# FRACTURE CONTROL PLAN FOR JSC SPACE-FLIGHT HARDWARE

JSC Fracture Control Board



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National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas 77058

**JSC 25863, FRACTURE CONTROL PLAN
FOR JSC SPACE-FLIGHT HARDWARE, REVISION C
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## DOCUMENT HISTORY LOG

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| Basic | May 1992 | | | Fracture Control Plan for JSC Flight Hardware |
| A | August 1998 | | | Fracture Control Plan for JSC Flight Hardware |
| B | April 2009 | | | Fracture Control Plan for JSC Space-flight Hardware |
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**INDEX**

## 1.0 Introduction

All flight hardware shall be assessed and classified for fracture criticality. Any part or component whose individual failure would result in a catastrophic event will be evaluated under Fracture Control. The design manufacture, and use shall be managed to minimize the risk of catastrophic failure due to manufacturing and service-induced flaws, damage or crack-like defects.

This Fracture Control Plan (FCP) presents the Johnson Space Center (JSC) implementation methodology for meeting Fracture Control Requirements on all NASA human space flight programs as well as those crewed or un-crewed vehicles that approach or dock with a NASA spacecraft such as the International Space Station (ISS) or Orion.

Hardware developer (HD) shall include description of the hardware that includes picture, diagram, text, and table of components.

Many projects may be relatively small and generation of an FCP for each individual project, as required by applicable specifications, may be overly demanding of available resources. The project may accept this FCP or another FCP that is approved by the JSC Fracture Control Monitor (FCM). The JSC FCM may be contacted for assistance with programmatic implementation of Fracture Control.

Experience has shown that relatively few parts or components will be truly "fracture critical". Some hardware will have no fracture critical parts. Use of this plan will simplify classification of parts and systems. Designers and analysts are encouraged to develop a working familiarity with this FCP to minimize Fracture Control implementation problems and/or costs. Appendix A defines the terms for proper understanding and implementation of this FCP.

A viable Fracture Control program depends on proper design, analysis and procurement screening for quality parts/components that are used in flight structures and pressurized or mechanical systems. Design and quality requirements for critical-flight hardware are expected to be consistent with aerospace standards. Fracture Control supplements well-designed, high-quality hardware with significant additional assurance against catastrophic failures resulting from unexpected and/or undetected defects.

Fracture Control does not replace other applicable requirements for flight hardware such as vibration, strength, and structural life/fatigue, etc.

Basic assumptions that underlie Fracture Control implementation include:

(a) All individual structural parts contain flaws or crack-like defects. The minimum service life capability of the part may be determined by considering one and only one flaw in the worst-case location and orientation.

(b) Utilizing the optimum Non-Destructive Evaluation (NDE) techniques does not negate the assumption stated in (a). The NDE techniques establish a probable upper bound on the size of the assumed initial flaw for crack growth assessment at a specified confidence level.

(c) All space-flight hardware will be of good design for static and cyclic loading, certified for the application, acceptance tested as required, and manufactured and assembled using high-quality processes.

(d) There are no differences between in-house and contracted efforts as to when Fracture Control is required.

(e) Fracture Control is not intended to compensate for poor design, analytical errors, misuse, or poor quality.

Implementation of Fracture Control enhances the safety and mission reliability of the flight hardware by reducing the risk of catastrophic failure.

The FCM does not normally determine the hazard associated with a structural failure on given hardware, but is available to both the project and safety organizations for consultation in such determinations and does have the prerogative to question classifications. Since Fracture Control is implemented to assure safety, the FCM will respect the Safety and Mission Assurance (S&MA) position.

If hardware that was certified to earlier Fracture Control requirements levied under earlier programs is to be flown under a new program, then the hardware should be re-assessed using this FCP. Additionally, hardware that experiences service life conditions that deviate from the certified design configuration or conditions, either through off-nominal service conditions or degradation during service, is to be re-assessed in accordance with the FCP.

NASA-HDBK-5010, Fracture Control Implementation Handbook for Payloads, Experiments, and Similar Hardware, provides useful guidelines and examples in meeting the Fracture Control requirements.

With the approval of the FCM, individual provisions of this document may be tailored based on application specific experience and sufficient technical rationale. If there are any discrepancies between this document and applicable Fracture Control requirements, the requirements take precedence over this FCP.

JSC Procedural Requirement (JPR) 7120.10, Experimental Flight Hardware Class 1-E Procedural Requirements, establishes a new classification of space flight hardware, Class 1-E, and directs JSC institutional organizations to change, as required, the Quality Management System (QMS) processes and instructions to implement this policy directive. Permitted changes to the QMS requirements for configuration management, part identification and tracking, hardware shipping and receiving, control of non-conforming product and mitigation of counterfeit parts or materials for Class 1-E hardware are exclusive of safety-critical or fracture-critical components for which institutional processes will take precedence per section 2.4.12 of JPR 7120.10. It is recommended that Class I-E Project Managers consult with the JSC FCM prior to the Coordination Meeting or involve the JSC FCM in the Coordination Meeting.

## 2.0 Purpose

The purpose of this document is to provide a general FCP for implementation of Fracture Control programs on NASA/JSC controlled space-flight hardware to meet the requirements specified in NASA-STD-5019, Fracture Control Requirements for Spaceflight Hardware; SSP 30558, Fracture Control Requirements for Space Station; and SSP 52005, Payload Flight Equipment Requirements and Guidelines for Safety-Critical Structures. The latest issuances of cited documents will be used unless otherwise approved by the FCM.

## 3.0 Applicability

This plan is applicable to all JSC controlled manned space-flight hardware that is the responsibility of NASA/JSC. Other NASA centers or agencies may adopt this plan with the concurrence of the responsible Fracture Control group.

Additionally, all hardware that deviates from the certified design configuration will require an update to the existing Fracture Control analysis and classification in accordance with this FCP.

## 4.0 Responsibilities

### 4.1 Program/Project

It will be the responsibility of the HD or specifically designated Fracture Control Coordinator (FCC) to provide for implementation of Fracture Control on the respective hardware. The HD/FCC will assure that Fracture Control is properly implemented in a timely manner. Fracture Control responsibilities will be established prior to the project formulation or Project/System Requirements Review (P/SRR).

The HD/FCC shall:

(a) Perform Fracture Control classification of all parts.

(b) Identification and specification of required NDE inspections or proof test or any other special requirements to screen for flaws on fracture critical parts.

(c) Perform testing or fatigue/fracture mechanics analyses for all low-risk and fracture critical parts.

(d) Review documentation traceability of raw materials, manufacturing processes, verification testing, etc. showing compliance and adherence of flight hardware to approved drawings, specifications, plans and procedures.

(e) Evaluate anomalies on fracture critical parts and justify decisions relating to Fracture Control.

(f) Generate and deliver Fracture Control Summary Report (FCSR).

Designers and analysts will conduct a hardware assessment to determine the extent of Fracture Control to be applied. The HD/FCC will assure that the Fracture Control activity is coordinated to the extent necessary with the FCM and will expedite the generation of a FCSR for the program/project per Fracture Control requirements.

For 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 in-situ or for easy removal inspection. Avoid welds in locations that are inaccessible.

(c) Avoid high risk processes that tend to produce cracks, flaws, and low toughness zones.

(d) Use well-characterized standard aerospace materials for which the strength, fatigue, toughness and fracture properties are established in Metallic Materials Properties Development and Standardization (MMPDS).

(e) Use aerospace qualified fasteners with rolled threads in fatigue sensitive applications.

(f) Avoid severe stress concentrations and stress concentration interactions; such as holes with close spacing (< 3 diameters center to center, or < 2 diameters center to free edge).

### 4.2 JSC Fracture Control Monitor (FCM)

The responsibilities of the JSC FCM include:

(a) Review and approve FCP.

(b) Interpretation of Fracture Control requirements.

(c) Support Safety Review Panels (SRP) at JSC.

(d) Present off-nominal cases to the JSC Fracture Control Board (FCB).

(e) Review FCSR to support SRP and issue Fracture Control certification of JSC integrated flight hardware.

### 4.3 Fracture Control Milestones

The HD shall meet the following milestones for Fracture Control Data Submittal to the FCM.

*Phase I Safety Review or Preliminary Design Review (PDR):*

(a) Submission of a FCP.
(b) Pressure vessel(s) design and qualification, as applicable.
(c) Identification of Damage Threat Assessment (DTA) and Damage Control Plan (DCP) for structural composite/bonded structures and Composite Overwrapped Pressure Vessel (COPV)

*Phase II Safety Review or Critical Design Review (CDR):*

(a) Fracture Control status and categorization of the hardware.

(b) Any unique or alternate approaches used in Fracture Control that require the approval of the FCM.

*Phase III Safety Review or System Acceptance Review (SAR):*

FCSR or certification of compliance from a center or agency with whom an inter-center agreement has been established.

### 4.4 JSC Fracture Control Board (FCB)

The JSC FCB is an assembly of experts in various aspects of Fracture Control including fracture mechanics, Fracture Control methodology, structures, materials, NDE, and S&MA.

The FCB will be available to assess and resolve Fracture Control issues and/or provide Fracture Control directions and recommendations. The JSC FCM and cognizant Project/Program personnel will determine when action by the FCB is warranted and will solicit specific FCB action.

In addition, the FCB will assure that the latest Fracture Control data and methodology consistent with NASA Fracture Control policy are implemented in JSC programs. This will be achieved by participation in NASA inter-Center Fracture Control meetings and activities, periodic internal meetings and discussions, and the determination of when revision in Fracture Control implementation is warranted.

## 5.0 Applicable Documents

The latest issuances of cited documents will be used unless otherwise approved by the FCM. The applicable documents are accessible via the NASA Technical Standards System at https://standards.nasa.gov, directly from the Standards Developing Organizations, or from other document distributors.

NASA-STD-5019; Fracture Control Requirements for Spaceflight Hardware

SSP 30558; Fracture Control Requirements for Space Station

SSP 52005; Payload Flight Equipment Requirements and Guidelines for Safety-Critical Structures

NASA-HDBK-5010; Fracture Control Implementation Handbook for Payloads, Experiments, and Similar Hardware

NASGRO®; Fracture Mechanics and Fatigue Crack Growth Analysis Software Reference Manual, www.nasgro.swri.org

MSFC-STD-3029; Guidelines for the Selection of Metallic Materials for Stress Corrosion Cracking Resistance in Sodium Chloride Environments

NASA-STD-5009; Non Destructive Evaluation Requirements for Fracture Critical Metallic Components

NASA-STD-6008; NASA Fastener Management and Control Practices

NASA-STD-6016; Standard Materials and Processes Requirements for Spacecraft

JSC 20793; Crewed Space Vehicle Battery Safety Requirements

NASA-STD-5018; Strength Design and Verification Criteria for Glass, Ceramics, and Windows in Human Space-Flight Applications

DOT Title 49; United States Government Code, Department of Transportation

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

ANSI/AIAA S-081A; Space Systems - Composite Overwrapped Pressure Vessels (COPVs)

API-579-1; Fitness For Service, Section 9

ASME Boiler and Pressure Vessel Code

Department of Energy PNNL-18696, Pressure Systems Stored-Energy Threshold Risk Analysis

JSC 66901; Damage Threat Assessment (DTA) and Damage Control Plan (DCP) Template for Composite Overwrapped Pressure Vessels

ES4-02-050; Levels of Containment Guidelines for Payloads Utilizing Hazardous/Toxic Materials

ES4-07-031; Fracture Control of Mechanisms

JPR 7120.10, Experimental Flight Hardware Class I-E Procedural Requirements

MMPDS-10, Metallic Materials Properties Development and Standardization (MMPDS), April 2015

## 6.0 Fracture Control Classification of Parts

Fracture Control will be initiated by a structure/system screening for potential fracture critical parts/components, based on structural failure modes, consequence of failure, applicable requirements, and experience. The list of potential fracture critical parts will serve as a contributing base for establishing the necessary Fracture Control rigor in the program according to the methodology in this FCP.

Hardware may be classified as:
(a) Exempt,
(b) Non-fracture critical, or
(c) Fracture critical

Fracture control requirements on any payload are applied independently of any mechanism fault tolerance requirements per ES4-07-031 (Appendix D), Fracture Control of Mechanisms.

Exempt parts typically include non-structural items or items that do not have a credible failure mode related to the presence of a flaw, such as flexible insulation blankets, metallic locking devices to prevent fastener or connector back-off, enclosed electrical circuit components/boards, wire bundles, tangs, seals, certain small batteries, etc. The FCM may accept other items as exempt based on rigorous development programs and process control that establish their safety and functional reliability.

Non-fracture critical parts generally includes the classifications of low-released mass, contained part, fail-safe, non-hazardous leak-before-burst (LBB) pressurized lines, fittings & components, low-speed/low-energy components, low-strain composite parts, low-risk parts and fasteners, and protected glasses. Section 6.1 gives a detailed explanation of each of these classifications and suggestions for classifying specific hardware items.

Fracture critical parts includes pressure vessels, high-energy or high-momentum rotating machinery components, hazardous fluid containers (HFC), habitable modules, solid rocket motor cases and propellant tanks, and any remaining hardware that do not fit the first two categories of exempt or non-fracture critical. All fracture critical hardware will be shown to meet damage tolerance requirements through analysis, test, or fleet leader management. Section 6.2 provides criteria for classifying and assessing specific types of fracture critical hardware.

The assessment of hardware criticality will be examined to the applicable mission phases including launch, on-orbit, and return-to-ground (including a contingency abort without ground services) 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 will address the on-orbit phase as well as potential effects of other phases on the on-orbit performance.

Fracture critical parts will be identified as such on the drawings. This alerts all who use the drawing as to the criticality of the part. Designers and analysts will work together to assure that required notations, including NDE and/or proof test requirements, etc., are provided on the drawing for any fracture critical part.

### 6.1 Non-Fracture Critical Parts/Components

If the structural failure of a part/component is clearly not a catastrophic hazard, no further Fracture Control assessment is required with the prior approval of FCM and Safety organization. Otherwise it could be classified as non-fracture critical if it can be shown to meet one of the following categories addressed in Section 6.1.1 thru Section 6.1.12. Any remaining parts are deemed fracture critical and processed as described under Section 6.2.

#### 6.1.1 Low-Released Mass Parts

For a payload component to be classified as a low released mass part, it shall meet the following requirements:

(a) It can be shown that the release of this component will not cause a catastrophic hazard because of subsequent damage to the payload from which it came or to any other structures, systems, or crew.

(b) <u>Launch/Landing:</u> Total mass of the part or any other released part must be less than 0.25 lb (113 gm). Use of this option requires prior approval of FCM, SRP and Commercial Orbital Transportation System (COTS) organization. Supporting information will be documented in FCSR.

(c) <u>On-orbit:</u> The released mass inside the habitable module will not be able to 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 (1.21 kg-m/sec).

External released mass or parts, including those that would be subjected to aerodynamic flow, may only be classified low-released mass when the program has established an acceptable debris field criterion and the parts fall within it. Any released mass external to the ISS and other manned spacecraft is considered catastrophic unless shown otherwise.

(d) For parts which have low fracture toughness and are preloaded in tension, a fragment may be released at high velocity immediately following failure; therefore, the total released mass may not exceed 0.03 lb (14 gm). A part shall be considered to have low fracture toughness when its material property ratio $K_{Ic}/F_{ty} < 0.33 \sqrt{in}$ (1.66 $\sqrt{mm}$), where $K_{Ic}$ is the plane strain fracture toughness and $F_{ty}$ is the allowable yield tensile strength. If the part is a steel bolt and the $K_{Ic}$ value is unknown, low fracture toughness shall be assumed when the specified minimum $F_{tu} > 180$ ksi (1,240 MPa), where $F_{tu}$ is the A-basis allowable ultimate tensile strength.

#### 6.1.2 Contained Parts

A part confined in a container or housing, or otherwise positively restrained from free release, and whose failure would not result in a catastrophic event as a result of subsequent damage to the payload in which it was installed or to any other structures, systems, or crew, can be classified non-fracture critical.

Pressurized components and rotating devices within stowed or contained hardware will be assessed independently, as delineated in this FCP, to assure against explosion and/or release of fragments, hazardous fluids, over-pressurization and catastrophic failure of the container/compartment.

Containment of rotating devices will consider the combined effect of rotational speed and potential for mass release to determine classification. Guidance for calculating containment of high-energy rotating devices is given in Appendix B of NASA-HDBK-5010.

Hardware not in lockers/containers but having internal parts will be assessed on their individual merit for containment of loose internal parts. Enclosures with openings will be assessed for containment of parts larger than accessible openings.

Engineering judgment supported by documented technical rationale may be used when it is obvious that an enclosure, a barrier, or a restraint exists that prevents the part from escaping. When engineering judgment is used in lieu of a detailed analysis or testing, the criteria for the judgment will be coordinated with the FCM and documented in the FCSR.

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 safety-wired will be assumed non-credible. All safety wired fasteners can be classified non-fracture critical if failure does not result in a catastrophic event due to loss of structural integrity of the fastener.

Assessment of containers with mechanically secured closures, i.e., hinges, latches, etc. shall show the design is at least one fault tolerant (e.g., fail-safe) against release of the contents.

### 6.1.3 Fail-Safe

A structure (including fasteners, latches, and mechanisms) may be classified as fail-safe when it can be shown by analysis or test that due to structural redundancy, the structure remaining after any single failure can withstand the redistributed limit loads with a minimum factor of safety (FS) of 1.0 on ultimate strength for metallic structure or 1.15 on ultimate strength for composite/bonded structure.

Failure of the part shall not generate pieces or debris that would violate the low-released mass (Section 6.1.1).

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) will be removed separately to assess fail-safe capability.

When determining redundancy the effect of altered coupling shall be considered unless:
(a) the design loads are conservative with respect to dynamic coupling variations, or,
(b) failure of the part would not significantly alter dynamic response of the hardware.

For composite/bonded structure, the structural models and analytical methodology used in the fail-safe analysis will be test-verified for the intact/nominal configuration. All fail-safe composite/bonded structures shall be subjected to the DTA and DCP.

When engineering judgment is used in lieu of a detailed analysis or testing, the criteria for the judgment will be coordinated with the FCM and documented in the FCSR.

In cases of significant cyclic loading potential, the remaining structure will be assessed for fatigue or durability and coordinated with the FCM. Joint gapping is allowed for fail-safe components under emergency or abort landing conditions as they are unlikely events.

For multi-mission flight hardware, it will be verified before re-flight that the structural redundancy of a fail-safe part is still intact or sufficient fatigue life is available in the remaining structure to reach end-of-service life. As a minimum, this will be accomplished by a close visual inspection (aided by cameras, video borescopes, or other assistance if necessary) of the hardware for signs of damage. If damage is indicated, it will be coordinated with FCM and more rigorous inspection will be made as warranted including NDE or other applicable analysis for the verification of fail-safe parts.

An alternative to reverification of structural redundancy by inspection 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 life with minimum factor of four (4) on life.

Fasteners made of Ti-6Al-4V, cp-Ti, and other titanium alloys are not acceptable without prior approval of the FCM because of generic environmental assisted cracking (EAC) or sustained load cracking (SLC) failure modes, as well as low fracture toughness [$K_{Ic}/F_{ty} < 0.33 \sqrt{in}$ ($1.66 \sqrt{mm}$)].

All rivet applications shall be designed fail-safe and are subject to conventional verification and quality assurance requirements only. (Note: Fracture Control for damage tolerant rivets is impractical and not realistically implemented).

#### 6.1.4 Low-Risk Structural Parts (Metallic)

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.

The low-risk parts shall meet the following criteria:

(a) It will not be the pressure shell of a human-tended module or personnel compartment, pressure vessel, pressurized lines, fittings, and components containing a hazardous material, or high-energy rotating equipment, solid rocket motor cases and propellant tanks.

(b) A part whose failure will directly result in a catastrophic hazard is excluded, except when the total (unconcentrated) tensile stresses (e.g., maximum principal or von Mises, whichever is larger) in the part at limit load are no greater than 30% of the ultimate tensile strength for the material used.

(c) The raw material shall be inspected using suitable NDE (such as ultrasound) for internal defects. Otherwise, prior approval of the FCM is required.

(d) If the part contains metallic materials, it will not be sensitive to stress-corrosion cracking as defined in MSFC-STD-3029, Guidelines for the Selection of Metallic Materials for Stress Corrosion Cracking Resistance in Sodium Chloride Environments. If other than Table I or A-rated materials are used for low-risk classification, an approved Materials Usage Agreement (MUA) will be submitted along with the FCSR.

(e) All metallic parts will have a material property ratio of $K_{Ic}/F_{ty} > 0.33 \sqrt{in}$ (1.66 $\sqrt{mm}$).

(f) Aluminum parts loaded in the short transverse direction with a dimension greater than 3 in (7.62 cm) require prior approval of the FCM.

(g) The part will not be fabricated using a process which has a significant probability of introducing flaws including welding, forging, casting, or quenching heat treatment on materials sensitive to quench cracking unless special testing or NDE, acceptable to the FCM for a specific application, is applied to screen potential flaws. It will be assumed that significant crack-like defects do not occur during machining of sheet, bar, extrusion, or plate products that are produced in accordance with aerospace quality specifications and that are known to have good machinability properties.

(h) At a minimum, all low-risk fracture parts will receive a visual inspection for surface defects.

(i) A high-margin on fatigue strength is that $S_{max} < F_{tu}/[(4(l\text{-}0.5\ R)]$, where $S_{max}$ is the local concentrated stress, and R is the ratio of minimum stress to maximum stress ($\sigma_{min}/\sigma_{max}$) in a fatigue cycle.
or,
A conventional fatigue analysis (e.g., Miner's rule) that accounts for the effects of notches and mean stress, and shows a minimum of four (4) complete service lifetimes on alternating stress with a FS of 1.5.
or,
A fracture mechanics damage tolerance analysis using a 0.005 in (0.127 mm) initial crack that accounts for the effects of notches and mean stress, and shows a minimum of four (4) complete service lifetimes on alternating stress with a FS of 1.5.
or,
A fracture mechanics damage tolerance analysis using a 0.025 in (0.63 mm) initial crack that accounts for the effects of notches and mean stress, and shows a minimum of four (4) complete service lifetimes on alternating stress with a FS of 1.0.

### 6.1.5 Fasteners and Shear Pins

Designers are encouraged to design parts with redundancy and avoid single-point catastrophic failures in joints and structures when it is reasonable to do so.

Fasteners and shear pins that cannot be categorized fail-safe, may be classified as low-risk if the following are met:

(a) Fasteners shall be in a local pattern of two or more similar fasteners. They are not required to meet 30% of limit load to ultimate tensile strength ratio.

(b) Fasteners less than 3/16 in (0.48 cm) diameter will generally be avoided for low-risk application. If use is unavoidable, specific Fracture Control methodology will be coordinated with the FCM.

(c) The raw material shall be inspected using suitable NDE (such as ultrasound) for internal defects. Otherwise, prior approval of the FCM is required.

(d) Fasteners shall be fabricated from well-characterized metal not sensitive to stress-corrosion cracking as defined in MSFC-STD-3029, Guidelines for the Selection of Metallic Materials for Stress Corrosion Cracking Resistance in Sodium Chloride Environments.

(e) Fasteners are fabricated, procured, and inspected in accordance with NASA-STD-6008, NASA Fastener Procurement, Receiving Inspection, and Storage Practices for Spaceflight Hardware, or an equivalent military standard, NASA, proprietary, or commercial aerospace specification approved by the procuring organization.

(f) Due to generic EAC or SLC failure modes, fasteners in tension applications shall not be fabricated from low fracture toughness alloys [$K_{Ic}/F_{ty} < 0.33 \sqrt{in}$ (1.66 $\sqrt{mm}$)] or specifically, Ti-6Al-4V, cp-Ti, and other titanium alloys without prior approval of the FCM.

(g) Fasteners shall have rolled threads with the rolling process occurring after all thermal treatment of the material. Fasteners with cut threads shall require prior approval of the FCM.

(h) Fasteners shall be fatigue-rated by the manufacturer or meet appropriate pre-loads and fatigue requirements with no joint gapping (gapping is allowed under fail-safe and/or emergency conditions only) using <u>one</u> of the following approaches:

(i) A conventional fatigue analysis (e.g., Miner's rule) of the thread root, shank, and head/shank transition shows a minimum of four (4) complete service lifetimes on alternating stress with a FS of 1.0.

or,

(ii) A fracture mechanics damage tolerance analysis of the thread root, shank, and head/shank transition using a 0.005 in (0.127 mm) initial crack shows a minimum of four (4) complete service lifetimes on alternating stress with a FS of 1.0.

(i) Re-worked or custom-made fasteners require prior approval of FCM.

### 6.1.6 Sealed Containers

This section addresses inherently pressurized hardware (e.g., a sealed electronic box) that is not a part of a pressure system.

The pressure of the sealed containers is less than 100 psia (689.5 KPa) and stored energy is less than 14,240 ft-lb (19,310 J).

Sealed containers do not contain a hazardous fluid and loss of pressure in the system shall not result in a catastrophic hazard.

Sealed containers shall comply with one of the following:

(a) If the container is pressurized to 22 psia (151.7 KPa) or less and E (Energy) < 14,240 ft-lb (19,310 J):
  (i) Demonstrate LBB design.
  (ii) No further assessment is required.

(b) If the container is pressurized in between 22 psia (151.7 KPa) and 100 psia (689.5 KPa), E < 14,240 ft-lb (19,310 J):
  (i) Demonstrate LBB design.
  (ii) Ultimate FS of 2.5 on MDP or greater, or
  Proof test to a minimum of 1.5 X MDP.

Containers with pressure exceeding 100 psia (689.5 KPa) or contained energy exceeding 14,240 ft-lb (19,310 J) shall be treated as pressure vessel per Section 6.2.1.

In LBB design approach, the surface crack of the pressure shell will grow to a through crack as such that the critical length is at least 10 times the wall thickness ($2c \geq 10t$) for linear mechanics fracture mechanics (LEFM) approach OR, 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.

Hardware utilizing common materials of construction and showing high fracture toughness [$K_{Ic}/F_{ty}$ > 0.33 √in (1.66 √mm)] typically demonstrate LBB failure modes and may be considered acceptable in lieu of analysis with the approval of the FCM.

Sealed container made of non-metallic or composite materials require prior approval of FCM.

The container portion of a sealed containers does not require NDE to screen for flaws. The container supports/bracket may or may not require NDE depending on their individual Fracture Control classification.

Guidance for calculating the stored energy in pressurized hardware is given in Appendix G of NASA-HDBK-5010.

### 6.1.7 Pressurized Lines, Fittings, and Components

This section addresses pressurized membranes where flaws cannot grow to instability before a sizable leak has developed, and release of contained fluid is not a catastrophic event.

Pressurized lines, fittings, and components such as regulators, valves, filters, bellows, etc. can be classified as non-fracture critical provided all of the following are met:

(a) They do not contain a hazardous fluid, and loss of pressure in the system shall not result in a catastrophic event and the hardware is designed to carry primarily pressure loads.

(b) The components shall be made from materials typically used for commercially available pressurized systems procured to an aerospace standard or equivalent. Custom-made part requires prior approval of FCM to ensure the parts are reliable and present a low risk of containing detectable flaws that result in crack growth related to environmental, loading, or other conditions.

(c) The components shall not have coatings, barriers, liners, or other means that prevent or inhibit leakage through a flaw.

(d) The surface crack of the pressure shell shall grow to a through crack as such that the critical length is at least 10 times the wall thickness ($2c \geq 10t$) for LEFM approach OR, 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, thereby demonstrating leak-before-burst (LBB) design.

Hardware utilizing common materials of construction and showing high fracture toughness [$K_{Ic}/F_{ty} > 0.33\ \sqrt{in}$ ($1.66\ \sqrt{mm}$)] typically demonstrate LBB failure modes and may be considered acceptable in lieu of analysis with the approval of the FCM.

(e) The leak is automatically detected and further pressure cycling is prevented, or there is no repressurization.

(f) Proof and leak test shall be performed in accordance with structural and pressure system requirements.

(g) System supports and brackets are evaluated per Fracture Control and may or may not require NDE depending on their individual Fracture Control classification.

Lines, fitting and components that are built to commercial standard and containing non-hazardous fluids, having less than 100 psia internal pressure and less than 1000 ft-lb energy may be acceptable without further assessment with the prior approval of FCM. This approach is consistent with Department of Energy PNNL-18696, Pressure Systems Stored-Energy Threshold Risk Analysis.

Catastrophic hazards for LBB assessment include unacceptable dilution or toxicity of breathing environment, increases in oxygen above specification limits, release of gases with a flammability hazard rating of 2 or greater into cabin environments, or loss of a safety critical function.

Non-hazardous LBB shall not be applied to habitable module and enclosures.

The methodology given in API-579-1, Fitness-for-Service (Section 9) may also be used as a guideline in calculating the leakage requirement for LBB design.

#### 6.1.8 Bellows

A Fracture Control program for non-fracture critical bellows shall require coordination with the FCM.

#### 6.1.9 Shatterable Components and Structures

Glass shall meet the requirements of NASA-STD-5018, Strength Design and Verification Criteria for Glass, Ceramics and Windows in Human Space-Flight Applications.

Internal and external shatterable components that are prone to brittle mode of failures (e.g., glass, ceramics, synthetic sapphires, etc.) and/or are subjected to impact or sustained loading can be classified as non-fracture critical if they meet the criteria specified in NASA-STD-5018 Section 4.8.5 on containment

Camera lenses and similar pieces that are recessed or protected during non-use periods are considered protected and can be classified non-fracture critical.

### 6.1.10 Low-Energy Rotating Machinery

This section addresses rotating machinery that do not possess sufficient energy to present a catastrophic hazard risk and will be classified as non-fracture critical.

Rotating machinery that has kinetic energy less than 14,240 ft-lb (19,310 J) and does not present a catastrophic hazard risk can be classified as non-fracture critical.

The low-energy rotating component will be examined for protection against a catastrophic occurrence resulting from release of fragments. Rotating machinery whose failure results in release of fragments will be shown to be contained by analysis or test.

The mounts and brackets for rotating machinery will be addressed as standard structure for Fracture Control.

Shrouded or enclosed fans [8000 rpm (50265.5 rad/s) 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, or the full intent of requirements, and can be classified non-fracture critical without further assessment.

Guidelines for containment analysis of rotating equipment are given in Appendix B of NASA-HDBK-5010.

### 6.1.11 Tools/Mechanisms

All tools and mechanisms whose single-point failure shall not result in catastrophic hazard may be classified non-fracture critical if they meet the requirements for low-released mass (Section 6.1.1), or are contained (Section 6.1.2) during all phases of the mission.

Fracture Control requirements on any tool/mechanism are applied independently of any mechanism fault tolerance requirements per ES4-07-031 (Appendix D), Fracture Control of Mechanisms.

#### 6.1.12 Batteries

For Fracture Control, batteries are unique forms of pressurized containers.

Batteries and battery systems can be classified non-fracture critical by meeting one of the following:

(b) Sealed container requirements (Section 6.1.6).

(a) Pressurized Lines, Fittings, and Components requirements (Section 6.1.7). It is a common practice to mitigate the leakage by adequate absorbent material to prevent the liquid electrolytes coming in contact with the crew or ground personnel.

(c) JSC 20793, Crewed Space Vehicle Battery Safety Requirements.

Small batteries that fall under the non-critical category as mentioned in JSC 20793 are exempt from Fracture Control.

#### 6.1.13 Composite/Bonded Structures

Composite/bonded structures or components may be classified as non-fracture critical if it is shown that one of the following conditions is satisfied:

(a) The structure or component meets the requirements of low released mass (section 6.1.1), contained (section 6.1.2) or fail-safe (section 6.1.3) criteria.

(b) The strain level at limit load is less than the composite/bonded structure’s damage tolerance threshold strain level. The threshold strain level shall be determined by using available data or testing pre-flawed coupons and require prior approval of the FCM.

(c) For multi-mission hardware, it will be verified by inspection (visual or NDE, as applicable) before re-flight that flaws or other structural anomalies have not occurred during use.

(c) The structure or component shall be protected from inadvertent damage by appropriate DTA and DCP.

### 6.2 Fracture Critical Parts/Components

Those parts/components that are identified as fracture critical will be shown acceptable by compliance with Section 7.0 (Methodology for Assessing Fracture Critical Hardware) of this document unless specifically stated otherwise.

#### 6.2.1 Pressurized Systems (Pressure Vessels / Lines, Fittings & Components)

All pressure vessels are fracture critical by definition. Any pressurized lines, fittings & components that contain a fluid whose release would be a catastrophic hazard, shall also be classified as fracture critical.

For all pressure vessels the service fluid, operating temperature range, toxic release, asphyxiation hazards, flammable mixture release, mounting, vibration, external loading, vacuum, radiation, and Micrometeoroid and Orbital Debris (MMOD) requirements consistent with aerospace environments need to be addressed as needed to ensure the safety and mitigate the hazard.

For loading (stresses) to be considered pressure dominant, all other loads (stresses) should be no greater than 20 percent of the pressure loads (stresses).

LBB is the preferred design practice for pressurized hardware.

All welds in fracture critical pressure shell/enclosure that is proof tested for acceptance require pre and post-proof surface and volumetric NDE to screen for cracks.

A pressurization history log shall be maintained for all vessels to assure that allowable pressurizations are not exceeded. Attention will be given to ensure the compatibility of vessel materials with fluids used in cleaning, testing, and operation.

##### 6.2.1.1 Metallic Pressure Vessels

Metallic 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:

(a) MDP shall be substituted for all references to Maximum Expected Operating Pressure (MEOP).

##### 6.2.1.2 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), with the following tailoring:

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

(b) LBB of the metallic liner may not be required when sufficient damage tolerance (safe-life) is demonstrated with prior approval of the FCM.

(c) The peak strain in the composite at MDP shall be less than or equal to 50% of the design ultimate composite strength or prior approval of FCM is required.

(d) Mounting of the pressure vessel via clamps or straps must be approved by the NASA pressure vessel technical discipline authority.

(e) A DCP shall be submitted to FCM. A DCP template is shown in JSC 66901, Damage Threat Assessment (DTA) and Damage Control Plan (DCP) Template for Composite Overwrapped Pressure Vessels.

#### 6.2.1.3 ASME Code and DOT Title 49 Pressure Vessels

American Society of Mechanical Engineers (ASME) Code or United States Department of Transportation (DoT) Title 49 pressure vessels shall meet following additional requirements:

(a) Provide the manufacturer's certificate/qualification/life cycle test report and non-catastrophic classification rationale. Use of ASME Code or DoT Pressure Vessels where leakage is catastrophic requires prior approval of the RFCA

(b) The MDP is maintained at or below the rated pressure.

(c) A DCP is be generated for the COPV per JSC 66901 template.

(d) The pressure vessel will be rated for the internal and external fluids and for temperature environments by the PD or manufacturer.

(e) Mounting of the pressure vessel via clamps or straps must be approved by the NASA pressure vessel technical discipline authority.

#### 6.2.1.4 Un-lined All-Composite Pressure Vessels

A Fracture Control program for un-lined all-composite pressure vessels shall require coordination with the FCM.

#### 6.2.1.5 Bellows

A Fracture Control program for fracture critical bellows shall require coordination with the FCM.

#### 6.2.1.6 Pressurized Lines, Fittings, and Components

Pressurized lines, fittings, and 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 pressure would result in a catastrophic hazard.

Fracture critical lines, fittings, and components shall be proof tested to a minimum of 1.5 x MDP and leak tested at a minimum pressure of 1.0 x MDP to demonstrate no leakage above the required threshold.  Damage tolerance is not required for no high cycle fatigue environment.

Fracture critical lines, fittings, and components that are proof tested to < 1.5 x MDP and leak-tested at 1.0 x MDP shall meet the damage tolerance analysis per section 7.0.

Volumetric and surface inspection of fracture critical fusion joints shall be made after proof testing, of the final assembly to determine acceptable conditions both on the surface and within the fusion joint.

Custom-made lines, fittings, and components require prior approval of FCM to ensure the parts are reliable and present a low risk of containing detectable flaws that result in crack growth related to environmental, loading, or other conditions.

In instances where NDE is not feasible, the HD or manufacturer may employ a process control program that assures the quality of the un-inspectable welds.  The process control is an alternate approach that must be coordinated with the FCM.  Section 5.2.1.4 of NASA-HDBK-5010 contains an outline and guidance for building an acceptable process control program for specific components.

### 6.2.2 Hazardous Fluid Containers (HFCs)

This hardware type is not part of a pressurized system nor is it intended to transfer stored fluid as part of a pressurized system.

The HFC shall be made from materials typically used for commercially available pressurized systems procured to an aerospace standard or equivalent.

The HFC is always fracture critical and shall be damage tolerance against rupture and leak when release of its fluid would cause a catastrophic hazard. Pre-proof and post-proof volumetric and surface inspection of all fusion joints in the HFC shall be made to determine acceptable conditions both on the surface and within the fusion joint.

Containers shall meet all the requirements of pressure vessels (Section 6.2.1) when the contained fluid has a pressure greater than 22 psia (151.7 kPa).

In instances where NDE after proof test is not feasible, the manufacturer will employ a process control program that assures the quality of un-inspectable welds and will be coordinated with the FCM. Section 5.2.1.4 of NASA-HDBK-5010 contains an outline and guidance for building an acceptable process control program for specific component.

Integrity against leaks shall be verified by test at 1.0 X MDP with no leakage above the required threshold.

Alternatively, additional Levels of Containment (LOC) may be added to isolate potential leakage. The individual levels of containment in the LOC approach are not "fracture critical" and Fracture Control measures need not be applied when the LOC approach is used as documented in ES4-02-050, Levels of Containment Guidelines for Payloads Utilizing Hazardous/Toxic Materials (Appendix C).
Or,
A container that has a pressure less than 22 psia (151.7 kPa), a minimum factor of 2.5 times MDP on burst pressure, and is proof tested to a minimum proof factor of 1.5 X MDP can be classified non-fracture critical.

HFC container made of non-metallic or composite materials require prior approval of FCM.

#### 6.2.3 Habitable Modules

All habitable modules designed to support human life are classified as fracture critical.

The pressure shell/enclosure shall be shown to be a damage tolerance design that protects against a burst failure mode from all applied mechanical and thermal loading because internal pressure integrity will be maintained.

The pressure shell/enclosure shall require pre-proof and post-proof NDE to screen for cracks.

LBB is the preferred design practice for pressurized hardware, including a habitable module, because a component that can tolerate a through-flaw without rupture demonstrates increased residual strength capability. However, habitable modules are always fracture critical and will not be classified as LBB because pressure must always be maintained.

The damage tolerance assessment of the pressure shell/enclosure shall consider the worst-case design parameters such as materials allowable, fusion joint peaking, mismatch, and residual stresses.

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

Integrity against leaks shall be verified by test at 1.0 X MDP to demonstrate no leakage above the required threshold.

Structures made of materials that cannot be analyzed using conventional fracture mechanics methodologies (e.g., inflatable non-metallic structures) will be designed and tested to demonstrate adequate failure tolerances or minimum risk of failures and require FCM approval.

Operation of the habitable modules will be monitored and documented to ensure that certification is not invalidated.

### 6.2.4 High-Energy Rotating Machinery

A rotating mechanical assembly is fracture critical if it has a kinetic energy in excess of 14,240 ft-lb (19,310 J), based on $\frac{1}{2} I\omega^2$.

All fracture critical rotating machinery shall be proof tested (spin-tested) to a minimum rotational energy factor of 1.05, i.e., rotational test speed = $\sqrt{(1.05\ \omega^2)}$ and subjected to NDE before and after proof testing.

If NDE after proof testing is not practical, then the rotating part will be shown to be contained, and loss of function will not be safety critical, or it will be shown that the proof test adequately screens for flaws.

The structural mounts for the rotating hardware and the enclosure are evaluated as standard structure to meet Fracture Control requirements.

Guidelines for containment analysis of rotating equipment are given in Appendix B of NASA-HDBK-5010.

### 6.2.5 Fasteners

Designers are encouraged to make fastener applications fail-safe (Section 6.1.3) or non-fracture critical (Section 6.1.4). Potential catastrophe because of a single fastener failure must be avoided. Fasteners that do not comply with the various non-fracture critical criteria applicable to fasteners will be classified fracture critical and shall meet the following criteria:

(a) The raw material shall be inspected using suitable NDE (such as ultrasound) for internal defects. Otherwise, prior approval of the FCM is required.

(b) Fasteners shall be fabricated from well-characterized metal not sensitive to stress-corrosion cracking as defined in MSFC-STD-3029, Guidelines for the Selection of Metallic Materials for Stress Corrosion Cracking Resistance in Sodium Chloride Environments.

(c) Fasteners are fabricated, procured, and inspected in accordance with NASA-STD-6008, NASA Fastener Procurement, Receiving Inspection, and Storage Practices for Spaceflight Hardware, or an equivalent military standard, NASA, proprietary, or commercial aerospace specification approved by the procuring organization.

(d) Fasteners less than 3/16 in (0.48 cm) diameter will generally be avoided for low-risk application. If use is unavoidable, specific Fracture Control methodology will be coordinated with the FCM.

(e) Due to generic EAC or SLC failure modes, fasteners in tension applications shall not be fabricated from low fracture toughness alloys [$K_{Ic}/F_{ty} < 0.33\ \sqrt{in}$ (1.66 $\sqrt{mm}$)] or specifically, Ti-6Al-4V, cp-Ti, and other titanium alloys without prior approval of the FCM.

(f) Fasteners will have rolled threads with the rolling process occurring after all thermal treatment of the material. Fasteners with cut threads will require prior approval of FCM.

(g) Fasteners will meet appropriate preloads with no joint gapping (gapping is allowed under fail-safe and/or emergency conditions only).

(h) For the purpose of screening flaws, fasteners will be NDE inspected by the eddy current method. Alternate NDE methods will require prior approval of the FCM.

(i) Damage tolerance analysis will assume a flaw size in the thread root, shank, and head/shank transition consistent with NDE sensitivity or proof test level and a service life factor of 4 with SF of 1.0 on load.

(j) Fracture critical fasteners and shear pins used in applications designed primarily for shear loading where bending stresses are present will be assessed by damage tolerance analysis and examined for crack-like defects.

(k) Inserts used in conjunction with fracture critical fasteners will be proof load tested to a minimum factor of 1.2 x limit load after installation. This would include, for example, inserts bonded or potted into composite and sandwich structures as well as inserts installed into metallic structures.

(l) After inspection or testing, fracture critical fasteners will be stored and controlled to keep them isolated from other fasteners.

(m) Re-worked or custom-made fasteners require prior approval of FCM.

#### 6.2.6 Shatterable Components and Structures

Fracture critical glass shall meet the requirements of NASA-STD-5018, Strength Design and Verification Criteria for Glass, Ceramics and Windows in Human Space-Flight Applications.

#### 6.2.7 Tools/Mechanisms

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

This classification includes safety critical tethers.

Structural parts of fracture critical tools or mechanisms will be treated in the same general manner as structure.

Each fracture critical tool or mechanism shall be NDE inspected or proof tested to screen for cracks. Damage tolerance assessment shall be performed to assure that flaws, which could cause failure during use, are not present.

When NDE methods are not sufficient to screen for critical defects, rationale shall be presented to the FCM for approval that could include proof testing, and other testing/analysis for the acceptance of the part.

Fracture critical springs require prior approval of FCM.

Fracture critical tools/mechanisms, as applicable, will also be assessed for compliance with the requirements of low-released mass (Section 6.1.1) and contained part (Section 6.1.2) during all phases of the mission.

Fracture control requirements on any tool/mechanism are applied independently of any mechanism fault tolerance requirements per ES4-07-031 (Appendix D), Fracture Control of Mechanisms.

#### 6.2.8 Batteries

Batteries not meeting the criteria of section 6.1.11 shall be classified as fracture critical. Fracture critical batteries shall meet the requirements of pressure vessel (Section 6.2.1).

#### 6.2.9 Single-Event or Expendable Fracture critical Components

Single-event fracture critical components (such as pyrotechnic components) or expendable fracture critical components can be shown to be acceptable without the need of damage tolerance assessment if all four (4) of the following conditions are met:

(a) The hardware is metallic.

(b) The component is not subject to any other significant fatigue loading beyond acceptance and/or normal proto-flight testing (if any) and transportation.

(c) The single-event loading involves a single-cycle or multiple-cycles with rapidly decaying subsequent cycles.

(d) It possesses a margin of 1.4 on fracture toughness.

The margin on fracture toughness will either be determined analytically or demonstrated by test per the following:

<u>Analytical Demonstration:</u> The margin on fracture toughness of 1.4 shall be determined analytically using the following:

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

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

Demonstration by Test:

When the material properties are not properly characterized and applied loads are complex to analyze, the margin on fracture toughness will be established by test. The test article will have a flaw in the worst location and orientation.

Flaw sizes and load amplitudes will be established using one of the following [(a) or (b)]:

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

(b) Loads are difficult to be determined or not well-characterized:
   (i) The flaw size will be at least twice as large in all dimensions as the requirements of NASA-STD-5009.
   (ii) A sufficient number of articles will be tested for the validation of the data and is subject to the prior approval of the FCM.

Single-Event or Expendable Fracture critical Components meeting the requirements addressed in this section will not be required to meet the damage tolerance requirements of Section 7.0.

#### 6.2.10 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, shall be shown acceptable by demonstrating no HCF flaw growth from the detectable NDE flaw size.

The metallic component is acceptable if the calculated HCF stress-intensity is below the stress-intensity-factor threshold for the metallic material.

The composite component is acceptable if the calculated HCF total strain energy is below the total strain energy threshold for the composite material.

The threshold value used for an HCF assessment will be approved by the FCM.

An HCF component meeting the requirements addressed in this section will not be required to meet the damage tolerance requirements of Section 7.0.

## 7.0 Methodology for Assessing Fracture Critical Metallic Hardware

The damage tolerance assessment for fracture critical hardware shall be conducted using one of the following criteria:
(a) Damage tolerance analysis, or
(b) Damage tolerance test, or
(c) Fleet leader testing

The damage tolerance demonstration shall assume that an undetected flaw is in the most critical location(s) and orientation(s) for the fracture critical component.

The damage tolerance demonstration shall be based on an undetected flaw in the most critical area and orientation for that part. This flaw size shall be established by:
(a) NDE, or
(b) Proof testing, or
(c) Process control.

Analysis or test shall consider all significant loadings, both cyclic and sustained, that the part will experience during ground and flight phases for the life of the hardware. The total of all significant loading events and environments comprise one service life (see definitions for service life, and service life factor).

Damage tolerant parts shall be shown to have at least four (4) analytical lifetimes at limit load to account for material data scatter. However it is recommended to run the NASGRO® (NASA Crack Growth Computer Program) to failure to understand the service life capability of the hardware.

If the four (4) analytical lifetimes are not achieved, the part shall be redesigned or a more sensitive inspection technique may be employed with the approval of FCM.

A reusable component that shows a service life of less than four (4) times the required analytical life shall be classified as a "limited life" part. If a "limited life" part is to be employed, the project management shall be informed of the presence of such components and their potential use. At the end of the service life, it shall be coordinated with the FCM for replacement or in-service NDE or re-verification of damage tolerance analysis to re-base the service life.

Guidelines for damage tolerance assessment of fracture-critical parts are given in NASA-HDBK-5010.

### 7.1 Damage Tolerance Assessment

#### 7.1.1 Damage Tolerance Analysis

The damage tolerance analysis shall assume that an undetected flaw is in the most critical location(s) and orientation(s) for the fracture critical component.

In damage tolerant analysis, flaw screening shall be based on appropriate:
(a) NDE techniques, or
(b) Proof testing, or
(c) Process control.

FCM prior approval shall be required for flaw screening by proof test or process control.

The latest version of NASGRO® is an approved analysis tool for deterministic method of damage tolerant assessment of metallic space-flight hardware. Other computer programs or analysis shall require prior approval of FCM.

The NASGRO® version used for the original design and analysis is acceptable for the life of the hardware. However, if loading/design changes are made or there are any significant changes in the current version of NASGRO®, the most current version of the NASGRO® program shall be used for any life assessment. If the predicted life is lacking after assessment, or if valid concern about fracture life of other hardware occurs, the matter shall be brought to the FCM for resolution.

The damage tolerance analysis could be determined by:
(a) Deterministic method, or
(b) Probabilistic method.

In the deterministic method, the flaw screening will be based on appropriate NDE techniques, proof testing, or process control. The latest version of NASGRO® is an approved analysis tool for deterministic method of damage tolerance assessment of metallic space-flight hardware. Other computer programs or analysis requires prior approval of FCM.

The probabilistic method uses knowledge of the statistical variability of the damage tolerance variables to select criteria for achieving an overall success confidence level and requires prior approval by FCM on an individual-case basis.

#### 7.1.2 Damage Tolerance Testing

Damage tolerance testing will be used whenever a valid procedure for fracture mechanics damage tolerance analysis is not available.

Testing will be performed in the operational environment on specimens representative of the materials, design, structural loading (sustained and cyclic), boundary conditions and initial defect sizes located at critical locations.

Any damage tolerance testing program for fracture critical part shall require prior approval of the FCM.

#### 7.1.3 Fleet Leader Testing

In cases where loading conditions are poorly defined or sub-scale component testing does not provide representative results, a ground test fleet leader program will be developed to assess for damage tolerance.

Fleet leader testing program for fracture critical component requires prior approval of the FCM.

### 7.2 Flaw Screening for Fracture Critical Parts

#### 7.2.1 Non-Destructive Evaluation (NDE)

NDE shall be done on fracture critical parts to establish that pre-existing flaws in the hardware are no larger than those assumed as initial flaws in the damage tolerance analysis.

For metallic components, NDE inspections for Fracture Control shall be performed in accordance with NASA-STD-5009, Non Destructive Evaluation Requirements for Fracture Critical Metallic 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.

When effective Fracture Control requires inspection sensitivity that exceeds the accepted levels for standard NDE delineated in NASA-STD-5009, special NDE may be performed on the fracture critical parts for damage tolerance analysis. If the need has been identified, plans for implementing special NDE will be addressed in the FCP and coordinated with FCM.

Except for translucent materials (e.g., glass), visual inspection will not be used for the purpose of detecting flaws to be used in damage tolerance assessments without documented rationale and specific approval by the FCM.

### 7.2.2 Proof Test

Proof testing may be used to screen for flaws when NDE is impractical due to (a) the complexity of the hardware, and (2) access and NDE method limitation, etc.

Proof test to screen for flaws shall require prior approval of the FCM.

The component is not expected to experience significant crack growth during the proof test for flaw screening.

The effect of service temperature and environment will be considered during proof testing. An Environmental Correction Factor (ECF) can be used with the approval of the FCM if the service condition is not well defined properly or cannot be readily achieved in a ground test environment.

### 7.2.3 Process Control

Process control to screen for flaws and damage tolerance analysis and/or testing shall require prior approval of the FCM.

There may be cases where NDE of the fracture critical part is not feasible. In these cases, process control with sufficient rationale may be used to accept the part. An acceptable rationale will include:

(a) Statement of why NDE techniques are not practical and why an alternative approach is required.

(b) The list of parts covered by this alternative approach rationale.

(c) Materials (including condition), dimensions, and construction of the part.

(d) Consequences of structural failure, mitigating factors and safeguards in place.

(e) The Manufacturers' experience of the component and/or assembly. Manufacturing process control with critical processes such as heat treatment, machining, material raw stock processes from the mill, etc.

(f) Operating environment and temperature extremes for the item.

(g) Qualification and acceptance test program for the item.

(h) Summary arguments for the alternative approach rationale.

Section 5.2.1.4 of NASA-HDBK-5010 contains an outline and guidance for building an acceptable process control program for specific components.

### 7.3 Material Selection and Properties

Fracture critical parts will be fabricated from materials and/or components with specific verification of applicable supplier data/certifications or equivalent materials/hardware control.

Materials will be compatible with NASA-approved standards and specifications in accordance with the requirements of NASA-STD-6016 and MMPDS (metallic alloys).

Factors affecting materials properties are addressed below:

(a) General Consideration: A good practice for materials selection is to choose a material with a plane strain fracture toughness to yield strength ratio greater than 0.33 √in ($K_{Ic}/F_{ty}$ > 0.33 √in). Although not an explicit Fracture Control requirement, it is good practice to maintain a minimum of 3% elongation (in 4 or 5 diameters gage length) in the service environment.

(b) Service Environment: The effect of temperature and exposure to harmful media on materials properties and crack growth will be documented in the FCSR. An approved MUA for materials not rated as highly resistant to stress-corrosion cracking per MSFC-STD-3029 will be included in the FCSR.

(c) Product Form: Specimens used in determining toughness and crack growth rate will be representative of the flight hardware. Fracture properties of representative welds and brazed joints will be developed and used in the damage tolerance analysis.

(d) Material Orientation: Depending on the degree of anisotropy in the material, the fracture properties will be developed in all orientations and used in the analysis. Properties of the weakest material orientation will be used in the strength and life analysis unless material orientation is fully traceable throughout the manufacturing and design process.

Additively manufactured (AD) or 3D-printed materials that are categorized as low-risk or fracture critical parts require prior approval of the FCM.

### 7.4 Fracture Mechanics Material Properties

For damage tolerance analysis of fracture critical parts, the fatigue crack growth rate (da/dN) and fracture toughness values ($K_c$) for predicting crack instability will be average or typical values.

The da/dN curve and $K_c$ will correspond to the temperature and environments of the flight hardware.

The latest version of NASGRO® is an approved analysis tool for damage tolerance analysis of metallic space-flight hardware. Other computer programs or analysis requires prior approval of the FCM.

Modification of the NASGRO® material parameters shall be approved by the FCM.

Where environmental effects on crack growth will be considered, the lower bound values of $K_{EAC}$ for the relevant fluid and material combinations will be used in fracture mechanics analysis.

Strength and fracture toughness testing of representative material (same heat lot or out of remnant material used in fabrication of the part) will be used for an alloy having a wide range of fracture toughness data (values falling below 20% of the average value).

Retardation effects on crack growth rates from variable amplitude loading will not be considered without the approval of the FCM.

A lower-bound fracture toughness will be assumed when the amount of analytical crack growth is small, where the initial and critical cracks are of similar size.

Material properties for use in elastic-plastic or non-linear (J-integral) damage tolerance analysis shall be coordinated with the FCM.

### 7.5 Loading Spectra

A load spectrum will be developed for each fracture critical part to perform an adequate damage tolerance assessment.

All significant loadings including mechanical, thermal, pressure, etc. and environments during ground, flight, orbital and planetary phases will be compiled into a service life spectrum for the hardware. An aborted mission and subsequent re-flight will be included in the service life.

The total of all these significant loading events and environments comprise one (1) service life. The service life factor to be used for damage tolerance assessment shall be four (4).

Both cyclic and sustained loads, as well as residual stresses and preloads will be considered in the damage tolerance assessment.

### 7.6 Detected Cracks in Fracture Critical Metallic Hardware

The use of fracture critical hardware with detected cracks shall require prior approval of the FCM.

## 8.0 Methodology for Assessing Fracture Critical Composite/Bonded Structure

Fracture critical composite/bonded structure will demonstrate structural FS requirements using a 90% reliability, 95% confidence, statistically derived design allowable with damage that is credible and likely in accordance with the DTA and DCP.

Fracture critical composite/bonded structures will be shown acceptable by one of the following:

(a) Proof test in limited applications, or
(b) Damage tolerance testing.

The damage tolerance test is the preferred approach to assessing fracture critical parts. With prior approval of the FCM, proof test may be used in limited applications.

### 8.1 Proof Test of Fracture Critical Composite/Bonded Structure

The proof test of fracture critical composite/bonded structure will be limited to hardware that has well-defined loads, load paths, and boundary conditions.

The flight hardware shall be proof tested to a minimum of 1.2 x limit load.

The proof test will be conducted in the service temperature and environments of the flight hardware or by using an ECF.

The proof test loads shall be less than 80% of the ultimate strength of the structure for the appropriate mode of failure (i.e., tension, compression, shear) to avoid detrimental deformation during proof testing.

For multi-mission components and structures, the structural integrity of the part in between flights will be verified using purposeful inspection or test for signs of damage.

If damage is indicated, a more rigorous inspection will be made as warranted including NDE or other applicable analysis for the verification of the parts.

Fracture Critical Composite/Bonded Structure shall be protected from inadvertent damage by appropriate DTA and DCP.

Acceptance of fracture critical composite/bonded structure using proof test shall be coordinated with the FCM.

### 8.2 Damage Tolerance Test of Fracture Critical Composite/Bonded Structure

Flight hardware require damage tolerance testing of fracture critical/bonded structure will requiring project-specific FCP to meet NASA-STD-5019A.

### 8.3 Detected Damage in Fracture Critical Composite/Bonded Hardware

The use of fracture critical hardware with detected damage above the NDE detection threshold requires prior approval of the FCM.

## 9.0 Tracking for Fracture Critical Parts

(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(s) to be used on the part or raw material.

(b) All materials used in fracture critical parts shall be traceable by certification of compliance (COC) to material standards, serialization, an MUA, and/or engineering requirements stated on the drawing.

(c) The type of NDE and the NDE acceptance criteria should be specified on the drawing.

(d) Composite or bonded material (such as epoxies, adhesives, etc.) should have their shelf life requirements.

(e) The HD shall include tracking to provide for Fracture Control assessment of load changes, modifications, or redesigns of the fracture critical part. Discrepancy report (DR) reviews, or equivalent, will be conducted for anomalies that could affect part fracture characteristics and life.

(f) The load history shall be maintained the entire life of the fracture critical part which includes load level, number of cycles, and environments in which the loads occurred.

## 10.0 Fracture Control Verification

### 10.1 Fracture Control Summary Report (FCSR)

To certify Fracture Control compliance of hardware, the HD shall prepare a FCSR on the total system for review and approval by the FCM. The FCSR contains the information or summarizes and points to the detailed reports necessary to show fracture control compliance of all parts to the requirements.

The FCSR will be submitted before the Phase III 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) A statement that the flight hardware configuration has been controlled and verified for all fracture critical parts.

(b) Lists non-fracture critical parts, along with their classification and supporting rationale.

(c) Identification of low-released mass and contained category and a brief statement of the basis for classification.

(d) Identification of fail-safe parts and a brief statement of the basis for classification. Confirmation that for re-flown fail-safe hardware any required "between mission" inspections have been performed for fail-safe hardware that is intended to be re-flown.

(e) List of low-risk parts with a summary of the basis for their acceptance.

(f) Lists fracture critical parts with a summary of the basis for their acceptance.

(g) A statement that inspections or tests specified for Fracture Control were applied and that results showed structural integrity requirements were met.

(h) Identification of the NDE and/or tests applied for Fracture Control purposes to each fracture critical part.

(i) Fracture critical parts that have limited life shall be specifically identified.

(j) A summary of the discrepancy reviews, or equivalent reviews, of anomalies that could affect the performance of fracture critical parts.

(k) A summary discussion of alternative approaches or specialized assessment methodology applied, not specifically covered by this FCP.

(l) Identification of any special considerations involving fracture mechanics properties or data, inspections, analysis, or other parameters not covered by this FCP.

(m) A summary of the Configuration Management (CM) system used to store records.

(n) Documentation of the proof tests, damage tolerant tests, vibration tests, or other tests are used to justify Fracture Control compliance.

(o) Documentation of hardware configuration, test setup, loading schedule, and environments used to justify Fracture Control compliance.

(p) For the routine proof test of lines, fittings, and pressurized components, the manufacturer data sheet will suffice.

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

### 10.2 Inspection Report

The inspection report will 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 flaws inspected for; the results of the inspection; and the inspector’s signature, date, and stamp.

For long-term programs, a permanent CM system may be implemented to store inspection report records.

## 11.0 Alternatives

In the event of specialized hardware or applications where the assessments or techniques delineated in this FCP are not feasible or effective, or where potential cost savings are significant while maintaining an acceptable level of Fracture Control, alternatives may be proposed.

Any alternatives shall be subject to the approval of the FCM and S&MA.

## 12.0 Other Requirements

It will be understood that implementation of Fracture Control and full compliance with Fracture Control requirements does not relieve the hardware from compliance with structural design/test requirements, quality assurance requirements, materials requirements, etc. that are applicable independent of Fracture Control.

## Appendix A: Definition of Terms

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

**Acceptance Test:** Test performed to demonstrate that the hardware is acceptable for flight. Also serves as a quality control screen to detect deficiencies in the flight build and is performed at levels and durations which reflect the expected flight environment.

**Adhesive Bond (Bond):** The joining of parts, components, or materials using a joining substance or agent.

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

**B-Basis Allowable:** A statistically-calculated number which at least 90 percent of the population of material values is expected to equal or exceed with a confidence of 95 percent.

**Bond:** The adhesion of one part to another through the use of an adhesive as a bonding agent.

**Bonded Structure:** A structure that is assembled using parts that are joined together with bonds.

**Brittle Fracture:** Sudden rapid fracture under stress (residual or applied) where the material exhibits little or no evidence of ductility or plastic deformation.

**Burst Factor:** The burst factor is a multiplying factor applied to the MDP to obtain the design burst pressure. Burst factor is synonymous with ultimate pressure factor.

**Critical Hazard:** Any condition which may cause a non-disabling personnel injury or illness, loss of a major ISS element, loss of redundancy (i.e. with only a single hazard control remaining) for on-orbit life sustaining function, or loss of use of the Space Station Remote Manipulator System (SSRMS).

**Catastrophic Event:** Loss of life, disabling injury, or loss of a major national asset.

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

**Catastrophic Hazard:** Any condition which may cause a disabling or fatal personnel injury or one of the following: loss of ISS, loss of a crew-carrying vehicle, or loss of a major ground facility.

**Component:** Hardware item considered a single entity for the purpose of Fracture Control. The terms “component” and “part” are interchangeable in this document.

**Composite Material:** A combination of materials differing in composition or form on a macro scale. The constituents retain their identities in the composite; that is, they do not dissolve or otherwise merge completely into each other, although they act in concert. Normally, the constituents can be physically identified and exhibit an interface between one another. Composite material is not intended to mean an assembly of parts.

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

**Composite/Bonded Structure:** Structure (excluding COPV or pressurized components) of fiber/matrix configuration and structure with load carrying non-metallic bonding agent, such as sandwich structure or bonded structural fittings.

**Composite Hardware (Structure):** Hardware (structure) assembled with parts made from composite materials.

**Contained Part:** 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.

**Contamination:** Any material included within or on the hardware that is not called for on the engineering drawings. Examples of contamination are dust, grease, solvent, solid objects, etc.

**Crack or Crack-like Defect:** A discontinuity assumed to behave like a crack for Fracture Control purposes.

**Critical Stress Intensity Factor:** The stress intensity factor at the initiation of crack growth in the part resulting in a catastrophic failure that is representative of the failure mode of concern for the metallic material process condition, weakest orientation, and thickness being evaluated.

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

**Damage:** See definitions of Flaw and Impact Damage.

**Damage Threat Assessment (DTA):** An evaluation of potential sources of flaws in composite or bonded hardware that includes definition, quantification, and an assessment of the residual strength sensitivity to flaws.

**Damage Control Plan (DCP):** A plan for composite or bonded hardware to mitigate risk of damage to the flight hardware.

**Damage tolerance:** Fracture Control design concept under which an undetected crack or flaw (consistent in size with the flaw screening method or residual threat determination (RTD)) is assumed to exist and is demonstrated by fracture mechanics analysis or test that it will not grow to catastrophic failure (leak or instability) during the period equal to the service life factor times the service life. “Damage tolerance” has replaced the term “Safe Life” in this document and other NASA Standards to avoid confusion with other technical documents.

**Environmental Correction Factor (ECF):** A load or stress 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 tested.

**Environmentally Assisted Cracking (EAC):** A cracking process in which the environment promotes crack growth or higher crack growth rates than would occur without the presence of the environment (ASTM E1681, Standard Test Method for Determining Threshold Stress Intensity Factor for Environment-Assisted Cracking of Metallic Materials). An example is available in published literature (Lewis and Kenny, 1976)

**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:** A condition where a redundant load path exists within a part (or hardware), so that after loss of any single individual load path, the remaining load path(s) has sufficient structural capability to withstand the redistributed loads, and the loss of the load path will not cause a catastrophic hazard.

**Fastener:** For Fracture Control, any single part that joins other structural elements and transfers loads from one element to another across a joint.

**Flaw:** A discontinuous or incongruous presence in hardware that has the potential for adversely affecting strength or life. Examples of flaws include: cracks, cuts, scratches, delaminations, porosity/voids, disbonds, wrinkles, FOD, impact damage, etc. Damage (used alone) and flaw are equivalent.

**Fleet Leader:** A series of tests that are used to identify a failure mode before it occurs in the fleet to provide early warning of known and unexpected risks to the rest of the fleet. The fleet leader tests are designed to identify/capture a failure mode that is not well understood.

**Flight (Space-flight) Hardware:** Any structure, payload, experiment, system, or parts built to space-flight requirements and carried by a launch vehicle, crew module, transfer stage, landing craft, etc.

**Flight-like Component:** A component assembled and made of parts that are of flight specifications. Flight-like components are usually intended for qualification tests. Any deviations from flight have to be insignificant with respect to test objectives.

**Foreign Object Debris (FOD)**: A solid form of contamination that is entwined into the composite lay-up or embedded into a bonded joint. Some examples of FOD include backing paper, peel ply, paper clips, tape, knife blades, writing pens, or small tools.

**Fracture Control Board (FCB):** A group of experts in the various Fracture Control disciplines that is responsible for Fracture Control methodology and which has the authority to interpret Fracture Control requirements and make decisions regarding Fracture Control questions and issues.

**Fracture Control Coordinator (FCC):** A designated individual(s) experienced in 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 Control Monitor (FCM):** The designated individual(s) at NASA/JSC responsible for effective Fracture Control methodology and who have has the authority to interpret Fracture Control requirements.

**Fracture Control Plan:** The plan which specifies Fracture Control activities to be imposed on the design, analysis, testing, change control, and documentation of components. The intent of this document is to establish procedures required to prevent catastrophic damage associated with cracks or crack−like flaws from occurring during the service life of these components.

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

**Fracture Critical:** Classification that identifies a part whose failure due to the presence of flaw is a catastrophic event, and requires damage tolerance assessment. Parts under this classification receive flaw screening by NDE, proof test, or process control and are subjected to traceability, materials selection and usage, documentation, and engineering drawing requirements.

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

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

**$F_{tu}$:** A-basis material ultimate strength.

**$F_{ty}$:** A-basis material strength.

**Habitable Module:** A pressurized, life–supporting enclosure or module that is normally intended to support life without the need for spacesuits or special breathing apparatus. The enclosure may be one that is continuously inhabited, or one that is used for crew transference, or for crew accessible stowage so long as life support is a requirement for the design. Single mission or multi–mission module designs are included.

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

**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.

**High-Energy Rotating Machinery:** For the purpose of Fracture Control, a rotating mechanical assembly that has a kinetic energy of 14,240 ft-lb (19,310 J) or greater based on $\frac{1}{2} I\omega^2$.

**Impact Damage:** The injury or harm inflicted by impingement of another object upon the hardware in question such as a dropped tool, hail, or runway debris; or the bumping or striking between the hardware in question and another object such as a support cradle or building during handling or lifting. Impact damage is a subset of the more general term, damage (or flaw).

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

**$K_c$:** Critical stress intensity factor for fracture; also known as plane stress fracture toughness. $K_c$ varies with the material, specimen size, and thickness. $K_c$ is used in NASGRO® to represent fracture toughness as a function of thickness for use in crack growth calculations.

**$K_{Ic}$:** Plane strain fracture toughness. The crack extension resistance under conditions of crack-tip plane strain in Mode I for slow rates of loading in linear elastic fracture mechanics (LEFM).

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

**$K_{EAC}$:** 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.

**$K_{Iscc}$:** $K_{EAC}$ is often denoted $K_{Iscc}$ in the literature. $K_{EAC}$ is interchangeable with $K_{Iscc}$.

**$\Delta K_{th}$:** Threshold stress intensity factor range below which flaw growth will not occur under cyclic loading conditions.

**Leak-Before-Burst:** A fracture mechanics design concept in which it is shown that any initial flaw will grow through the wall of a pressurized membrane or pressurized component and cause benign leakage rather than burst or fragmentary fracture or tearing rupture (catastrophic failure) at MDP. For pressurized hardware, the critical length of through-crack as determined by analysis or sample testing is at least 10 times the wall thickness for LBB design condition. The methodology given in API-579-1, Fitness-for-Service may also be used for guidance in meeting the leakage requirement for LBB design.

**Life Factor:** See Service Life Factor.

**Lifetime:** See definition of Service Life. Refers to a specified life, as opposed to an analytically predicted life.

**Limit Load:** The maximum anticipated load, or combination of loads, which a structure may experience during its service life under all expected conditions of operation or use.

**Limited Life Part:** A part that has a predicted damage tolerance life that is less than the required service life factor of four times the complete service life. See definition of Service Life.

**Low-Fracture Toughness:** Material property characteristic, in the applicable environment, for which the ratio is $K_{Ic}/F_{ty} < 1.66 \sqrt{mm}$ ($0.33 \sqrt{in}$). For steel bolts with unknown $K_{Ic}$, low fracture toughness is assumed when $F_{tu} > 1240$ MPa (180 ksi). Parts made with materials of this characteristic may be at risk of a brittle fracture.

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

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

**Maximum Expected Operating Pressure (MEOP):** MDP shall be substituted for all references to MEOP in ANSI/AIAA S-080-1998 and ANSI/AIAA S-081A-2006.

**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.

**Net-Section Stress or Strain:** The stresses or strains computed for a hypothetical cut across a part, based on strength-of-materials theory. Possible bending loads can produce stress gradients across the net section, in which case the net-section stress is found to be the maximum combination of tension and bending stress, ignoring geometric stress concentrations. An example of net-section stress calculation detailed in the NASGRO® User's Manual,

**Non-Destructive 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, eddy current, etc. NDE is sometimes referred to as nondestructive testing (NDT) or non-destructive inspection (NDI).

**Non-Hazardous Fluid:** For Fracture Control, a fluid whose release would not create a catastrophic hazard. If the leakage of fluid cause a critical hazard, it is assumed non-hazardous for the purpose of Fracture Control.

**Part:** Hardware item considered a single entity for the purpose of Fracture Control. The terms “component” and “part” are interchangeable in this document.

**Pressure Vessel:** A container designed primarily for pressurized storage of gases or liquids and the following:
(a) Contains stored energy of 14,240 ft-lb (19,310 J) or greater based on adiabatic expansion of a perfect gas; or
(b) Stores a gas that will experience an MDP greater than 100 psia (689.5 kPa).
(c) Contains a gas or liquid in excess of 22 psia (151.7 kPa) that will create a catastrophic hazard if released; or
*[The pressure ceiling in item (c) in this FCP is slightly higher from the definition in AIAA S-080/81 to make it consistent with HFC section].*

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

**Pressurized Hardware:** Any of the various hardware items that support an internal pressure

**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 include pressure vessels, lines, fittings and components.

**Proof Test:** A test on the flight article that is performed to verify structural acceptability or to screen flaws. The proof test load and/or pressure level is the proof test factor times limit load and/or MDP.

**Proof Test Factor:** A factor that is multiplied by the limit load and/or MDP to arrive at the proof test levels. When proof tests are performed to establish structural acceptability, the proof test factor is specified. When screening for flaws with a proof test, the proof test factor is derived by fracture mechanics principles.

**Qualification Test:** Test performed on hardware that is intended to demonstrate that the test item will function within performance specifications after being exposed to levels which demonstrate margin over the expected flight environment.

**Residual Strength:** The maximum value of load (both externally applied and internal self-equilibrating loading, such as residual stresses) that a flawed or damaged part is capable of sustaining without catastrophic failure.

**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.

**R-Ratio:** The ratio of minimum stress to maximum stress ($\sigma_{min}/\sigma_{max}$).

**Rupture:** An instance of breaking or bursting suddenly and completely.

**Safe-Life:** See definition of Damage Tolerance.

**Safety Critical:** For fracture control, a part, component, or system whose failure or loss would be a catastrophic hazard *(Note: this definition is copied from NASA-STD-5019A)*.

**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 and that has pressure less than 100 psia and stored energy of less than 14,240 ft-lb (19,310 J).

**Service Life:** Time interval for a part beginning with manufacture, acceptance testing and extending through its planned and specified usage. This includes all relevant loadings, conditions, environments encountered that will affect flaw growth, including all manufacturing, testing, storage, transportation, launch, on-orbit, descent, landing, and if applicable, post-landing events, refurbishments, retesting, and repeated flights until the hardware is retired from service. 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 tolerance 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 that could release many small pieces into the surrounding environment.

**Standard NDE:** NDE methods of metallic materials for which a statistically based flaw detection capability has been established. Standard NDE methods addressed by this document are limited to fluorescent penetrant, radiography, ultrasonic, eddy current, and magnetic particle. NDE of fracture-critical hardware shall detect the initial crack sizes used in the damage tolerance analysis with a capability of 90/95 (90 percent probability of detection at a 95 percent confidence level).

**Special NDE:** Formal crack-detection procedure using inspection techniques and/or equipment that exceeds common industrial standards, or where assumed detection capability exceeds that specified in NASA-STD-5009.

**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.

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

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

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

**Ultimate Load, Pressure, or Strength/Stress:** The maximum load, pressure, or strength/stress that a structure will withstand without incurring rupture or collapse; also, the product of the limit load multiplied by the ultimate FS.

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

## Appendix B: Abbreviations and Acronyms

| | |
|---|---|
| ω | Maximum Operating Rotational Speed |
| μm | micrometer |
| AIAA | American Institute of Aeronautics and Astronautics |
| AD | Additively Manufactured |
| ANSI | American National Standards Institute |
| API | American Petroleum Institute |
| ASME | American Society of Mechanical Engineers |
| CAI | Compression After Impact |
| CDR | Critical Design Review |
| cm | centimeter |
| CM | Configuration Management |
| COC | Certification of Compliance |
| COPV | Composite Overwrapped Pressure Vessel |
| COTS | Commercial Orbital Transportation System |
| cp-Ti | Commercially Pure Titanium |
| da/dN | Fatigue Crack Growth Rate |
| DCP | Damage Control Plan |
| DOT | Department of Transportation |
| DR | Discrepancy Report |
| DTA | Damage Threat Assessment |
| E | Energy |
| EAC | Environmental Assisted Crack |
| ECF | Environmental Correction Factor |
| EVA | Extra Vehicular Activity |
| FCB | Fracture Control Board |
| FCC | Fracture Control Coordinator |
| FCM | Fracture Control Monitor |
| FCP | Fracture Control Plan |
| FCSR | Fracture Control Summary Report |
| FOD | Foreign Object Debris |
| FS | Factor of Safety |
| ft/sec | foot per second |
| ft-lb | foot-pound |
| ft-lb/sec | foot-pound per second |
| $F_{tu}$ | Ultimate Tensile Strength |
| $F_{ty}$ | Yield Tensile Strength |
| gm | grams |
| HCF | High-Cycle Fatigue (HCF) |
| HD | Hardware Developer |

| | |
|---|---|
| HDBK | Handbook |
| HFC | Hazardous Fluid Container |
| in | inch |
| ISS | International Space Station |
| J | Joules |
| JPR | JSC Procedural Requirement |
| JSC | Johnson Space Center |
| K | Stress Intensity Factor |
| $K_c$ | Critical Stress Intensity Factor |
| $K_{EAC}$ | Stress-intensity-factor Threshold for EAC |
| Kg | kilogram |
| kg-m/sec | kilogram-meter per second |
| $K_{Ic}$ | Plane Strain Fracture Toughness. |
| $K_{Ie}$ | Effective Fracture Toughness for Surface or Elliptically Shaped Crack. |
| $K_{Iscc}$ | $K_{EAC}$ is Often Denoted $K_{Iscc}$ in Literature (They are Interchangeable) |
| KPa | KiloPascals |
| ksi | Kilo pound per square ibch |
| lb | pound |
| LBB | Leak-Before-Burst |
| LOC | Levels of Containment |
| m | meter |
| m/sec | meter per second |
| MDP | Maximum Design Pressure |
| MEOP | Maximum Expected Operating Pressure |
| MIL-HDBK | Military Handbook |
| MIL-STD | Military Standard |
| mm | millimeter |
| MMOD | Micrometeoroid and Orbital Debris |
| MMPDS | Metallic Materials Properties Development and Standardization |
| MPa | MegaPascals |
| MUA | Materials Usage Agreement |
| NASA | National Aeronautics and Space Administration |
| NASA-HDBK | NASA Handbook |
| NASA-STD | NASA Standard |
| NASGRO® | NASA Crack Growth Computer Program |
| NDE | Non-Destructive Evaluation |
| N-m-s | Newton-meter-second |
| P/SRR | Project/System Requirements Review |
| PDR | Preliminary Design Review |
| psia | pound per square inch absolute |
| R | Ratio of minimum stress to maximum stress ($\sigma_{min}/\sigma_{max}$) in fatigue cycle. |
| rad/s | radian per second |

| | |
|---|---|
| rpm | Revolution per Minute |
| S&MA | Safety and Mission Assurance |
| SAR | System Acceptance Review |
| SLC | Sustained Load Cracking |
| $S_{max}$ | Maximum cyclic tensile stress |
| SRP | Safety Review Panel |
| SRR | System Requirements Review |
| SSP | Space Station Program |
| SSRMS | Space Station Remote Manipulator System |
| Ti | Titanium |
| V | Vanadium |

## Appendix C: ES4-02-050; Levels of Containment Guidelines for Payloads Utilizing Hazardous/Toxic Materials

National Aeronautics and
Space Administration
**Lyndon B. Johnson Space Center**
2101 NASA Road 1
Houston, Texas 77058-3696

August 27, 2002

ES4-02-050

TO: EA4/Engineering Representative, Payload Safety Review Panel
FROM: ES4/Integration Technical Manager for Fracture Control and Pressure Vessels

SUBJECT: Levels of Containment Guidelines For Payloads Utilizing Hazardous/Toxic Materials

There have been occasional problems and misunderstandings when addressing containment of hazardous materials by payloads. This letter is intended to provide guidelines, and clarify methodology and controls, for assuring against release of toxic or otherwise hazardous materials in space flight applications.

Control against release of hazardous materials is accomplished by a "levels of containment" approach or, in some cases, by a "design for minimum risk" approach. Generally, failure tolerance (having appropriate levels of containment for a given hazard rating) is the approach used for containment of hazardous/toxic materials. NHB/NSTS 1700.7B, paragraphs 200.1 through 200.3, 209.1b, and 220.1a(3) delineate the basic requirements for acceptable containment. Appropriate levels of containment must exist for both stowage and operational phases of hardware containing hazardous material/fluids.

The levels of containment (LOC) approach requires essentially concentric "layers" of containment where each individual layer is of a design integrity able to contain the hazardous material. In hazard control by LOC, two levels of containment (single failure tolerant) are required for materials with a critical hazard potential, and three levels (two failure tolerant) are required for materials with a catastrophic hazard potential. Joints and closures, whether metallurgically fused, sealed, or chemically/thermally bonded, are considered to be single barriers for their respective layer (level) when employing the LOC approach for hazard control. When independent seals are used, a single seal closure is acceptable for a given single level of containment.

Each individual level must be functionally separate, independent, and capable of containment under all conditions of use. Conditions of use generally include handling, exposure durations, temperature extremes, and pressure differentials including module depressurization. It is incumbent on the Payload Developer to provide the appropriate verification information that this is the case, including design, qualification, compatibility assessments, and related testing information and data. The design integrity of each layer or level of containment on flight units must be verifiable by testing or other defined procedure approved by the SRP. Compatibility of the contained material and the materials used for the levels of containment, including joints and seals, must be established. If the levels of containment are opened during a mission, and then resealed for continued containment, resealing must be verified by leak test, approved procedure, or design certification. Verification method(s) must be approved by the SRP. The individual levels of containment in the LOC approach are not "fracture critical" and fracture control measures need not be applied when the LOC approach is used.

"Sealed Containers," as defined in NASA-STD-5003 for single barrier containment of non-hazardous fluids, may be used as an individual level or levels of containment in a LOC approach to control a hazard provided that, at a minimum, they are also demonstrated compatible with the contained material and each containment level demonstrated to be leak-tight on the flight hardware. When used in an a LOC application "Sealed Containers" are to be addressed on a unique hazard report which cites LOC as a hazard control and defines the verification method for each level of containment. The JSC Form 1230 is not to be used for "Sealed Containers" in LOC applications.

In addition to use of physically enclosing layers of containment, unique substitutes for a physical layer may sometimes be appropriate and acceptable. An intermediate vacuum or a negative pressure might be counted as a level of containment under certain circumstances. A vacuum or negative pressure as a level of containment must be independently applied and maintainable, and must exhaust safely and not present a danger of contamination to another system. The use of a vacuum or a negative pressure as a level of containment must be specifically approved by the SRP. There may be other approaches that under certain circumstances might be considered as equivalent to a single level of containment, including use of absorbent materials, scrubbers, catalysts, etc. However, unique approaches to compliance with LOC requirements must be reviewed and specifically approved by the SRP, and documentation of the full rationale/justification for acceptability included in the safety data package.

The LOC approach to hazard control differs significantly from the "design for minimum risk" (DFMR) approach for safe containment of hazardous/toxic materials. The DFMR approach may utilize a single containment barrier for hazard control. Utilization of a single containment barrier for hazard control necessitates rigor consistent with DFMR philosophy and methodology. For example, fracture control is required, in addition to high quality, for containment of materials whose release would be a catastrophic hazard when the single barrier approach is used. A single container of high quality and demonstrated capability, and approved by the SRP, may be used to contain materials whose release would be a critical hazard. If individual seals are used with single-barrier DFMR containers, their number should be consistent with the hazard level, i.e., two for critical and three for catastrophic. Single, high quality, leak tested metallurgical welds are acceptable barriers in DFMR designs. In general, single non-metallic adhesive or heat/chemical-fused joints are not acceptable in DFMR designs. However, they are acceptable for LOC applications provided that such joints are specifically evaluated for structural capability and compatibility.

Although LOC and DFMR may be acceptable in combination (e.g., approved single wall container with dual o-ring seals for a critical-level fluid), these two approaches are nevertheless separate and distinct methods for hazard control. When a single barrier is the only rational design solution for containment they must be DFMR barriers. Connections and closures, etc., may be mechanical with redundant seals or acceptably metallurgically fused. To avoid confusion, and possible error, the respective requirements for LOC versus DFMR (including those for joining methods, number of barriers/seals to control hazards, fracture control, materials certification, etc.) should be considered as totally separate approaches.

Hazard control for containment of hazardous/toxic materials, whether by LOC or DFMR, should be addressed on a unique hazard report.

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## Appendix D: ES4-07-031; Fracture Control of Mechanisms

National Aeronautics and
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June 19, 2007

ES4-07-031

TO: NE/R. Guidry
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FROM: ES4/S. Forth
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SUBJECT: Fracture Control of Mechanisms

The JSC Fracture Control Board met and approved this memorandum is written to clarify the application of the fracture control fail safe methodology to mechanisms.

The intent of fracture control is to assure the structural integrity of safety critical components from a usage induced failure mechanism as a result of mechanical loading, thermal loading, and environmental influences that determine the propagation rate of preexisting defects to a critical size, which in turn results in a catastrophic failure. Fracture control mitigates this failure scenario by establishing a safe interval of operation that provides adequate margin on the required service life and critical defect size in the structure.

Traditionally, fracture control is applied to the as-designed (per-print) structural configuration. Therefore, operationally-induced structural degradation is deemed a structural failure and continued hardware use requires a re-assessment of fracture control. However, the fail-safe fracture control category incorporates a potential structural failure of a single primary load path element by means of assuring structural integrity through redundant load paths.

The two fault tolerance requirement for mechanisms induces a structural degradation that is a result of an operational failure, not a service loading induced structural failure. As mentioned above, applying fracture control to a structural configuration of this nature is beyond the traditional scope of fracture control. The two fault tolerance requirement for mechanisms imposes a boundary condition state that rapidly becomes intractable for complex interfaces and/or complex structural arrangements. An accurate depiction of a multi-failure scenario requires the following:

- Quantification of the resulting structural dynamic response
- Identification of changes in the corresponding load-stress transfer function
- Augmentation of the fatigue spectrums with updated load-time histories and limit load magnitudes
- Modification of the crack case solutions to account for critical location changes
- Review of the entire structural arrangement, *e.g.*, at a structural interface, the examination of only the fasteners is not sufficient to ensure fracture control structural integrity – the joined members and structural elements that direct the load through the joint must also be evaluated.

Since all flight hardware elements are subjected to a rigorous certification program that entails the proper level of analysis and testing to demonstrate successful operational deployment in worst-case conditions of environment and assembly tolerances, it is concluded that the mechanism two fault tolerance requirement addresses an off-nominal operational state that has a low probability of occurrence. A low probability of occurrence, coupled with the insurmountable task of properly implementing fracture control a priori to a problem set that is beyond the established domain of fracture control, has led to the board decision that fracture control implementation will not be applied sequentially with respect to the mechanism fault tolerance requirements. Fracture control requirements will instead be applied independently of the mechanism requirements. This methodology is consistent with established fracture control policy.

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