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FRACTURE CONTROL PLAN FOR JSC SPACE-FLIGHT HARDWARE

JSC Fracture Control Board

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1.0 Introduction

Any part or component whose individual structural failure would be a catastrophic event will be evaluated for Fracture Control. These parts will be treated with appropriate Fracture Control rigor to assure that a catastrophic failure is not caused by manufacturing and service-induced flaws, damage, or cracks existing in the materials of construction.

This Fracture Control Plan (FCP) presents the JSC implementation methodology for compliance with Fracture Control requirements on all manned space-flight programs.

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 other FCP that is approved by the JSC Fracture Control Monitor (FCM). The NASA/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. Terms defined in Appendix A of this document and in glossary sections of applicable requirements documents will be consulted for proper understanding and implementation of this FCP.

A viable Fracture Control program relies on proper design and analysis and on high quality of parts/components in-flight structures and pressurized or mechanical systems. Design and quality requirements for critical-flight hardware are expected to be consistent with aerospace standards. It is beyond the scope, or intent, of this FCP to specify requirements of flight hardware that already exist. Fracture Control supplements well-designed, high-quality hardware with significant additional assurance against catastrophic failures resulting from unexpected and/or undetectable flaws.

Fracture Control does not replace other applicable requirements for flights such as vibration testing, strength, 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 most critical area of the part and in the most unfavorable orientation.

(b) The use of Non-Destructive Evaluation (NDE) techniques does not negate the above assumption. The NDE techniques establish a probable upper bound on the size of the assumed initial flaw at a specified confidence level.

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

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

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. Although Fracture Control can be effective in assuring mission success, it is not specifically required for that purpose and is up to the discretion of the Hardware Developer (HD) to use for that purpose.

Fracture Control of the hardware will implement the required rigor based on the 'hazard' criticality evaluation and agreement. The FCM will verify that acceptable Fracture Control has been implemented on JSC flight hardware. The FCM does not normally determine the criticality of 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.

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.

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. This plan will also meets the intent of NASA-STD-5007, NASA-STD-5003, SSP 30558C, and SSP 52005C.

3.0 Applicability

This plan is applicable to all JSC controlled 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 Hardware Developer (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 have the following responsibilities:

(a) Fracture Control classification of 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) Testing or fatigue/fracture mechanics analyses for all low-risk and fracture-critical parts.

(d) Implementation of traceability and documentation showing compliances, adherence of flight hardware to approved drawings, specifications, plans and procedures.

(e) Assessment of anomalies on low-risk and fracture-critical parts and decisions regarding questions or issues relating to Fracture Control.

(f) Compilation of the 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 Fracture Control Summary Report (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 so they can be inspected. Avoid welds that are not inspectable on all sides.

(c) Avoid processes that tend to be prone to cracking such as welding, custom-forging, casting, etc.

(d) Use well-characterized standard aerospace materials for which the strength, fatigue, and fracture properties are known, or provide for adequate material testing.

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, PSRP, FESRRP, etc.) at JSC.

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

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

4.3 Fracture Control Milestones

The Hardware Developer (HD) will meet the following milestones for Fracture Control Data Submittal to the FCM.

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

(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).

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

(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.

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

(a) 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 http://standards.nasa.gov, directly from the Standards Developing Organizations, or from other document distributors.

NASA-STD-5007; General Fracture Control Requirements for Manned Spaceflight Systems

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

NASA-STD-5003; Fracture Control Requirements for Payloads Using the Space Shuttle

SSP 30558C; Fracture Control Requirements for Space Station

SSP 52005C; 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

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

NSTS 1700.7B; Safety Policy and Requirements for Payloads Using the Space Transportation System

NSTS 1700.7B, ISS ADDENDUM; Safety Policy and Requirements for Payloads Using the International Space Station

JSC 62550; 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-080-1998; Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components

ANSI/AIAA S-081A-2006; Space Systems - Composite Overwrapped Pressure Vessels (COPVs)

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

ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 or 2, September 2004; Rules for Construction of Pressure Vessels, Section VIII, Division 1 or Division 2, Alternative Rules

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

ES4-07-031; Fracture Control of Mechanisms

6.0 Fracture Control Classification of Parts

Where feasible, 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, or
(b) Non-fracture-critical, or
(c) Fracture-critical.

<u>Exempt</u> hardware typically includes items such as insulation blankets, switches, sensors, enclosed electrical circuit components/boards, electrical connectors, pins, tangs, lock wire, etc. used for fastener back-off prevention, wire bundles, seals, etc.

<u>Non-fracture-critical</u> hardware generally includes the classifications of low-released mass, contained, fail-safe, non-hazardous leak-before-burst (NHLBB) pressurized lines, fittings & components, low-speed/low-energy and low-momentum rotating machineries, 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 hardware includes pressure vessels, high-energy or high-momentum rotating equipments, hazardous material containers, 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-tolerant requirements through analysis or test or fleet-leader testing. Section 6.2 provides criteria for classifying and assessing specific types of fracture-critical hardware.

The assessment of hardware criticality will examine the different phases of application 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. If the hazard is unclear, 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 6.1.11. These parts will be processed under conventional aerospace verifications and quality assurance procedures.

6.1.1 Low-Released Mass

Potential mass releases as a result of a single-point structural failure will be examined for hazard potential. Any part of any size in this category whose release would not be a catastrophic hazard either to the source of the mass or to any other structures, systems, or crew that could be impacted by the mass during any phase of launch/reentry or flight can be classified non-fracture-critical. A released mass may either be internal or external to the spacecraft.

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 10.7 m/sec (35 ft/sec) or a momentum of more than 1.24 kg-m/sec (8.75 ft-lb/sec).

Fasteners pre-loaded in tension which have a low-fracture toughness, $K_{Ic}/F_{ty} < 1.66 \sqrt{mm}$ ($0.33 \sqrt{in}$), will be limited to 14 gm (0.03 pound) potential free mass.

For steel bolts with unknown K_{Ic}, low-fracture toughness is assumed when F_{tu} > 1240 MPa (180 ksi).

Parts/components whose single-point failure would exceed low-released mass limits would, preferably, be shown to be contained (Section 6.1.2), or meet the low-risk criteria (Section 6.1.11) and, therefore, be classified as non-fracture-critical. Otherwise, applicable requirements of fracture-critical parts must be applied.

6.1.2 Contained

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, 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.

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.

When containment is furnished by a compartment with doors or other opening hardware, the closure design will be one-fault tolerant of accidentally opening, i.e., hinges, latches, etc., will be redundant (e.g., fail-safe) for keeping a door closed in the event one fails.

6.1.3 Fail-Safe

For purposes of Fracture Control, structures (including fasteners, latches, and mechanisms) will be identified as fail-safe and classified non-fracture-critical when it can be shown that, due to structural redundancy, structure remaining (assumed unflawed) after any credible

single structural failure can withstand the redistributed loads with a minimum safety factor of 1.0 on limit load for metallic structure or 1.15 on limit load for composite/bonded structure.

Failures that are classified fail-safe will not result in release of an unacceptable free 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 will 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 will be subjected to Task 1 of the Damage Threat Assessment (DTA) (Section 8.2.1) and Damage Control Plan (DCP) (Section 8.2.2).

In some cases, fail-safe categorization will be a matter of engineering judgment based on high-structural margins, design experiences, materials characteristics, overall configurations, etc. 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 under fail-safe or emergency or abort landing conditions as they are unlikely events.

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

For multi-mission flight hardware, it will be verified before reflight that the structural redundancy of a fail-safe part is still intact or sufficient fatigue life is available in the remaining structure to reach end-of-service life. This will be accomplished by a close visual inspection (aided by cameras, boroscopes, or other assistance if necessary) of the hardware for signs of damage. If damage is indicated, a more rigorous inspection 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-tolerant analysis or test to reach end-of-service life with minimum factor of four (4) on life.

6.1.4 Non-Hazardous Leak-Before-Burst (NHLBB) 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. are accepted as NHLBB designs and they 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 will not result in a catastrophic event.

(b) The critical length of through-crack is at least 10 times the wall thickness 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 LBB design.

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

(d) System supports and brackets are evaluated per Fracture Control.

Catastrophic hazards for LBB assessment include unacceptable dilution or toxicity of breathing environment, increases in oxygen or flammable material beyond flammability limits, or loss of a safety-critical function.

Hardware meeting required design factors and utilizing common materials of construction that typically exhibit LBB failure modes may be considered acceptable in lieu of analysis with the approval of the FCM.

NHLBB will not be applied to habitable module and enclosures.

To be classified NHLBB, the components will not have coatings, barriers, liners, or other means that prevent or inhibit leakage through a flaw. Pressure vessels may also be of NHLBB design, but they are always considered fracture-critical.

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

6.1.5 Low-Energy Rotating Machineries

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

Rotating machinery that has kinetic energy less than 19,310 Joules (14,240 foot-pounds) and angular momentum less than 136 Newton-meter-seconds (100 pound-foot-seconds) and does not present a catastrophic hazard risk can be classified as non-fracture-critical.

The low-energy and low-momentum rotating equipment will be examined for protection against a catastrophic occurrence resulting from release of fragments. Rotating equipment 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 [50265.5 rad/s (8000 rpm) and 20.4 cm (8 in) 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.

6.1.6 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) Fastener will be in a local pattern of two or more similar fasteners.

(b) Fastener will be fabricated and inspected in accordance with military standard, national aircraft standard, or equivalent commercial aerospace specifications.

(c) Fastener will be fabricated from well-characterized metal not sensitive to stress- corrosion cracking as defined in NASA-STD-6016, Standard Materials and Processes Requirements for Spacecraft.

(d) Tensile-loaded fastener will not be made from a low-fracture toughness alloy [$K_{Ic}/F_{ty} < 1.66 \sqrt{mm}$ ($0.33 \sqrt{in}$)] or, Ti-6Al-4V STA titanium.

(e) Fasteners will have rolled threads.

(f) Fasteners will 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 fracture mechanics damage-tolerant analysis of the thread root, shank and head/shank transition using a 0.127 mm (0.005 in) initial crack and shows a minimum of four (4) complete service lifetimes on alternating stress with a safety factor of 1.0.
> or,
> (ii) A conventional fatigue analysis (e.g., Miner's rule) of the thread root, shank and head/shank transition and shows a minimum of four (4) complete service lifetimes on alternating stress with a safety factor of 1.0.

(g) Re-worked or custom-made fasteners require FCM approval.

6.1.7 Shatterable Components and Structures

Internal and external shatterable components that are prone to brittle mode of failures (e.g., glass, ceramics, etc.) and/or subjected to impact or sustained loading can be classified as non-fracture-critical if they meet the criteria specified in Section 6.1.7.1 or Section 6.1.7.2.

6.1.7.1 Shatterable Components and Structures Inside Habitable Module

Shatterable components in habitable module can be classified as non-fracture-critical by meeting the requirements of contained parts (Section 6.1.2).

With the approval of the FCM, small shatterable parts can be accepted for use based on vibration environmental testing, inspection, and functional tests that verify the integrity.

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

6.1.7.2 External Shatterable Components and Structures

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

(a) A Damage Threat Assessment (DTA) and Damage Control Plan (DCP), as defined in Section 8.2.1 and 8.2.2 respectively, will be developed to mitigate catastrophic hazards due to credible impacts from vehicle loss of external surface mass, crew exposure, Micrometeoroid and Orbital Debris (MMOD), Extra Vehicular Activity (EVA) inadvertent contacts, and EVA tool impact hazards.

(b) The design will be redundant in function and strength such that loss of a primary member does not result in catastrophic loss of function or required strength that prevents the spacecraft from safely completing the mission.

6.1.8 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 container is less than 689.5 KPa (100 psia) and stored energy is less than 19,310 Joules (14,240 foot-pounds).

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

Sealed containers will comply with one of the following:

(a) If the container will be pressurized to 151.7 KPa (22 psia) or less:
  (i) No further assessment is required.

(b) If the container is pressurized in between 151.7 KPa (22 psia) and 689.5 KPa (100 psia), it will demonstrate:
  (i) Ultimate factor of safety (FOS) of 2.5 on MDP or greater,
  or,
  (ii) Proof-test to a minimum of 1.5 X MDP.

Containers with pressure exceeding 689.5 KPa (100 psia) or contained energy exceeding 19,310 Joules (14,240 foot-pounds) will be treated as pressure vessel per Section 6.2.1.

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

The container portion of a sealed container 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.

6.1.9 Tools/Mechanisms

All tools and mechanisms whose single-point failure will 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 contained (Section 6.1.2) during all phases of the mission.

6.1.10 Batteries

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

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

(a) NHLBB requirements (Section 6.1.4). 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.

(b) Sealed container requirements (Section 6.1.8)

(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.

6.1.11 Low-Risk Structural Parts

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 will 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 / high-momentum 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 in the part at limit load are no greater than 30% of the ultimate tensile strength for the material used.

(c) If the part contains metallic materials, it will not be sensitive to stress-corrosion cracking as defined in NASA-STD-6016, Standard Materials and Processes Requirements for Spacecraft. 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.

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

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

(f) The part will not be fabricated using a process which has a significant probability of introducing flaws including welding, forging, casting, or quenching heat treatments 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.

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

(h) A high-margin on fatigue strength is that $S_{max} < F_{tu}/[(4(l-0.5\ R)]$, 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 safety factor of 1.5.
or,

A fracture mechanics damage-tolerant analysis using a 0.127 mm (0.005 in) 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 safety factor of 1.5.
or,
A fracture mechanics damage-tolerant analysis using a 0.127 mm (0.005 in) initial crack that accounts for the effects of notches and mean stress and shows a minimum of ten (10) complete service lifetimes on alternating stress with a safety factor of 1.0.
or,
A fracture mechanics damage-tolerant analysis using a 0.63 mm (0.025 in) 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 safety factor of 1.0.

(i) In addition to meeting (a) through (g) [as applicable], composite/bonded low-risk structure will also meet the following:

- (i) Strain of the part will be below the no-growth threshold strain.
- (ii) The part will be assessed for impact flaw size detectable by the purposeful inspection and DTA (Section 8.2.1) and DCP (Section 8.2.2).
- (iii) For multi-mission hardware, it will be verified by inspection (visual or NDE, as applicable) before reflight that flaws or other structural anomalies have not occurred during use.

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, will also be classified as fracture-critical.

Pressure vessels that are LBB designs that do not contain a hazardous fluid will be acceptable without a damage-tolerant assessment as addressed in Section 7.0 when all other applicable requirements for space-flight hardware are met. Other pressure vessels will be shown to meet damage-tolerant requirement combined with appropriate inspections or tests.

Damage-tolerant pressure vessels will be re-inspected after acceptance proof-testing in addition to inspections that may have been performed prior to acceptance tests.

A pressurization history log will 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.

Pressure vessels designed and manufactured in accordance with the rules of the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 or 2, or DoT Title 49, that also meet the

NHLBB requirements of Section 6.1.4, will not be required to meet the damage-tolerant requirements of Section 7.0.

6.2.1.1 Metallic Pressure Vessels

Metallic pressure vessels will 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 will be substituted for all references to maximum expected operating pressure (MEOP).

(b) LBB and NHLBB will be interpreted in the context of this FCP.

6.2.1.2 Composite Overwrapped Pressure Vessels (COPVs)

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

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

(b) LBB and NHLBB will be interpreted in the context of this FCP.

The failure of a COPV may be catastrophic, leading to loss of vehicle, ground personnel, or crew, and is therefore fracture critical. Fracture Control requirements dictate that all credible catastrophic failure modes are mitigated. The COPV catastrophic failure modes are:

- Burst from over-pressurization
- Fatigue failure of the metallic liner
- Burst resulting from damage to the metallic liner or composite overwrap
- Stress rupture of the composite overwrap

Explanations of the mitigation of each failure mode are in the following paragraphs.

Burst from Over-Pressurization:
The instantaneous burst of a COPV from over-pressurization is mitigated by designing the materials to an A-basis material allowable and requiring that the operating pressure be one half of the burst pressure or less. The A-basis is a statistically calculated number indicating that at least 99% of the population of material properties equals or exceeds the design value, with a confidence of 95%. Additionally, each pressure vessel is proof-tested during acceptance to a minimum of 1.25 X MDP to screen for manufacturing defects that could cause an unexpected burst. Translating the design factor of safety (FOS) to an actual FOS on nominal properties, the FOS on the burst is always greater than a 1.5. With a FOS greater than 1.5 and the design being based off of the lower 1% of the material population, the risk of static burst failure is mitigated.

Fatigue Failure of the Metallic Liner:
The fatigue failure of the metallic liner is mitigated by inspection and testing. The NDE of the liner at by manufacturer assures that critical flaw sizes are screened for adequately. The COPV design is also cycle tested during qualification to a factor of four times the design life to assure adequate margin on life. Additionally, the failure of a liner in a COPV does not result in a burst of the vessel, only leakage. Therefore, if the fluid or gas inside the vessel is non-hazardous, and the loss of function is not catastrophic, the liner failure is benign. In the case where leakage is a hazard, the combination of inspection and testing has mitigated liner failure from both damage and fatigue.

Burst Resulting from Damage to the Metallic Liner or Composite Overwrap:
Failure of the COPV from damage to the composite overwrap is mitigated by the Damage Control Plan (DCP) and damage tolerance testing. The DCP outlines manufacturing, processing and handling methods to minimize the risk of damage to the composite. The level of protection is defined by the damage tolerance testing (NASA TP-2002-210769) performed at White Sands Test Facility (WSTF). The DCP is implemented such that the COPVs are manufactured in controlled environments, and are padded in protected crates for shipment to NASA. The COPVs are then integrated into systems that are either closed out prior to shipment to Kennedy Space Center (KSC) or are wrapped and delivered with protective covers. For ground processing at Kennedy Space Center (KSC) and on-orbit installation and operation, the COPVs are protected from inadvertent damage within covers or containers. Therefore, the risk of failure from inadvertent damage is minimized by process-control.

Stress Rupture of the Composite Overwrap:
Stress rupture, or creep failure of the composite, is mitigated to an acceptable level of flight and ground risk to the programs and NASA centers. The stress analysis for the COPV design is used to compute the fiber stress ratio and data on the material system are used to predict the stress rupture risk. The classical Weibull stress rupture reliability model (such as Robinson or Phoenix) should be used. The mean reliability should be used for presenting the flight risk to program. The NASA Center responsible for ground processing may require a level of confidence to be attached to the stress rupture reliability for assessing the risk to ground personnel. The recommendation for using mean reliabilities, instead of some other confidence bound, is predicated on the fact that failure data is typically a normal distribution, the mean is a better tool for forecasting, and the mean is more accurate for small sample sizes. The acceptable level of risk for both flight and ground processing is defined by the program and NASA center respectively.

6.2.1.3 Un-lined All-Composite Pressure Vessels

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

6.2.1.4 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) will 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 will be proof-tested to a minimum proof-factor of 1.5 X MDP and leak checked at a minimum pressure of 1.0 X MDP. Fracture-critical lines, fittings, and components proof-tested to 1.5 X MDP and leak-checked at 1.0 X MDP will not be required to meet the damage-tolerant requirements of Section 7.0 provided pressure is the dominant load and all design/test requirements are met.

Volumetric inspection of fracture-critical fusion joints will be made after proof-testing, and for lines and fittings, after proof-test of the final assembly to determine acceptable conditions both on the surface and within the fusion joint.

In instances where NDE is not feasible, the manufacturer will employ a process-control program that assures the quality of the un-inspectable welds and 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 High-Energy Rotating Machineries

A rotating mechanical assembly is fracture-critical if it has a kinetic energy in excess of 19,310 Joules (14,240 foot-pounds), based on $\frac{1}{2} I\omega^2$, or an angular momentum ($I\omega$) exceeding 136 Newton-meter-seconds (100 pound-foot-seconds).

All fracture-critical rotating machinery will be proof-tested (spin-tested) to a minimum factor of 1.05 on stress 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.

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

6.2.3 Fasteners

Designers are encouraged to make fastener applications fail-safe (Section 6.1.3) or non-fracture-critical (Section 6.1.6). Potential catastrophe because of a single fastener failure will be avoided. Fasteners that do not comply with the various non-fracture-critical criteria applicable to fasteners will be classified fracture-critical and meet the following criteria:

(a) Fastener will be in a local pattern of two or more similar fasteners.

(b) Fastener will be fabricated and inspected in accordance with military standard, national aircraft standard, or equivalent commercial aerospace specifications.

(c) Fastener will be fabricated from well-characterized metal not sensitive to stress- corrosion cracking as defined in NASA-STD-6016, Standard Materials and Processes Requirements for Spacecraft.

(d) Tensile-loaded fastener will not be made from a low-fracture toughness alloy [$K_{Ic}/F_{ty} < 1.66 \sqrt{mm}$ ($0.33 \sqrt{in}$)] or, Ti-6Al-4V STA titanium.

(e) Fasteners will have rolled threads.

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

(g) Damage-tolerant analysis will assume a flaw size in the thread root, shank and head/shank transition consistent with NDE sensitivity or proof-test level.

(h) Fasteners less than 0.48 cm (3/16 inch) diameter will generally be avoided for a fracture-critical application. If use is unavoidable, specific Fracture Control methodology will be coordinated with the FCM.

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

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

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

(l) Re-worked or custom-made fasteners require FCM approval.

6.2.4 Shatterable Components and Structures

Fracture-critical shatterable components and structures will meet the requirements of JSC 62550, Strength Design and Verification Criteria for Glass, Ceramics and Windows in Human Space-Flight Applications.

6.2.5 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, including classification as low-risk fracture parts where appropriate.

Each fracture-critical tool or mechanism will be proof-tested or adequately inspected to assure that flaws, which could cause failure during use, are not present.

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

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 (Section 6.1.2) during all phases of the mission.

6.2.6 Batteries

Fracture-critical batteries will meet the requirements of pressure vessel (Section 6.2.1).

6.2.7 Hazardous Fluid Container (HFCs)

The hazardous fluid container (HFC) will be damage-tolerant against rupture and leak when release of a fluid would cause a catastrophic hazard.

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

A container that has a pressure less than 151.7 kPa (22 psia), a minimum factor of 2.5 times MDP on burst pressure and proof-tested to a minimum proof-factor of 1.5 X MDP can be classified non-fracture-critical.

Volumetric inspection of the fusion joints in the container will be made after proof-testing to determine acceptable conditions both on the surface and within the fusion joint.

In instances where NDE is not feasible, the manufacturer will employ a process-control program that assures the quality of the un-inspectable welds and 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 will be verified by test at 1.0 X MDP with no leaks permitted.

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.

6.2.8 Habitable Modules

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

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

At a minimum, the pressure shell/enclosure will require post-proof NDE test. Pre-proof NDE is highly recommended for quality control to protect high-value structures and facilities.

LBB is the preferred design practice for pressurized hardware including 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 NHLBB because pressure will always be maintained.

The damage-tolerant assessment of the pressure shell/enclosure will 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 will be verified by test at 1.0 X MDP.

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.

6.2.9 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-tolerant 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:

Analytical Demonstration: The margin on fracture toughness of 1.4 will 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-tolerant 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, will be shown acceptable by demonstrating no HCF flaw growth.

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-tolerant requirements of Section 7.0.

7.0 Methodology for Assessing Fracture-Critical Metallic Hardware

The damage-tolerant assessment for fracture-critical hardware will be conducted as delineated in Section 4.2 of NASA-STD-5019 and shown to be damage-tolerant by:
(a) Damage-tolerant analysis, or
(b) Damage-tolerant test, or
(c) Fleet-leader testing.

The damage-tolerant demonstration will be based on an undetected flaw in the most critical area and orientation for that part.

This flaw size will be established by:
(a) NDE, or
(b) Proof-testing, or
(c) Process-control.

Analysis or test will 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 will be shown to have a service life factor of at least four (4) at limit load to account for material data scatter.

If the service life factor of four (4) is not achieved, the part will 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 mission life will be classified as a "limited life" part. If a "limited life" part is to be employed, the project management will be informed of the presence of such components and their potential use. At the end of the service life, it will coordinated with the FCM for replacement or in-service NDE or reverification of damage-tolerant analysis to re-base the service life.

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

7.1 Damage-Tolerant Assessment

7.1.1 Damage-Tolerant Analysis

The damage-tolerant analysis will assume that an undetected flaw is in the most critical location and orientation for that part.

Models for crack growth rate and fracture mechanics analyses may vary from version to version and may also vary from equations published in the literature. The version used for the original design and analysis is acceptable for the life of the hardware. However, if fracture life has driven the design, or if loading/design changes are made, the most current version of the analysis program will be used for life assessment using settings appropriate for the particular application. If the predicted life is lacking after reassessment, or if valid concern about fracture life of other hardware occurs, the matter will be brought to the FCM for resolution.

The damage-tolerant analysis could be:
(a) Deterministic method, or
(a) Probabilistic method.

In <u>deterministic method</u>, the flaw screening will be based on appropriate NDE techniques, proof-testing, or process-control. The latest version of NASGRO® (NASA Crack Growth Computer Program) is an approved analysis tool for deterministic method of damage-tolerant assessment of metallic space-flight hardware. The NASGRO® version used for the original design and analysis will be acceptable for the life of the hardware unless loading and/or design changes take place. Other computer programs or analysis requires prior approval of FCM.

The <u>probabilistic method</u> uses knowledge of the statistical variability of the damage-tolerant 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-Tolerant Testing

Damage-tolerant testing will be used whenever a valid procedure for fracture mechanics damage-tolerant 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.

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.

Any fleet-leader testing program requires prior approval of the FCM.

7.2 Flaw Screening for Fracture-Critical Parts

(a) NDE, or
(b) Proof-testing, or
(c) Process-control.

FCM approval will be required for flaw screening by proof-test or process-control.

7.2.1 NDE

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

NDE inspections for Fracture Control will be performed in accordance with NASA-STD-5009 for metallic components.

Hardware that is proof-tested as part of its acceptance (i.e., not screening for specific flaws) will 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-tolerant 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 material (e.g., glass), visual inspection will not be used for the purpose of detecting flaws to be used in damage-tolerant assessments without documented rationale and specific approval by the FCM.

7.2.2 Proof-Test

Proof-test may be is used to screen for flaws when NDE is impractical due to the complexity of the hardware.

Proof-test to screen for flaws will 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 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-tolerant analysis and/or testing will require prior approval of the FCM.

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

(a) Statement of why NDE is impractical and alternative approach is required.
(b) List of parts covered by this rationale.
(c) Materials, dimensions, and construction of the part.
(d) Consequences of structural failure and mitigating factors and safeguards in place.
(e) Manufacturers' experience base in use of the part including process-control, heat treatment, NDE of material raw stock, etc.
(f) Operating environment and temperature extremes.
(g) Qualification and acceptance test program for the part.
(h) Summary arguments for the 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.

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 $\sqrt{in}$ ($K_{Ic}/F_{ty} > 0.33 \sqrt{in}$).

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 operational temperature and exposure to harmful media on materials properties and crack growth will be documented in the FCSR.

An approved Materials Usage Agreement (MUA) for materials not rated as highly resistant to stress-corrosion cracking per NASA-STD-6016 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-tolerant 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.

7.4 Fracture Mechanics Material Properties

For damage-tolerant 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-tolerant analysis of metallic space-flight hardware. Other computer programs or analysis requires prior approval of the FCM.

Modification of the NASGRO® material parameters will be coordinated with 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) models damage-tolerant analysis will 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-tolerant 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 reflight 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-tolerant assessment will be four (4).

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

7.6 Detected Cracks in Fracture-Critical Metallic Hardware

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

8.0 Methodology for Assessing Fracture-Critical Composite/Bonded Structure

Fracture critical composite/bonded structure will demonstrate structural FOS 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-tolerant test (preferred practice).

The damage-tolerant 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 will 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 will 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.

Parts in this category will be assessed for durability to damage size detectable by the purposeful inspection, damage identified as credible in the DTA (Section 8.2.1) and not mitigated through the DCP (Section 8.2.2).

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

8.2 Damage-Tolerant Test of Fracture-Critical Composite/Bonded Structure

Verification of composite/bonded flight structure involves a series of tailored test programs with test articles of increasing complexity. A damage-tolerant test of fracture-critical composite/bonded structure will be assessed for the following:

(a) Damage Threat Assessment (DTA)
(b) Damage Control Plan (DCP)
(c) Damage-Tolerant Coupon Test
(d) Damage-Tolerant Development Test
(e) Damage-Tolerant Full-Scale Component Test
(f) NDE
(g) Proof-Test
(h) Spectrum Truncation
(i) Load-Enhancement Factor

Fracture-critical composite/bonded structure will demonstrate that the structure has 90% reliability on life with 95% confidence (e.g. Load-Enhancement Factor with a minimum of 4 lifetimes) with worst case credible damage as determined by the DTA and DCP.

8.2.1 Damage Threat Assessment (DTA)

All fracture-critical composite/bonded structures will be assessed using a DTA.

The purpose of the DTA is to define and quantify the damage or manufacturing flaws that may reduce the structure's static or cyclic capability in the damage-tolerant approach.

Results from the DTA serve as input to the DCP and the damage-tolerant tests (coupon, development, and full-scale component).

Flaws from impact damage during manufacturing, handling, test, storage, transportation, and in-service use and maintenance will be included in the DTA.

The DTA includes the following three tasks:

Task 1: (Identification of the source and type of impact damage that poses a credible threat to the hardware)

These events will include (but are not limited to) incidents such as tool drops, runway debris, hail, bumping during handling, etc.

The results of Task 1 will be used as input to Task 2.

Task 2: (Characterization of the size and energy level associated with impact damage)

The impact damage sizes and energy levels will be used as input to the damage-tolerant test (coupon, development, and full-scale tests). The DTA will evaluate worst case damage location(s) and orientation on the hardware.

Task 3: (Generation of an as-manufactured initial flaw type and size assessment of the hardware)

The material, processing and design will be evaluated to determine the types and size of initial flaws in the as-manufactured hardware.

Cuts, surface scratches, porosity/voids, delaminations, disbonds, wrinkles, cracking, potential existence of contamination and FOD will be considered in this assessment.

The initial flaw type and size will be used as input to the damage-tolerant (coupon, development, and full-scale) tests.

8.2.2 Damage Control Plan (DCP)

The DCP will address each threat identified in the DTA and provide a method for protecting the flight hardware from that threat.

Protection devices may include covers, blankets, sacrificial composite layers, shipping containers or handling plans to mitigate risk associated with impact damage to the hardware.

Implementation of the DCP is designed to mitigate, not eliminate, the risk associated with impact damage. Therefore, damage-tolerant testing is required regardless of the various impact damage mitigation steps taken.

In cases where direct protection is not feasible, procedures that minimize the threat or monitoring devices that detect damage such as video cameras or other sensors may be used with the concurrence of the FCM.

8.2.3 Damage-Tolerant Coupon Tests

Tests on coupons representative of the flight material and lay-up/with flaws will be run to tested to ensure damage tolerance in materials level

The test will correspond to the temperature and environments of the flight hardware.

These curves will be used in conjunction with damage-tolerant development tests and the damage-tolerant full-scale component tests to support hardware processing.

The residual-strength tests will be based on compression and for impact damage, compression after impact (CAI) for compressive-loaded structure.

The DTA, Task 1, Task 2 and Task 3 will be used in determining the flaw sizes to use in the damage-tolerant coupon tests.

Existing data of the material system and design may be used to reduce the number of required tests with the approval of the FCM.

8.2.4 Damage-Tolerant Development Tests

The damage-tolerant development test will be administered on structural elements representative of the flight design with induced flaws compatible with the DTA and planned NDE including special visual inspection.

All salient features of the flight design including material, lay-up and configuration will be included in the tests. The tests will include residual strength tests and life tests under spectrum loading.

Tests will generally be conducted on full-scale parts, components, and subassemblies, however, subscale tests may be used when they will suffice for a specific demonstration or provide the desired design guidance.

8.2.5 Damage-Tolerant Full-Scale Component Tests

These are design verification tests that are conducted on full-scale, flight-like components with induced flaws.

The full-scale testing is intended to address issues of production manufacturing processes, size and scale effects and design features in the full-scale test articles.

The components to be tested will generally be subassemblies of the total flight article, however, a component could be a single part or it could be a replica of the total flight article.

Component tests will meet the following:

(a) Component boundary conditions will be adequately accounted for in the tests.

(b) The test will correspond to the temperature and environments of the flight hardware.

(c) Tests will account for material degradation over time.

(d) Induced flaws on the component will be in the worst location/orientation and compatible with the DTA and the level of NDE planned on the flight hardware.

Damage-tolerant full-scale testing requires inserting flaws during manufacture as well as inducing impact damage. In all cases, flaws will be of the worst-case, credible configuration and located in the lowest stress-margin areas.

The damage-tolerant full-scale component test program will be approved by the FCM prior to its implementation.

8.2.6 NDE

All damage-tolerant parts will be designed to provide accessibility for inspections.

The part will receive NDE immediately after manufacture to establish quality assurance of the part and post-proof NDE to screen for flaws. No detrimental flaw growth or relevant flaw initiation will be allowed.

The NDE plan of the fracture-critical composite will be presented to the FCM by the PDR or Phase I Safety Review.

Composite components and bonded hardware will receive a preflight visual close-out inspection to verify that no damage has occurred during transportation, assembly, handling, etc.

Guidance for selecting appropriate NDE methods is given in MIL-HDBK-17F, Volume 3, Section 8.3.

8.2.7 Proof-Test

Flight articles using the damage-tolerant approach to Fracture Control will be acceptance proof-tested to a minimum of 1.05 times limit load.

The test will correspond to the temperature and environments of the flight hardware.

Proof-test loads will be less than 80% of the flight article ultimate strength.

8.2.8 Load Spectrum

A load spectrum will be developed of fracture-critical composite/bonded part (or bond) for the damage-tolerant test.

All service life phases and events including fabrication, assembly, acceptance testing, ground handling, transportation, storage, launch, on-orbit, landing, maintenance, etc. will be considered in the assessment. An aborted mission and subsequent reflight will be included in the service life.

The load spectrum will include the load level and the accompanying number of cycles and duration at each level during the hardware service life.

Loads from mechanical, thermal, pressure, and atmospheric sources will be included in the spectrum as appropriate.

The loads in the load spectrum will correspond to the temperature and environments of the flight hardware.

8.2.9 Spectrum Truncation

The load spectrum may be truncated when the no-growth threshold strain level is known.

In cases where an ECF and/or an load-enhancement factor (LEF) are used with the load spectrum in a test, care will be taken to ensure that the fatigue failure mode is preserved.

Depending on the results of the coupon testing, the load spectrum may be truncated to eliminate all loads that are less than the no-growth threshold strain for life cycle testing.

8.2.10 Load-Enhancement Factor (LEF)

The LEF is a factor that is multiplied by the load level in the spectrum of a fatigue test on the coupon level testing in order to demonstrate a specified level of reliability and confidence.

A LEF sufficient to establish a 90% reliability with a 95% confidence will be applied to the load spectrum of damaged test articles.

Guidance for computing the appropriate LEF for composites is given in MIL-HDBK-17F, Volume 3, Section 7.6.3.

The LEF methodology will be reviewed and approved by the FCM.

8.2.11 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 will contain notes that identify the part as fracture-critical and specify the appropriate flaw-screening method to be used on the part or raw material.

(b) All materials used in fracture-critical parts will be traceable by certification of compliance (C of C) to material standards, an MUA, or engineering requirements stated on the drawing.

(c) The HD will include sufficient tracking to provide for Fracture Control assessment of load changes, modifications, or redesigns of the fracture-critical part. Discrepancy reviews, or

equivalent, will be conducted for anomalies that could affect part fracture characteristics and life.

(d) The load history will 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 Fracture Control Documentation

10.1 Fracture Control Summary Report (FCSR)

To certify Fracture Control compliance of hardware, the HD will prepare a FCSR on the total system for review and approval by the FCM.

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

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 will be provided in the FCSR:

(a) Identification of fracture-critical parts and low-risk fracture parts, showing the material and heat treatment used and the basis for part acceptability (i.e., damage-tolerant analysis, test, acceptable durability or insignificant fatigue loading).

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

(b) Fracture-critical parts that are limited life will be specifically identified.

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

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

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

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

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

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

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

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

(k) A summary of the configuration management (CM) system used to store records.

(l) Proof-tests, damage-tolerant tests, vibration tests, or other tests are used to justify Fracture Control compliance, the test results will be documented in the FCSR.

(m) The hardware configuration, test setup, loading schedule, and environments will be documented in the FCSR.

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

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

Angular Momentum: The momentum of a rotating component is expressed as $I\omega$, where I is the mass moment of inertia and ω is the rotational speed in radians per second.

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

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

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.

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

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

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

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

Composite 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 Overwrapped Pressure Vessel (COPV): A pressure vessel with a composite structure fully or partially encapsulating a liner. The liner serves as a fluid (gas 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-metallurgical bonds, such as sandwich structure or bonded structural fittings.

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

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

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

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

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

Environmental Correction Factor (ECF): 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.

Fail-Safe: For Fracture Control, a condition where, after failure of a single individual structural member, the remaining structure (considered unflawed) can withstand the redistributed loads with a factor of safety of 1.0 on limit load, and the failure will not release a potentially catastrophic free body.

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.

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

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-Critical: Classification that identifies a part whose failure due to the presence of flaw is a catastrophic event, and requires damage-tolerant assessment.

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

F_{ty}: A-basis material strength.

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

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

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

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

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

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

High-Momentum Rotating Machinery: For the purpose of Fracture Control, a rotating mechanical assembly that has an angular momentum greater than 136 N-m-s (100 pounds-foot-seconds) based on $I\omega$.

Impact Damage: Impact damage is used to describe 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 Size: The crack size that is assumed to exist at the beginning of a damage-tolerant analysis, as determined by NDE or proof-testing.

K_{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_c: Critical stress-intensity-factor for fracture.

K_{Ic}: Plane strain fracture toughness.

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

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

Leak-Before-Bursts (LBB): For pressurized hardware, the critical length of through-crack is at least 10 times the wall thickness 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. The methodology given in API-RP-579, Fitness-for-Service can be used for guidance in meeting the leakage requirement for LBB design.

Life Factor: See Service Life Factor.

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

Load-Enhancement Factor (LEF): A factor that will be multiplied by the load level in the load spectrum of a fatigue test in order to have the test demonstrate a specified level of reliability and confidence in composites/bonded structures. The factor is dependent upon the material/construction, the number of test articles, and the length of the tests. MIL-HDBK-17F, Volume 3, Section 7.6.3 gives an approach for calculating the LEF.

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).

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

Maximum Design Pressure (MDP): The maximum design pressure (MDP) for a pressurized system is the highest pressure defined by the maximum relief pressure, maximum regulator pressure, maximum temperature and transient pressure excursions.

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.

No-growth Threshold Strain: The largest strain level (where strain level is the maximum absolute value of strain in a load cycle) below which flaws compatible with the sizes established by NDE, special visual inspection, the damage threat assessment, or the minimum sizes imposed, do not grow in 10^6 cycles (10^8 cycles for rotating hardware) at a load ratio appropriate to the application. Thresholds will be determined on specimens with flaws for which sufficient load/cycles have been initially applied to cause flaw growth. The no-growth threshold strain is a function of the material and lay-up and will be determined from test data in the appropriate environment for the applicable orientation of strain and flaw for a particular design.

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, and eddy current.

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

Pressure Vessel: A container designed primarily for pressurized storage of gases or liquids and the following:
(a) Contains stored energy of 19,310 Joules (14,240 foot-pounds) or greater based on adiabatic expansion of a perfect gas;
or
(b) Contains a gas or liquid in excess of 151.7 kPa (22 psia) that will create a catastrophic hazard if released;
or
(c) Stores a gas that will experience an MDP greater than 689.5 kPa (100 psia).
[The definition of pressure vessels in the FCP is slightly different from the definition in AIAA S-080/81 and other industry documents].

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 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.

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

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

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

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

Safe-Life: See Damage-Tolerant.

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 a stored energy of less than 19,310 Joules (14,240 foot-pounds).

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

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

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

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.

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

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 Factor of Safety (FOS).

Yield Strength: The maximum load or stress that a structure or material can withstand without incurring yielding.

Appendix B
(Acronym /Definitions)

AIAA	American Institute of Aeronautics and Astronautics
ANSI	American National Standards Institute
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
CAI	Compression After Impact
CDR	Critical Design Review
CFS	Critical Flaw Size
CM	Configuration Management
COPV	Composite Overwrapped Pressure Vessel
DoT	Department of Transportation
DCP	Damage Control Plan
DR	Discrepancy Report
DTA	Damage Threat Assessment
EAC	Environmental Assisted Crack
ECF	Environmental Correction Factor
EVA	Extra Vehicular Activity
FCB	Fracture Control Board
FCM	Fracture Control Monitor
FCP	Fracture Control Plan
FCSR	Fracture Control Summary Report
FESRRP	Flight Equipment Safety and Reliability Review Panel (Formerly known as SMART)
FMEA/CIL	Failure Mode and Effects Analysis and Critical Items List
FOD	Foreign Object Debris
FOS	Factor of Safety
HCF	High-Cycle Fatigue
HD	Hardware Developer
HDBK	Handbook
HFC	Hazardous Fluid Container
ISS	International Space Station
JSC	Johnson Space Center
KSC	Kennedy Space Center
LBB	Leak-Before-Burst
LEF	Load-Enhancement Factor
MDP	Maximum Design Pressure
MEOP	Maximum Expected Operating Pressure
MIL-HDBK	Military Handbook
MIL-STD	Military Standard
MMOD	Micrometeoroid and Orbital Debris
MUA	Materials Usage Agreement
NASA	National Aeronautics and Space Administration
NASGRO®	NASA Crack Growth Computer Program
NDE	Non-Destructive Evaluation
NHLBB	Non-Hazardous Leak-Before-Burst
P/SRR	Project/System Requirements Review
PDR	Preliminary Design Review
PSRP	Payload Safety Review Panel

RQMT	Requirements
SAR	System Acceptance Review
S&MA	Safety and Mission Assurance
SMART	Safety and Mission Assurance Review Team
SRP	Safety Review Panel
SSP	Space Station Program
STD	Standard
TPS	Thermal Protection System
WSTF	White Sands Test Facility

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 PSRP/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 PSRP/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 PSRPISRP. 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 PSRPISRP, 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 PSRP/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

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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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