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George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM 20

MULTIPROGRAM/PROJECT COMMON-USE
DOCUMENT

Fracture Control Requirements for
Composite and Bonded Vehicle and
Payload Structures

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SIGNATURE PAGE

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FOREWORD

These requirements were developed to provide a minimum set of fracture control requirements to be used across MSFC programs in designing and assessing composite and bonded structures. The scope includes manned launch, retrieval, transfer, and landing vehicles, space habitats, and payloads or experiments that are launched, retrieved, stored, or operated during any portion of a manned spaceflight mission. It is applicable to in-house and contract activities.

These requirements have been developed under the auspices of the MSFC Fracture Control Board.

Requests for information, corrections, or additions to these requirements should be directed to the Damage Tolerance Assessment Branch, EM20, George C. Marshall Space Flight Center, AL 35812.

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1. SCOPE

1.1 Scope

This document provides the fracture control requirements for composite and bonded structures used in the construction of MSFC manned vehicle and payload hardware. The scope includes manned launch, retrieval, transfer, and landing vehicles, space habitats, and payloads or experiments that are launched, retrieved, stored, or operated during any portion of a manned spaceflight mission.

Fiber reinforced polymer matrix composites, sandwich construction (bonded metallic and nonmetallic), and bonds between metallic or composite parts fall within the scope of this document.

Metal and ceramic matrix structures, foam, flexible inflatable structures, liquid-fueled rocket engines, and solid propellants are specifically excluded. Also, fracture control of metallic parts/structures are not specifically covered by this document, but where metallics are used in conjunction with composites or bonds, all the provisions of this document shall be met.

1.2 Purpose

The purpose of this document is to provide a minimum set of fracture control requirements to be used in designing and assessing composite and bonded structures.

1.3 Applicability

This document applies to in-house and contract activities and should be cited in program and contract documents as a technical requirement. All prime contractors and subcontractors performing activities to the requirements of this document shall be on-site audited and approved by NASA as to their quality management system and process controls as specified herein. With the prior approval of the MSFC Fracture Control Board (FCB), individual provisions of this document may be tailored based on application specific experience and sufficient technical rationale.

This document is applicable to all new, used, or repaired flight hardware that is within its scope.

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2. APPLICABLE DOCUMENTS

2.1 General

The applicable documents cited in this document are listed in this section; however, the specified technical requirements listed in the body of this document must be met whether or not the source document is listed in this section.

2.2 Government Documents

2.2.1 Specifications, Standards, and Handbooks

The following specifications, standards, and handbooks form a part of this document to the extent specified herein.

DEPARTMENT OF DEFENSE

MIL-HDBK-17F

Composite Materials Handbook

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA-STD-5007

General Fracture Control Requirements for Manned Spaceflight Systems

NASA-STD-5003

Fracture Control Requirements for Payloads Using the Space Shuttle

NASA-HDBK-5010

Fracture Control Implementation Handbook for Payloads, Experiments, and Similar Hardware

NASA-STD-5001

Structural Design and Test Factors of Safety for Spaceflight Hardware

MWI 8071.1

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(Copies of the above handbooks and standards are available and may be downloaded, free-of-charge from the NASA Technical Standards website: <http://standards.nasa.gov>. The MSFC Work Instruction is available from the MSFC Integrated Document Library at the Inside Marshall website: <http://inside.msfc.nasa.gov/>.)

2.3 Non-Government Publications

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The following documents form a part of this document to the extent specified herein.

American National Standards Institute/
American Institute of Aeronautics and Astronautics

ANSI/AIAA S-081-2000 *Space Systems – Composite Overwrapped Pressure Vessels (COPVs)*

Society of Automotive Engineers

SAE-ARP-5089 *Composite Repair NDI and NDT Handbook*

Aerospace Industries Association of America

NAS 410 *NAS Certification & Qualification of Nondestructive Test Personnel*

(Copies of the above documents are available and may be downloaded, free-of-charge from the NASA Technical Standards website: <http://standards.nasa.gov>)

2.4 Order of Precedence

Where this document is adopted or imposed by contract on a program or project, the technical requirements of this document take precedence, in the case of conflict, over the technical requirements cited in other applicable documents.

3. DEFINITIONS AND ACRONYMS

3.1 Definitions

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.

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 NSTS or Space Station.

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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. An assembled set of individual parts that comprise a unit that is generally a subassembly of the totally completed article.

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 or may not carry substantive pressure loads. The composite generally carries pressure and environmental loads.

Composite Structure. A structure assembled with parts made from composite materials.

Contained Part. A part for which a suitable housing, container, barrier, restraint, etc., prevents it or pieces thereof from becoming free bodies outside the enclosure if the part or its supports fail. Contained parts are non-fracture critical and must meet the requirements of Section 5.2.3.

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.

Damage. See **Flaw** and **Impact Damage**.

Damage Tolerant Part. A fracture critical part for which it is shown by test that flaws will not cause failure (leak or instability) within four lifetimes. Damage tolerant parts must meet the requirements of Section 5.3.2.

Design Ultimate Load (DUL). Limit load multiplied by the ultimate factor of safety.

Design Limit Load (DLL). See **Limit Load**.

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

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Fail Safe Part or Bond. A part or bond where there is sufficient structural redundancy in the system to safely carry the redistributed loads if the part or bond should fail. Fail safe parts are non-fracture critical and must meet the requirements of Section 5.2.2.

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-Like Component. A component assembled and made of parts that are of flight specifications. Flight like components are usually intended for damage tolerant tests. Any deviations from flight must be insignificant with respect to test objectives.

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

Fracture Control Board (FCB). A formally appointed multi-discipline group of experts that has the authority to develop, interpret, and approve fracture control requirements and the responsibility for overseeing and approving the technical adequacy of all fracture control activities at MSFC.

Fracture Critical Part (Bond). A part (or bond) whose failure due to the presence of a flaw would result in a catastrophic hazard.

Habitable Modules. Flight containers/chambers designed for life support of personnel.

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

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 has stored energy of less than 14,240 foot-pounds (19,310 Joules) with an internal pressure of less than 100 psia (689.5 kPa).

Health Monitoring. The monitoring of the structural integrity of hardware through diagnostic sensors and other instrumentation that automatically detect flaw initiation or growth (including

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impact damage) and communicate these detections directly to hardware operators and/or to automated data processing equipment.

High Energy Rotating Machinery. For the purpose of fracture control, a rotating mechanical assembly that has a kinetic energy of 14,240 foot-pounds (19,310 Joules) 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 100 pounds-foot-seconds (136 N-m-s) based on $I\omega$.

$\frac{1}{2} I\omega^2$. See **Rotational Energy**.

$I\omega$. See **Angular Momentum**.

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).

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

Lifetime. See **Service Life**.

Limit Load. Maximum expected load on a structure during its service life. Limit load and design limit load are equivalent.

Load Enhancement Factor (LEF). A factor that must be multiplied by the load level in the load spectrum of a fatigue test(s) in order to have the test(s) demonstrate a specified level of reliability and confidence. 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.

Material Usage Agreement (MUA). A formal document, approved by MSFC, showing that a non-compliant material or process is acceptable for the specific application identified.

Maximum Design Pressure (MDP). The highest pressure defined by maximum relief pressure, maximum regulator pressure, or maximum temperature. Transient pressures must be considered. Where pressure regulators, relief devices, and/or a thermal control system (e.g., heaters) are used to control pressure, collectively they must be two-fault tolerant from causing the pressure to exceed the MDP of the system. When determining MDP the maximum temperature to be

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experienced during an abort to a site without cooling facilities must also be considered. When designing, analyzing, or testing pressurized hardware, loads other than pressure that are present shall be considered and added to the MDP loads as appropriate. MDP in this document is to be interpreted as including the effects of these combined loads when the non-pressure loads are significant.

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

Must Work Function. See **Safety Critical Function**.

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 shall 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 layup and must be determined from test data in the appropriate environment for the applicable (or worst) orientation of strain and flaw for a particular design.

Nondestructive Evaluation (NDE). Examination of parts or components for flaws using established and standardized inspection techniques that are harmless to the hardware.

Non-Hazardous Leak Before Burst (NHLBB). A fracture control concept that requires that a container with a specified through flaw will leak at the flaw rather than catastrophically burst when the MDP is applied and also requires that the leak itself will not cause a catastrophic hazard. NHLBB is a non-fracture critical *classification* for containers, lines, etc., that meet Section 5.2.5. NHLBB is a *characteristic* of pressure vessels (excluding COPVs) that meet items 2 through 11 of Section 5.2.5.

Part. Hardware item considered a single entity for the purpose of fracture control.

Pressure Vessel. A container designed primarily for pressurized storage of gases or liquids, and:

1. Stores energy of 14,240 foot-pounds (19,310 Joules), or greater, based on the adiabatic expansion of a perfect gas, or:
2. Holds a gas or liquid at an MDP in excess of 15 psia (103.4 kPa) that will create a hazard (catastrophic) if released, or:
3. Has an MDP greater than 100 psia (689.5 kPa).

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

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

Proof Test. A load or pressure in excess of limit load or MDP which is applied to verify structural acceptability.

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

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

R Ratio. The ratio of minimum load to maximum load during a cycle of constant amplitude loading.

Safety Critical Function. The function of a single device, part, or mechanism whose loss would be a catastrophic hazard. Safety critical function is sometimes referred to as a *must work function*.

Sealed Container. Any single, independent (not part of a pressurized system) container, equipment, or housing that is sealed to maintain an internal non-hazardous environment and that has a stored energy of less than 14,240 foot-pounds (19,310 Joules) and an internal pressure of less than 100 psia (689.5 kPa). Sealed containers generally contain approximately 15 psia internal pressure or less.

Service Life. Service interval for hardware beginning with manufacture and extending through its planned and specified usage. All loadings and environments encountered during this period shall be addressed in the load spectrum, Section 6.3. A *service life* is also referred to as a *lifetime*.

Service Life Factor. The factor on service life required in fracture control life analysis and damage tolerant test. A minimum service life factor of four (4) is required. The *service life factor* is often referred to as the *life factor*.

Special Visual Inspection. See Section 6.1.2.

Spectrum Truncation. Deletion of cycles in a load spectrum that are below the no-growth threshold strain. See Section 6.3.

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Ultimate Factor of Safety. A specified factor to be applied to limit load. There shall be no ultimate structural failure for a load equal to the ultimate factor of safety multiplied times limit load.

Ultimate Strength. The strength determined by the A Basis statistical value as defined in MIL-HDBK-17F.

Walk Around Inspection. See Section 6.1.1.

3.2 Acronyms

AIAA	American Institute of Aeronautics and Astronautics
ANSI	American National Standards Institute
CAI	Compression After Impact
COPV	Composite Overwrapped Pressure Vessel
DTA	Damage Threat Assessment
DLL	Design Limit Load
DUL	Design Ultimate Load
ECF	Environmental Correction Factor
FCB	Fracture Control Board
FCP	Fracture Control Plan
FOD	Foreign Object Debris
IDPP	Impact Damage Protection Plan
ISS	International Space Station
LEF	Load Enhancement Factor
MIL-HDBK	Military Handbook

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MDP	Maximum Design Pressure
MRB	Material Review Board
MSFC	Marshall Space Flight Center
MUA	Material Usage Agreement
NASA	National Aeronautics and Space Administration
NHLBB	Non-Hazardous Leak Before Burst
NDE	Nondestructive Evaluation
NSTS	National Space Transportation System
SAE	Society of Automotive Engineers

4. INTRODUCTION

4.1 Background

The top level NASA fracture control requirements document, NASA-STD-5007, imposes fracture control on all manned spaceflight systems and all payloads on manned spaceflight systems. NASA-STD-5003 imposes fracture control on Space Shuttle payloads. The intent of fracture control in both these documents is to prevent a catastrophic failure/event due to the presence of cracks or flaws (see their Sections 1. and 1.2 respectively). Both of these documents address composites (and bonds). NASA-STD-5007 provides the top level requirement that composites be addressed, but doesn't develop detailed requirements for them. NASA-STD-5003 provides additional lower level requirements, but is silent on many important issues. This document provides the level of detail necessary to be responsive to NASA-STD-5007 and covers a broader scope of hardware than does NASA-STD-5003.

NASA fracture control requirements use the notion of a fracture critical part as being one whose failure due to the presence of a flaw could be catastrophic for the crew or vehicle. They include the following definitions of fracture critical parts:

NASA STD-5007 (Section 1.2)

"Parts are Fracture Critical if it is credible that cracks in the part could lead to a catastrophic failure. For composite materials, the term crack also includes

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delaminations, defects due to manufacturing, impact damage, and in-service damage.”

NASA-STD-5003 (Definitions, Section 3.12)

“Classification which assumes that fracture or failure of the part resulting from the occurrence of a crack will result in a catastrophic hazard as defined in NSTS 1700.7. Such classification is required unless the contrary is demonstrated using the criteria of 4.2.2.”

Both definitions are essentially the same with the theme that a part is fracture critical if structural failure due to a flaw will set up the potential for a catastrophic failure or event.

Fracture control is required to facilitate safety involving manned spaceflight. Its imposition on other hardware is optional for each program but may be warranted in other situations. NASA-STD-5007, Section 1.1 states:

“These requirements are not imposed on systems other than manned spaceflight but may be tailored for use in specific cases where it is prudent to do so such as for personnel safety or when national assets are at risk.”

4.2 Current Document

This document provides specific requirements for composite material applications as defined in Sections 1.1 and 1.3. Composite and bonded structures meeting the requirements herein satisfy all MSFC fracture control requirements and specifically those of NASA-STD-5007 and NASA-STD-5003.

A complete set of definitions is provided in Section 3.1, but the following terminology regarding flaw, damage, impact damage, and fracture critical is highlighted here for readily understanding their definition and usage in this document.

Flaw and damage are used interchangeably and are equivalent. Impact damage is a specific type of flaw. Treating damage and flaw as equivalent is consistent with NASA-STD-5007 and NASA-HDBK-5010 which treat damage tolerant and safe life (traditionally associated with flaw) as the same concept. 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).

Fracture critical is used to indicate a part (or bond) whose failure due to a flaw would result in a catastrophic hazard.

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4.3 MSFC Fracture Control Board (FCB)

All activities regarding fracture control shall be documented and submitted to the FCB for approval (see Section 7 for documentation requirements). A government project specific engineer shall be responsible for coordinating the project fracture control activities with the FCB. In addition to the documentation requirements listed in Section 7, hardware developers/projects shall make presentations to the FCB upon request.

4.4 Fracture Control Plan

A fracture control program shall be implemented through a Fracture Control Plan (FCP). The FCP shall provide project specific activities and responsibilities for carrying out fracture control per the requirements of this document for each separate hardware project within a program. The Plan shall be approved by the FCB and for Shuttle payloads submitted to the Payload Safety Review Panel (PSRP) at the Phase 1 Safety Review.

4.5 Process Controls

Composite hardware and bonds are highly susceptible to process variations; therefore they shall be manufactured and verified to high quality control standards to assure aerospace quality hardware. The hardware developer shall use only manufacturing processes and controls (coupon tests, sampling techniques, etc.) that are demonstrated to be reliable and consistent with established aerospace industry practices for composite/bonded structures. The hardware developer shall enforce a rigorous program to control contamination and foreign object debris (FOD) during processing. Chemical contamination may weaken the material and FOD with sharp edges may cause fiber cutting or breakage and thin FOD such as tape may create delaminations. So it is extremely important that contamination including FOD be rigorously controlled. All mechanical interfaces shall be carefully scrutinized for materials compatibility.

4.6 Other Requirements

As stated in the Scope, this document is focused on fracture control of composites and bonded joints and as such covers a limited set of requirements and is a subset of all the structural, material, design, and other verifications that must be done to qualify a composite structure or a bonded joint for flight. It is anticipated that fracture control will be accomplished in collaboration with or perhaps as part of the overall structural development and qualification process. For example, it may be advantageous to include the damage tolerant test program (Section 5.3.2) as a subset of the materials development and structural strength tests programs that would also be required for a composite vehicle or spacecraft. In any event, the fracture control program shall meet the requirements of this document.

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Nothing in this document shall be construed as requiring the duplication of effort dictated by other requirements. Conversely, requirements stated herein shall not be interpreted to preclude compliance with requirements invoked by other provisions. For example, this document levies proof test requirements in relation to fracture control of composites and bonded structures. There are other applicable proof test requirements such as those specified in NASA-STD-5001 that must also be met for structural integrity regardless of fracture control.

5. CLASSIFICATION AND DISPOSITION OF PARTS FOR FRACTURE CONTROL

All parts (and bonds) shall be evaluated for fracture criticality. Hardware is either exempt, non-fracture critical, or fracture critical. Hardware is further classified as discussed below and shown in FIGURE 1. A summary of classifications and requirements is provided in the form of a table in APPENDIX B.

5.1 Exempt Parts

Parts that are clearly non-structural and do not have a safety critical function are exempt from fracture control. Non-structural items such as insulation blankets and enclosed electrical circuit boards are generally exempt from fracture control. A (composite) thermal protection system intended to protect structural integrity required for safe flight is not exempt from fracture control and must be assessed per the requirements of this document. Exempted composite parts shall be identified to the FCB for approval and submitted with the fracture control documentation (FCP, summary and detailed assessment reports, Section 7.).

5.2 Non-Fracture Critical Parts/Bonds

Composite parts or bonds may be considered non-fracture critical if they meet one of the following classifications:

- Low released mass
- Fail safe
- Contained
- Low risk
- Non-hazardous leak before burst (NHLBB)

Requirements for each of these non-fracture critical classifications are given below.

5.2.1 Low Released Mass

Low released mass is a classification intended for “small” items whose separation from the parent structure will not cause a catastrophic hazard. Since composites are particularly susceptible to impact damage, assessment of their load carrying capability from impacts of the

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assumed released items is required. A composite part/component classified as low released mass shall meet the following:

1. Separation of part/component from the parent structure shall not cause a catastrophic hazard.
2. Part shall be located internally to the vehicle, habitat, payload, or payload bay.
3. Non-fracture critical composite structures that may be impacted shall support DUL (verified by tests) with the worst case impact damage from the released mass.
4. Fracture critical composite structures that may be impacted shall be evaluated by damage tolerant full-scale component tests (Section 5.3.2.6) to verify life and residual strength after impact. The worst case impact damage from the released mass shall be tested in addition to the other flaws listed in item 5 of Section 5.3.2.6.
5. Shuttle payload parts shall also meet the low release mass requirements of NASA-STD-5003.

Note: This document specifically addresses fracture control of composites. A “low released mass” metallic item must also meet the above requirements if it could impact composite structures.

5.2.2 Fail Safe

The fail safe classification is intended for composite parts or bonds where there is sufficient structural redundancy in the system to safely carry the redistributed loads if the part or bond should fail. Fail safe composite hardware shall be manufactured and verified to high quality control standards to assure aerospace quality hardware. This classification applies on a one-flight-at-a-time basis. In order for the classification to be extended to the next flight/mission for multi-mission hardware, fail safe items must be inspected to the extent necessary to ensure that full structural redundancy is assured. A composite part or bond classified as fail safe shall meet the following:

1. If the part or bond structurally fails (i.e. load path is severed), the remaining composite structure (bonds) shall analytically carry 1.15 times the redistributed limit load without ultimate failure. The structural models and analytical methodology used in the fail safe analysis shall be test verified for the intact configuration. This verification may occur during the proof and/or other structural testing required by the structural standard, NASA-STD-5001. Fail safe analysis of rotating machinery shall be similarly verified. (Note. If the remaining structure is metallic, it shall meet the fail safe factor requirements for metallic structures).
2. The dynamic response of structure in the “failed” configuration shall be assessed in determining the redistributed limit load.
3. Part failure shall not cause the loss of a safety critical function.
4. Failure of the part shall not generate pieces/debris that would violate the low-mass requirements above.
5. If the failed part can move, swing, etc., so that impact with remaining composite structure is credible, then one of the following shall be met:

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- If remaining impacted composite structure is non-fracture critical, then it shall support without ultimate failure, 1.15 times the redistributed limit load with the worst case impact damage from the failed part. This capability shall be verified by test.
 - If remaining impacted composite structure is fracture critical, then it shall be evaluated by damage tolerant full-scale component tests (Section 5.3.2.6) to verify life and residual strength after impact. The worst case impact damage from the failed part shall be tested in addition to the other flaws listed in item 5 of Section 5.3.2.6.
6. The composite part or bond shall receive pre and post proof NDE including special visual inspection. Note that NASA-STD-5001 requires that all composite structures be proof tested.
 7. The composite part or bond shall be addressed in Task 1 of the damage threat assessment (DTA) (See Section 5.3.2.1).
 8. The composite part or bond shall be included in the impact damage protection plan (IDPP) (See Section 5.3.2.2).
 9. For multi-mission hardware, it shall be verified before reflight that the structural redundancy of a fail-safe part is still intact. At a minimum, a special visual inspection shall be performed to verify that flaws or other structural anomalies have not occurred during use.

In conservative, multiply redundant designs where structural response is obviously not significantly altered by the loss of a load path and there is obviously sufficient strength to meet the fail safe requirements above, the hardware developer may propose accepting a part as fail safe based on engineering judgment. In these cases, the developer shall provide written technical rationale to the FCB addressing the above points and shall receive approval from the FCB prior to implementing this option.

5.2.3 Contained

The contained classification is intended for parts mounted inside enclosures that would safely contain the part in the event the part became loose within the enclosure. Some common enclosures are electronic boxes, cameras, gear boxes, and experiment housings. The user should be aware that there are safety requirements for redundancy and failure tolerance beyond fracture control for latching and relatching of enclosures with doors designed to be opened. Therefore, appropriate safety requirements should be imposed in addition to fracture control on enclosures used for containment when these enclosures have doors or similar hardware.

A. Metallic Enclosure – Composite Part

A composite part inside a metallic enclosure classified as contained shall meet the following:

1. Part shall not have a safety critical function (that would be lost if it became separated from the enclosure).

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2. The assumed loose part shall not cause any other part within the enclosure to lose a safety critical function.
3. Part shall be larger than openings or holes in the enclosure.
4. Loose part shall not penetrate or fracture the enclosure with a factor of safety of 1.0 on tensile yield strength as used in the punch equation or otherwise yield or deform the enclosure so that part escapes.
5. Containment shall be demonstrated by analysis or test.

B. Composite Enclosure – Metallic or Composite Part

A metallic or composite part inside a composite enclosure classified as contained shall meet the following:

1. Part shall not have a safety critical function (that would be lost if it became separated from the enclosure).
2. The assumed loose part shall not cause any other part within the enclosure to lose a safety critical function.
3. Part shall be larger than openings or holes in the enclosure.
4. The enclosure shall not be fracture critical for some other reason such as providing a single point failure support that would result in a catastrophic hazard if the enclosure failed.
5. It shall be shown by test (or analysis supported by test) using a factor of 1.15 on impact load (or 1.32 on impact energy) that the loose part does not penetrate, fracture, or otherwise escape the enclosure.
6. The enclosure shall support DUL (verified by test) with the worst case of the following impact damage:
 - The impact flaw size detectable by the planned NDE, or
 - The impact damage from the loose part, or
 - That identified by the DTA, or
 - That caused by a 1.0 inch diameter impactor @ 100 ft-lbs of kinetic energy or a dent 0.10 inch deep, whichever is smaller. If this required minimum flaw/impact damage size is inappropriate for the application, the developer may propose other sizes along with supporting rationale to the FCB for consideration.
7. Enclosure shall receive pre and post proof NDE including special visual.
8. Enclosure shall be addressed in Tasks 1 and 2 of the DTA.
9. Enclosure shall be included in the IDPP. It is not necessary to protect against impacts from the assumed loose parts within the enclosure in the IDPP.
10. Pressurized enclosures shall have the *characteristic* of being NHLBB (Section 5.2.5).
11. For multi-mission hardware, it shall be verified before reflight that the enclosure is still structurally sound. At a minimum, a special visual inspection shall be performed to verify that flaws or other structural anomalies have not occurred during use.

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In conservative designs where the enclosure obviously has sufficient strength to meet the containment requirements above, the hardware developer may propose accepting a part as contained based on engineering judgment. In these cases, the developer shall provide written technical rationale to the FCB addressing the above points and shall receive approval from the FCB prior to implementing this option.

5.2.4 Low Risk

The low risk classification is intended for parts (bonds) that are lightly loaded and meet a set of rigorous controls that assure structural integrity thereby resulting in “low” (acceptable) risk of catastrophic failure due the presence of flaws. A composite part (bond) classified as low risk shall meet the following:

1. Part shall not be a pressure vessel, high energy rotating machinery, high momentum rotating machinery, habitable module, single point failure bond, and shall not contain a hazardous fluid.
2. Part shall be covered by a DTA (Tasks 1, 2 and 3. Task 2 is required to the extent needed to establish the impact damage size used in items 3 and 5 below. Task 3 is required to the extent needed to determine the no-growth threshold strain in item 3 below).
3. Part limit strain shall be below the no-growth threshold strain.
4. Part shall be inspected pre and post proof (NDE and special visual) for flaws.
5. Part residual strength shall meet DUL (verified by test) with the worst case of the following impact damage:
 - The impact flaw size detectable by the planned NDE, or
 - That identified by the DTA, or
 - That caused by a 1.0 inch diameter impactor @ 100 ft-lbs of kinetic energy or a dent 0.10 inch deep, whichever is smaller. If this required minimum flaw/impact damage size is inappropriate for the application, the developer may propose other sizes along with supporting rationale to the FCB for consideration.
6. Part shall be covered by an IDPP.
7. For multi-mission hardware, it shall be verified before reflight that the Part is still structurally sound. At a minimum, a special visual inspection shall be performed to verify that flaws or other structural anomalies have not occurred during use.

5.2.5 Non-Hazardous Leak Before Burst

This classification is intended for composite walls of sealed containers or other non-hazardous fluid containers, trapped volumes, lines, or other pressurized components that hold or transfer fluid under pressure and would leak down rather than burst at the MDP and specified through flaw sizes. For this condition to apply, the pressure container must have a capacity to leak

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sufficiently at the specified flaws to relieve the pressure load before burst. Coatings or other items must not prevent leakage at the flaw. A container that can sustain a leak before rupture is inherently safer than one that cannot; therefore a NHLBB design is generally preferred. Pressure containing walls classified as NHLBB shall meet the following:

1. The container shall not be a pressure vessel.
2. The walls shall not be fracture critical for some other reason such as providing a single point failure support that would result in a catastrophic hazard if the wall failed.
3. Release of fluid shall not cause a catastrophic hazard.
4. Walls shall be covered by a DTA (Tasks 1 and 2. Task 2 is required to the extent needed to establish the impact damage size used in item 7 below).
5. Walls shall leak at or below MDP (verified by test in the appropriate environment) at the flaw size used in verifying item 6 below.
6. Walls shall not burst nor shall there be any flaw growth at MDP x the ultimate safety factor (verified by test in the appropriate environment) with a through flaw length that is the maximum of:
 - 10 x the wall thickness, or
 - 1.0 inch (25.4 millimeters)
7. Walls shall support MDP x ultimate safety factor (verified by test) with impact damage that is the maximum of:
 - The impact flaw size detectable by the planned NDE, or
 - That identified by the DTA, or
 - That caused by a 1.0 inch diameter impactor @ 100 ft-lbs of kinetic energy or a dent 0.10 inch deep, whichever is smaller. If this required minimum flaw/impact damage size is inappropriate for the application, the developer may propose other sizes along with supporting rationale to the FCB for consideration.
8. There shall be no repressurization as the pressure leaks down. If the Project wants to use the container while it is leaking, the developer must provide an assessment to show that no catastrophic hazard will result from container usage while it leaks down.
9. Walls shall receive pre and post proof NDE including special visual. Note that NASA-STD-5001 requires that all composite structures be proof tested.
10. Walls shall be covered by an IDPP.
11. For multi-mission hardware, it shall be verified before reflight that the container is still structurally sound. At a minimum, a special visual inspection shall be performed to verify that flaws or other structural anomalies have not occurred during use.

For overwrapped pressurized hardware that is not a pressure vessel to be classified as NHLBB, the composite overwrap shall meet this Section. Metallic liners for this type hardware shall meet the NHLBB requirements of NASA-STD-5003. NASA-HDBK-5010 provides an acceptable method to assess metallic hardware for NHLBB.

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Note that composite pressure vessels (excluding COPVs) that meet items 2 through 11 above are said to have the *characteristic* of being NHLBB. Pressure vessels are always considered fracture critical.

5.3 Fracture Critical Parts/Bonds

Parts (bonds) are fracture critical if their failure due to the presence of a flaw could cause a catastrophic hazard. Due to the potential for catastrophe, the following are always considered fracture critical:

- Pressure vessels
- High energy rotating machinery
- High momentum rotating machinery (where credible rotor sudden stop jamming events exist due to structural failure from flaws in the mechanical assembly. See NASA-HDBK-5010, Appendix. K)
- Hazardous fluid containers
- Lines, ducts and fittings with hazardous fluid
- Habitable modules
- Solid rocket motor cases
- Propellant tanks

Other parts are fracture critical by default unless they are exempt or there is a non-fracture critical classification (Section 5.2) they are shown to fit.

Fracture critical composite parts (and bonds) shall be shown acceptable by one of the following:

- Proof test (limited applications), or a
- Damage tolerant approach (preferred)

The damage tolerant approach is the preferred approach and it is always acceptable to use a damage tolerant program to process fracture critical parts. With the prior approval of the FCB, proof test may be used in limited applications as stated below.

5.3.1 Proof Test Approach for Accepting Fracture Critical Parts

Proof test is a classification available on a limited use basis. Hardware developers who want to use this classification shall work with the FCB early in the program to evolve an approved approach. The proof test classification shall generally be limited to payload structures. These structures shall have well defined load paths, loads, and boundary conditions. The proof test shall adequately load all appropriate members and sections of the structure. In cases where shear and/or compression dominate, proof test may not be appropriate due to delamination growth under these load conditions. When it is deemed that proof test is an acceptable fracture control approach and approval of the FCB has been obtained, the proof test approach shall include the following steps:

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1. The flight article shall be proof tested to 1.2 x limit load. The proof test shall be conducted in the appropriate environment or test loads shall be adjusted using a test verified environmental correction factor (ECF).
2. Flight article shall receive pre and post proof NDE including special visual inspection.
3. Flight article shall be subjected to a DTA (Task 1)
4. Flight article shall follow an IDPP
5. Multi-mission hardware shall be reproofed between flights and receive pre and post proof NDE as well as special visual inspection.

Detected flaws shall be repaired (or assessed) using conservative techniques and procedures and submitted to the FCB for approval. No flaw growth (or initiation) is allowed at any of the NDE steps. Repairs shall receive NDE, be proofed to 1.2, and then receive post proof NDE.

It is required that the proof test loads be less than 80 percent of ultimate strength of the structure for the appropriate mode of failure (i.e., tension, compression, shear). Structures proof tested must be designed with a sufficient ultimate factor of safety to meet the 80 percent requirement. Structures with an ultimate safety factor of 1.5 or greater will meet the 80 percent requirement, therefore hardware developers should plan accordingly. If the developer deems it advantageous to the government to proof test beyond the 80 percent requirement, supporting rationale based on application specific experience shall be submitted to the FCB for consideration. This submittal shall be made to the FCB early in the program when developing an approved proof test approach.

It is likely that composite hardware will include some metallic parts, particularly fasteners. The structure must be designed so that detrimental yielding of the metallic parts does not occur during the proof test.

5.3.2 Damage Tolerant Approach for Accepting Fracture Critical Parts

The development and adaptation of a damage tolerant approach to specific hardware requires close coordination with the FCB. The approach shall be described in the FCP in specific hardware terms. The FCP shall be submitted to the FCB and Board approval shall be obtained by the hardware developer prior to FCP implementation.

The damage tolerant approach described in this Section is intended to be applicable to composite structures and to bonded joints (metallic to metallic, composite to composite, and metallic to composite). In the event the required steps listed in this section cannot be accomplished for a specific structure or joint, the developer may propose alternate steps. The alternate steps shall establish equivalent confidence in the structure or joint damage tolerance as the steps listed here. The developer shall identify such cases early in the program and shall submit the proposed alternate steps to the FCB for approval along with supporting rationale. The alternate steps shall

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be based on application specific experience and shall be test-based. Once the developer has obtained the approval of the FCB, the alternate steps shall be included in the FCP.

Fracture control of composite structures using the damage tolerant approach shall meet the steps listed below. Note that the damage tolerant approach does include a proof/acceptance test of the flight article. The steps given here are the minimum required.

1. Damage threat assessment
2. Impact damage protection plan
3. Damage tolerant coupon tests
4. Damage tolerant development tests
5. Analytical support
6. Damage tolerant full-scale component tests
7. Implement impact damage protection plan
8. NDE parts
9. Proof test to 1.05 minimum
10. Post proof NDE
11. In-service inspection

The steps given above are shown on the flow diagram in FIGURE 2 and discussed in the following sections. Additional hardware specific requirements are given in Appendix A.

5.3.2.1 Damage Threat Assessment (DTA)

The primary purpose of the DTA is to define and quantify flaws for testing in the damage tolerant approach. Flaws from impact damage and initial manufacturing imperfections shall be included in the DTA. Results from the DTA serve as inputs to the Impact Damage Protection Plan (IDPP) (Section 5.3.2.2) and the damage tolerant tests; coupon, development, and full scale component (Sections 5.3.2.3, 5.3.2.4, and 5.3.2.6). The DTA consist of three tasks as described below. As shown in TABLE I, some tasks are also required for parts other than those classified as damage tolerant. All composite structures, except those that are exempt from fracture control or those classified as low released mass or contained, shall be addressed by the DTA as indicated in TABLE I.

TABLE I. DTA Tasks Required¹

Part	Task 1	Task 2	Task 3
Damage tolerant	X	X	X
Other Parts:			
Fail safe	X		

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Composite containment enclosure	X	X ²	
Low risk	X	X ²	X ²
NHLBB container	X	X ²	
Proof tested	X		

Notes:

1. X = Task required.
2. Required to extent specified in the respective sections of this document.

In developing the DTA, all hardware phases shall be considered including manufacturing, handling, test, storage, transportation, and in-service use and maintenance. The DTA includes the following three tasks:

1. Identify the source and type of impact damage that poses a credible threat to the hardware.
2. Characterize the impact damage size and energy level to be considered in the damage tolerant coupon tests, damage tolerant development tests, and damage tolerant full-scale component tests.
3. Generate an as-manufactured initial flaw type and size assessment for the hardware.

Task 1. All events and credible possibilities shall be considered for the specific hardware under consideration when identifying the potential impact damage. These events would include but not be limited to incidents such as tool drops, runway debris, hail, and bumping during handling. It should be noted that for relatively large structures, placement of the structure onto storage supports or cradles can result in significant impact damage. The impact damage sources identified shall be used as input to Task 2 and the impact damage protection plan (Section 5.3.2.2).

Task 2. The impact damage size and energy level shall be characterized for the specific hardware application. The impact damage size range shall be determined as a function of impact energy and impacting object profile (FIGURE 3). This characterization shall be done based on impact test results of the specific material, layups, and representative designs using the identified impact damage sources from Task 1. Also, impacts that could occur from; low released mass parts, failed fail safe parts, and loose parts within composite containment enclosures shall be included in this characterization. The derived characteristic impact damage sizes (and energy levels) shall be used as input to the damage tolerant coupon, damage tolerant development, and damage tolerant full-scale component tests.

Task 3. The material, design configuration, and processing shall be evaluated to determine the types and estimate the size of initial flaws that it is reasonable to expect in the as-manufactured hardware. Cuts, surface scratches, porosity/voids, delaminations, disbonds, wrinkles, and cracking shall be considered in this assessment as well as the potential existence of contamination and FOD. Each specific hardware developer shall tailor this list (by additions and/or deletions) to define a credible set of flaw types to be included in the damage tolerant tests

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(coupon, development, and full-scale). This tailored set of flaws shall be arrived at by considering the likelihood of their occurrence in the hardware and their potential to adversely affect strength or life. Approval of the tailored flaw list shall be obtained from the FCB prior to proceeding into the damage tolerant tests. (Note: *All* flaws detected on the flight hardware shall be processed as manufacturing anomalies and worked as MRB actions). The flaw tailoring activity shall rely heavily on experience and lessons learned and should involve experienced personnel from all appropriate disciplines. The results of this collaborative activity shall be summarized in an as-manufactured initial flaw assessment and be included in the damage threat assessment documentation.

5.3.2.2 Impact Damage Protection Plan (IDPP)

An IDPP shall be done for all composite structures except those that are exempt from fracture control or those classified as low released mass or contained. Specifically, an IDPP shall be done for all the parts listed in TABLE I for which Task 1 is required. The DTA (Task 1) shall serve as input to the IDPP and the IDPP shall be compatible with the DTA. The IDPP shall address each threat identified in the DTA and provide a method for protecting the flight hardware from the threat. Protection devices may include covers, blankets, sacrificial composite layers, shipping containers, etc. 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 approval of the FCB. It is not required that protection be provided from the assumed impacts of parts classified as low released mass or fail safe (Sections 5.2.1, Items 3 and 4, and Section 5.2.2, Item 5).

It should be noted that implementation of an IDPP is required to *mitigate* risk associated with impact damage to the hardware. This risk can never be totally eliminated since the hardware must be handled during manufacture, inspection, test, shipping, use, maintenance, etc. The potential for impact is always present, even when protective covers are used, the hardware could be impacted during cover installation. Therefore, implementation of an IDPP doesn't completely eliminate risk and impact damage must always be addressed in the damage tolerant tests (coupon, development, and full-scale component).

5.3.2.3 Damage Tolerant Coupon Tests

Tests on coupons representative of the flight material and layup and with flaws shall be run to generate a family of life and residual strength curves (FIGURE 4). The test data shall be generated for the applicable environments. These curves shall be used in conjunction with damage tolerant development tests and analytical support to design the hardware (and to support hardware processing) so that it will meet the damage tolerant full-scale component tests and flight requirements (FIGURE 2). The residual strength tests shall be based on compression and for impact damage, compression after impact (CAI). State-of-the-art methods shall be used to define the test program so as to minimize the tests necessary to develop a reliable family of

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curves. Coupon tests shall also be used to establish a no-growth threshold strain if low risk classifications are used. With the approval of the FCB, existing data that is directly applicable to the material system and design may be used to reduce the number of required tests provided sufficient tests are done to confirm that the existing data are indeed applicable. Coupon tests must be designed so that the mode of failure in the coupon and in the hardware is compatible, for example, coupons should be designed so that edge effects that are not present in the actual hardware do not invalidate the coupon test results.

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

The range of impact damage sizes (and energies) to be considered in the damage tolerant coupon tests are those determined in Task 2 of the DTA. This range shall cover an impact damage size at least as severe as the smaller of a 0.10 inch deep dent or that caused by a 1.0 inch diameter impactor @ 100 ft-lbs of kinetic energy. If this required minimum flaw/impact damage size is inappropriate for the application, the developer may propose another size along with supporting rationale to the FCB for consideration.

The types of flaws and the range of initial flaw sizes to be assessed in the damage tolerant coupon tests shall be determined using the DTA Task 3 as-manufactured initial flaw assessment and the sensitivity level of NDE planned for the hardware. Characteristic initial flaw sizes used in the damage tolerant coupon test shall include at least those in the range from 75% to 3 times the level (flaw size) of the NDE planned. This range shall be adjusted as deemed appropriate based on the DTA Task 3 input. For example, if the DTA Task 3 activity suggests that flaws larger than the 3 X NDE are likely, it would be appropriate that the range be expanded accordingly.

Development of the damage tolerant coupon test program requires close coordination with the FCB and shall be approved by the FCB prior to its implementation.

5.3.2.4 Damage Tolerant Development Tests

Damage tolerant development tests shall be run to evaluate and guide the design as well as assist in anomaly resolution. These tests shall be run on structural elements representative of the flight design with induced flaws compatible with the DTA and planned NDE including special visual inspection. Tests shall include residual strength tests and life tests under spectrum loading. All salient features of the flight design including material, layup and configuration shall be included in the tests. Tests shall 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. A sufficient number and types (strength, life, and design configuration) of tests shall be run to develop confidence that the damage tolerant full-scale component tests will be successful.

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The evolution of the damage tolerant development test program requires close coordination with the FCB and shall be approved by the FCB prior to its implementation.

5.3.2.5 Analytical Support

The damage tolerant verification of composite structures shall be done by full-scale component tests; however, state-of-the-art analytical methods are encouraged where appropriate to assist in assessing the design, defining the tests, establishing inspection criteria, etc. Analytical methods shall be correlated with test results. Some acceptable analytical methods are given in Volume 3 of MIL-HDBK-17F. Analysis methods must be presented to the FCB for approval.

5.3.2.6 Damage Tolerant Full-Scale Component Tests

These are design verification tests that are conducted on full-scale, flight-like components with induced flaws. They are required for all fracture critical structures dispositioned as damage tolerant. 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. Only one component test article of each type identified is required to be tested except as noted in Appendix A. A component may (will likely) include more than one fracture critical part. Each fracture critical part in a component shall be damage tolerant tested. With the approval of the FCB, fracture critical parts of similar design may be accepted by similarity, i.e., only one of the similar fracture critical parts need have flaws imposed during the component test. Parts with different designs may be tested concurrently during a single component test run provided the proper load conditions/environments are applied or enveloped. Otherwise, parts shall be tested in sequential component test runs. Several component test runs may be required to test all fracture critical parts in a component. When sequential tests are required, a part may be refurbished/replaced between tests to prevent failure in subsequent tests unless the sequential test in question is required to verify that part. Component tests shall meet the following:

1. Component boundary conditions shall be adequately accounted for in the tests. (Simulators representing other interfacing structures may be required).
2. Tests shall be conducted in the appropriate environment (or a test verified environmental correction factor (ECF) shall be used).
3. Tests shall account for material degradation over time.
4. Induced flaws shall be in the worst (credible) location and orientation.
5. Induced flaw types and flaw sizes shall be compatible with the DTA and the level of NDE planned on the flight hardware (including special visual). Impact damage resulting from low released mass parts (Item 4, Section 5.2.1) and failed fail safe parts (Item 5, Section 5.2.2) shall also be considered when establishing the impact damage size to test. The induced flaws shall always include impact damage. The minimum impact damage inflicted on the component shall be at least that caused by a 1.0 inch diameter impactor @ 100 ft-lbs of kinetic energy or a dent 0.10 inch

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deep, whichever is smaller. If this required minimum flaw/impact damage size is inappropriate for the application, the developer may propose other sizes along with supporting rationale to the FCB for consideration.

6. Component shall receive full NDE (including special visual) prior to test. *All* detected flaws (and types), not just those induced, shall be documented and tracked at other NDE points throughout the tests. With the approval of the FCB, the developer may choose to repair non-induced detected flaws prior to initial test.
7. Component shall be cyclic load tested for four (4) lifetimes per the component load spectrum (Section 6.3; see also FIGURE 5 for a test load and NDE schedule).
 - a. Generally, loading events within a lifetime should be applied in the test spectrum in the same sequence in which they occur in actual life.
 - b. Spectrum loads shall include a LEF. The LEF and rationale shall be submitted to the FCB for approval.
 - c. Following the initial full NDE, component shall be cyclic load tested for one lifetime.
 - d. Component shall receive full NDE (including special visual) at the end of one lifetime. Again, all flaws shall be documented and compared to the previous documentation. No flaw growth of the previously documented flaws (step 6) or the initiation of new flaws is allowed.
 - e. Component shall be tested for residual strength to DUL (or other level approved by the FCB and based on technical rationale supported by application specific experience) following NDE at the end of one lifetime.
 - f. Component shall receive full NDE (including special visual) following the DUL test. Again, all flaws shall be documented and compared to the previous documentations. No flaw growth of the previously documented flaws (steps 6, and 7.d) or the initiation of new flaws is allowed.
 - g. Component shall then be cyclic tested for three more lifetimes.
 - h. Following the fourth lifetime test, the component shall receive full NDE (including special visual). All flaws shall be documented and compared to the previous documentations. Flaw growth is allowed over the last three lifetime tests, however, no initiation of new flaws is allowed during these tests.
 - i. Following the fourth full NDE, the design limit load shall be applied to the component.

No structural failures are allowed at any time during the tests. During the design limit load test, or following it if appropriate, it shall be demonstrated by test(s) that no structural or mechanical anomalies occur due to flaws that would be a catastrophic event during flight, and that the hardware will perform as structurally and mechanically intended. This demonstration shall show there is no structural failure including burst, no catastrophic leak, no catastrophic mechanical malfunctions, and that the hardware structurally and mechanically performs its design function. For example, it shall be demonstrated that a propellant tank will support MDP and other

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prevailing loads without rupture or leaking during the limit load test. Failure of any of the damage tolerant tests requires redesign.

Detailed damage tolerant full-scale component test plans shall be included in the FCP and approved by the FCB prior to testing.

5.3.2.7 Implement Impact Damage Protection Plan

The IDPP shall be implemented on the flight parts, flight components, and flight article as they are manufactured and assembled. The hardware shall be covered by the IDPP during all phases including development, tests, handling, transportation, storage, and in-service to the extent specified by the plan.

5.3.2.8 NDE Flight Parts

All damage tolerant parts shall receive NDE immediately after manufacture to establish initial integrity of the parts. These inspections shall include state-of-the-art methods including special visual inspections. The NDE method(s) chosen for a particular part shall be approved by the FCB for application on that specific part. Parts must be designed to provide accessibility for inspections. Detected flaws shall be repaired (or assessed) using conservative techniques and procedures and submitted to the FCB for approval. Repairs shall receive NDE prior to proof test.

5.3.2.9 Proof Test Flight Article

Flight articles using the damage tolerant approach to fracture control shall be acceptance proof tested to a minimum of 1.05 times limit load. Note, each project should verify if higher test factors are required for reasons other than to meet damage tolerance requirements; e.g., NASA-STD-5001 requires a test factor of 1.2 for protoflight hardware. The proof test(s) shall be done in the applicable environment or properly adjusted with a test verified ECF to account for the flight environment. Proof test loads shall be less than 80 percent of the flight article ultimate strength (See Section 5.3.1). A proof test failure requires redesign, reverification, and reproof.

5.3.2.10 Post Proof NDE of Flight Article

The flight article shall receive post proof NDE comparable to the preproof NDE. No flaw growth (or initiation) is allowed.

5.3.2.11 In-Service Inspections

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Once the hardware is put in service, it shall be periodically inspected for impact damage, flaw initiation, flaw growth, or other structural anomaly. It is imperative that hardware be designed so that it can be inspected. The following minimum in-service inspections shall be carried out.

a. Visual

(1) Walk Around

Immediately after a landing and the latest time feasible prior to launch, a walk around inspection of the hardware shall be done.

(2) Special Visual

After every third flight or other times as may be required by this document, a special visual inspection of the hardware shall take place.

b. NDE

In-service NDE shall be carried out on the hardware when there is an indication from the special visual inspection and at other times as may be specified by the program.

6. REQUIREMENTS FOR SUPPORTING (SUPPLEMENTARY) FRACTURE CONTROL ACTIVITIES

Fracture control activities are a subset of a larger set of activities that must occur in the development of composite and bonded hardware. Rigorous and thorough activities are required in:

- material evaluations and selection
- design
- analytical assessment and test for structural integrity
- manufacturing and process control
- quality assurance

MIL-HDBK-17F provides detailed discussions of the total activities required to develop composite and bonded hardware. This section provides requirements for those activities directly associated with fracture control that must occur in support of the disposition of parts as described in Section 5.

6.1 Hardware Inspections

Hardware inspections shall be carried out as specified in Section 5. This Section gives the requirements for these inspections.

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6.1.1 Walk Around Inspection

This is a visual look at the exterior of the composite hardware without removal of access panels or doors. Unaided visual looks shall be augmented with binoculars when the hardware is greater than 20 feet from the observer. Walk around inspections shall be done independently by two inspectors. Indications of impact damage (e.g., dents, fiber breakout), flaws, or other structural anomaly shall receive special visual inspection.

6.1.2 Special Visual Inspection

This is a, close proximity, intense visual examination of localized areas of internal and/or external structure for indications of impact damage, flaws, or other structural anomaly. Appropriate access to gain proximity (e.g., removal of fairings and access doors, use of ladders and work stands) is required. High intensity lighting along with other inspection aids such as mirrors, magnifying lenses (at least 10X), and surface cleaning shall be used. Special visual inspections shall be done independently by two inspectors. When special visual indications are found, NDE shall be done.

6.1.3 Non-Destructive Evaluation (NDE)

NDE for composite structures and bonds shall be accomplished using state-of-the-art methods in techniques such as ultrasonic C-scan, infrared thermography, X-radiography with or without X-ray opaque penetrant enhancement, and X-ray computed tomography. Guidance for selecting the method(s) most appropriate to construction and flaw type can be found in MIL-HDBK-17F, Volume 3, Section 8.3 and in SAE-ARP-5089. Inspectors shall be certified to standards traceable to NAS 410.

For electronic based methods, the signal to noise ratio shall be greater than 3 to 1. NDE methods shall demonstrate capability to detect relevant process FOD.

6.1.4 Health Monitoring

Implementation of health monitoring shall be considered where appropriate to augment or enhance the effectiveness of hardware inspections. With the approval of the FCB, definitive health monitoring systems may be used to reduce inspection requirements.

6.2 Detected Flaws

Generally, detected flaws shall be repaired and the repair subjected to the provisions of this document. If a known flaw is left in the hardware, it shall be evaluated using conservative techniques and procedures. The intent to leave a detected flaw in the hardware shall be

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identified as soon as possible to the FCB along with supporting technical rationale that must be approved by the FCB prior to proceeding.

6.3 Load and Environment Spectrum

A load spectrum shall be developed for each damage tolerant part (or bond) to be used in the damage tolerant full-scale component tests and assessments. All service life phases and events including fabrication, assembly, testing, ground handling, transportation, storage, launch, on orbit, landing, maintenance, etc. shall be considered. Note that the proof test loads shall also be included. The part's load spectrum shall 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 shall be included as appropriate. The environment of each event within the spectrum shall be considered as part of the spectrum and its effect on the test and assessment results shall be accounted for. For example, for a composite matrix that can store moisture, the expansion load due to moisture can be a significant loading.

If the appropriate environment cannot be directly applied in tests that use the load spectrum, then the spectrum shall be modified by applying a test verified environmental correction factor (ECF) to account for environmental effects.

A load enhancement factor (LEF) sufficient to establish A-basis reliability on life shall be applied to the load spectrum. MIL-HDBK-17F, Volume 3, Section 7.6.3 gives an approach for calculating the LEF.

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

The load spectrum may be truncated when the no-growth threshold strain level is known. That is, cycles for which the applied strains (including ECF/LEF as appropriate) are less than the no-growth threshold strain, may be deleted from the load spectrum. Since the threshold is a function of flaw size, the final decision on truncation in a cyclic test cannot be made until the point of intended truncation is reached and it is confirmed that for the current flaw size the remaining cycles are indeed below threshold.

6.4 Traceability

Due to the process sensitive nature of composite and bonded structures, full traceability (over the service life of the part) is required by fracture control for the following parts:

- Fail safe parts
- Composite containment enclosures
- Low risk parts

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- NHLBB containers
- Fracture critical (proofed and damage tolerant) parts

Each part shall be identified with a unique serial number and process records maintained so a complete life history can be established at any point in the life of the part. Records shall include at a minimum:

- Procurement files
- Materials type, condition, processing, source
 - Storage and handling logs
 - Maintenance/processing logs
- Certificates of compliance
- Design documentation
- Manufacturing process
- Inspections, results and resolutions of findings
- Hardware deviations from design and their resolutions
- Impact damage
- Repairs
- Procedures
- Test documentation
- Load/use/flight history
- Environmental exposure

The traceability process shall include forward as well as backward capabilities for the items listed above.

7. DOCUMENTATION

The fracture control program activities shall be documented. Addition guidance for fracture control documentation can be found in Section 8 of NASA-HDBK-5010. Prevailing systems of documentation such as engineering drawings, configuration management documentation, and quality assurance documentation shall be augmented to cover the traceability requirements in Section 6.4. The engineering drawings shall identify fracture critical parts (bonds) and specify their inspection criteria, including both visual and NDE. Inspection criteria shall also be called out on the engineering drawings for fail safe parts (bonds), the enclosure for contained parts, low risk parts (bonds), and the walls of NHLBB containers. For reuse structures where in-service inspections, repairs, reproof, etc. occur, full documentation shall be provided and approved by the FCB prior to reflight. Specific fracture control reports shall be provided for the following, fully documenting the indicated activity:

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1. Fracture Control Plan (Section 4.4)
2. Damage Threat Assessment, Tasks 1, 2, and 3 (Section 5.3.2.1)
3. Impact Damage Protection Plan (Section 5.3.2.2)
4. Proof Test (Sections 5.3.1 and 5.3.2.9)
5. Damage Tolerant Coupon Tests (Section 5.3.2.3)
6. Damage Tolerant Development Tests (Section 5.3.2.4)
7. Damage Tolerant Full-Scale Component Tests (Section 5.3.2.6)
8. Inspection Report(s) (Section 7.1)
9. Fracture Control Summary Report (Section 7.2)
10. Fracture Control Detailed Assessment Report (Section 7.3)

With the approval of the FCB, reports may be combined in situations where it is advantageous to the government to do so.

7.1 Inspection Report(s)

The inspector(s) shall record the results of inspections (visual and NDE) on data sheets. The sheets shall identify the part by name and part number, serial number, type NDE and a sketch of the part (or photograph, drawing, etc.) showing the area inspected and type of flaw inspected for, the results of the inspection and the inspector's signature, date, and stamp. The data sheets shall be included in an inspection report. The inspection report shall also include permanent spatial records of the inspection findings. These records shall be provided as part of the hardware deliverables so they will be available for repeat inspections of the hardware should some unknown impact or other damage occur to flight hardware before flight so a reassessment is feasible.

7.2 Fracture Control Summary Report

The Fracture Control Summary Report shall provide sufficient information to certify that fracture control requirements have been met. For Space Shuttle Payloads it must be submitted as part of the Phase 3 Safety Review. It shall include the following:

1. Identification of exempted hardware.
2. A tabular listing of all non-exempt composite parts (bonds), providing for each part: name, drawing number, material, NDE, fracture control classification, and reference to part sketch or drawing included in the report.
3. Identification of whether or not pressure vessels, high energy rotating machinery, or high momentum rotating machinery are present.
4. Evidence for reused hardware that between-mission inspections have been done.
5. Evidence that hardware configuration has been controlled and verified for fail safe parts (including redundant load paths), composite containment enclosures, low risk parts, NHLBB items, and fracture critical parts.

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6. Evidence that materials usage has been verified for fail safe parts (including redundant load paths), composite containment enclosures, low risk parts, NHLBB items, and fracture critical parts.
7. List of material usage agreements (MUAs) for fail safe parts (including redundant load paths), composite containment enclosures, low risk parts, NHLBB items, and fracture critical parts. Also, a summary of any discrepancies or deviations from design that could affect the structural integrity of these parts is required.
8. A summary of flaw detections and their resolutions.
9. Drawings and sketches referenced in tabular summary.

7.3 Fracture Control Detailed Assessment Report

The Fracture Control Detailed Assessment Report shall pull together all the fracture control activities into one report. It may reference other published fracture control reports or include them as appendices. It shall contain all the information in the Fracture Control Summary Report (the actual MUAs are to be included instead of a list) plus supporting analysis, tests results, and tests evaluations. The loading scenario shall be described along with the assumptions for its derivation and the analytical justification for LEFs, ECFs, and spectrum truncations used. Analytical and tests assessments shall be included for acceptance of any detected flaws with or without repair.

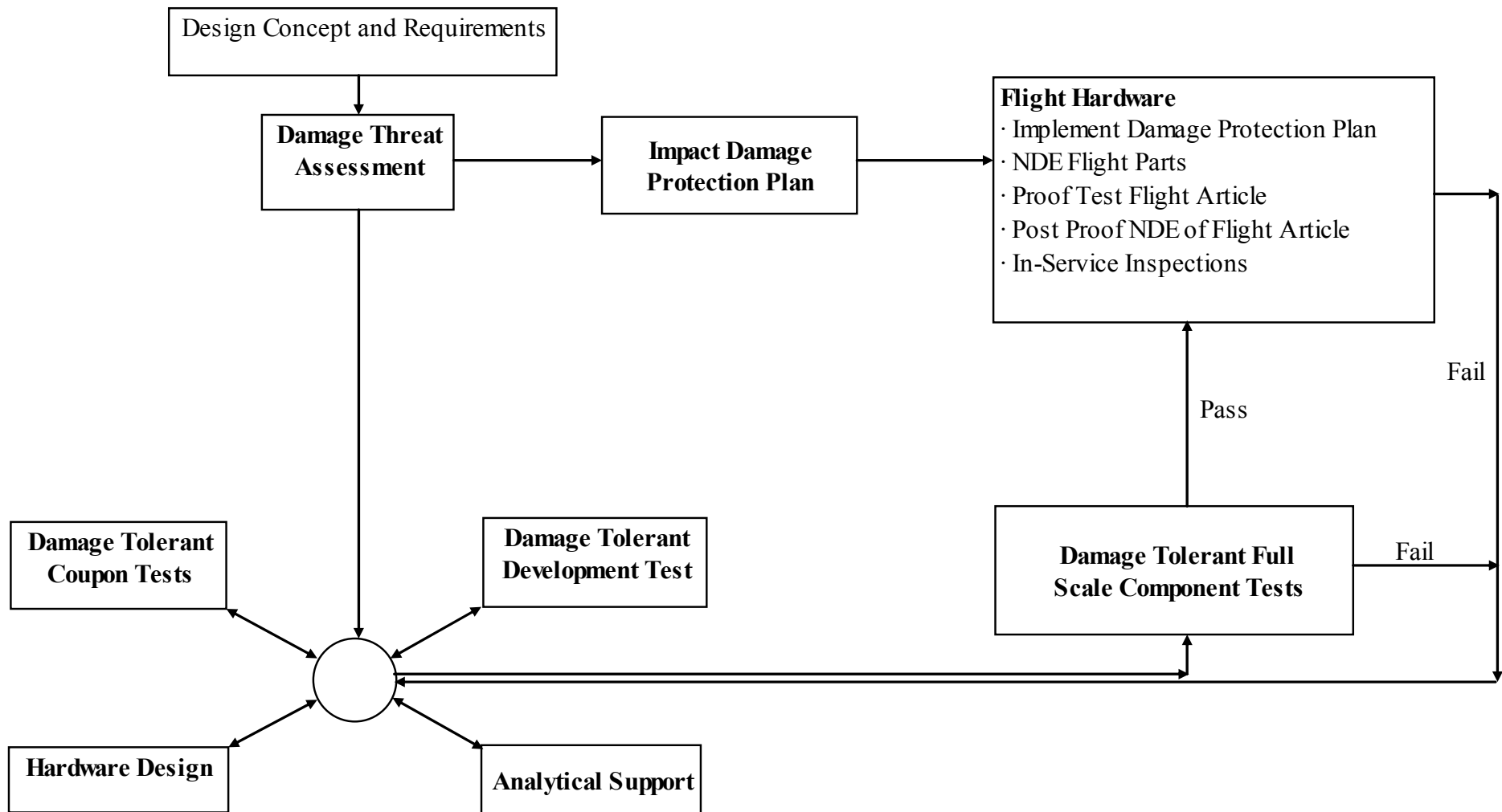
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A part (or bond) is fracture critical if its failure due to the presence of a flaw would result in a catastrophic hazard. All composite parts and bonds shall be classified according to the following:

Exempt	Non-Fracture Critical	Fracture Critical
<ul style="list-style-type: none"> • Non-structural and no safety critical function 	<ul style="list-style-type: none"> • Low released mass • Fail safe • Contained • Low risk • Non-hazardous leak before burst (NHLBB) 	<ul style="list-style-type: none"> • Proofed • Damage tolerant

FIGURE 1. Classification of Composite Parts and Bonds for Fracture Control

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FIGURE 2. Steps in Establishing Damage Tolerance

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- Determine impact damage sizes.
- Each impactor, material, layup, design, and construction type to be addressed.
- Characteristic impact damage size range is [D1, D2].

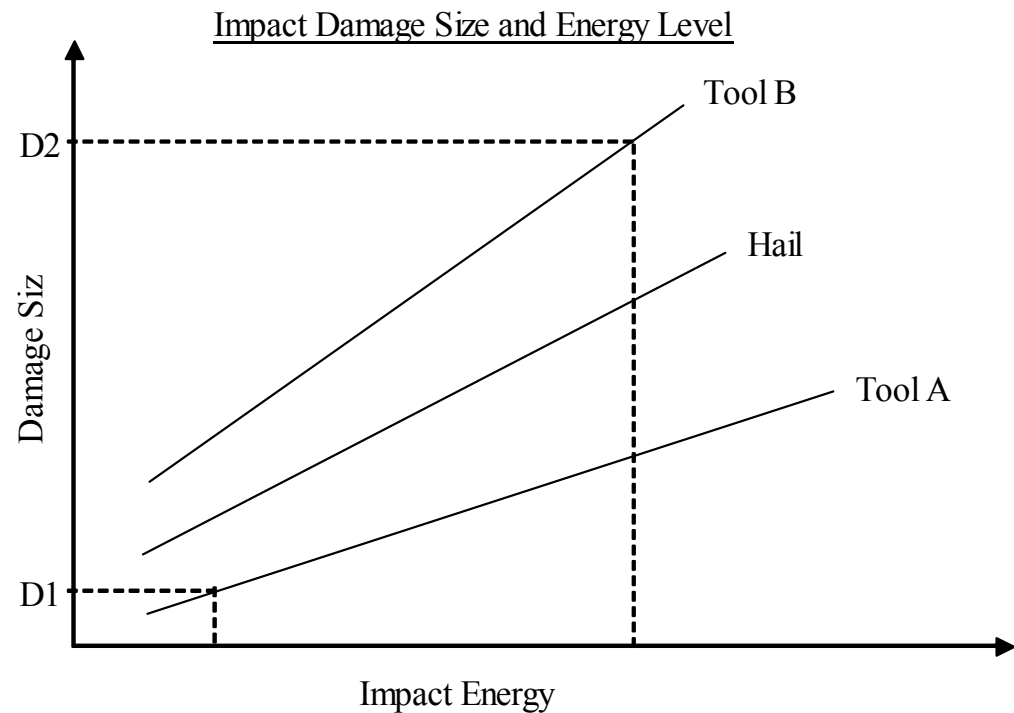


FIGURE 3. Characteristic Impact Damage Size Range Determination Schematic

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- Produce design curves/data to be used in designing the flight hardware and determine a threshold strain for low risk classifications.
- Each flaw/damage type, material, layup, construction type to be addressed.

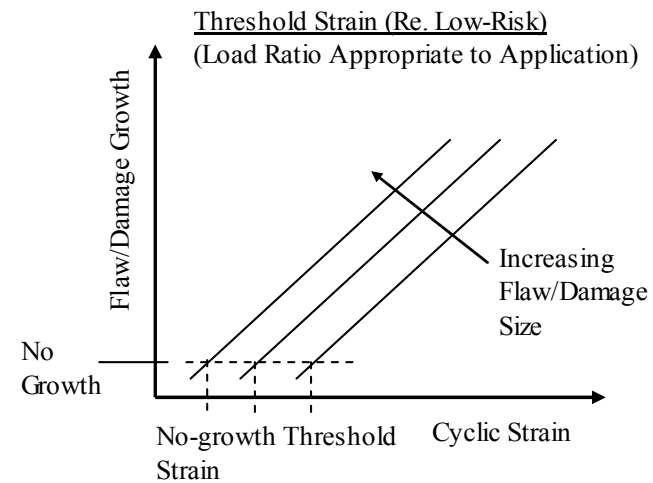
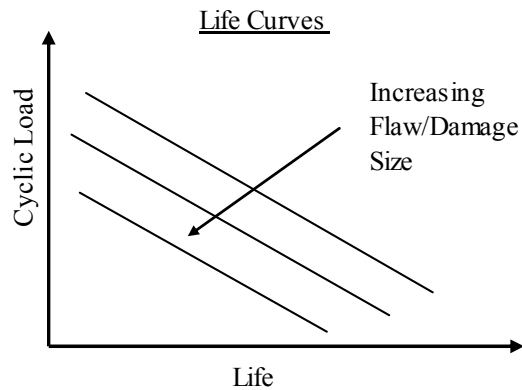
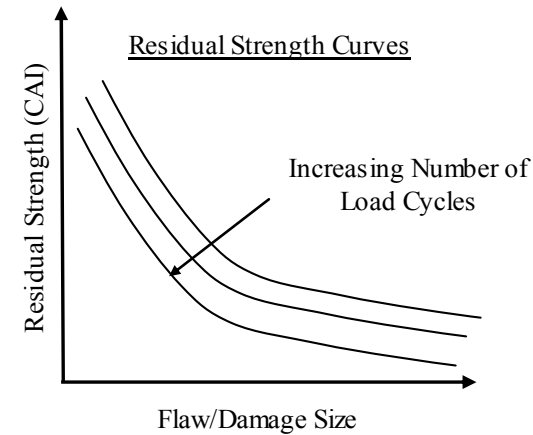
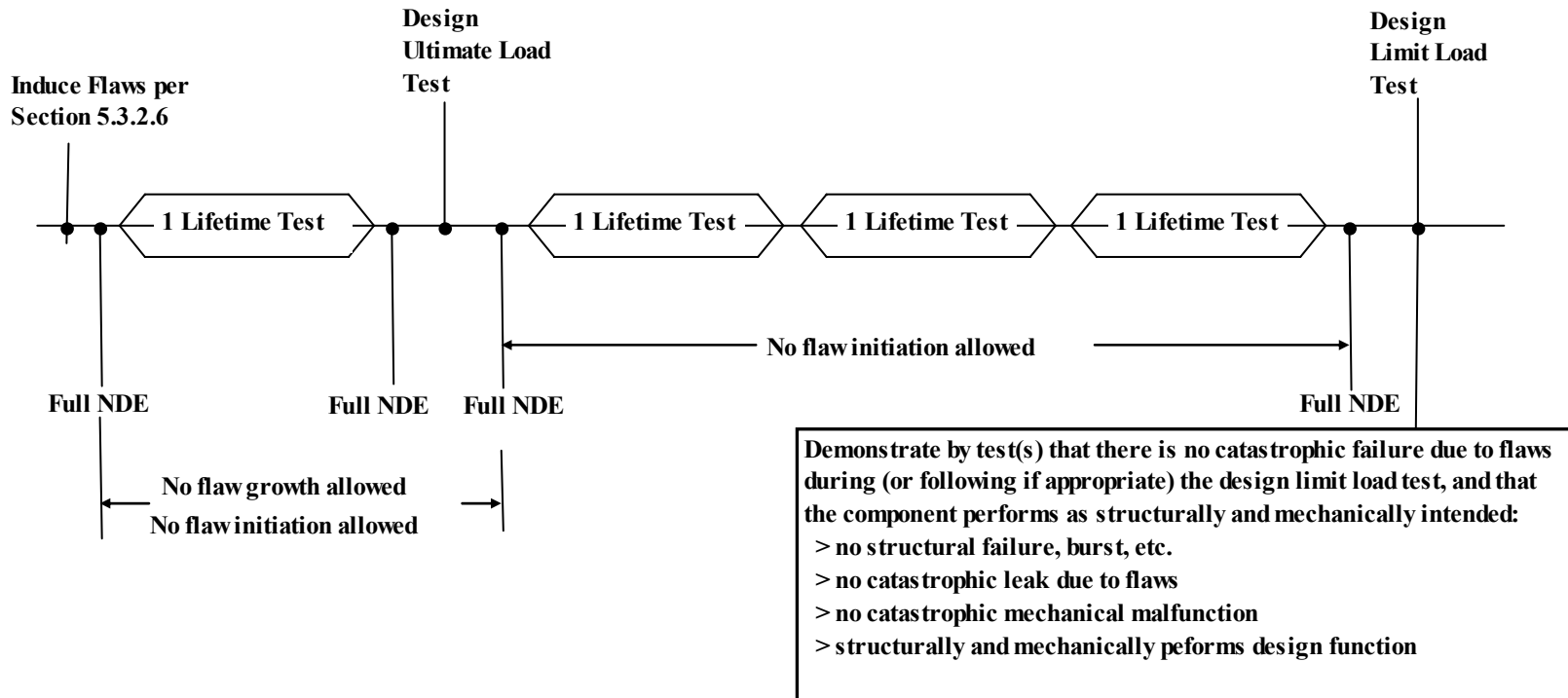


FIGURE 4. Damage Tolerant Coupon Tests Schematics

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Notes:

1. Component shall be tested and inspected with flaws present as described in Section 5.3.2.6.
2. Spectrum loads are to include a LEF. An ECF is to be applied as appropriate.
3. Truncation is allowed for cycles below the no-growth threshold.
4. Generally, loading events within a lifetime should be applied in the test spectrum in the same sequence in which they occur in actual use.
5. Care should be exercised to insure that metallics are sufficiently designed so that they do not yield excessively or fail during this test.
Generally, metallic parts should not be tested for damage tolerance during a composite damage tolerant test.
6. Special visual inspection is required along with NDE.
7. Proof test loads are to be included in the lifetime definition.
8. No flaw growth is allowed during the first lifetime test or during the design ultimate load test.
9. No flaw initiation is allowed during any of the lifetime test.
10. No structural failures are allowed at any time.

FIGURE 5. Damage Tolerant Full-Scale Component Test

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APPENDIX A

SPECIFIC HARDWARE REQUIREMENTS

A.1 Introduction

This appendix gives hardware specific requirements and is a mandatory part of the requirements of this document. Except as noted, all the requirements, applicable documents, and definitions in the document body apply to the hardware discussed here.

A.2 Hardware Requirements

A.2.1 Pressure Vessels

A.2.1.1 Composite Overwrapped Pressure Vessels (COPVs)

COPVs shall follow the requirements of ANSI/AIAA S-081-2000.

A.2.1.2 Other Composite Pressure Vessels

Pressure vessels that are not lined shall not be used. Unlined propellant tanks shall follow A.2.6.

A.2.2 High Energy (or Momentum) Rotating Machinery

High energy (or momentum) rotating machinery shall be classified as damage tolerant and meet the requirements of Section 5.3.2, except that there shall be at least two distinct full scale test articles for each component type (Section 5.3.2.6) and the flight article shall be proof tested to 1.20 times limit load. Proof test loads shall be less than 80 percent of the flight article ultimate strength (See Section 5.3.1). NASA-HDBK-5010, Appendix K, provides an example of classifying high momentum rotating machinery as fracture critical.

A.2.3 Hazardous Fluid Containers (Including Lines, Ducts, and Fittings)

Hazardous Fluid Containers shall be classified as damage tolerant and meet the requirements of Section 5.3.2, except that there shall be at least two distinct full scale test articles for each component type (Section 5.3.2.6) and the flight article shall be proof tested to 1.50 times MDP. Note that a 1.50 proof test requires that the burst factor be at least 1.88 (Section 5.3.1).

A.2.4 Habitable Modules

Parts within a habitable module are to be dispositioned per Section 5. The pressure bearing walls shall be classified as damage tolerant and meet the requirements of Section 5.3.2. It shall also be demonstrated by test on a flight-like full-scale component that the pressure bearing walls will support MDP times the ultimate safety factor with a through flaw in the wall of a length that

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is the maximum of 10 times the wall thickness or one inch (25.4 millimeters). This test may be done on a separate full-scale component or on the one used for the four lifetime damage tolerant full-scale component test after that test is completed. Also, the proof test factor for the flight article shall be 1.50 times MDP which requires an ultimate factor of safety of 1.88 (Section 5.3.1).

A.2.5 Solid Rocket Motor Cases and Nozzles

Solid rocket motor cases and nozzles shall be classified as damage tolerant and meet the requirements of Section 5.3.2. with the following additional requirements:

1. An actual motor case and nozzle shall be inflicted with flaws as in the damage tolerant tests, subjected to a full rocket hot firing and then be subjected to design ultimate load without failure or leak.
2. The proof test factor on the flight articles shall be 1.20 times MDP which requires an ultimate factor of safety of 1.50 (Section 5.3.1).
3. The flight article shall be proof tested between flights and receive post proof NDE.

A.2.6 Propellant Tanks

Propellant tanks that are COPVs shall follow A.2.1.1. Other propellant tanks shall be classified as damage tolerant and meet the requirements of Section 5.3.2, except that there shall be at least two distinct full scale test articles for each component type (Section 5.3.2.6) and the flight article shall be proof tested to 1.20 times MDP. Note that a 1.20 proof test requires that the burst factor be at least 1.50 (Section 5.3.1). The flight article shall be proof tested between flights and receive post proof NDE.

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APPENDIX B

SUMMARY TABLE – FRACTURE CONTROL CLASSIFICATIONS AND REQUIREMENTS

B.1 Table Description

This appendix provides a summary table for the nonexempt fracture control classifications and the requirements for each classification. Fracture control personnel will find the table useful in comparing the requirements of the various classifications and in choosing the classification to pursue for a particular hardware item. The reader should not rely on TABLE II alone for fracture control decisions, but should refer to the document for the official requirements.

The nonexempt fracture control classifications are listed in the columns and the requirements are listed in the rows. An “x” in a cell means the requirement in the corresponding row is imposed for the classification in the corresponding column. Many of the cells contain brief explanations of the requirement. A reference to the appropriate section of the document is provided in row 4.

B.2 Table II Abbreviations and Acronyms

In order to get the brief explanations to fit the space available, non-standard abbreviations and acronyms were used. These are included here since they are unique to TABLE II and it is convenient to have them near the table. Standard acronyms used in TABLE II are listed in Section 3.2.

Short Form	Meaning	Short Form	Meaning
anlys	analysis	p'tratn	penetration
dyn	dynamic	s/b	supported by
FC	fracture critical	SCF	safety critical function
FOS	factor of safety	SPF	single point failure
Fty	yield strength in tension	struc	structure
hab mod	habitable module	TTF	through thickness flaw
HERM	high energy rotating machinery	Ult	ultimate
HMRM	High momentum rotating machinery	verf	verified
meth	method	w/	with
NFC	non-fracture critical		

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TABLE II. Composite Fracture Control Classifications and Requirements Summary

	A	B	C	D	E	F	G	H	I
1	Non-Fracture Critical							Fracture Critical	
2	Contained								
3	Requirements	Low Released Mass	Fail Safe	Metallic Enclosure	Composite Enclosure	Low Risk	NHLBB	Proof Tested	Damage Tolerant
4	Reference Section	5.2.1	5.2.2	5.2.3.A	5.2.3.B	5.2.4	5.2.5	5.3.1	5.3.2
5	No catastrophic hazard/loss of SCF	x	x	x	x		x		
6	Part must be larger than open holes			x	x				
7	Enclosure/container not FC				x		x		
8	Not a pressure vessel					x	x		
9	No hazardous fluid					x	x		
10	FOS on containment			1.0 Fty, analysis or test	1.15 p'tratn test, or 1.15 p'tratn anlysis/b test				
11	DUL capability	NFC impacted parts - verf by test			w/impact damage > NDE, from loose part, DTA, or imposed - verf by test	w/impact damage > NDE, DTA, or imposed - verf by test	at Ult FOS x MDP w/impact damage > NDE, DTA, or imposed - verf by test		Per Fig. 5
12	Inspections								
13	1. Visual								
14	a. Walkaround								between each flight
15	b. Special Visual		pre and post proof, and between flights		pre and post proof, and between flights	pre and post proof, and between flights	pre and post proof, and between flights	pre and post proof, and between flights	pre and post proof, and after every 3 rd flight
16	2. NDE		pre and post proof		pre and post proof	pre and post proof	pre and post proof	pre and post proof	pre and post proof
17	Proof tested (< 80% Ult) ¹	Foot Note 1	Foot Note 1	Foot Note 1	Foot Note 1	Foot Note 1	Foot Note 1	1.2 x limit, initially and between flights	Initially, 1.05 min x limit
18	DTA Task 1		x		x	x	x	x	x
19	DTA Task 2				x ²	x ^{2,3}	x ²		x
20	DTA Task 3					x ³			x
21	IDPP		x		x		x	x	x
22	Damage tolerant coupon tests					x ³			x
23	Damage tolerant development tests								x
24	Damage tolerant full-scale component tests	FC impacted parts	FC impacted parts						Per Fig. 5
25	Traceability (Section 6.4)		x		x	x	x	x	x
26	Unique Requirements								
27	Pressurized enclosures shall have the characteristic of being NHLBB				x				
28	Walls shall leak ≤ MDP, Verf. by test						for TTF 10 t or 1 inch		
29	Wall shall not burst @ Ult x MDP, Verf. By test						for TTF 10 t or 1 inch		
30	Flaw shall not grow @ Ult x MDP, Verf. By test						for TTF 10 t or 1 inch		
31	No repressurization as pressure leaks down						x		
32	Generally limited to payloads							x	
33	Internal to payload, vehicle, module	x		implied	implied				
34	Debris shall meet low mass		x						
35	Below no-growth threshold strain					x			
36	Remaining struc analytically assessed at 1.15 x redistributed dyn load		x - analytical meth verified by test						
37	Remaining impacted struc must support 1.15 x redistributed limit load		x - NFC parts - verf by test						
38	See also 5003 for Shuttle payload	x							
39	No HERM, HMRM, hab mod, SPF bond					x			
40	Foot Notes:								
41	1. NASA-STD-5001 requires proof test of all composite parts/structures to 1.05/1.20.								
42	2. Required to the extent needed to establish impact damage size for DUL capability test (Line 11).								
43	3. Required to the extent needed to determine no-growth threshold strain (Line 35).								

CHECK THE MASTER LIST - VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE