INTERIM NASA TECHNICAL STANDARD	NASA-STD-(I)-5019
National Aeronautics and Space Administration Washington, DC 20546-0001	Approved: 09-12-2006 Expiration Date: 09-11-2007

FRACTURE CONTROL REQUIREMENTS FOR SPACEFLIGHT HARDWARE

MEASUREMENT SYSTEM IDENTIFICATION:

INCH/POUND (METRIC)

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This document represents the technical consensus of the developing group but does not yet have final NASA approval.

DOCUMENT HISTORY LOG

Status	Document Revision	Approval Date	Description
Interim		09-12-2006	Interim Release

FOREWORD

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

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

This document establishes the fracture control requirements (replacing NASA-STD-5007) for all human-rated spaceflight systems, payloads, propulsion systems, orbital support equipment, and planetary habitats. It was developed by a NASA-wide Fracture Control Working Group to harmonize and 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.

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09-12-2006

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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 good engineering practices in the design, analyses, inspections, testing, fabrication, and operation of flight structures. In keeping with this policy, all human-rated space systems shall be subjected to fracture control to preclude catastrophic failure. Fracture control encompasses the consequences of naturally occurring and service-induced flaws, damage, or cracks into 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, non-destructive evaluation, and tracking of fracture-critical hardware. It is expected that all spaceflight hardware will be manufactured consistent with aerospace 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 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."

1.4 Responsibilities

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 Responsible Program Authority (RPA), in conjunction with 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 shall expedite the generation of the required documentation according to section 4.4 of this standard. This shall be done with the oversight, advice, and approval of the Responsible Fracture Control Authority (RFCA). Fracture control program responsibilities shall be identified prior to the Phase I Safety Review or the Preliminary Design Review (PDR). 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 nondestructive evaluation (NDE) inspections 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 activity 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 failures in joints and structures when it is reasonable to do so.
b. Design parts for inspectability. Avoid welds that are not inspectable from both 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.

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 RFCA, as defined in this document, shall replace all definitions of a fracture control authority or board in all applicable documents. The latest issuances of cited documents shall be used unless specified by version control descriptor. 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

MIL-HDBK-17 – Composite Materials Handbook, Guidelines for Characterization of Structural Materials, December 12, 2002

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

NASA-STD-5009 – Non-Destructive Evaluation Requirements for Fracture Critical Metallic Components (**Release Pending**)

NASA-STD-5017 – Design and Development Requirements for Mechanisms, June 13, 2006

JSC 20793 – Manned Space Vehicle Battery Safety Handbook, September 1985

JSC 23642 – JSC Fastener Integrity Testing Program, October 22, 2001

JSC 62550 – Structural Design and Verification Criteria for Glass, Ceramics and Windows in Human Space Flight Applications, August 30, 2005

MSFC-RQMT-3479 – Fracture Control Requirements for Composite and Bonded Vehicle and Payload Structures, June 29, 2006

MSFC-STD-2594 – MSFC Fastener Management and Control Practices, June 1997

MSFC-STD-3029 – Guidelines for the Selection of Metallic Materials for Stress Corrosion Cracking Resistance in Sodium Chloride Environments, May 22, 2000

2.3 Non-Government Documents

ANSI/AIAA S-080 – Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components, Latest Revision

ANSI/AIAA S-081 – Space Systems – Composite Overwrapped Pressure Vessels (COPVs), Latest Revision

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
COPV	Composite Overwrapped Pressure Vessel
ECF	Environmental Correction Factor
EVA	Extra Vehicular Activity
FCC	Fracture Control Coordinator
FCSR	Fracture Control Summary Report
HCF	High-Cycle Fatigue
HD	Hardware Developer
JSC	Johnson Space Center
LCF	Low-Cycle Fatigue
MDP	Maximum Design Pressure
MEOP	Maximum Expected Operating Pressure

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
RFCA	Responsible Fracture Control Authority
RPA	Responsible Program Authority
SSMA	System Safety and Mission Assurance

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 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 substantive 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 (consistent in size with the sensitivity of the NDE applied) is assumed to exist, and it 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 Authority: See Responsible Fracture Control Authority.

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.

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.

G_{Ic}: Total strain energy fracture toughness as defined using Modes I, II, and III.

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. The HD is accountable to the Responsible Program Authority.

Hazardous Fluid: For fracture control, a fluid whose release would create a catastrophic hazard. Hazardous fluids include liquid chemical propellants 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 part 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: Maximum expected load on a structure during its service life.

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 Fatigue (LCF): A low frequency, high amplitude loading condition created by thermal, pressure, or structural loads that can propagate flaws to failure. An example of an LCF loading condition is the aerothermal loading of a turbine blade during launch.

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

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

Maximum Design Pressure (MDP): The highest pressure defined by maximum relief pressure, maximum regulator pressure, or maximum temperature. Transient pressures shall be considered. When determining MDP, the maximum temperature to be experienced during a launch abort to a site without cooling facilities shall also be considered. In designing, analyzing, or testing pressurized hardware, loads other than pressure that are present shall be considered and added to the MDP loads as appropriate. MDP in this standard is to be interpreted as including the effects of these combined loads when the non-pressure loads are significant. Where pressure regulators, relief devices, and/or a thermal control system (e.g., heaters) are used to control pressure, collectively they shall be two-fault tolerant from causing the pressure to exceed the MDP of the system.

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.

Must-Work Function: The function of a single device, part, or mechanism whose loss would be a catastrophic hazard.

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): Pressurized components whose only credible failure mode is development of a non-hazardous leak, as opposed to catastrophic fragmentation or abrupt rupture.

Part: See Component.

Potentially Fracture-Critical Part: Any part or component that is identified for more rigorous assessment for purposes of fracture control classification, i.e., a part whose failure due to a flaw is not clearly a non-catastrophic hazard at the time of initial assessment.

Pressure Vessel: A container designed primarily for pressurized storage of gases or liquids and having energy and pressure levels as defined in section 4.1.2.1.

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 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 during a cycle of constant amplitude loading.

Responsible Fracture Control Authority (RFCA): The designated individual, panel, or group at the NASA Center or sponsoring institution responsible for fracture control methodology, which has the authority to interpret fracture control requirements.

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.

Responsible Program Authority (RPA): Program director/project manager at the NASA Center or sponsoring agency responsible for the specific hardware.

Responsible Safety Authority: The safety panel or board that rules on the acceptability of the hardware for flight.

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.

Safety-Critical Function: See Must-Work Function.

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 which is prone to brittle failures which could release many small pieces into the surrounding environment.

Single-Point Direct Catastrophic Failure: Direct catastrophic failure resulting from fracture in a structural joint where the load path is transmitted through a single fastener or pin or other single structural element.

Single-Point Failure: One failure at any one location at any given time that results in the failure of a structure or pressurized hardware.

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 which are consistent with common industrial inspection standards. Standard procedures include penetrant, magnetic particle, eddy current, ultrasonic, and x-ray.

Static Fatigue: Strength degradation with time resulting from the 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 in/in.

4. REQUIREMENTS

4.1 Fracture Control Classification of Parts

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. All spaceflight hardware shall be examined to determine its fracture control classification. 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. Additionally, all hardware that deviates from the certified design configuration, either through off-nominal conditions or degradation during service, requires 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 strong 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 RFCA.

Non-fracture-critical hardware includes low released or contained mass, fail safe, non-hazardous leak before burst (NHLBB) pressurized components, low speed and low momentum rotating machinery, low strain composite parts, low-risk parts and fasteners, and protected glass. Section 4.1.1 gives a detailed description of each of these 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. 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.

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, fracture control assessments shall address the on-orbit phase as well as other phases and their potential effects on the on-orbit performance.

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 which are identified as non-fracture critical shall comply 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. Where uncertainty exists as to consequences of a released mass inside a volume, the released mass shall not be able to credibly achieve (for example, via contact with crew or release during launch) a velocity of more than 35 ft/sec (10.7 m/sec) or a momentum of more than 8.75 ft-lb/sec (1.24 m-kg/sec). Released mass external to a volume shall be shown to present acceptable risk (section 4.1.1.8.1) after impact upon all potential impact surfaces if applicable.

Fasteners pre-loaded in tension which have low fracture toughness, $K_{Ic}/F_{ty} < 0.33$ in$^{1/2}$ (1.66 mm$^{1/2}$) shall be limited to 0.03 pound (14 gm) potential free mass. If a fastener is steel and the K_{Ic} value is not known, low fracture toughness shall be assumed when the A basis ultimate strength is greater than 180 ksi (1241 N/m^2). Parts with a single-point failure that would exceed low released mass limits shall, preferably, 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

A failed part confined in a container or housing or otherwise positively restrained from free release and that does not result in a catastrophic hazard can be classified non-fracture critical. Pressurized components or rotating devices within stowed or contained hardware shall be assessed independently, as provided for in this standard, to ensure against explosion and/or release of fragments or hazardous fluids outside the container, or over-pressurization and catastrophic failure of the container/compartment. 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.

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

Enclosures with openings shall only be assessed for containment of parts larger than accessible openings. 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 will be redundant for keeping a door closed in the event one device fails. Otherwise, containment cannot be assumed. 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 structure (including fasteners, latches, and mechanisms) can be identified as "fail safe" and classified as non-fracture critical when it meets the following criteria:

a. Due to structural redundancy, the structure remaining (assumed unflawed) after any single structural failure shall withstand all redistributed loads with a minimum ultimate safety factor of 1.0 on limit load.
b. The structural failure shall not release a potentially catastrophic mass in violation of section 4.1.1.1.

Joint gapping is allowed under fail-safe or emergency conditions. In doing fail-safe analysis, it is usually sufficient to remove separately the member with the highest load and the member with the lowest margin (these may not be the same) to assess fail-safe capability. In highly redundant complex structures, the analyst shall document the rationale for member selection and present it to the RFCA for approval. Structural fault tolerance requirements for mechanisms (NASA-STD-5017) unrelated to fracture control shall also be met. Structures that are classified fail safe shall not result in the release of unacceptable free masses (see sections 4.1.1.1 and 4.1.1.2).

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

a. The design loads are shown to be conservative with respect to dynamic coupling variations, or

b. Failure of the part does not significantly alter dynamic response of the hardware.

Redundancy against catastrophic failure shall be re-verified between missions for a fail-safe redundant 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. An alternative to re-verification of structural redundancy is to show the remaining structure has sufficient fatigue capability to reach end of service using concentrated stresses and a scatter factor of 4.0 on total cycles.

4.1.1.4 Non-Hazardous Leak Before Burst (NHLBB) Pressurized Components

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 a. through e. below can be classified as NHLBB, provided that slow release of the fluid contents is not a catastrophic hazard. 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. NHLLB does not apply to habitable structures and enclosures. See section 4.1.2.10.

Pressurized lines, fittings, and other system components such as regulators, valves, filters, and bellows are accepted as NHLBB designs and can be classified as non-fracture critical provided all of the following are met:

a. A leak is not a catastrophic hazard.
b. System supports and brackets meet fracture control.
c. Components are made of aerospace quality materials.
d. The crack opening displacements of the critical flaw size at typical operating pressures are large enough to allow a controlled leak that will reduce the internal pressure. Methodology is given in API-RP-579 for verifying that the critical flaw size requirement for cylindrical pressure components is met.
e. 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 14,240 foot-pounds (19,130 Joules) or angular momentum less than 100 pound-foot-seconds (136 Newton-meter-seconds) and does not present a catastrophic hazard risk can be classified as non-fracture critical. 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. Rotating equipment whose failure could be catastrophic shall be shown to be contained (section 4.1.1.2). 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. The mounts for rotating machinery shall be addressed as standard structure and assessed for fracture criticality.

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

4.1.1.6 Fasteners

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 as non-fracture critical. Non-fracture-critical fasteners shall meet the requirements of sections 4.1.1.1, 4.1.1.2, or 4.1.1.3, and be classified accordingly. In cases where the classification is not obvious, analysis or test is required to support the disposition. All rivet applications shall be designed fail safe (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, and high quality shall be relied on for assured performance.

4.1.1.7 Composite/Bonded Structures

Composite/bonded structures shall be assessed for fracture criticality and meet the requirements of MSFC-RQMT-3479, Fracture Control Requirements for Composite and Bonded Vehicle and Payload Structures, and shall meet the intent of MIL-HDBK-6870A.

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. Coupon testing may be substituted, with prior approval of the RFCA, 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. Single-flight mission hardware shall be replaced after each flight.

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 safety 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

Any component manufactured from a material which is prone to brittle failures, such as glass and ceramics, which could release pieces larger than $2x10^{-3}$ in (50 microns) are unacceptable in habitable volumes, and therefore shall be contained (section 4.1.1.2) to be classified non-fracture critical. In uninhabited volumes, shatterable materials shall be low-released mass (section 4.1.1.1) or contained (section 4.1.1.2) to be non-fracture critical. When determining released mass, it can be assumed that shatterable parts such as ceramic discs, mirrors, or glass lenses will break into releasable pieces no larger than 1/3 of original size. 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

This section addresses inherently pressurized hardware (e.g., a sealed electronic box) that is not a part of a pressure system. Sealed containers that are NHLBB (section 4.1.1.4) can be classified as non-fracture critical if the container supports meet fracture control requirements and the container complies with both of the following:

a. The container is made from materials typically used for commercially available sealed containers.

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

The container portion of a low-risk sealed container does not require NDE to screen for flaws. The container supports may or may not 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

For fracture control, batteries are unique forms of pressurized components. It is expected that batteries and battery systems will be built to existing requirements and guidelines for flight applications (JSC 20793), thereby providing basic assurance for battery safety. If batteries and/or their applications still generate a safety concern because of credible, potentially destructive pressure build-up or possible release of a product that would be a catastrophic hazard, they shall be assessed as fracture critical. Battery cells and cases (battery boxes) shall be assessed as unique pressurized hardware or sealed containers. Battery cells shall be examined for structural failure modes at design operating conditions and for hazard categories if contents are released. Sealed battery cases (containers of battery cells), if used, shall be given similar evaluation.

Battery cells/cases that have an NHLBB failure mode can be classified non-fracture critical. This includes nickel-hydrogen (Ni-H) batteries because of the relatively small amounts of released hydrogen that would be involved. Battery cells that are not NHLBB or whose open release of contents would be a catastrophic hazard can be classified non-fracture critical if the respective failures would be suitably contained by a battery case, or by levels of containment including absorbent layers. 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. For a part to be classified low risk, it shall meet the requirements of sections 4.1.1.12.1 and 4.1.1.12.2 below. Low-risk fasteners and shear pins shall meet only the requirements of section 4.1.1.12.3.

4.1.1.12.1 Limitations on Applicability

The part shall be constructed from a commercially available material. Aluminum parts shall not be loaded in the short transverse direction if this dimension is greater than 3 in (7.62 cm). The part shall not be the pressure shell of a human-tended module or personnel compartment, a pressure vessel, or a pressurized component in a pressurized system containing a hazardous fluid. Rotating machinery shall operate below the kinetic energy and angular momentum limits set for automatic classification as fracture critical (section 4.1.2.2). A part whose failure will directly result in a catastrophic hazard is also excluded, 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 the requirements in section 4.1.1.12.2 are met.

4.1.1.12.2 Inherent Assurance Against Catastrophic Failure from a Crack-Like Flaw

The part shall possess inherent assurance against catastrophic failure from a crack-like flaw by compliance with a. and b. below:

a. Assurance against the presence of a flaw can be achieved by compliance with the following criteria:

(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 MSFC-STD-3029. If other than table I or A-rated materials as classified respectively in these documents is used, suitability for the specific application shall be documented by a

Materials Usage Agreement (MUA). Metallic parts shall have a material property ratio of $K_{Ic}/F_{ty} > 0.33\ in^{1/2}$ ($1.66\ mm^{1/2}$). With the approval of the RFCA, the effect of material thickness on K_{Ic} value may be considered, and the K_{Ie} value may be used in lieu of K_{Ic} 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 RFCA, is applied to sufficiently screen for flaws. It can be assumed that significant crack-like defects do not occur for standard metallic forgings or during machining of standard metallic forgings, sheet, bar, extrusions, or plate products that are produced in accordance with aerospace quality specifications and are known to have good machining properties.

(3) Parts classified as low-risk fracture parts can be accepted using normally applied methods that ensure aerospace quality flight hardware. At a minimum, these parts shall receive a visual inspection for surface defects. Defects that could affect part life are cause for rejection. Inspections shall be made on individual parts prior to assembly to maximize accessibility for inspection.

b. Assurance against significant flaw growth can be achieved by demonstrating the part possesses a high safety margin on fatigue strength by one of the following methods:

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

(2) A fatigue or durability analysis from a 0.005 in (0.127 mm) 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 safety factor of 1.5 on alternating stress.

(3) A fatigue crack growth analysis that shows a credible initial flaw caused by handling, machining, assembly, or testing will not propagate to failure in four (4) complete service lives.

4.1.1.12.3 Fasteners and Shear Pins

Fasteners and shear pins may be classified as low risk if the following are met:

a. Fastener shall be in a local pattern of two or more similar fasteners.

b. Fastener and joint shall be of conventional design and within the Shuttle or International Space Station experience base.

c. Fastener shall be fabricated and inspected in accordance with high-quality military standard, national aircraft standard, or equivalent commercial aerospace-type specifications.

d. Fasteners shall be procured using MSFC-STD-2594 or JSC 23642.

e. Fasteners used in multi-cycle applications shall have rolled threads and be fatigue rated.

f. Fastener shall be fabricated from a well-characterized metal not sensitive to stress corrosion cracking.

g. If used in tension applications, the fastener shall not be made from a low toughness alloy as defined in section 4.1.1.1 or, specifically, Ti-6Al-4V STA titanium.

h. Fasteners shall meet appropriate preloads and stress requirements, with no joint gapping (gapping is allowed under fail-safe and/or emergency conditions).

i. Fasteners shall have positive back-off prevention consistent with their criticality. Back-off prevention guidelines are given in MSFC-STD-561A.

j. Reworked or custom-made fasteners require RFCA approval.

k. For fasteners that are classified as mechanisms according to NASA-STD-5017, the design condition to which fracture control shall be applied is established by first meeting the requirements of NASA-STD-5017.

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 Pressure Vessels and Pressurized Components

All pressure vessels (see definition in section 3.2) and all pressurized hardware that contain hazardous fluids shall be classified fracture critical. A pressurization history log shall be maintained for pressure vessels to ensure that allowable numbers of pressurizations are not exceeded and to document that required conditions for pressurization (such as temperature and rate) are adhered to.

4.1.2.1.1 Metallic Pressure Vessels

Metal pressure vessels shall comply with sections 4 and 5.1 of the latest revision of ANSI/AIAA Standard S-080, Space Systems-Metallic Pressure Vessels, Pressurized Structures, and Pressure Components. The following requirements also apply when implementing S-080:

a. The welds on pressure vessels required to be damage tolerant shall be re-inspected after acceptance proof testing in addition to inspections that may have been performed prior to acceptance tests.

b. MDP shall be substituted for all references to maximum expected operating pressure (MEOP) in S-080.

4.1.2.1.2 Unlined Composite Pressure Vessels

Unlined composite pressure vessels shall comply with MSFC-RQMT-3479, Fracture Control Requirements for Composite and Bonded Vehicle and Payload Structures and shall meet the intent of MIL-HDBK-6870A.

4.1.2.1.3 Composite Overwrapped Pressure Vessels (COPVs)

COPVs shall comply with the latest revision of ANSI/AIAA Standard S-081, Space Systems-Composite Overwrapped Pressure Vessels (COPVs). The following requirements also apply when implementing S-081:

a. MDP shall be substituted for all references to MEOP in S-081.

b. COPVs shall have a minimum of 0.999 probability of no stress rupture failure during the service life.

4.1.2.1.4 Lines, Fittings, and Other Pressurized Components

Lines, fittings, and other pressurized components (equipment that is 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. All fusion joints in fracture-critical systems shall be 100 percent inspected using a qualified NDE method that will determine the presence of unacceptable lack of penetration or other unacceptable conditions both on the surface and within the fusion joint. Inspection of fracture-critical fusion joints shall be made after proof testing, and for lines and fittings after proof test of the final assembly. In instances where NDE is not feasible, or is incapable of being dealt with successfully, a process control program that demonstrably assures the quality of the uninspectable fusion joints can be employed. The requirements for a process control program are given in section 4.2.4.4.3. Concurrence of the RFCA is required where full NDE is required but not considered practical. Any type of flaw indication in the final product that does not meet specification requirements shall be cause for rejection. 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. Damage tolerant analysis is not required for lines, fittings, and other pressurized components which are proof tested to a minimum of 1.5 times the MDP.

4.1.2.2 Rotating Machinery

A rotating mechanical assembly is fracture critical if it has a kinetic energy exceeding 14,240 foot-pounds (19,310 Joules) or an angular momentum exceeding 100 pound-foot-seconds (136 Newton-meter-seconds). In addition to other requirements for fracture-critical components, fracture-critical rotating machinery shall be proof tested (spin tested) and subjected to NDE before and after proof testing. If NDE after proof testing is not practical, then the rotating part shall be contained (see section 4.1.1.2), and loss of function shall not be safety critical, or it shall be shown that the proof test adequately screens for flaws (see section 4.2.4.4.2) with RFCA approval. NASA-HDBK-5010 contains guidance on classifying fracture-critical rotating hardware.

4.1.2.3 Fasteners

Designers and analysts are strongly encouraged to make fastener applications fail safe (section 4.1.1.3) or low risk (section 4.1.1.12.3). Potential catastrophe because of a single fastener failure shall be avoided. Fasteners that do not comply with the various non-fracture-critical criteria applicable to fasteners in section 4.1.1 are classified fracture critical. Fracture-critical fasteners shall meet items c. through k. of the low-risk criteria in section 4.1.1.12.3. Fasteners less than 3/16 in (0.48 cm.) diameter shall be avoided for a fracture-critical application. If use is unavoidable, fracture control shall be coordinated with the RFCA.

Fracture-critical fasteners shall be assessed for damage tolerance. Preload and its effect on flaws and cyclic stresses shall be considered in the damage tolerance assessment. All fracture-critical fasteners shall be inspected by the eddy current NDE technique or be proof tested to screen for flaws. Damage tolerance analysis shall assume a flaw in the thread root of a size consistent with NDE sensitivity or proof-test level. Acceptable NDE flaw sizes are given in NASA-STD-5009.

Pins, tangs, lock wire used for assurance against fastener back-off, nuts, threaded inserts, and any similar fastener parts shall be of high quality when used in a fracture-critical fastener application. These items are not classified as fracture critical and are exempt from fracture control.

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.

After inspection or testing, fracture-critical fasteners shall be stored and controlled in a manner that will keep them isolated from other fasteners.

4.1.2.4 Composite/Bonded Structures

Fracture-critical composite structures shall meet the requirements contained in MSFC-RQMT-3479, Fracture Control Requirements for Composite and Bonded Vehicle and Payload Structures, and shall meet the intent of MIL-STD-6870A.

4.1.2.5 Shatterable Components and Structures

All shatterable components and structures that do not meet the criteria in section 4.1.1.8 shall be classified as fracture critical. Fracture control of fracture-critical external components and structures shall be coordinated with the RFCA.

Fracture-critical windows and shatterable components in volumes shall meet the requirements contained in JSC 62550, Structural Design and Verification Criteria for Glass, Ceramics and Windows in Human Space Flight Applications. If approved by the RFCA, small shatterable parts can be accepted for use based on vibration environmental testing, inspection, and functional tests that verify the integrity.

4.1.2.6 Tools/Mechanisms

Tools or mechanisms which 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. Fatigue-rated springs shall be used for fracture-critical spring applications when large numbers of cycles are required.

Each fracture-critical tool or mechanism shall be proof tested or adequately inspected to assure that defects which could cause failure during use are not present. 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 and NASA-STD-5017.

4.1.2.7 Batteries

Batteries not meeting the criteria of section 4.1.1.11 shall be classified as fracture critical and assured acceptable by compliance with fracture control procedures for hazardous fluid containers (section 4.1.2.8).

4.1.2.8 Hazardous Fluid Containers

Hazardous fluid containers shall be damage tolerant against rupture and leak when release of a fluid would cause a catastrophic hazard. Containers shall meet all the requirements of pressure vessels (section 4.1.2.1) when the contained fluid has a delta pressure greater than one atmosphere. When the container has a delta pressure less than one atmosphere, the container shall have a minimum safety factor of 2.5 times MDP, and shall meet the fracture control requirements for pressurized components (section 4.1.2.1.4). When a proof test to a minimum factor of 1.5 is impractical (as required in section 4.1.2.1.4), damage tolerance can be assured by appropriate NDE applications and crack growth analysis. Integrity against leaks shall be verified by test at 1.0 times MDP.

4.1.2.9 Habitable Structures and Enclosures

All habitable structures and enclosures designed to support life shall be classified as fracture critical. The following requirements apply:

a. Pressure shells shall be classified as damage tolerant.
b. Pressure shells shall be proof tested and verified leak-tight.

c. 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.

d. 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. Verification shall be approved by the RFCA.

e. Habitable structures or enclosures shall not be classified as NHLBB, because pressure shall be maintained. The continued pressure cycling due to the “make up” air can grow the crack, so the module will require damage tolerant classification and post-proof inspection.

f. Damage tolerant assessment of habitable structures and enclosures shall consider worst case, design allowable, fusion joint peaking, mismatch, and residual stresses.

g. The influence of coatings/barriers on leak detection during proof and other testing shall be assessed.

h. Operation shall be monitored and documented to ensure that certification is not invalidated.

4.1.2.10 Single-Use 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 safety of 1.4 against fracture toughness instead of a factor of four (4) on life if all of the following conditions apply:

a. The single-event loading is a single cycle or a single cycle with rapidly decaying subsequent cycles.

b. The component is not subject to any other significant loads.

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

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

where K_{Ic} is the plane strain fracture toughness and $K_{applied}$ is the peak applied stress intensity for metallic structures. Single-use fracture-critical composite structures shall comply with MSFC-RQMT-3479; any deviation shall be approved by the RFCA.

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. Demonstration tests shall be coordinated with the RFCA. The test articles shall each contain a flaw in the worst location and orientation. Flaw sizes and load amplitudes shall be one of the following (a. or b.):

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

b. Loads are difficult to apply or not well characterized.
(1) The flaw size shall be at least twice as large in all dimensions as the requirements of NASA-STD-5009.
(2) Load application shall simulate worst-case flight conditions.
(3) A sufficient number of articles shall be tested to ensure test conditions approached maximum flight conditions.

4.1.2.11 High-Cycle Fatigue (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. The threshold value used for an HCF assessment shall be approved by the RFCA. The following procedure is used to meet this requirement:

a. The initial NDE flaw size shall be assumed in the worst location and orientation.
b. The flaw shall be propagated for four (4) times the required design life using the low-cycle fatigue (LCF) loads (thermal, pressure, speed).
c. The final flaw size from the LCF calculations (b.) shall be used in calculating the stress intensity due to the HCF environment.
d. The metallic component is acceptable if the calculated HCF stress intensity is below the stress intensity factor threshold for the metallic material.
e. 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

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). The damage tolerant demonstration is based on an initial flaw size that could be present in the part. This flaw size shall be established by NDE, proof testing, or process control. General damage tolerance requirements are defined in section 4.2.4. Analysis or test shall consider all significant loadings, both cyclic and sustained, that the part will experience during ground, flight, orbital, and planetary phases. Loads from these phases shall be considered for each mission the hardware will 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). Damage tolerant parts shall be shown to have a service life factor of at least four (4). If four (4) is not achieved, the part shall be redesigned, or a special inspection technique can be employed. Special inspection techniques shall be approved by the RFCA. If feasible, the life requirement can be reduced (limited life) and the part replaced or reinspected when available life is used. If “limited life” parts are to be employed, project management shall be informed; and it shall be determined whether replacement of the part, re-verification of damage tolerance is feasible; e.g., the part will be accessible for NDE inspections in service, or an acceptable level of risk can be defined.

4.2.1 Damage Tolerant Analysis

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.

4.2.1.1 Deterministic Methods

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

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 RFCA 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 RFCA. 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 RFCA 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

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. Materials shall be compatible with NASA-approved standards and specifications. Several factors shall be considered in material selection with respect to fracture performance as listed below.

4.2.4.1.1 Service Environment

The effect of environmental factors, such as temperature and exposure to harmful media, on flaw growth and fracture properties shall be documented. A metallic material not rated with a high resistance to stress corrosion cracking in MSFC-STD-3029 shall have an approved MUA. Composite materials not developed and qualified in accordance with the guidelines in MIL-HDBK-17, Composite Materials Handbook, Polymer Matrix Components Guidelines for Characterization of Structural Materials, Volumes 1 and 3 shall have an approved MUA. An MUA shall include documentation on the suitability of the alloy for the specific application and shall be included in the Fracture Control Summary Report (FCSR).

4.2.4.1.2 Product Form

Specimens used to characterize a material shall be representative of the stock used to manufacture the hardware. Fracture properties for welded and/or brazed joints shall be developed for parts requiring damage tolerant analysis.

4.2.4.1.3 Material Orientation

Fracture properties for all material orientations shall be developed for materials where anisotropic behavior is noted. 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 fracture toughness values for predicting crack instability shall be average or typical values. The NASGRO® material database is an acceptable source of properties. Use of properties outside the NASGRO® database shall be coordinated with the RFCA using supporting test data.

b. Fracture properties shall be appropriate for the product form, thickness, environment, and constraint condition. For NASGRO® analyses that require the approval of the MSFC or Ames Research Center RFCA, the fitting parameter 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. 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 RFCA.

d. A material with a wide range in fracture toughness, defined as one with the minimum value falling below 20 percent of 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 shall be coordinated with the RFCA.

e. Fracture toughness testing is explicitly required for components with predicted damage tolerance life less than 1000 cycles and shall be coordinated with the RFCA.

f. Average fatigue crack growth rate properties are to be used for crack growth calculations. All crack growth rate data shall correspond to the expected in-service temperature and chemical environments. The NASGRO® material database is an acceptable source of fatigue crack growth rate properties. Use of properties outside the NASGRO® database shall be coordinated with the RFCA using supporting test data.

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

h. NASGRO® 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. The NASGRO® version used for the original design and analysis is acceptable for the life of the hardware unless loading and/or design changes take place. If fracture life has driven the design, or if loading/design changes are made, the most current version of the NASGRO® program shall be used for life assessment using settings appropriate for the particular application. 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 RFCA for resolution.

4.2.4.3 Loading Spectra

A load spectrum shall be developed for each fracture-critical part so that a damage tolerant assessment can be made. 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. Both cyclic and sustained loading spectra shall include effects of preloads, residual stresses, and design-allowable welding joint discontinuities such as peaking and mismatch. 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. 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

Fracture-critical parts shall be screened for flaws by NDE, proof testing, or process control. RFCA approval is required for flaw screening by proof tests or process control.

4.2.4.4.1 Nondestructive Evaluation (NDE)

NDE is done on fracture-critical parts to establish that a low probability of preexisting flaws is present in the hardware. NDE inspections for fracture control shall be performed in accordance with NASA-STD-5009 for metallic components and meet the intent of MIL-HDBK-6870A for composite components. 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.

4.2.4.4.2 Proof Test

Prior approval is required from the RFCA when a proof test is used as the flaw screening technique. 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. 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 environmental correction factor (ECF) can be used as approved by the RFCA.

4.2.4.4.3 Process Control

Prior approval is required from the RFCA when process control is used to determine the initial defect sizes for damage tolerant analysis and/or testing. Process control rationale submitted for RFCA 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

When a crack of any size is detected in fracture-critical hardware, it shall be removed or repaired. If removal/repair of the crack is not feasible, with approval of the RFCA, a specific damage tolerance assessment can be performed to justify the use of any fracture-critical part with detected cracks.

4.3 Tracking for Fracture-Critical Parts

4.3.1 Materials

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

During the development phase, a program shall be in place to assure that a delivered fracture-critical part is as designed and assessed. This program shall include sufficient tracking to provide for fracture control assessment of load changes, modifications, or redesigns of the fracture-critical part. Discrepancy reviews, or equivalent, shall be conducted for anomalies that could affect part fracture characteristics and life.

4.3.3 Load History

The load history shall be maintained for fracture-critical parts. The load history shall include the load level, the number of cycles, and the environments in which the loads occurred. The history shall cover the entire life of the part, as described in section 4.2.4.3. For multi-mission hardware, the used life of the hardware shall be documented against the remaining life so that assessment of flight readiness from a fracture control point of view can readily be made between missions.

4.3.4 Flaw Screening

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. A record of part NDE and findings shall be maintained by the responsible NDE organization. Inspection records shall bear the stamp and/or signature of the inspector. Proof test results shall be documented in a report.

4.4 Fracture Control Documentation

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:

a. Fracture Control Plan
b. Engineering Drawings

c. A Fracture Control Summary Report
d. Presentation Summarizing the Fracture Control Program
e. A Detailed Fracture Control Analysis Report
f.. Inspection Report
g. Proof and Damage Tolerant Test Reports
h. Load/Use History

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

4.4.1 Fracture Control Plan

The fracture control plan describes how fracture control will be met. A fracture control plan shall be written early in the program, prior to the PDR and shall be available at a Preliminary Requirements Review (PRR). A fracture control plan lists all the specific activities that will be done to satisfy fracture control; e.g., if the structure included a major glass component, the plan would address the approach that will be used to show an acceptable fracture control process for the glass.

4.4.2 Engineering Drawings

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. The type of NDE shall be specified (eddy current, penetrant, radiographic, or other technique) along with a statement that “no detected cracks are allowed.” Any detected cracks shall be reported for assessment according to section 4.2.4.5. As applicable, processing or fabrication requirements shall be specifically called out on the part drawing, requirements that would affect fracture properties of a fracture-critical part in a given application, including heat treatments, welding requirements, grain or fiber direction, and other critical parameters.

4.4.3 Fracture Control Summary Report (FCSR)

To certify fracture control compliance of hardware, the hardware developer (HD) shall prepare a fracture control summary report on the total system for review and approval by the RFCA. Supporting detailed documentation such as drawings, calculations, analyses, data printouts, inspection plans, records, specifications, certifications, reports, and procedures shall not be submitted as a part of the FCSR, but shall be made available for review by the RFCA if requested. The FCSR shall be submitted by the Phase 3 Safety Review or by the final acceptance review for flight certification of the hardware. As a minimum, the following information shall be provided in the FCSR:

a. 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

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

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

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

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

d. 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.

e. A statement that inspections or tests specified for fracture control were applied.

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

g. A statement that materials usage has been verified for fracture-critical parts.

h. 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.

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

j. 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.

k. 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.

4.4.4 Presentation Summarizing the Fracture Control Program

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

4.4.5 Detailed Fracture Control Analysis Report

A detailed Fracture Control Analysis Report shall be prepared to document the analyses that have been performed to support fracture control. This report shall contain sufficient detail to allow reviewers to check and reconstruct all calculations. 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.

4.4.7 Test Report

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

4.4.8 Load/Use History

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

4.5 Verification

Verification of compliance with fracture control requirements shall be the approved Fracture Control Plan and the approved Fracture Control Summary Report based on approved supporting information which is maintained under configuration control by the applicable Project Office. Approval shall be verified by a concurrence memorandum from the RFCA to the applicable Project Office. In the event of conflict between the RFCA 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. 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. 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, May 24, 2005

MSFC-STD-561A – Threaded Fasteners, Securing of Flight Hardware Used on Shuttle Payloads and Experiments, February 28, 1995

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