or potted into composite and sandwich structures as well as inserts installed into metallic structures. Note that composite structures require additional considerations as given in section 4.1.2.4.

g. After inspection or testing, fracture-critical fasteners shall be stored and controlled to keep them isolated from other fasteners.

4.1.2.4 Composite/Bonded Structures

Fracture-critical polymer matrix composite structures that meet the requirements contained in MSFC-RQMT-3479 and meet the intent of MIL-HDBK-6870 are not required to meet the requirements of section 4.2.

All other fracture-critical composites shall require prior approval by the RFCB.

4.1.2.5 Shatterable Components and Structures

a. All shatterable components and structures that do not meet the criteria in section 4.1.1.8 shall be classified as fracture critical.

b. Fracture-critical shatterable components in volumes shall meet the requirements contained in JSC 62550.

c. Fracture control of fracture-critical external components and structures shall be coordinated with the RFCB.

4.1.2.6 Tools/Mechanisms

a. Tools or mechanisms that are the only (not back-up) means for performing a function where failure to perform the function would result in a catastrophic hazard, or a tool/mechanism whose failure during use would, in itself, result in a catastrophic hazard, shall be classified fracture critical.

This classification includes safety-critical tethers.

b. Each fracture-critical tool or mechanism shall be proof tested or adequately inspected to assure that defects that could cause failure during use are not present.

c. Fatigue-rated springs shall be used for fracture-critical spring applications when greater than 1,000 cycles are required.

d. Fracture-critical tools/mechanisms shall, as applicable, also be assessed for compliance with the requirements of sections 4.1.1.1 or 4.1.1.2.

4.1.2.7 Batteries

a. Batteries not meeting the criteria of section 4.1.1.11 shall be classified as fracture critical.

b. Fracture-critical batteries shall meet both the requirements of JSC 20793, Manned Space Vehicle Battery Safety Handbook, and hazardous fluid containers (section 4.1.2.8).

4.1.2.8 Hazardous Fluid Containers

a. Hazardous fluid containers shall be damage tolerant against rupture and leak when release of a fluid would cause a catastrophic hazard.

b. Containers shall meet all the requirements of pressure vessels (section 4.1.2.1) when the contained fluid has a delta pressure greater than 1.5 atmosphere.

A container that has a delta pressure less than 1.5 atmosphere, a minimum factor of 2.5 times MDP on burst pressure, and meets the fracture control requirements for pressurized components (section 4.1.2.1.4) can be classified non-fracture critical.

c. Integrity against leaks shall be verified by test at 1.0 times MDP.

4.1.2.9 Habitable Structures and Enclosures

a. All habitable structures and enclosures designed to support life shall be classified as fracture critical.

b. The following requirements apply:

(1) Pressure shells shall be classified as damage tolerant.
(2) Pressure shells shall be proof tested and verified leak-tight.
(3) At a minimum, the damage tolerant required NDE shall be performed post-proof test. Pre-proof NDE is highly recommended to protect high-value structures and facilities.
(4) Structures made of polymer matrix composites shall also meet the requirements of MSFC-RQMT-3479 and the intent of MIL-HDBK-6870A.
   A. Other structures made of materials that cannot be analyzed using conventional fracture mechanics methodologies (e.g., inflatable non-metallic structures) shall be designed and tested to demonstrate adequate failure tolerance.
   B. Verification shall be approved by the RFCB.
(5) Habitable structures or enclosures shall not be classified as NHLBB, because pressure shall be maintained.

(6) Damage tolerant assessment of habitable structures and enclosures shall consider worst case, design allowable, fusion joint peaking, mismatch, and residual stresses.
(7) The influence of coatings/barriers on leak detection during proof and other testing shall be assessed.
(8) Operation shall be monitored and documented to ensure that certification is not invalidated.

4.1.2.10 Single-Event Fracture-Critical Components

Fracture-critical components with a single-event life loading history, such as pyrotechnic components, can be shown acceptable by demonstrating a factor of 1.4 against fracture toughness instead of a factor of four (4) on life if all of the following conditions apply:

(1) The single-event loading is a single cycle or a single cycle with rapidly decaying subsequent cycles.
(2) The component is not subject to any other significant loads.

a. The margin on fracture shall be either determined analytically or demonstrated by test. When determined analytically, the margin for the 1.4 factor on toughness can be computed as shown:

$$\text{Margin on Toughness} = K_{Ic} / (1.4 * K_{applied}) - 1$$

where K_{Ic} is the plane strain fracture toughness and $K_{applied}$ is the peak applied stress intensity for metallic structures.

b. Any deviation shall be approved by the RFCB.

Demonstration by test can be used in situations where the applied loads are difficult to determine, the material properties are uncharacterized, or other factors make the damage tolerance analyses difficult.

c. Demonstration tests shall be coordinated with the RFCB.

d. The test articles shall each contain a flaw in the worst location and orientation.

e. Flaw sizes and load amplitudes shall be one of the following (1 or 2):

(1) Loads are known and can be readily applied to test articles.
A. The test load shall be 1.4 times the maximum expected flight load.
B. The flaw size shall be at least as large as the requirements of NASA-STD-(I) 5009.

(2) Loads are difficult to apply or not well characterized.

A. The flaw size shall be at least twice as large in all dimensions as the requirements of NASA-STD-(I)-5009.
B. Load application shall simulate worst-case flight conditions.
C. A sufficient number of articles shall be tested to ensure test conditions approached maximum flight conditions.

4.1.2.11 HCF Components

Fracture-critical components operating in a potential HCF environment, such as turbine blades, rotors, impellers, and other high-speed elements that are subject to local modes of high-frequency vibration and large numbers of loading cycles, can be shown acceptable by demonstrating no HCF flaw growth.

a. The threshold value used for an HCF assessment shall be approved by the RFCB.

b. The following procedure shall be used to meet this requirement:

(1) The initial NDE flaw size shall be assumed in the worst location and orientation.
(2) The flaw shall be propagated for four (4) times the required design life using the low-cycle loads such as thermal, pressure, or speed.
(3) The final flaw size from the calculations in (2) shall be used as the initial flaw size in calculating the stress intensity due to the HCF environment.
(4) The metallic component is acceptable if the calculated HCF stress intensity is below the stress intensity factor threshold for the metallic material.
(5) The composite component is acceptable if the calculated HCF total strain energy is below the total strain energy threshold for the composite material.

4.2 Methodology for Assessing Fracture-Critical Hardware

a. Those parts identified as fracture critical shall be shown to be damage tolerant by damage tolerance analysis (section 4.2.1), damage tolerance test (section 4.2.2), or fleet leader testing (section 4.2.3).

b. The damage tolerant demonstration shall be based on an initial flaw size that could be present in the part.

c. This flaw size shall be established by NDE, proof testing, or process control.

General damage tolerance requirements are defined in section 4.2.4.

d. Analysis or test shall consider all significant loadings, both cyclic and sustained, that the part can experience during ground, flight, orbital, and planetary phases.

e. Loads from these phases shall be considered for each mission the hardware may undertake.

The total of all significant loading events and environments comprise one (1) service life (see definitions for damage tolerant, service life, and service life factor).

f. Damage tolerant parts shall be shown to have a service life factor of at least four (4) and subsequently have a positive margin on toughness.

g. If four (4) is not achieved, the part shall be redesigned, or a special inspection technique can be employed.

h. Special inspection techniques shall be approved by the RFCB. If feasible, the life requirement can be reduced (limited life) and the part replaced or re-inspected when available life is used.

i. If "limited life" parts are to be employed, project management shall be informed and determination made to replace the part, re-verify damage tolerance if feasible (e.g., make the part accessible for NDE inspections in service), or define an acceptable level of risk.

4.2.1 Damage Tolerant Analysis

a. Damage tolerant analysis shall assume that an undetected flaw is in the most critical area and orientation for that part using the requirements in section 4.2.4.

Models for crack growth rate and fracture mechanics analyses may vary from version to version and may also vary from equations published in the literature.

b. The version used for the original design and analysis shall be acceptable for the life of the hardware unless loading and/or design changes take place.

c. If fracture life has driven the design, or if loading/design changes are made, the most current version of the analysis program shall be used for life assessment using settings appropriate for the particular application.

d. If predicted life is lacking after re-assessment, or if valid concern about fracture life of other hardware occurs, the matter shall be brought to the RFCB for resolution.

4.2.1.1 Deterministic Methods

a. To show that a part meets fracture control requirements, it shall be demonstrated that the part can survive at least four (4) service lives from an initial flaw with the exception of single-use hardware (section 4.1.2.10).

b. The size of the flaw shall be based on appropriate NDE techniques, proof testing, or process control as defined in section 4.2.4.4.

The computer program NASGRO® (NASA Crack Growth Computer Program) is an approved analysis tool for the damage tolerance life assessment of metallic spaceflight hardware. Other computer programs or analysis methods are acceptable with prior approval by the RFCB.

4.2.1.2 Probabilistic Methods

Standard NASA damage tolerance analyses are deterministic, and experience has shown these deterministic methods to be adequate. The probabilistic method uses knowledge (or assumptions) of the statistical variability of the damage tolerance variables to select criteria for achieving an overall success confidence level.

Any proposed use of probabilistic damage tolerance criteria to meet fracture control requirements shall be approved by the RFCB on an individual-case basis.

4.2.2 Damage Tolerant Testing

Damage tolerant testing can be used whenever fracture mechanics analysis methodologies are not applicable or in lieu of analysis if approved by the RFCB.

The general requirements in section 4.2.4 shall be implemented in damage tolerance testing.

4.2.3 Fleet Leader Testing

In cases where loading conditions are poorly defined, a ground test fleet leader program can be developed to allow hardware use.

A fleet leader testing program shall be developed with RFCB approval.

4.2.4 General Damage Tolerance Requirements

Damage tolerance analyses (section 4.2.1) and tests (section 4.2.2) shall be undertaken with the following requirements on input parameters.

General considerations, guidance, and comments on the effects of input variation on damage tolerance are provided in NASA-HDBK-5010.

4.2.4.1 Material Selection and Fracture Mechanics Properties

a. Fracture-critical parts shall be fabricated from materials and/or components with specific verification of applicable supplier data/certifications and obtained from bonded storage or equivalent materials/hardware control.

b. Materials shall be compatible with NASA-approved standards and specifications. The NASGRO® material database contains fracture mechanics properties for several materials that can be utilized with concurrence from the RFCB.

c. Several factors shall be considered in material selection with respect to fracture performance as listed below.

4.2.4.1.1 Service Environment

a. The effect of environmental factors, such as temperature and exposure to harmful media, on flaw growth and fracture properties shall be documented.

b. Materials not developed and qualified in accordance with the requirements of NASA-STD-(I)-6016 shall have an approved MUA.

c. An MUA shall include documentation on the suitability of the alloy for the specific application and be included in the Fracture Control Summary Report (FCSR).

4.2.4.1.2 Product Form

a. Specimens used to characterize a material shall be representative of the stock used to manufacture the hardware.

b. Fracture properties for welded and/or brazed joints shall be developed for parts requiring damage tolerant analysis.

4.2.4.1.3 Material Orientation

a. Fracture properties for all material orientations shall be developed for materials where anisotropic behavior is noted.

b. Properties of the weakest material orientation shall be used in the life and strength analysis unless material orientation is fully traceable throughout the design and manufacturing process.

4.2.4.1.4 Material Processing

Fracture properties shall be representative of the material process condition found in the hardware.

4.2.4.2 Fracture Mechanics Material Properties

Requirements on material properties used in damage tolerant analyses are provided below:

a. The fatigue crack growth rate and fracture toughness values for predicting crack growth and instability shall be average or typical values.

(1) All data shall correspond to the expected in-service temperature and chemical environments.

When the amount of predicted crack growth is small (initial and critical cracks are of similar size), or if either sections 4.2.4.2(d) or (e) are applicable, then the RFCB may require use of a lower bound fracture toughness at the end of four (4) service lifetimes to ensure there is a positive fracture margin.

b. Fracture properties shall be appropriate for the product form, thickness, environment, and constraint condition.

(1) For NASGRO® analyses, the fitting parameter on instability, B_k, shall be set to zero unless specific data is available to justify a non-zero value.

c. Environmental effects on crack growth shall be taken into account.

(1) The lower bound values of K_{eac}, or equivalent, for the relevant fluid and material combinations shall be used in fracture mechanics analysis unless approved by the RFCB.

d. A material with a wide range in fracture toughness, defined as one with the minimum value falling 20 percent below the average value, shall have samples tested from material out of the same heat lot or out of remnant material used in fabrication of the part and be coordinated with the RFCB.

e. Fracture toughness testing shall be explicitly required and coordinated with the RFCB for components that are design-limited by fracture toughness.

f. Retardation effects on crack growth rates from variable amplitude loading shall not be employed in analyses without the approval of the RFCB.

4.2.4.3 Loading Spectra

a. A load spectrum shall be developed for each fracture-critical part.

b. The load spectrum (mechanical, thermal, and environmental) shall include the load level and the number of cycles or duration for each significant load during the hardware's service life.

c. Both cyclic and sustained loading spectra shall include effects of preloads, residual stresses, and design-allowable welding joint discontinuities such as peaking and mismatch.

d. If pressure loading is present and assumed to decrease due to leakage from cracks, the influence of all coatings/barriers on assumed leakage shall be assessed.

e. Assessments for external structures and components shall consider impact loads and damage from mission environments including, but not limited to, credible impacts from vehicle loss of external surface mass, MMOD, EVA inadvertent contacts, and EVA tool impact hazards.

4.2.4.4 Flaw Screening for Fracture-Critical Parts

a. Fracture-critical parts shall be screened for flaws by NDE, proof testing, or process control.

b. RFCB approval shall be required for flaw screening by proof tests or process control.

4.2.4.4.1 NDE

a. NDE shall be done on fracture-critical parts to establish that a low probability of preexisting flaws is present in the hardware.

b. NDE inspections for fracture control shall be performed in accordance with NASA-STD-(I)-5009 for metallic components and meet the intent of MIL-HDBK-6870 for composite components.

c. Hardware that is proof tested as part of its acceptance (i.e., not screening for specific flaws) shall receive post-proof NDE at critical welds and other critical locations identified in the Fracture Control Plan.

4.2.4.4.2 Proof Test

a. Prior approval shall be required from the RFCB when a proof test is used as the flaw screening technique.

b. Documented rationale shall be provided, demonstrating the component is not expected to experience significant crack growth during the proof test, and/or a presumed crack size after the proof test adequately accounts for growth during the test and demonstrates adequate damage tolerant life.

c. When it is judged that a proof test is appropriate to screen a component or structure for flaws, the proof test shall occur at the in-service temperature and environment.

If this is not feasible, an ECF can be used as approved by the RFCB.

4.2.4.4.3 Process Control

a. Prior approval shall be required from the RFCB when process control is used to determine the initial defect sizes for damage tolerant analysis and/or testing.

b. Process control rationale submitted for RFCB approval shall include a statement explaining why this alternate approach is being applied, an overview of the hardware, the manufacturer’s experience base, process control during manufacture and subsequent life of the component, all component testing, and summary arguments.

NASA-HDBK-5010 contains an outline and guidance for building an acceptable process control program for specific components.

4.2.4.5 Detected Cracks in Fracture-Critical Hardware

a. When a crack of any size is detected in fracture-critical hardware, the part shall be scrapped or the crack removed or repaired.

If removal/repair of the crack is not feasible, with approval of the RFCB, a specific damage tolerance assessment can be performed to justify the use of a fracture-critical part with detected cracks.

b. If fracture mechanics analysis is used as part of the specific damage tolerance assessment, upper bound crack growth rate, lower bound fracture toughness, and lower bound fatigue crack growth threshold values shall be used.

c. The damage tolerant assessment shall also show adequate margin against fracture toughness at four (4) times the service life.

4.3 Tracking for Fracture-Critical Parts

4.3.1 Materials

a. All materials used in fracture-critical parts shall be traceable by certificate of compliance to material standards, an MUA, or engineering requirements stated on the drawing.

b. Material drawing notes shall be explicit and control the product form, condition, and heat treatment of the material.

c. Processes with consequences for fracture control such as welding, etching, or plating shall be controlled and documented.

4.3.2 Design, Analysis, and Hardware Configuration

a. During the development phase, a program shall be in place to assure that a delivered fracture-critical part is as designed and assessed.

b. This program shall include sufficient tracking to provide for fracture control assessment of load changes, modifications, or redesigns of the fracture-critical part.

c. Discrepancy reviews, or equivalent, shall be conducted for anomalies that could affect part fracture characteristics and life.

4.3.3 Load History

a. The load history shall be maintained for fracture-critical parts.

b. The load history shall include the load level, the number of cycles, and the environments in which the loads occurred.

c. The history shall cover the entire life of the part, as described in section 4.2.4.3.

d. For multi-mission hardware, the used life of the hardware shall be documented against the remaining life to assess flight readiness between missions from a fracture control point of view.

4.3.4 Flaw Screening

a. Engineering drawings and equipment specifications for fracture-critical parts shall contain notes that identify the part as fracture critical and specify the appropriate flaw-screening method to be used on the part or raw material.

b. A record of part NDE and findings shall be maintained by the responsible NDE organization.

c. Inspection records shall bear the stamp and/or signature of the inspector.

d. Proof test results shall be documented in a report.

4.4 Fracture Control Documentation

a. The fracture control program activities shall be documented and maintained under configuration control for the life of the hardware.

Examples and guidance on documentation for fracture control are given in NASA-HDBK-5010. Fracture control programs typically provide the following documentation:

(1) *Fracture Control Plan*
(2) *Engineering drawings*
(3) *A fracture control summary report*
(4) *Presentation summarizing the fracture control program*
(5) *A detailed fracture control analysis report*
(6) *Inspection report*
(7) *Proof and damage tolerant test reports*
(8) *Load/use history*

b. Projects shall review the above list with technical and engineering personnel so that the appropriate data requirements can be levied.

Projects may combine plans, reports, and supporting documentation if documented in the Fracture Control Plan.

4.4.1 Fracture Control Plan

The Fracture Control Plan describes how fracture control requirements are expected to be met.

a. The Fracture Control Plan shall be written early in the program, prior to the Preliminary Design Review (PDR).

b. The Fracture Control Plan shall be available at a Preliminary Requirements Review (PRR).

c. The Fracture Control Plan shall list all the specific activities to be done to satisfy fracture control; e.g., if the structure included a major glass component, the plan shall address the approach to be used to show an acceptable fracture control process for the glass.

4.4.2 Engineering Drawings

a. The engineering drawings shall identify the parts that are fracture critical in the notes of the individual part drawing along with the inspection and other pertinent criteria.

b. The type of NDE shall be specified (eddy current, penetrant, radiographic, or other technique) along with a statement that "no detected cracks are allowed."

c. Any detected cracks shall be reported for assessment according to section 4.2.4.5.

d. As applicable, processing or fabrication requirements that would affect fracture properties of a fracture-critical part in a given application, such as heat treatments, welding requirements and peaking/mismatch allowables, grain or fiber direction, and other critical parameters, shall be specifically called out on the part drawing.

4.4.3 FCSR

a. To certify fracture control compliance of hardware, the HD shall prepare an FCSR on the total system for review and approval by the RFCB.

b. Supporting detailed documentation such as drawings, calculations, analyses, data printouts, inspection plans, records, specifications, certifications, reports, and procedures should not be submitted as a part of the FCSR, but shall be made available for review by the RFCB, if requested.

c. The FCSR shall be submitted by the Phase 3 Safety Review or by the final acceptance review for flight certification of the hardware.

d. As a minimum, the following information shall be provided in the FCSR:

(1) Identification of fracture-critical parts and low-risk fracture parts, showing the material and heat treatment used and the basis for part acceptability (i.e., damage

tolerant analysis, test, acceptable durability, insignificant fatigue loading), including the referencing of documents which contain and describe the supporting data (as defined in section 4.4.5) required to demonstrate fracture control requirements of the Agency, responsible Center, and Program.

(2) Fracture-critical parts that are limited life shall be specifically identified.

  A. A statement to the effect that all other parts were examined and determined to be non-fracture critical shall be included.

(3) A statement as to whether or not the hardware contains pressure vessels or fracture-critical rotating equipment.

(4) Identification of the NDE and/or tests applied for fracture control purposes to each fracture-critical part.

(5) Identification of fail-safe parts and a brief statement of the basis for classification. Re-flown fail-safe hardware shall have verification that any required “between mission” inspections have been performed.

(6) A statement that inspections or tests specified for fracture control were applied.

(7) A statement that the flight hardware configuration has been controlled and verified for all fracture-critical parts.

(8) A statement that materials usage has been verified for fracture-critical parts.

(9) Copies of MUAs for fracture-critical or low-risk parts and a summary of the discrepancy reviews, or equivalent reviews, of anomalies that could affect the performance of fracture-critical parts.

(10 If applicable, a summary discussion of alternative approaches or specialized assessment methodology applied, but not specifically covered by guidelines.

(11) If applicable, identification of any special considerations involving fracture mechanics properties or data, inspections, analysis, or other parameters not covered by the requirements set here.

(12) If during the program, no parts or procedures are identified that require information as listed above, a statement to that effect with reference to supporting documentation shall be submitted as the FCSR.

(13) If applicable, a summary of the configuration management (CM) system used to store records.

4.4.4 Presentation Summarizing the Fracture Control Program

A presentation shall be made summarizing the fracture control program for review committees and RFCB.

4.4.5 Detailed Fracture Control Analysis Report

a. A detailed fracture control analysis report shall be prepared to document the analyses that have been performed to support fracture control.

b. This report shall contain sufficient detail to allow reviewers to check and reconstruct all calculations.

c. Hardware descriptions, program requirements, and analysis assumptions shall be clearly stated.

4.4.6 Inspection Report

The inspection report shall contain a record of the inspection results identifying the part name; part number; serial number; material and condition; NDE type and sensitivity level; a sketch of the part showing the area inspected and type of crack inspected for; the results of the inspection; and the inspector's signature, date, and stamp.

Instead of a separate report, the inspection report may be included in an appendix of the detailed fracture control analysis report (section 4.4.5), if available at the time that the inspection report is published. Alternately, for long-term programs, a permanent CM system can be implemented to store inspection records. A description of the CM system can be included in the Fracture Control Plan to satisfy this requirement.

4.4.7 Test Report

a. If a proof test, damage tolerant test, vibration test, or other test is used to justify fracture control compliance, the test results shall be documented in a report.

b. The hardware configuration, test setup, loading schedule, and environments shall be documented.

c. Conclusions as to the acceptability of the hardware based on the test performed shall be included in the report according to the criteria established in the detailed fracture control analysis report (section 4.4.5).

For the routine proof test of lines, fittings, and pressurized components, the data sheets from the manufacturer may suffice. Instead of a separate report, the test report may be included in an appendix of the detailed fracture control analysis report (section 4.4.5), if available at the time that the test report is published. Alternately, for long-term programs, a permanent CMCM system can be implemented to store test reports. A description of the CM system can be included in the Fracture Control Plan to satisfy this requirement.

4.4.8 Load/Use History

a. The project shall maintain a load and use history of fracture-critical items for the life of the project.

b. The report shall track projected use against remaining life for each fracture-critical part at appropriate intervals to document that the hardware is being operated within fracture control requirements.

Alternately, for long-term programs using a permanent CM system to store load/use records, a description of the CM system can be included in the Fracture Control Plan to satisfy this requirement.

4.5 Verification

a. Verification of compliance with fracture control requirements shall be the approved Fracture Control Plan and the approved FCSR.

b. Approval shall be verified by a concurrence memorandum from the RFCB to the applicable project office.

c. In the event of conflict between the RFCB and project office concerning verification of compliance with fracture control requirements, the procedures in place at each NASA Center to resolve technical conflict shall be followed, with the option to appeal to the NASA Chief Engineer for final resolution.

4.6 Alternatives

In the event of specialized hardware or applications where the requirements in this standard are not feasible or effective, or where potential cost savings are significant while maintaining an acceptable level of safety, alternatives may be proposed.

a. Alternatives shall be approved by the responsible fracture control and safety authorities.

General alternatives such as special risk assessments, special analysis or testing, unique NDE approaches, special kinds of flaw screening, or flaw retardation may be proposed when alternative methods are viable candidates for effective and efficient fracture control.

b. Approval shall be requested by the program/project immediately upon identification of the need for an alternative procedure.

4.7 Other Requirements

It shall be understood that implementation of fracture control and full compliance with fracture control requirements does not relieve the hardware from compliance with structural design and test requirements, quality assurance requirements, or materials requirements that are applicable independent of fracture control.

5. GUIDANCE

5.1 Reference Documents

API-RP-579	*Fitness-for-Service*
NASA-HDBK-5010	*Fracture Control Implementation Handbook for Payloads, Experiments, and Similar Hardware*
NASGRO®	*Fatigue Crack Growth Computer Program* www.nasgro.swri.org