Office of the NASA Chief Engineer

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METRIC (SI)/ENGLISH

FRACTURE CONTROL IMPLEMENTATION HANDBOOK FOR SPACEFLIGHT HARDWARE

VOLUME 1: GUIDANCE FOR IMPLEMENTATION

DOCUMENT HISTORY LOG

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Baseline		05-24-2005	Initial Release
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FOREWORD

This NASA Technical Handbook is published by the National Aeronautics and Space Administration (NASA) as a guidance document to provide engineering information; lessons learned; possible options to address technical issues; classification of similar items, materials, or processes; interpretative direction and techniques; and any other type of guidance information that may help the Government or its contractors in the design, construction, selection, management, support, or operation of systems, products, processes, or services.

Volume 1 of this Handbook provides interpretations of fracture control requirements and acceptable methodology and approaches for implementation of fracture control requirements for spaceflight hardware. Following the interpretations and guidelines of Volume 1 for this hardware will satisfy the intent of the applicable NASA fracture control requirements in NASA-STD-5019A, Fracture Control Requirements for Spaceflight Hardware. Volume 2 provides examples of acceptable methodology and detailed assessment approaches for fracture control of spaceflight hardware.

This Handbook was developed under the auspices of the NASA Fracture Control Methodology Panel. Special thanks are extended to those members who have diligently provided inputs, written various sections, provided helpful suggestions, and reviewed the various drafts of this Handbook.

Submit requests for information via “Email Feedback” at https://standards.nasa.gov. Submit requests for changes to this Handbook via Marshall Space Flight Center (MSFC) Form 4657, Change Request for a NASA Engineering Standard, or the “Suggest a Change to this Standard” link on the Standard’s Summary Page at https://standards.nasa.gov

Original Signed by:

12-15-2023

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Approval Date

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VOLUME 1, GUIDANCE FOR IMPLEMENTATION

1. SCOPE

1.1 Purpose

It is NASA Policy that fracture control be imposed on all human-rated spaceflight systems to promote safety by mitigating the risk of catastrophic failure due to the presence of flaws. This document, Volume 1 of NASA-HDBK-5010A, provides interpretation of fracture control requirements and methodology and approaches that are acceptable to NASA for implementation of fracture control requirements for spaceflight hardware. Following the interpretations and guidelines of Volume 1 for this hardware will satisfy the intent of the applicable NASA fracture control requirements in NASA-STD-5019A, Fracture Control Requirements for Spaceflight Hardware. Volume 2 of NASA-HDBK-5010A, Fracture Control Implementation Handbook for Spaceflight Hardware, Example Applications and Additional Guidelines, provides examples of acceptable methodologies, assessment approaches, and other resources for the implementation of fracture control requirements of spaceflight hardware.

The requirement for imposing fracture control on hardware used in human spaceflight is based upon safety. Any program, human spaceflight or otherwise, may choose to impose fracture control to enhance mission success, although it is not specifically required for that purpose. NASA requires fracture control only to advance the safety of human spaceflight hardware.

In the fracture control concept, it is given that material and manufacturing processes may produce hardware with flaws of a sufficient size that can reduce the strength and life of the hardware. Fracture control is a multi-disciplinary process for accepting the risk associated with flaws that are undetected and may be present in hardware. If flaws are detected, the part will normally be repaired or scrapped. Flight of parts with known flaws is not permitted without specific analysis and approvals as described in section 8.1.5 of NASA-STD-5019A and within this Handbook under the same section numbering.

Fracture control programs can significantly supplement properly designed, high-quality hardware with additional assurance against catastrophic structural failures caused by unexpected or undetected flaws. A viable fracture control program relies on design, analysis, testing, nondestructive evaluation (NDE), and tracking of fracture critical hardware. It is expected that all spaceflight hardware will be manufactured consistent with aerospace standards, practices, and quality. It is beyond the scope, or intent, of fracture control to address technical or quality disciplines that should already exist and be in place regardless of fracture control. Fracture control is not intended to compensate for poor design, analytical errors, misuse, or poor quality.

The purpose of this Handbook is to provide fracture control implementation guidance applicable to a wide range of hardware designs and uses. A variety of fracture control considerations and options are addressed, some of which may not be applicable to a given design. Information is provided to assist the user in the development of an effective Fracture Control Plan (FCP), as well as other fracture control documentation.

Since fracture control deals with what might happen if flaw propagation leads to structural failure, reasonableness and credibility have to prevail. Many bad things can be imagined resulting from chained, unlikely events. Consequently, those who do fracture control and those who judge it should put some restraint on their imaginations and temper them with the likelihood that the events under consideration have a reasonable chance of occurring.

It is recommended that the fracture control analyst become familiar with all portions of this Handbook. This Handbook is organized by section to mirror the corresponding requirements in NASA-STD-5019A. The documents referenced in the Handbook are listed in section 2. Acronyms and definitions are listed in section 3. Section 4 addresses implementation of general requirements and responsibilities in fracture control. Section 5 addresses implementation of exempt fracture control requirements. The implementation of fracture control requirements and methodologies for assessing non-fracture critical hardware and fracture critical hardware are discussed in sections 6 and 7, respectively. Implementation of flaw screening, traceability, and material selection fracture control requirements are discussed in section 8. Section 9 provides information on implementation of verification of fracture control requirements, while section 10 discusses implementation of alternative approaches for fracture control.

Volume 2 of this Handbook provides additional resources such as specific examples, checklists, and approaches for the implementation of fracture control requirements.

1.2 Applicability

1.2.1 This Handbook is applicable to all human-rated spaceflight systems.

1.2.2 This Handbook is approved for use by NASA Headquarters and NASA Centers and Facilities. This language applies to the Jet Propulsion Laboratory (a Federally Funded Research and Development Center), other contractors, recipients of grants, cooperative agreements, or other agreements only to the extent specified or referenced in the applicable contracts, grants, or agreements.

1.2.3 References to “this Handbook” refer to NASA-HDBK-5010, Volume 1, Revision A; references to other documents state the specific document information.

1.2.4 This Handbook, or portions thereof, may be referenced in contract, program, and other Agency documents for guidance.

1.2.5 In this Handbook, the terms “may” or “can” denote discretionary privilege or permission, “should” denotes a good practice and is recommended but not required, “will” denotes expected outcome, and “is/are” denotes descriptive material or a statement of fact.

1.3 Tailoring

Tailoring of NASA-STD-5019A is allowed and anticipated. The requirements in NASA-STD-5019A are written to provide risk mitigation for catastrophic failure due to flaws for all types of spaceflight hardware. As such, a “one-size-fits-all” approach is used. Many of the requirements may not be applicable for some hardware systems. Alternative approaches are also allowed as discussed in section 10.

1.4 Overview

NASA-STD-5019A was written to provide three fundamental updates to the previous edition:

1. Include more detailed requirements for classification of composites or bonded hardware.

2. Organize the requirements to better represent how classification and implementation typically occur.

3. Minimize the number of actual requirements and provide corresponding rationale statements.

NASA-STD-5019A contains 26 requirements, some of which are to be selected from the most appropriate and applicable for each situation. The requirements in sections 5, 6, 7, and 8 are selected for each specific hardware and application. It is expected that the selected methodologies necessary to meet the fracture control requirements be documented in the FCP. The 5019A Fracture Control Diagram is repeated below for convenience in Figure 1-1, NASA-STD-5019A Fracture Control Requirements Diagram. A summary table of the NASA Technical Standards requirements is also included in section 9.2.

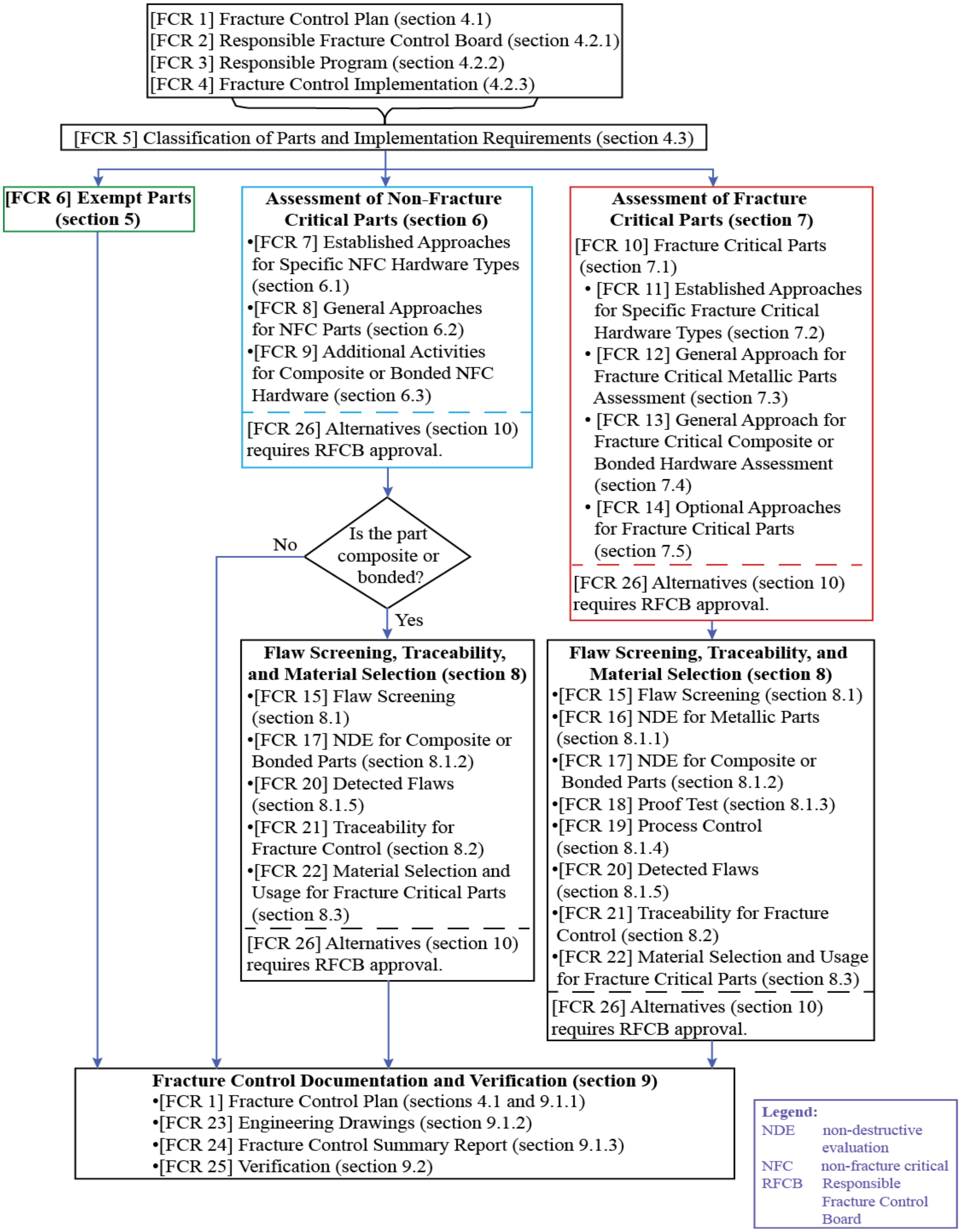

Figure 1-1—NASA-STD-5019A Fracture Control Requirements Diagram

2. REFERENCE DOCUMENTS

2.1 General

Documents listed in this section provide references supporting the guidance in this Handbook. Latest issuances of referenced documents apply unless specific versions are designated. Access reference documents at https://standards.nasa.gov or obtain documents directly from the Standards Developing Body, other document distributors, information provided or linked, or the office of primary responsibility designee for this Handbook.

2.2 Government Documents

The following documents contain specific fracture control requirements that programs should meet. Following the guidance of this Handbook will satisfy these requirements.

Department of Defense

MIL-HDBK-5H, Metallic Materials and Elements for Aerospace Vehicle Structures

MIL-HDBK-1823, Nondestructive Evaluation System Reliability Assessment

MIL-HDBK-6870, Nondestructive Inspection Program Requirements for Aircraft and Missile Materials and Parts

Department of Transportation (DOT)

DOT Title 49, Code of Federal Regulations Title 49, Transportation

Federal

FAR 25.305, Strength and deformation

NASA

NPR 7120.5, NASA Space Flight Program and Project Management Requirements

NPR 8705.2, Human-Rating Requirements for Space Systems

NASA-STD-5001, Structural Design and Test Factors of Safety for Spaceflight Hardware

NASA-STD-5009, Nondestructive Evaluation Requirements for Fracture Critical Metallic Components

NASA-STD-5017, Design and Development Requirements for Mechanisms

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

NASA-STD-5019A, Fracture Control Requirements for Spaceflight Hardware

NASA-STD-5020, Requirements for Threaded Fastening Systems in Spaceflight Hardware

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

NASA-STD-6030, Additive Manufacturing Requirements for Spaceflight Systems

NASA-STD-8739.14, NASA Fastener Procurement, Receiving Inspection, and Storage Practices for NASA Mission Hardware

NASA-HDBK-5010, Volume 2, Revision A, Fracture Control Implementation Handbook for Spaceflight Hardware, Volume 2, Example Applications and Additional Guidelines

JSC 20793, Crewed Space Vehicle Battery Safety Requirements

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

MSFC-STD-3716, Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals

MSFC-RQMT-3479, Fracture Control Requirements for Composite and Bonded Vehicle and Payload Structures

PRC-6509 (JSC), Process Specification for Eddy Current Inspection

541-PG-8072.1.2A, Goddard Space Flight Center (GSFC) Fastener Integrity Requirements

541-WI-5330.1.16B, Proof Testing of Flight Hardware Fasteners

NSTS/ISS 18798B, Interpretations of NSTS/ISS Payload Safety Requirements

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

NASA Newsletter: Pyrotechnic Device Evaluation, Testing and Analysis/Propellants and Aerospace Fluids (describes capabilities at the NASA White Sands Test Facility) dated June 10, 2015, last updated August 6, 2017 (https://www.nasa.gov/centers/wstf/testing_and_analysis/propellants_and_aerospace_fulids/pyrotechnic_device_evaluation.html)

2.3 Non-Government Documents

Boyer, R.R.; Spurr, W.F. (January 1978). “Characteristics of Sustained-Load Cracking and Hydrogen Effects in Ti-6Al-4V,” *Metallurgical Transactions A.* Vol. 9A, pp. 23-29

Everett, Jr., R.A., and Elber, W. The Significance of Small Cracks in Fatigue Design Concepts as Related to Rotorcraft metallic Dynamic Components," DTIC Accession Number ADP010634 (https://apps.dtic.mil/sti/citations/ADP010634)

Ewing, D.J.F., "Simple Methods For Predicting Gas Leakage Flows Through Cracks," Paper C376/047 In Proceedings of International Conference on Pipework Engineering And Operation, I. Mech. E., London, 21-22, Pp. 307-314, February, 1989

Lewis, J.C.; Kenny, J.T. (July 1976). *Sustained Load Crack Growth Design Data for Ti-6Al-4V Titanium Alloy Tanks Containing Hydrazine*. Paper presented at AIAA/SAE 12th Propulsion Conference. Palo Alto, CA (https://arc.aiaa.org/doi/pdf/10.2514/6.1976-769)

MPFR-14-031: Leak Before Break Evaluation of MSFC/MAF Steam Pipes

"Some Observations on Damage Tolerance Analyses in Pressure Vessels," 58th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 9-13 Jan. 2017, Grapevine, TX (https://arc.aiaa.org/doi/pdf/10.2514/6.2017-0887)

Aerospace Industries Association (AIA)/National Aerospace Standards (NAS)

NA0026, Procurement Specification, Metric C Fasteners, A-286 CRES Externally Threaded, 1100 MPa Tensile, 660 MPa Shear

NA0271, Procurement Specification, Metric Fasteners, CRES 300 Series, Externally Threaded, MJ Thread, 500 MPa Ftu and 700 MPa Ftu

NAM1312-111, Fastener Test Methods, Metric Method 111 Tension Fatigue

NAS410, NAS Certification and Qualification of Nondestructive Test Personnel

NAS4003, Fastener, A286 Corrosion Resistant Alloy, Externally Threaded, 160 Ksi Ftu, 95 Ksi Fsu, 1000 degrees F

NASM1312-6, Fastener Test Methods, Method 6, Hardness

NASM1312-8, Fastener Test Methods, Method 8, Tensile Strength

NASM1312-11, Fastener Test Methods, Method 11 Tension Fatigue

NASM1312-20, Fastener Test Methods, Method 20, Single Shear

NASM1312-108, Fastener Test Methods, Metric, Method 108, Tensile Strength

NASM1312-111, Fastener Test Methods, Metric Method 111 Tension Fatigue

NASM1312-113, Fastener Test Methods, Metric, Method 113, Double Shear

NASM85604, Bolt, Nickel Alloy 718, Tension, High Strength, 125 Ksi Fsu and 220 Ksi Ftu, High Temperature, Spline Drive

NASM85604, Bolt, Nickel Alloy 718, Tension, High Strength, 125 Ksi Fsu and 220 Ksi Ftu, High Temperature, Spline Drive

American Petroleum Institute (API)/American Society of Mechanical Engineers (ASME)

API 579-1/ASME FFS-1, Fitness-For-Service

American National Standards Institute (ANSI)/American Institute of Aeronautics and Astronautics (AIAA)

ANSI/AIAA S-080-1998, Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components

ANSI/AIAA S-080A-2018, Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components

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

ANSI/AIAA S-081B-2018, Space Systems – Composite Overwrapped Pressure Vessels

ASME

ASME BPVC-VIII-1, Boiler and Pressure Vessel Code, Section VIII, Division 1, Rules for Construction of Pressure Vessels

ASME BPVC-VIII-2, Boiler and Pressure Vessel Code, Section VIII, Division 2, Rules for Construction of Pressure Vessels - Alternative Rules

ASTM International (formerly American Society for Testing and Materials)

ASTM E399, Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness of Metallic Materials

ASTM E561, Standard Test Method for K-R Curve Determination

ASTM E740/E740M, Standard Practice for Fracture Testing with Surface-Crack Tension Specimens

ASTM E1049-85, Standard Practices for Cycle Counting in Fatigue Analysis

ASTM E1221, Standard Test Method for Determining Plane-Strain Crack-Arrest Fracture toughness, K_{Ia}, of Ferritic Steels

ASTM E1681, Standard Test Method for Determining Threshold Stress Intensity Factor for Environment-Assisted Cracking of Metallic Materials

ASTM E1820, Standard Test Method for Measurement of Fracture Toughness

ASTM E1823, Standard Terminology Relating to Fatigue and Fracture Testing

ASTM E2899, Standard Test Method for Measurement of Initiation Toughness in Surface Cracks Under Tension and Bending

Battelle

MMPDS, Metallic Materials Properties Development and Standardization

Composite Materials Handbook (CMH)

CMH-17, Composite Materials Handbook

SAE International

SAE AS7468, Bolts, Cobalt-Chromium-Nickel Alloy, UNS R30035, Tensile Strength 260 Ksi, Procurement Specification

Southwest Research Institute

NASGRO® User Manual

2.4 Order of Precedence

2.4.1 The guidance established in this Handbook do not supersede or waive existing guidance found in other Agency documentation.

2.4.2 Conflicts between this Handbook and other documents will be resolved by the delegated NASA Technical Authority.

3. ACRONYMS, ABBREVIATIONS, SYMBOLS, AND DEFINITIONS

3.1 Acronyms, Abbreviations, and Symbols

ΔK_{th}	cyclic threshold stress intensity range
ω	maximum operating rotational speed
$>$	greater than
$\sqrt{\quad}$	square root
®	registered trademark
µm	micrometre
ΔK_{th}	cyclic threshold stress intensity factor range
AIA	Aerospace Industries Association
AIAA	American Institute of Aeronautics and Astronautics
Al	aluminum
AM	additive manufacturing
ANSI	American National Standards Institute
API	American Petroleum Institute
ASME	The American Society of Mechanical Engineers
ASTM	ASTM International (formerly American Society of Testing and Materials)
atm	atmosphere
BBA	building block approach
BPVC	Boiler and Pressure Vessel Code
BVID	Barely Visible Impact Damage
cm	centimeter(s)
CMH	Composite Materials Handbook
CNC	computer numerical control
CNR	contract-to noise ratio
COPV	composite overwrapped pressure vessel
COTS	commercial off the shelf
cp-Ti	commercially pure titanium
CRES	corrosion resistant (steel)
CTE	coefficient of thermal expansion
DCP	damage control plan
DLL	design limit load
DOT	Department of Transportation
DR	discrepancy review
DTA	damage threat assessment
DUL	design ultimate load
EAC	environmentally assisted cracking
ECF	environmental correction factor
EPFM	elastic-plastic fracture mechanics
EVA	extravehicular activity
F_{su}	ultimate shear strength
F_{tu}	ultimate tensile strength

F_{ty}	yield tensile strength
FAA	Federal Aviation Administration
FAD	failure assessment diagram
FAR	Federal Acquisition Regulation
FCB	Fracture Control Board
FCP	Fracture Control Plan
FCR	Fracture Control Requirement
FCSR	Fracture Control Summary Report
FSR	factors of safety requirement
ft	foot (feet)
ft-lb	foot-pound(s)
GAS	get-away special
h/hr	hour(s)
HCF	high-cycle fatigue
HDBK	handbook
IDMP	Impact Damage Mitigation Plan
in	inch(es)
ITP	inspection and test plan
J	joule(s)
J_c	critical J-integral fracture toughness
J_{Ic}	plane strain J-integral fracture toughness
JSC	Johnson Space Center
K	stress intensity factor/thousand
K_c	plane stress fracture toughness
K_{EAC}	stress intensity factor threshold for EAC in a specific thickness
K_{Ic}	plane strain fracture toughness
K_{Ie}	effective fracture toughness
K_{IEAC}	stress intensity factor threshold for plane strain environmentally assisted cracking
K_{ISCC}	stress intensity factor threshold for plane strain stress corrosion cracking
K_{JIc}	stress intensity factor determined from the plane strain J-integral fracture toughness
K_{SLC}	stress intensity factor threshold for sustained load cracking
Kip	kilo-pound
kPa	kilo-pascal
ksi	kip(s) per square inch
L-PBF	laser powder bed fusion
LBB	leak-before-burst
LEF	load enhancement factor
LEFM	linear-elastic fracture mechanics
m	meter (s)
mA	milliampere
MDCP	Mechanical Damage Control Plan
MDP	maximum design pressure
MEOP	maximum expected operating pressure
MIL	military

mm	millimeter
MMOD	micro-meteoroid and orbital debris
MMPDS	Metallic Materials Properties Development and Standardization
MPa	megapascal(s)
MRB	Material Review Board
MSFC	Marshall Space Flight Center
MUA	Materials Usage Agreement
NaCl	sodium chloride
NAS	National Aerospace Standard
NASA	National Aeronautics and Space Administration
NASGRO®	fracture mechanics and fatigue crack growth analysis software
NDE	nondestructive evaluation
NDI	nondestructive inspection
NDT	nondestructive testing
NFC	non-fracture critical
NHLBB	non-hazardous-leak-before-burst
NPR	NASA Procedural Requirements
PDR	Preliminary Design Review
PLL	plastic limit load
PRC	process specification
psi	pound(s) per square inch
psia	pound(s) per square inch absolute
PTC	partly though crack
RFCB	Responsible Fracture Control Board
RQMT	requirement
RTD	residual threat determination
S	standard
SAE	SAE International (formerly Society of Automotive Engineers)
SI	Système Internationale or metric system of measurement
SLC	sustained load cracking
SMA	Safety and Mission Assurance
SSC	stress corrosion cracking
STA	solution treated and aged
STD	standard
Ti	titanium
V	Vanadium
VCCT	virtual crack closure technique
WCC	worst-case credible
Wh	Watt-Hours

3.2 Definitions

A-Basis: A statistically calculated number that at least 99 percent of the population of values is expected to equal or exceed with a confidence of 95 percent.[1]

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

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

B-Basis: A statistically calculated value that at least 90 percent of the population is expected to equal or exceed with a confidence of 95 percent.[2]

Barely Visible Impact Damage: In composites, the threshold for undetectable damage when detailed visual inspection techniques are used for service. Barely visible impact damage (BVID) establishes the strength design values to be used in analyses demonstrating compliance with the regulatory Ultimate Load requirements of FAR 25.305, Strength and deformation.

Bond: The joining of two parts through molecular attraction or through any non-mechanical means of connection.

Bonded Hardware (Structure): Hardware (structure) that is assembled using parts that are joined together with an adhesive.

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

Building Block Approach (BBA): A development methodology often used with composites or bonded hardware that (a) starts with selecting the material system and manufacturing approach; (b) moves on to experimentation and analysis of small samples to characterize the system and quantify behavior in the presence of flaws and damage; (c) progresses to examining larger structures to examine buckling behavior, combined loadings, and built-up structures in the presence of credible damage; and (d) finally moves to complicated subcomponents and full-scale components to establish their damage tolerance strength and life. Each step along the way is supported by detailed analysis to validate that the behavior of these structures is well understood and predictable.

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

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

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[1] See NASA-STD-6016, Standard Materials and Processes Requirements for Spacecraft; CMH-17, Composite Materials Handbook; Metallic Materials Properties Development and Standardization (MMPDS) (Appendix A.2), as appropriate.

[2] See NASA-STD-6016; CMH-17, MMPDS (Appendix A.2), as appropriate.

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

Component: A hardware unit considered a single entity for the purpose of fracture control. A component contains at least one part.

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

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

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

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

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

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

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

Critical Stress Intensity Factor: The stress intensity factor at the initiation of crack growth in the part resulting in a catastrophic failure that is representative of the failure mode of concern for the metallic material process condition, weakest orientation, and thickness being evaluated. Examples for metallic materials may include: K_{IEAC}, the stress intensity factor threshold for plane strain environment-assisted cracking; plane strain fracture toughness (K_{Ic}) may be appropriate for thick sections and/or as a lower bound value[3]; effective fracture toughness (K_{Ie}) is used in NASGRO® for crack growth analyses of surface or elliptical flaws; K_{JIc} calculated from J_{Ic} or a K_c calculated from J_c may be appropriate for the conditions described in the defining standard (see ASTM E1820, Standard Test Method for Measurement of Fracture Toughness) such as evaluation of ductile tearing and instability; constraint-based assessments (see ASTM E2899,

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[3] Proof test assessments need to use upper bound fracture toughness; see section 8.1.3 in NASA-STD-5019A.

Standard Test Method for Measurement of Initiation Toughness on Surface Cracks Under Tension and Bending), and/or tests may be needed for surface or other complex cracks in materials or conditions that invalidate the ability of Linear-Elastic Fracture Mechanics (LEFM) to represent crack growth.

Damage: See definitions of Flaw and Impact Damage.

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

Damage Tolerance: Fracture control design concept under which an undetected flaw or damage (consistent in size with the flaw screening method or residual threat determination [RTD]) is assumed to exist and is shown by fracture mechanics analysis or test not to grow to failure (leak or instability) during the period equal to the service life factor times the service life.

Design Limit Load (DLL): See definition of Limit Load.

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

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.

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

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

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

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

Flaw: For metallics, glass, or brittle materials, a crack-like defect. For composite or bonded materials, an anomaly in the hardware that has the potential for adversely affecting strength, damage tolerance life, or must-work function. Examples of flaws in metallics include cracks, deep scratches and sharp notches that behave like cracks, material inclusions, forging laps, welding incomplete fusion, penetration, and slag or porosity with a crack-like tail. Examples of flaws in composite or bonded materials may include cracks, cuts, scratches, delaminations, porosity/voids, disbonds, wrinkles, foreign object debris, impact damage, etc. Damage (used alone) and flaw are equivalent.

Fleet Leader: Articles representative of spaceflight hardware with respect to production methods, e.g., materials, manufacturing, testing that either have accumulated (or are scheduled to accumulate) more service lifetime in typical (or more severe) environments than the rest of the fleet and are monitored for indications of failure modes to provide early warning of known and unexpected risks to the rest of the fleet.

Flight (Spaceflight) Hardware: Any hardware (including spares) that is approved to be part of or carried by a launch vehicle, crew module, transfer stage, landing craft, payload, etc.

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

Fracture Control Board: A project or program-specific, multi-disciplinary group of experts that are responsible for implementing fracture control requirements, establish a project or program-specific fracture control plan, coordinate fracture control activities under the oversight of the NASA Responsible Fracture Control Board (RFCB). Some programs or projects may elect to use other titles such as Panel or Committee instead of Board. Some programs or projects may also elect to have an individual serve this purpose (usually smaller payloads or hardware projects). The project or program-specific Fracture Control Board typically functions at the prime contractor or hardware developer level.

Fracture Critical: Fracture control classification that identifies a part whose individual failure, caused by the presence of a crack, is a catastrophic hazard and that requires safe-life analysis or other fracture control assessment to be shown acceptable for flight. A part is fracture critical unless it can be shown that there is no credible possibility for a flaw to cause failure during its lifetime or the part failure does not result in a credible catastrophic hazard. Assessments for fracture critical parts include damage tolerance analysis, damage tolerance test, or defined approaches for specific categories. Parts under this classification receive flaw screening by NDE, proof test, or process control and are subjected to traceability, materials selection and usage, documentation, and engineering drawing requirements.

Habitable Modules or Volumes: Flight containers/chambers that are designated and designed to support human occupancy.

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

Hazardous Fluid: For fracture control, a fluid the release of which would create a catastrophic hazard. These types of fluids may include liquid chemical propellants, liquid metals, biohazards, and other highly toxic liquids or gases. The release of such fluids 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 the release of which would cause a catastrophic hazard and that is not classified as a pressure vessel.

Hazardous Material: For fracture control, a material the release of which would create a catastrophic hazard.

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 because of structural resonance.

Impact Damage: The injury or harm inflicted upon composite or bonded hardware by impingement of an object upon the hardware in question or the bumping or striking between the hardware in question and another object. Impact damage is a subset of the more general term damage (or flaw).

Impact Damage Mitigation Plan (IDMP): A plan for composite or bonded hardware to mitigate risk of impact damage to the flight hardware.

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

K_c: Plane stress fracture toughness. The value of stress intensity factor K at the tangency between a crack extension resistance curve (R-curve) and the configuration-dependent applied K curve (see ASTM E1823, Standard Terminology Relating to Fatigue and Fracture Testing). This crack extension occurs under conditions that do not approach crack-tip plane strain. The R-curve and K_c vary with the material, specimen size, and thickness. K_c is used in NASGRO® to represent fracture toughness as a function of thickness for use in crack growth calculations.[4]

K_{Ic}: Plane strain fracture toughness. The crack extension resistance under conditions of crack-tip plane strain in Mode I for slow rates of loading under predominantly linear-elastic conditions and negligible plastic-zone adjustment that is measured by satisfying a standardized procedure with validity requirements (see ASTM E399, Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{Ic} of Metallic Materials). Another quantity, K_{JIc}, defined for conditions with limited plasticity from J_{Ic} may also be useful (see ASTM E1820).

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[4] See NASGRO® User Manual where the K_c symbol is defined as "critical stress intensity" and section 2.1.4 that shows K_c as a function of material thickness and describes the usage of K_c.

K_{Ie}: Effective fracture toughness for a surface or elliptically shaped crack. The toughness is based on residual strength and the original crack dimensions. This parameter is meaningful only when crack-tip plastic zones are small and stable crack growth before failure is generally absent (ASTM E740/E740M, Standard Practice for Fracture Testing with Surface-Crack Tension Specimens, main body and section X1.2). For conditions with plastic effects and well-defined crack-tip stress fields with fracture controlled by crack initiation, an approach involving constraint may be applicable (see ASTM E2899). Testing of flaws in specimens representative of the structure is needed to determine damage tolerance for plasticity conditions when crack-tip stress fields collapse. K_{Ie} is used in NASGRO® for analyses of crack growth.[5]

K_{EAC}: The largest value of the stress intensity factor at which crack growth is not observed for a pre-cracked through-crack specimen of specified material, environment, and thickness that is tested for a significant duration in accordance with ASTM E1681.

K_{IEAC}: The largest value of the stress intensity factor at which crack growth is not observed for a pre-cracked through-crack specimen of specified material, environment, and thickness that is sufficient to meet requirements for plane strain and is tested for a significant duration in accordance with ASTM E1681.

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

ΔK_{th}: Threshold stress intensity factor range below which flaw growth will not occur under cyclic loading conditions.

Leak-Before-Burst (LBB): Characteristic of pressurized hardware whose only credible failure mode at or below maximum design pressure (MDP) with service life loads resulting from the presence of a potential flaw is a pressure-relieving leak at the flaw as opposed to burst or rupture at the critical stress intensity factor. As the hardware item leaks down, there is no re-pressurization or continued pressure cycles that could lead to continued crack growth. In this failure mode, the hardware will not fail in a fragmentary, catastrophic manner. Instead, only small, slow-growing leaks would develop, leaking in a controlled manner. Additional aspects of LBB assessments are described in section 6.2.4 in NASA-STD-5019A.

Life Factor: See definition of Service Life Factor.

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

Limit Load: The maximum load expected on the hardware during its design service life, including ground handling, transport to and from orbit, including abort conditions and on-orbit operations

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[5] See NASGRO® User Manual where the K_{Ie} symbol is defined as "effective fracture toughness for part-through (surface/corner) crack" and section 2.1.4 that describes how the K_{Ie} value is determined and how it is used.

Limited Life Part: Multi-mission part that has a predicted damage tolerance life that is less than the required service life factor times the complete multi-mission service life. See definition of Service Life Factor.

Load Enhancement Factor (LEF): A factor applied to the service life spectrum to satisfy a specified level of reliability and confidence with fewer cycles than would otherwise be required.

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

Low-Fracture Toughness: Material property characteristic, in the applicable environment, for which the ratio is $\mathrm{K_{Ic}/F_{ty}} < 1.66\sqrt{\mathrm{mm}}\ \left(0.33\sqrt{\mathrm{in}}\right)$. For steel bolts with unknown K_{Ic}, low-fracture toughness is assumed when material A-basis ultimate strength F_{tu} > 1,241 MPa (180 ksi). Parts made with materials of this characteristic may be at risk of a brittle fracture.

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

Maximum Design Pressure (MDP): The highest possible operating pressure considering maximum temperature, maximum relief pressure, maximum regulator pressure, and, where applicable, transient pressure excursions. MDP for human-rated hardware is a two-failure tolerant pressure, i.e., it will accommodate any combination of two credible failures that will affect pressure. Some programs have defined MDP as a two-fault tolerant pressure.

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.

Mission: A major activity required to accomplish an Agency goal or to effectively pursue a scientific, technological, or engineering opportunity directly related to an Agency goal. Mission needs are independent of any particular system or technological solution (NPR 7120.5, NASA Space Flight Program and Project Management Handbook).

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

No-Growth Threshold Strain: For a composite or bonded part, the largest strain range (where strain range 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 DTA, 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 are 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 is determined from test data in the appropriate environment for the applicable (or worst) 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. NDE is sometimes referred to as non-destructive testing (NDT) or non-destructive inspection (NDI).

Non-Hazardous-Leak-Before-Burst (NHLBB): A non-fracture critical classification for metallic pressurized hardware that contains a material that is not hazardous and that exhibits the LBB failure mode in a non-hazardous manner.

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 that also performs any of the following:

a. Contains stored energy of 19,307 J (14,240 ft-lb) or greater based on adiabatic expansion of a perfect gas.

b. Stores a gas that will experience an MDP greater than 690 kPa (100 psia).

c. Contains a gas or liquid in excess of 103 kPa (15 psia) that will create a catastrophic hazard if released.

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

Pressurized Fluid Container: A container designed primarily for pressurized storage of gases or liquids that is similar to a pressure vessel but does not satisfy the definition of a pressure vessel.

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

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

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

Proof Test: A test on the flight article that is performed to verify structural acceptability or to screen flaws. The proof test load and/or pressure level is the proof test factor times limit load and/or MDP. Proof tests may be conducted in the operational environment, or the test levels may be adjusted via an ECF. (Note that some sections within NASA-STD-5019A may specify when an ECF is optional versus when it is prescribed for the classification if the test is not conducted in the operational environment.)

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

R Ratio: The ratio of minimum stress to maximum stress in cyclic loading.

Re-flight Hardware: Hardware items that have already met the requirements in NASA-STD-5019A for service life, have flown on a flight vehicle, and are being manifested for an additional flight. Note that some fracture control categories in NASA-STD-5019A impose additional requirements that are to be satisfied before being re-flown.

Residual Strength: The maximum value of load (both externally applied and internal self-equilibrating loading, such as residual stresses) that a flawed or damaged part is capable of sustaining without catastrophic failure.[6]

Residual Threat Determination: An assessment that defines the worst-case credible flaw conditions that composite or bonded hardware will be designed to endure, considering all applicable flaw detection and mitigation strategies that are implemented for the flight hardware.

Responsible NASA Center: The NASA Center acting as the sponsor and/or coordinator for the program/project developing the payload/hardware.

Responsible Fracture Control Board (RFCB): A designated multi-discipline group of experts at the NASA Center 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 the Center.

Rotating Hardware: Hardware that has a rotational mode of operation and devices with spinning parts, such as fans, centrifuges, motors, pumps, gyros, and flywheels.

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

Safe Life: See definition of Damage Tolerance.

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[6] In the NASGRO® User Manual, version 7.1.1, section 2.1.5, and Appendix O, there is discussion of a related failure condition invoked when net section stress exceeds the material flow stress, as defined in the NASGRO® User Manual.

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

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

Service Life: Time interval for a part beginning with manufacture and extending throughout all phases of its specified mission usage. The period of time or number of cycles that includes all relevant loadings, conditions, and environments encountered during this period that will affect flaw growth, including all manufacturing, testing, storage, transportation, launch, on-orbit, descent, landing, and if applicable, post-landing events, refurbishments, retesting, and repeated flights until the hardware is retired from service.

Service Life Factor: The factor on service life required in damage tolerance analysis or testing. The service life factor is often referred to as the life factor. (Note: The service life factor is specified as 4 for metallic materials in section 7.3.2.c in NASA-STD-5019A. The service life factor is specified as the B-basis number of service lives with the corresponding LEF for composites or bonded materials in sections 7.4.7.b and 7.4.8.e in NASA-STD-5019A.)

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

Special Visual Inspection: 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, and surface cleaning, are used. Special visual inspections are performed independently by two inspectors. When special visual indications are found, NDE is performed.

Standard NDE: NDE methods of metallic materials for which a statistically based flaw detection capability has been established. Standard NDE methods addressed by NASA-STD-5019A and this Handbook are limited to fluorescent penetrant, radiography, ultrasonic, eddy current, and magnetic particle.

Sustained Load Cracking (SLC): Growth of a pre-existing crack in susceptible metallic alloys[7] under sustained stress without assistance from an external environment. A threshold stress intensity factor can be obtained by procedures such as those in ASTM E1681 for the case of an

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[7] SLC, because of the presence of interstitial hydrogen. occurs in titanium alloys, including commercially pure titanium (cp-Ti) and Ti-6Al-4V (Ti64), in both annealed and solution treated and aged (STA) conditions. Testing is necessary to determine the threshold stress intensity for the titanium alloy metallurgical condition and interstitial hydrogen content. Other materials with different crystalline structures such as steel and aluminum alloys that do not allow interstitial hydrogen may still exhibit SLC behaviors.

inert or vacuum environment. One publication determines the effects of hydrogen content and temperature on SLC in Ti-6Al-4V (Boyer and Spurr, 1978).

Ultimate Factor of Safety (Ultimate Safety Factor): A specified factor to be applied to limit load. No ultimate structural failure is allowed for a load equal to the ultimate factor of safety multiplied times limit load.

Ultimate Strength (Capability): The load, stress, or strain at which collapse, or rupture occurs.

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

4. GENERAL Requirements

4.1 Fracture Control Plan

NASA-STD-5019A:
4.1 Fracture Control Plan

A summary table of all FCRs in this NASA Technical Standard is shown in Appendix B in this NASA Technical Standard.

[FCR 1] A Fracture Control Plan shall be developed and maintained by the program for human-rated spaceflight hardware that satisfies all of the following:

a. Addresses all of the parts in the program-specific flight hardware.

b. Meets the requirements of this NASA Technical Standard.

c. Specifies fracture controls that are established to mitigate the risk of catastrophic failure caused by flaws throughout the service life of the hardware.

d. Has approval by the RFCB.

[Rationale: The FCP is necessary to document the hardware-specific fracture control requirements, such as parts classification, selected approaches for each part, and all required fracture control activities for the program or project. The RFCB-approved FCP is the working document that all responsible parties use for implementing fracture control requirements to a particular program or project.]

The FCP details the fracture control responsibilities, the classification of all parts for the specific hardware, the selected applicable fracture control approaches from the requirements of this NASA Technical Standard corresponding to each part's category, as well as the approaches for flaw screening, traceability, and material selection of fracture critical parts. The hardware-specific FCP also documents all alternative approaches in accordance with the requirement of [FCR 26] in this NASA Technical Standard.

Each separate hardware project within a program may develop an FCP for its hardware.

The initial FCP should be submitted early in the program. An early draft and subsequent updates of an FCP are necessary for appropriate cost estimation. The Data Requirements Deliverable for the FCP may need to be updated to require an earlier draft (potentially as part of the hardware proposal) for more accurate cost estimation. The FCP should be updated as needed to keep it current with the documented program fracture control approaches.

FCR 1 of NASA-STD-5019A requires the program to maintain an FCP for all human-rated spaceflight hardware. The responsible program designates the entities that assess the hardware, determines fracture control classification, and decides which of the requirements in sections 5, 6, 7, and 8 of NASA-STD-5019A are to be selected for each specific hardware and application. The classification of all parts and the tailored selections of methodologies necessary to meet the fracture control requirements are documented in the FCP. The FCP would also document all alternative approaches.

Once completed and approved by the RFCB, the FCP effectively becomes the tailored version of NASA-STD-5019A for implementation of risk mitigation activities for the part, component, hardware, or project. It is not recommended that the FCPs be a repetition of the Standard. Rather, it should be a methodical and logical selection of the appropriate fracture control requirements necessary to mitigate catastrophic hazard due to a flaw. The approaches selected should be for implementation to the specific hardware, focusing on the activities relevant to that hardware. The FCP should document the activities planned to be implemented for the project hardware according to FCR 1 of NASA-STD-5019A.

The FCP should be identified as a deliverable data document that requires approval by the program or project office and the RFCB. It is recommended that initial FCP be delivered early in the program to affect early design decisions. The Data Requirements Deliverable for the FCP should require an early draft (potentially as part of the hardware proposal) for more accurate cost estimation. As shown in Figure 4.1-1, Schematic Showing Fracture Control Activities through the Design and Hardware Phases, fracture control activities are involved early in the design phase as well as in the hardware phase of the program. The FCP should be updated as needed to keep it current with the documented program fracture control approaches as the design of the hardware matures. Forethought of the activities associated with meeting fracture control requirements is necessary throughout the design and hardware phases for accurate project cost and schedule estimations.

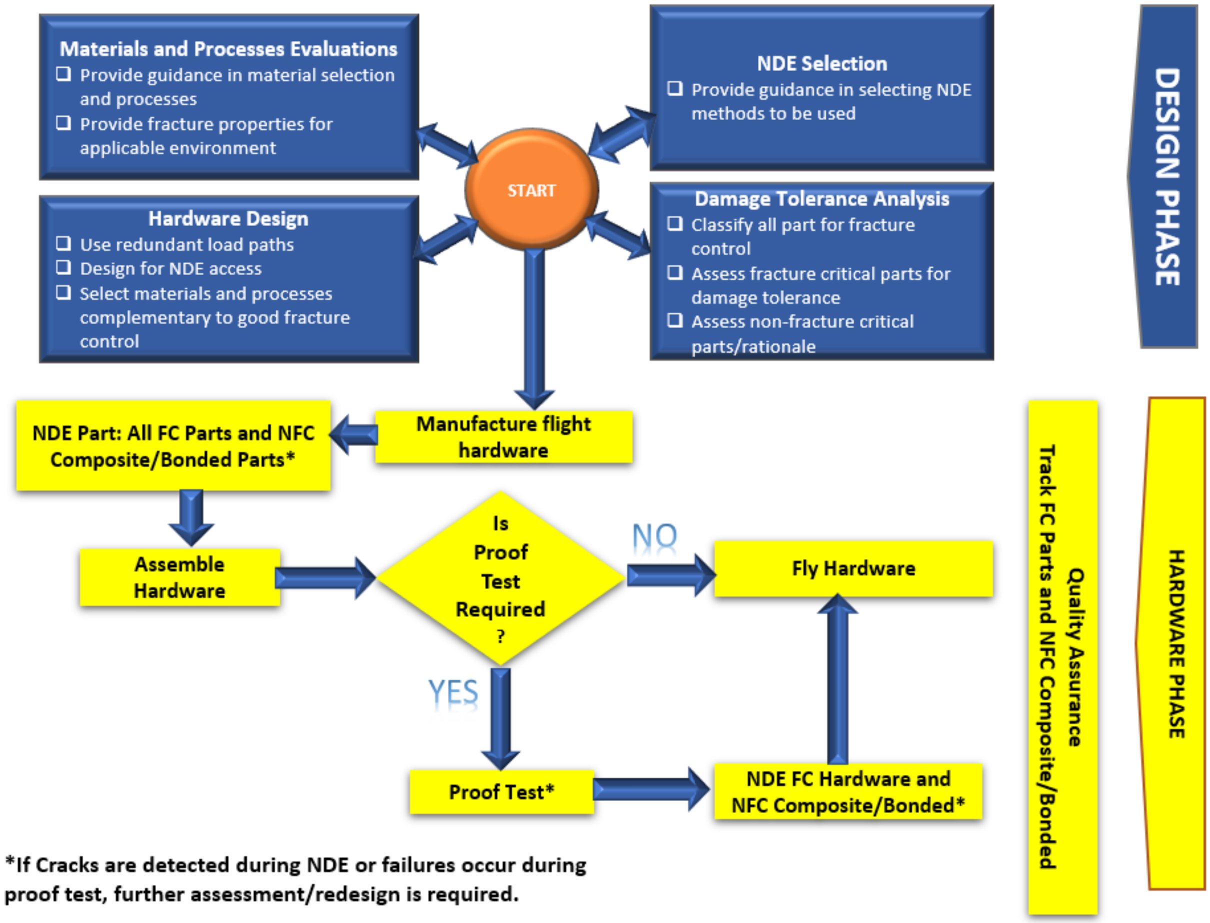


Figure 4.1-1—Schematic Showing Fracture Control Activities through the Design and Hardware Phases

4.2 Responsibilities

4.2.1 Responsible Fracture Control Board

NASA-STD-5019A:
4.2.1 Responsible Fracture Control Board

[FCR 2] The NASA Center responsible for the human-rated spaceflight hardware shall establish and designate a NASA RFCB to ensure compliance with the technical requirements of this document.

[Rationale: The purpose of this requirement is to clearly establish a NASA RFCB as the body responsible for assuring technical compliance with this NASA Technical Standard.]

The NASA RFCB may be an individual or an integrated multi-disciplinary group of individuals who have been authorized by the responsible NASA Center to review and approve the FCP and Fracture Control Summary Report (FCSR) to assure compliance with NASA Technical Standards. The disciplines represented in the RFCB may include materials and processes, damage tolerance, structures, NDE, Safety and Mission Assurance, and design. The NASA RFCB provides oversight to a hardware developer (HD) or prime contractor Fracture Control Boards (FCBs) established by the responsible programs of human-rated spaceflight hardware.

4.2.2 Responsible Program

NASA-STD-5019A:
4.2.2 Responsible Program

[FCR 3] Human-rated spaceflight programs shall impose fracture control on their projects to meet the requirements of this NASA Technical Standard.

[Rationale: The purpose of this requirement is to ensure this NASA Technical Standard is applied to all human-rated spaceflight programs, including those for unmanned vehicles that approach or dock with human-rated vehicles, such as the International Space Station or Orion. Implementation of fracture control mitigates the risk of catastrophic structural failure related to flaws, thereby increasing reliability of the hardware and the safety of the crew.]

The spaceflight program is required to implement fracture control risk mitigation activities for the hardware that is human rated. This is often performed in the program system specification by requiring the system to comply with the requirements in NASA-STD-5019A. This is typically combined with other technical specifications and standards.

Identify fracture control program responsibilities early in the program to support the development of the FCP. The program should identify the group, organization, or person(s) for effective fracture control implementation.

The program designates which entity will establish a program-specific FCB. In some programs, for example, the HD is designated that responsibility. The FCB works in conjunction with and receives oversight by the NASA RFCB in certain activities to ensure that fracture requirements are being met. In other cases, a program may designate the FCB to be a NASA entity. Early in the program, the FCB submits a customized FCP for their hardware to the RFCB for approval. The RFCB reviews that the requirements of NASA Technical Standards are being met. Once the FCP has been approved, that plan becomes the working document from which fracture activities are conducted for that project or program. Typically, day-to-day activities related to fracture control are conducted under the direction and oversight of the FCB (e.g., HD FCB). Special issues or problems, proposal of alternative methodologies, modifications to the FCP later in the program, etc., would be elevated to the RFCB for review. Other items that are elevated to the RFCB are indicated in the NASA-STD-5019A (e.g., activities in certain approaches require RFCB approval). The delegated Technical Authority may also request special evaluations regarding classifications, approaches, or methodologies. Later in the program, the FCSR is another product that requires review by the RFCB.

The lines of responsibility for fracture control activities can be complex. Responsibilities may involve both the line and the project organizations. Generally, the delegated Technical Authority is responsible for overseeing the technical adequacy of a given program or project; and the project organization (such as the HD) is responsible for implementing a technically adequate fracture control program on its hardware. The RFCB provides oversight by reviewing the FCP and FCSR to ensure the requirements are being met. The RFCB may also provide recommendations or evaluations as needed on specific approaches or methodologies.

4.2.3 Fracture Control Implementation

NASA-STD-5019A:
4.2.3 Fracture Control Implementation

[FCR 4] Fracture control implementation shall be performed with the oversight, advice, and approval of the RFCB.

[Rationale: This requirement identifies the RFCB as the technical body responsible for determining the adequacy of fracture control implementation. This determination includes assessing whether the project is deploying sufficient technical capabilities and processes for fracture control. It includes monitoring of damage tolerance assessments and hardware verification activities to assure that all hardware complies with the requirements in this document. To accomplish those goals, the RFCB should have opportunities to review and comment on these activities and have access to all the technical information needed to confirm compliance with this document.]

Each project should identify organizational elements (or technical disciplines) and their responsibilities for implementing and documenting fracture control aspects that affect hardware design, manufacturing, inspections, and planned operations. These responsibilities should be identified at project formulation and documented in the FCP. The organizational elements that implement fracture control and assess current hardware developments should be part of project milestone reviews associated with structural integrity and safety. The RFCB should have an opportunity to participate in and receive summaries of major project reviews as the program formulates system and hardware requirements, as well as when the hardware developer designs and selects technical approaches for meeting fracture control requirements, generates hardware fracture control assessments, and reports on relevant testing.

The program FCB and other entities such as the Safety and Mission Assurance (SMA) representative should assure that the fracture control activities are properly implemented and generate the required documentation in accordance with the NASA Technical Standard. All fracture control activities are performed with the oversight, advice, and approval of the NASA RFCB.

Figure 4.2-1, Lines of Responsibility for Fracture Control, shows a schematic of the lines of responsibilities for fracture control.

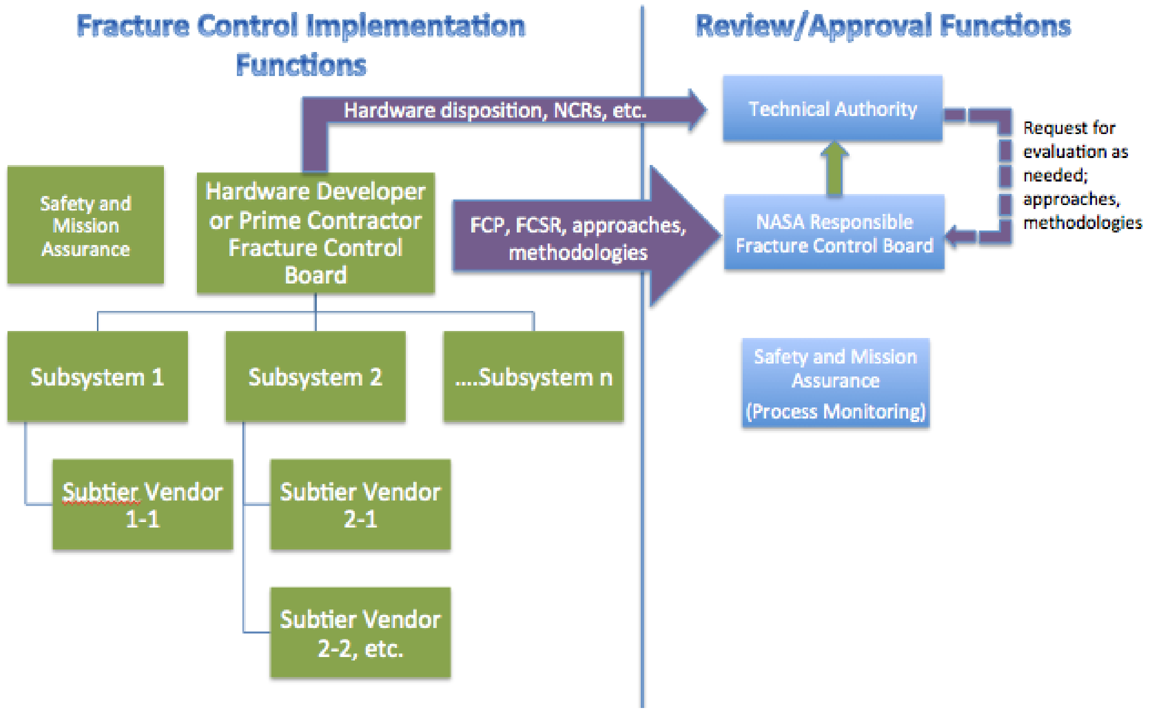


Figure 4.2-1—Lines of Responsibility for Fracture Control

For effective fracture control implementation, the hardware developer or prime contractor FCB should identify the group, organization, or person(s) who have fracture control responsibilities. Since the hardware developer is the entity most familiar with the hardware or system, it is recommended that they be responsible for identifying the relevant fracture control requirements, identifying specific fracture control activities and necessary documentation for the sub-tier piece parts. Following is a list of fracture control activities:

1. Fracture classification of parts/components.

2. Identification and specification of required NDE inspections or any other special requirements on fracture critical parts/components.

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

4. Structural analyses, analytical, and testing methodology used in fracture control.

5. Assessment of anomalies on fracture critical parts/components and for decisions regarding questions or issues relating to fracture control.

6. Compilation of the fracture control documentation.

It is important for designers and analysts to become familiar with fracture control requirements and conduct a hardware assessment to establish the fracture criticality of parts and components.

After a final list of fracture critical parts is determined, the required analyses, tests, inspections, and other fracture control activity should be implemented and monitored to assure timely and proper completion.

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

- Design parts with redundancy. Avoid single-point failures in joints and structures when it is reasonable to do so.
- Design parts and bonds so they can be inspected.
- Avoid through-the-thickness-tension stresses in layered composites.
- Avoid abrupt section changes and stress risers.

4.3 Classification of Parts and Implementation Requirements

NASA-STD-5019A:
4.3 Classification of Parts and Implementation Requirements

[FCR 5] All parts used in human-rated spaceflight hardware shall be evaluated to identify the following:

a. The fracture control classification of each part as either exempt, NFC, or fracture critical.

b. The corresponding approaches that follow the requirements of this NASA Technical Standard to be documented in the FCP.

[Rationale: To implement fracture control, all parts need to be evaluated for criticality to assure they are appropriately classified and to identify subsequent activities related to the classification. Not all parts are fracture critical.]

The approach implemented for fracture control classification of parts is documented in the FCP as described in section 4.1 [FCR 1].

All parts go through a fracture control classification process for all mission phases to determine which parts are fracture critical. Parts may be classified as one of the following:

a. Exempt.
b. NFC.
c. Fracture critical.

Parts classified as exempt are to be exempt for all phases of the service life of the part. Parts that are fracture critical in any phase of the service life of the part are classified as fracture critical. Parts that do not fit into the exempt or NFC categories are to be classified and evaluated as fracture critical parts.

Approaches to evaluate hardware in these three categories are presented in sections 5, 6, and 7 in this NASA Technical Standard. Figure 2, NASA-STD-5019A, Fracture Control Classification Logic Diagram, shows a logic diagram for the classification of parts and references to the applicable sections of this document. Figure 3, Fracture Control Assessment Process and Activities Corresponding to Parts Classifications, is a chart with a general description of activities associated with each classification.

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

Section 4.3 in NASA-STD-5019A requires the classification of parts as either exempt, NFC, or fracture critical, and requires the approaches to be documented in the FCP. Detailed guidance and Figures 2 and 3 of the Standard describe the classification process and the high-level requirements imposed on each classification.

Parts with different NFC classifications during their service life:
The classification of NFC parts may remain the same throughout the part's service lifetime. In some situations, the NFC classification of the part may be more complex. A part may possibly satisfy requirements of one or several NFC classifications during one phase of the service life and different NFC classifications during another phase of the part's service life.

Section 6.1.5 in this Handbook discusses classification of NFC tools, mechanisms, and tethers. A hypothetical example is provided there of a part's service lifetime with five sequential mission phases. The example discusses how the part could conceivably be classified in the following NFC classifications during its service lifetime: 6.2.2, NFC Contained when in storage; 6.2.3, NFC Fail-Safe while secured during some mission phases; and either 6.2.1, NFC Low-Released Mass, or 6.2.5, NFC Low-Risk Parts, during the remaining service life phases. A part such as the one described could also be classified as a part under section 6.1.5, NFC Tools, Mechanisms, and Tethers. In each case, it is assumed the approaches used to classify the part have been documented in the FCP per FCR 1 in NASA-STD-5019A, section 4.1.

Parts with both NFC phases and a fracture critical phase:
Contrast the example discussed in the previous paragraph with a similar, but different, situation where a hypothetical part may be able to satisfy one or several different NFC classification categories at the beginning of its service life and continuing in an NFC classification through more phases of the part's service life until a phase is encountered wherein the part is determined to be a fracture critical part. A question may then arise as to what approach is to be followed for the assessment of the part.

Note the guidance in section 4.3 in NASA-STD-5019A stating:

> *"...Parts that are fracture critical in any phase of the service life of the part are classified as fracture critical...."*

The part is to be classified as fracture critical, even though during phases of the part's lifetime it satisfies requirements for an NFC classification. Accordingly, fracture control requirements in sections 7, 8, and 9 in the NASA-STD-5019A would be applicable. Also note that per these cited requirements, all the loadings encountered from the beginning of the service life based on section 8.1 flaw screening, including loadings when the part could have been classified as NFC, and including the loading throughout the fracture critical phase of the part lifetime are applicable and should be included in the assessment.

Parts with a potential NFC phase after a fracture critical phase:
Now, suppose further that after the fracture critical phase of the service life, the part again satisfies some NFC risk classifications until the end of the part's service life. Note that the

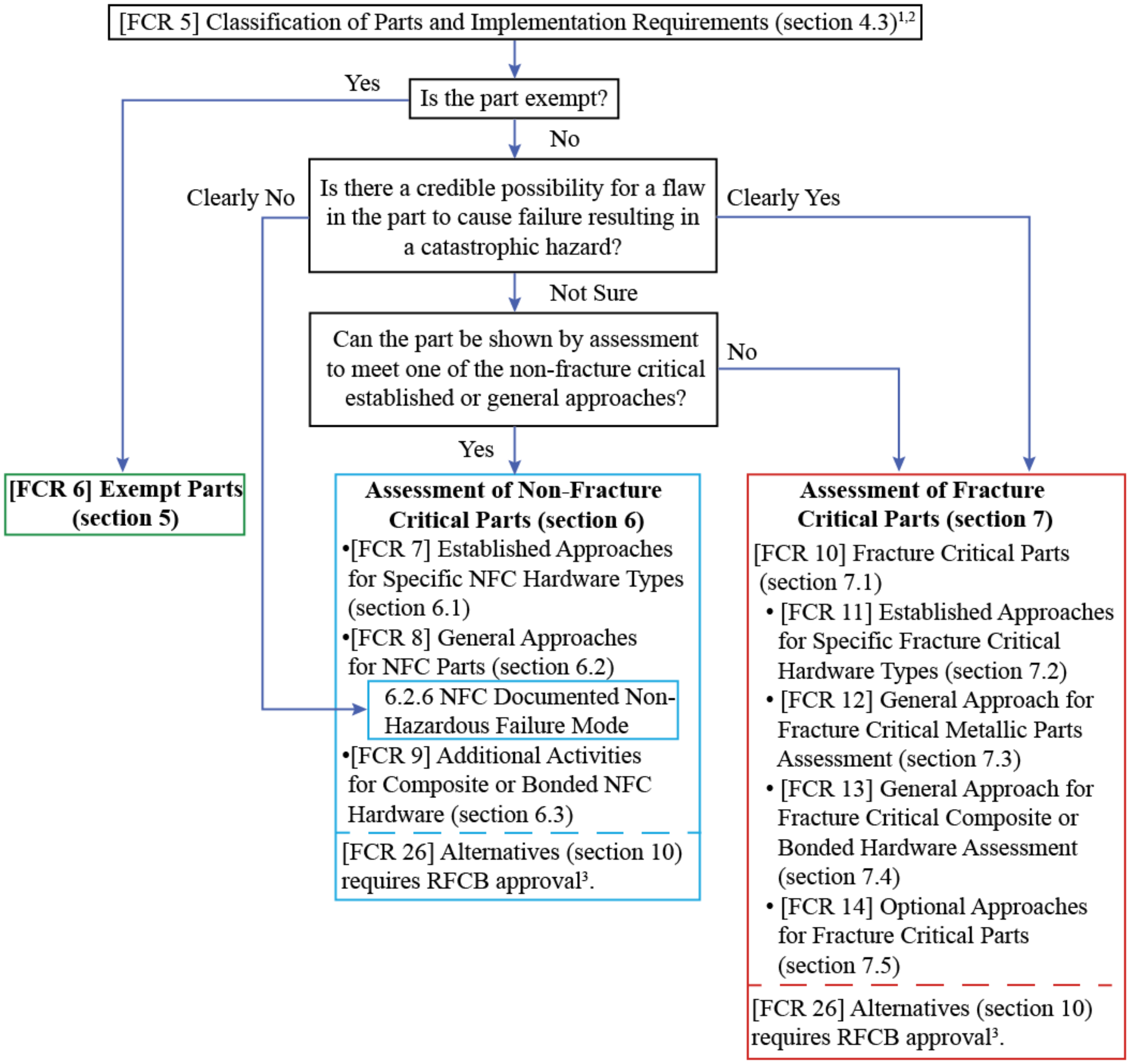
assessment of these latter potential NFC risk phases would have to start with the condition of the part that includes crack growth due to all the previous phases with the factor of 4 on life and demonstrate in that condition that these final phases are NFC.

If these later NFC phases of the part's lifetime are not followed by another fracture critical phase, none of the loadings nor environments acting upon the part in these latter NFC phases of the part's service lifetime affect the fracture control assessment of the part during the fracture critical phase, and they should not be included in the assessment of the fracture critical phase of the part's service life.

Re-flight of a part with NFC phase after a fracture critical phase:
If the part begins another utilization after the end of the defined service life, say as a re-flight of the part, then the loadings and environments occurring during the end of the part's previous service lifetime as an NFC classification would be applicable and should be included along with the rest of the previous service life loadings when performing the assessment for a fracture critical phase in the part's re-flight service lifetime.

Also, as noted in section 3.2 in NASA-STD-5019A under "Re-flight Hardware," "some fracture control categories in the NASA Technical Standard impose additional requirements that are to be satisfied before being re-flown." These categories are section 6.1.4, NFC Sealed Containers; section 6.2.3, NFC Fail-Safe; section 6.2.4, NFC NHLBB Pressurized Components; section 6.2.5, NFC Low-Risk Parts; section 7.4.3, Residual Threat Determination; section 7.5.3, Proof Test Approach for Composite or Bonded Hardware; and section 9.1.3.1, Detailed Information for the FCSR.

For convenience, the NASA-STD-5019A Fracture Control Classification Logic Diagram is included in Figure 4.3-1, NASA-STD-5019A Fracture Control Classification Logic Diagram; and Table 4.3-1, Fracture Control Assessment Process and Activities Corresponding to Parts Classifications, is a general description of activities associated with each classification.



Notes:

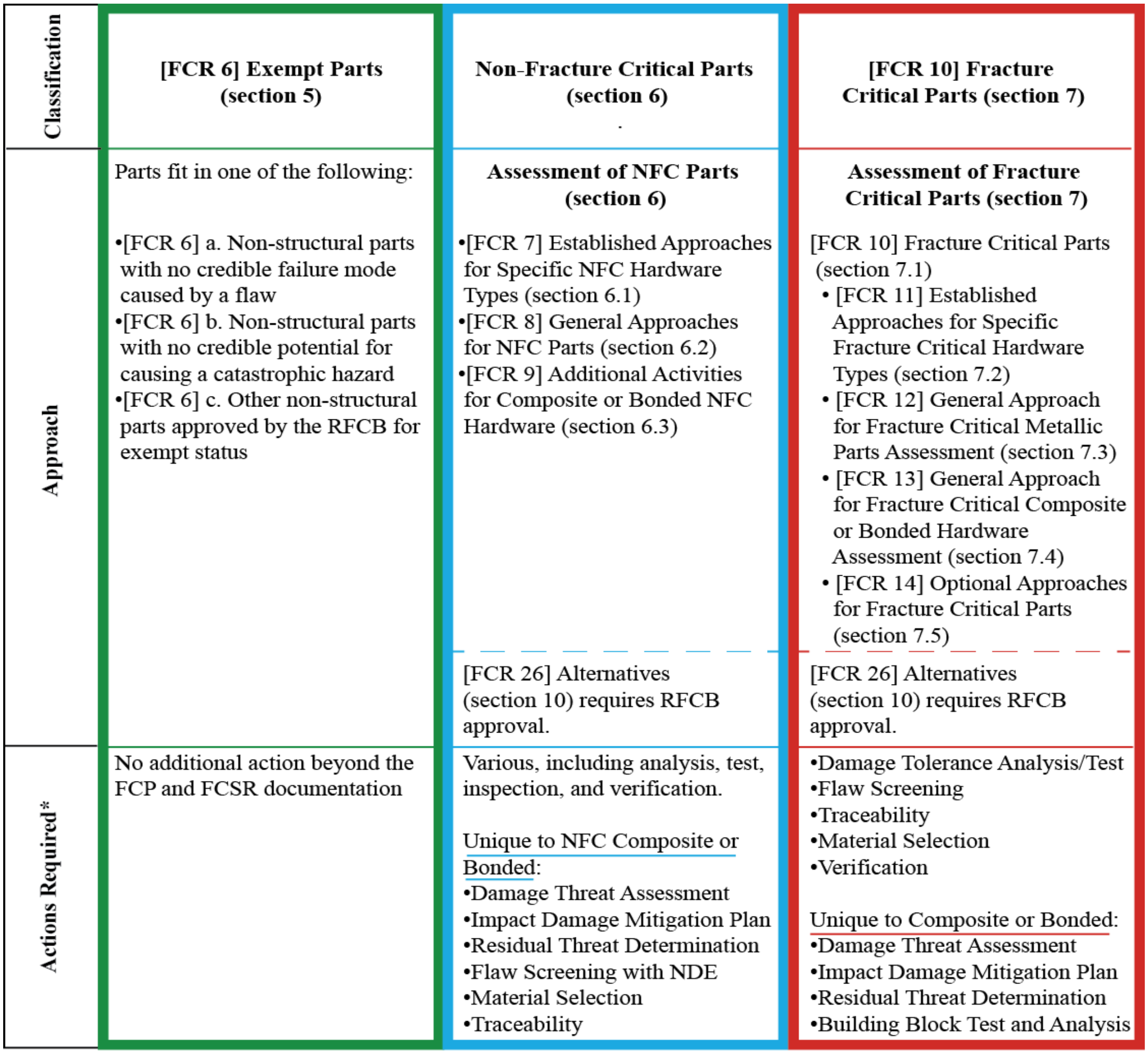
1. Each part is demonstrated to satisfy the selected classification by a process with documentation cited in the Fracture Control Summary Report.
2. A part may always be classified as fracture critical if there is doubt or concern related to demonstrating that it is NFC or exempt.
3. An alternative approach to any classification or category may be developed and presented with rationale to the RFCB for approval in accordance with section 10 in this Standard.

Legend:

NDE	non-destructive evaluation
NFC	non-fracture critical
RFCB	Responsible Fracture Control Board

Figure 4.3-1—NASA-STD-5019A Fracture Control Classification Logic Diagram

Table 4.3-1—Fracture Control Assessment Process and Activities Corresponding to Parts Classifications



Classification	**[FCR 6] Exempt Parts (section 5)**	**Non-Fracture Critical Parts (section 6)**	**[FCR 10] Fracture Critical Parts (section 7)**
Approach	Parts fit in one of the following: •[FCR 6] a. Non-structural parts with no credible failure mode caused by a flaw •[FCR 6] b. Non-structural parts with no credible potential for causing a catastrophic hazard •[FCR 6] c. Other non-structural parts approved by the RFCB for exempt status	**Assessment of NFC Parts (section 6)** •[FCR 7] Established Approaches for Specific NFC Hardware Types (section 6.1) •[FCR 8] General Approaches for NFC Parts (section 6.2) •[FCR 9] Additional Activities for Composite or Bonded NFC Hardware (section 6.3)	**Assessment of Fracture Critical Parts (section 7)** [FCR 10] Fracture Critical Parts (section 7.1) • [FCR 11] Established Approaches for Specific Fracture Critical Hardware Types (section 7.2) • [FCR 12] General Approach for Fracture Critical Metallic Parts Assessment (section 7.3) • [FCR 13] General Approach for Fracture Critical Composite or Bonded Hardware Assessment (section 7.4) • [FCR 14] Optional Approaches for Fracture Critical Parts (section 7.5)
		[FCR 26] Alternatives (section 10) requires RFCB approval.	[FCR 26] Alternatives (section 10) requires RFCB approval.
Actions Required*	No additional action beyond the FCP and FCSR documentation	Various, including analysis, test, inspection, and verification. Unique to NFC Composite or Bonded: •Damage Threat Assessment •Impact Damage Mitigation Plan •Residual Threat Determination •Flaw Screening with NDE •Material Selection •Traceability	•Damage Tolerance Analysis/Test •Flaw Screening •Traceability •Material Selection •Verification Unique to Composite or Bonded: •Damage Threat Assessment •Impact Damage Mitigation Plan •Residual Threat Determination •Building Block Test and Analysis

***Note:** Documentation is required for **all** classifications [FCR 1]. In addition to these unique actions, documentation of the approach used to demonstrate that each part satisfies the selected classification is to be cited in the Fracture Control Summary Report [FCR 24].

Legend:

FCP	Fracture Control Plan
FCSR	Fracture Control Summary Report
NDE	non-destructive evaluation
NFC	non-fracture critical
RFCB	Responsible Fracture Control Board

4.4 Other Requirements

Implementation of fracture control and full compliance with fracture control requirements do not relieve the HD from compliance with other hardware design and test requirements, quality assurance requirements, or materials requirements that are applicable independent of fracture control.

For example, NASA-STD-5001, Structural Design and Test Factors of Safety for Spaceflight Hardware, levies strength and structural test requirements on flight hardware and these requirements have to be met in addition to fracture control. In the case of other requirements that overlap with fracture control requirements, it is generally acceptable to combine requirements to minimize the effort. If fracture control required a proof test for flaw screening and structures required a proof test for structural integrity demonstration, it would be prudent to have one proof test do both.

5. EXEMPT PARTS (NASA-STD-5019A, Section 5)

NASA-STD-5019A:
5. EXEMPT PARTS

In some cases, parts may be classified as exempt.

[FCR 6] Each part classified as exempt shall fit into one of the following categories:

a. Non-structural parts with no credible failure mode caused by a flaw.
b. Non-structural parts with no credible potential for causing a catastrophic hazard.
c. Other non-structural parts approved by the RFCB for exempt status.

[Rationale: Non-structural parts that do not have a credible failure mode caused by a flaw and those with no credible potential for causing a catastrophic hazard do not need to be assessed for fracture criticality because they do not pose a catastrophic hazard.]

Use of an alternative approach requires unique rationale and approval by the RFCB as described in section 10 [FCR 26] in this NASA Technical Standard.

Parts that are identified and shown to meet the exempt classification criteria in documentation cited in the Fracture Control Summary Report (FCSR) in accordance with the requirements listed in section 9 of this NASA Technical Standard comply with fracture control requirements without further activity beyond conventional aerospace verification and quality assurance procedures, unless otherwise indicated in this document.

Exempt parts typically include non-structural items or items that do not have a credible failure mode related to the presence of a flaw, such as flexible insulation blankets, enclosed electrical circuit components/boards, wire bundles, and certain batteries listed in section 6.1.6 in this NASA Technical Standard. The RFCB may accept other items as exempt based on rigorous development programs that establish their safety and functional reliability.

Non-structural parts are generally those not intended to resist loads. A part that may be structural in one system or application may not be in another. Discussion with the RFCB may be necessary.

Parts with no failure modes of concern due to flaws such as structural failure, leakage, debris, or loss of function are likely to be considered as exempt. All electrical circuit elements are typically considered exempt. Non-structural items where loss of function is not catastrophic may also be considered exempt. Early coordination with the RFCB is essential for any part to be classified exempt other than the typical exempt parts such as flexible insulation blankets, enclosed electrical circuits, and wire bundles.

Exempt hardware typically includes non-structural items such as flexible insulation blankets, switches, sensors, enclosed electrical circuit components/boards, electrical connectors (including locking devices), wire bundles, small common batteries, and elastomeric seals. Small mechanical parts, such as washers, bearings, and valve seats that have been developed and qualified through required test programs and rigorous process control to demonstrate their reliability and whose failure does not directly lead to a catastrophic hazard may be exempt from fracture control. Common off-the-shelf tools such as pliers, wrenches, etc., are generally exempt from fracture control.

Items that do not lend themselves to the fracture control process and have verification programs that establish the reliability of their must-work functions may be exempt with RFCB approval. Some examples may include items such as sensors with embedded glass elements, roller/ball bearings, and pressure assisted seals used in ducting.

The HD identifies the parts that will be exempt from fracture control and obtain the approval of the RFCB for this classification. Individual listings of exempt parts do not need to be supplied to the RFCB. Parts with common application and characteristics may be collectively identified as exempt.

6. ASSESSMENT OF NON-FRACTURE CRITICAL (NFC) PARTS

6.1 Established Approaches for Specific NFC Hardware Types (NASA-STD-5019A, Section 6.1)

NASA-STD-5019A:
6.1 Established Approaches for Specific Non-Fracture Critical (NFC) Hardware Types

Parts in this category are classified NFC if documented assessment cited in the FCSR shows they satisfy the specified criteria listed in the item corresponding to the hardware type. Composite and bonded hardware are to satisfy section 6.3 in this NASA Technical Standard in addition to requirements for a specific hardware type.

[FCR 7] To be classified as NFC, each part that is described by a specific hardware type in the following list shall comply with the established approach given in the referenced subsection:

a. NFC metallic fasteners, rivets, shear pins, and locking devices comply with section 6.1.1 in this NASA Technical Standard.

b. NFC shatterable components and structures comply with section 6.1.2 in this NASA Technical Standard.

c. NFC rotating hardware complies with section 6.1.3 in this NASA Technical Standard.

d. NFC sealed containers comply with section 6.1.4 in this NASA Technical Standard.

e. NFC tools, mechanisms, and tethers comply with section 6.1.5 in this NASA Technical Standard.

f. NFC batteries comply with section 6.1.6 in this NASA Technical Standard.

[Rationale: Parts that can be shown to have no credible catastrophic hazard resulting from a failure of the part caused by a flaw or to have no credible possibility for flaws to cause failure are not fracture critical. These parts can be classified as NFC. To assist this classification process, a number of established approaches have been developed for specific hardware types that are documented in this NASA Technical Standard.]

Use of an alternative approach requires unique rationale and approval by the RFCB as described in section 10 [FCR 26] in this NASA Technical Standard.

The following sections discuss approaches for non-fracture critical classifications. Discussion will include some additional information that the analyst may also find useful in the implementation of the methodology for NFC parts.

Parts may be classified as non-fracture critical non-hazardous based on hazard assessment if their failure due to a flaw does not result in a catastrophic hazard. Items that do not lend themselves to the fracture control process and have verification programs that establish the reliability of their must-work functions would require discussion with RFCB.

6.1.1 NFC Metallic Fasteners, Rivets, Shear Pins, and Locking Devices (NASA-STD-5019A, Section 6.1.1)

NASA-STD-5019A:
6.1.1 NFC Metallic Fasteners, Rivets, Shear Pins, and Locking Devices

To classify a part as an NFC metallic fastener, rivet, shear pin, or locking device, satisfy any of the following items in sections 6.1.1.1 through 6.1.1.6, depending on application, hardware type, and failure modes, to comply with requirement [FCR 7], section 6.1.a in this NASA Technical Standard.

The following subsections provide guidance in assessing, testing, and classifying metallic fasteners, rivets, shear pins, and locking devices (collectively described as “fastening hardware” herein) as NFC per requirement [FCR 7], item 6.1.a, of NASA-STD-5019A.

6.1.1.1 NFC Low-Released Mass Fasteners, Rivets, or Shear Pins (NASA-STD-5019A, Section 6.1.1.1)

NASA-STD-5019A:
6.1.1.1 NFC Low-Released Mass Fasteners, Rivets, and Shear Pins

To classify a metallic fastener, rivet, or pin as NFC low-released mass, meet the requirements of section 6.2.1 in this NASA Technical Standard.

A metallic fastener, rivet, or pin that has an individual single-point structural failure or a group of fasteners, rivets, or pins where loss of any one fastener, rivet, or pin does not present a catastrophic hazard can be classified in one of these NFC categories.

Beyond showing that fracture of an NFC low-release mass fastening hardware does not cause a catastrophic hazard (or release of a hazardous fluid), one must include an assessment showing that all potentially impacted hardware, equipment, etc., also maintains structural integrity as outlined in NASA-STD-5019A, section 6.2.1. The analysis should utilize the maximum energy source for the released component.

In the case of NFC composite components, one is required to demonstrate the composite material still has positive structural margins under design ultimate loads combined with the assumed worst-case impact damage from a failed fastener, rivet, or shear pin. An approach with which many may be familiar includes using the "punch equation" to assess containment as outlined in section 6.2.2.1 in Volume 2 of this Handbook. But this type of assessment focuses on ductile materials with defined yield strength values, and extreme caution should be used in applying this to brittle composite structure. Because of the brittle nature of composite materials, a more appropriate path should be undertaken through a validated analysis approach (employing software such as LS-DYNA® or Marc™) in combination with appropriate test data, such as coupon or component impact testing. Note that the liberated debris from an NFC part needs to be accounted for potential impact to a fracture critical part. For fracture critical composite materials or bonded parts, the impact damage has to be included in the Damage Threat Assessment and Residual Threat Determination as detailed in NASA-STD-5019A, section 7.4.

All rivet applications should be designed NFC low release, contained, or fail safe (see below in section 6.1.1.3) and thus subject to conventional verification and quality assurance requirements only. Fracture critical rivets are unacceptable because fracture control for them is impractical and would be very difficult to implement.

Typically, shear pins are contained by design (i.e., trapped in a tight-fitting hole at the interface between two components) and would fall under classification in NASA-STD-5019A, section 6.1.1.2. For those atypical cases, one should design for NFC low-release mass, or be forced to classify as fracture critical per NASA-STD-5019A, section 7.3.

6.1.1.2 NFC Contained Fasteners, Rivets, or Shear Pins (NASA-STD-5019A, Section 6.1.1.2)

> **NASA-STD-5019A:**
> **6.1.1.2 NFC Contained Fasteners, Rivets, and Shear Pins**
>
> To classify a metallic fastener, rivet, or pin as NFC contained, meet the requirements of section 6.2.2 in this NASA Technical Standard.
>
> *A metallic fastener, rivet, or pin that has an individual single-point structural failure or a group of fasteners, rivets, or pins where loss of any one fastener, rivet, or pin does not present a catastrophic hazard can be classified in one of these NFC categories.*

Beyond showing that fracture of NFC-contained fastening hardware does not cause a catastrophic hazard (or release of a hazardous fluid), one must include an assessment to demonstrate the contained fastening hardware does not penetrate, fracture, or escape its enclosure per NASA-STD-5019A, section 6.2.2. For the containment analysis, all energy sources should be considered and the approach validated through testing or similar assessments.

Analysis of a metallic enclosure for penetration should use the "punch equation" approach and assume the minimum wall thickness, when known, or an appropriate uncertainty factor on nominal thickness. Details of the containment analysis can be found in section 6.2 in Volume 2 of this Handbook, including preloaded fasteners. One should keep in mind that larger masses may not penetrate through an enclosure, but simply require significant energy dissipation. In this case, a single fastener (or small group) may need to accept this energy input. So, one should consider the potential impact patterns and how they relate to the fastener joints, as well as how the joints may fail (e.g., in fastener tension or by extrusion of the fastener head through the enclosure wall); this is detailed in section 6.2.2.5 in Volume 2 of this Handbook. The resultant enclosure wall deflections and energy dissipation in the remaining fastened joints should also be evaluated. With the potential complexity of these analyses, impact tests under flight-like conditions should also be strongly considered and conducted if necessary.

In the case of NFC composite components, one is required to demonstrate the composite material still has positive structural margins under design ultimate loads combined with the assumed worst-case impact damage from a failed fastener, rivet, or shear pin. Use of the "punch equation" is not recommended without understanding its limitations. This type of assessment focuses on ductile materials with defined yield strength values, and extreme caution should be used in applying this to brittle composite structure. Because of the brittle nature of composite materials, a more appropriate path should be undertaken through a validated analysis approach (employing software such as LS-DYNA® or Marc™) in combination with appropriate test data, such as coupon or component impact testing. Note that the liberated debris from an NFC part needs to be accounted for potential impact to a fracture critical part. For fracture critical composite materials, the impact damage has to be included in the Damage Threat Assessment and Residual Threat Determination as detailed in NASA-STD-5019A, section 7.4.

In general, the enclosure and its own support structure also has to meet the appropriate fracture control requirements detailed in NASA-STD-5019A, sections 7 through 9, while continuing to meet all performance criteria after impact. In cases where the enclosure has openings which are secured closed by mechanisms, the design has to show single-fault tolerance against release of components.

All rivet applications should be designed NFC low release, contained, or fail safe (see below in section 6.1.1.3) and thus subject to conventional verification and quality assurance requirements only. Fracture control for fracture critical rivets is impractical and would be very difficult to implement.

Release of a free mass from a fastener that is mechanically constrained (e.g., using safety wire) can be ignored, as this is assumed to produce particles of negligible size. All constrained fasteners can be classified NFC if failure does not result in a catastrophic hazard due to loss of structural integrity of the fastener, or loss of a safety-critical function.

6.1.1.3 NFC Fail-Safe Rivets (NASA-STD-5019A, Section 6.1.1.3)

NASA-STD-5019A:
6.1.1.3 NFC Fail-Safe Rivets

To classify metallic rivet applications as NFC fail-safe, meet the requirements in section 6.2.3 in this NASA Technical Standard.

NFC fail-safe rivets have to satisfy the general requirements for all NFC fail-safe components per NASA-STD-5019A, section 6.2.3. This normally entails performing a structural analysis whereby the most highly loaded rivet in a local pattern is fully removed from the load path (i.e., to simulate a complete failure of the part). Multiple analyses may be required to investigate all mission phases. It is then demonstrated that all structural margins remain positive under the new load path distribution; this includes the remaining rivets as well as the surrounding structure. Dynamic response of the structure should also be considered in this assessment to ensure that primary launch frequencies are not altered so greatly as to effect load input amplification. Typically, it is acceptable to perform the margin calculations for this scenario using an FS = 1.0; but each project could approve varying approaches, so consultation is necessary with the responsible Technical Authority. This exercise also has to show that no resulting catastrophic hazard is created under load path re-distribution and/or fatigue damage is not present due to the NFC fail-safe scenario.

One must also keep in mind that this analysis has to continue to show that failure of the rivet does not create debris that would violate the NFC low-release mass requirements of NASA-STD-5019A, section 6.2.1.

In the case of NFC composite components, one is required to demonstrate the composite material still has positive structural margins under design ultimate loads combined with the assumed worst-case impact damage from the NFC fail-safe rivet. An approach with which many may be familiar includes using the "punch equation" to assess containment as outlined in section 6.2.2 in Volume 2 of this Handbook. But this type of assessment focuses on ductile materials with defined yield strength values, and extreme caution should be used in applying this to brittle composite structure. Because of the brittle nature of composite materials, a more appropriate path should be undertaken through a validated analysis approach (employing software such as LS-DYNA® or Marc™) in combination with appropriate test data, such as coupon or component impact testing. Note that the liberated debris from an NFC part needs to be accounted for potential impact to a fracture critical part. For fracture critical composite materials, the NFC-contained impact damage has to be included in the Damage Threat Assessment and Residual Threat Determination as detailed in NASA-STD-5019A, section 7.4.

6.1.1.4 NFC Low Risk Fasteners (NASA-STD-5019A, Section 6.1.1.4)

NASA-STD-5019A:
6.1.1.4 NFC Low Risk Fasteners

To classify metallic fasteners as NFC low risk, meet the following:

a. The fastener is in a local pattern of two or more similar fasteners.

b. The fastener satisfies all of the following general fastener attributes:

   (1) Fasteners are fabricated from a metal with high resistance to stress corrosion cracking, as defined in MSFC-STD-3029, Guidelines for the Selection of Metallic Materials for Stress Corrosion Cracking Resistance in Sodium Chloride Environments.

   (2) Fasteners are fabricated to a military, NAS, or commercial aerospace specification approved by the procuring organization.

      A. The standard and/or associated procurement specification includes tensile, shear, and fatigue testing as part of lot acceptance.

      B. Fasteners with complete traceability are delivered with the Material Test Report or equivalent that includes the following:

         i. The raw material and heat-treat certifications.

         ii. Documentation of applicable testing or processing required in the associated procurement specification.

Fasteners that are manufactured from the following list of ductile materials show a high tolerance for typical fastener defects and flaws. These are typically accepted as low-risk fasteners. Examples of procurement specifications for these commonly accepted low-risk fastener materials are:

- *Iron-based superalloy A286: NAS4003, Fastener, A286 Corrosion Resistant Alloy, Externally Threaded, 160 KSI F_{tu}, 95 KSI F_{su}, 1000 °F; NA0026, Procurement Specification Metric Fasteners, A-286 CRES Externally Threaded, 1100 MPa Tensile, 660 MPa Shear; or equivalent.*
- *Nickel-based superalloy Inconel 718: NASM 85604, Bolt, Nickel Alloy 718, Tension, High Strength, 125 KSI F_{su} and 220 KSI F_{tu}, High Temperature, Spline Drive; or equivalent.*
- *Cobalt-Chromium-Nickel-based superalloy MP35N: AS7468,*

Bolts, Cobalt-Chromium-Nickel Alloy, UNS R30035, Tensile Strength 260 Ksi, Procurement Specification; or equivalent.

- *Austenitic Stainless Steel 300 Series CRES: NA0271, Metric Fasteners, CRES 300 Series, Externally Threaded, MJ Thread, 500 MPa F_{tu} and 700 MPa F_{tu}; or equivalent.*

(3) Fasteners are not made from any titanium alloy.

Titanium alloys, such as Ti-6Al-4V, cp-Ti, and other titanium alloys are not acceptable in this category because of generic EAC or SLC failure modes, as well as low fracture toughness.

(4) The fastened joint complies with both of the following from NASA-STD-5020, Requirements for Threaded Fastening Systems in Spaceflight Hardware:

A. Preload control as detailed in section 6.1 of NASA-STD-5020.

B. No joint separation in the nominal loading configuration as described in sections 4.3 and 6.5 of NASA-STD-5020.

(5) Fasteners are subject to the following:

A. Have rolled threads, with the rolling process occurring after all thermal treatment of the material.

B. The results of the mandatory lot acceptance fatigue testing are required to establish that the fasteners meet the fatigue requirements in NASA-STD-5001.

C. For fastener types that do not require fatigue testing as part of lot acceptance, samples from the lot need to be submitted for fatigue testing in accordance with NASM1312-11, Fastener Test Methods, Method 11 Tension Fatigue, and NAM1312-111, Fastener Test Methods, Method 111 Tension Fatigue, or equivalent, to satisfy 6.1.1.4.b.(2) above.

(6) The fasteners are not made from a low fracture toughness alloy, as defined in section 3.2 in this NASA Technical Standard.

(7) Fasteners are not reworked or custom made unless the application is approved by the RFCB.

To be classified NFC low-risk, fasteners have to be in a pattern of two or more and comply with additional general requirements per NASA-STD-5019A, section 6.1.1.4. Some of these are common to other standards and include:

- Using materials not sensitive to stress corrosion cracking (see MSFC-STD-3029).
- Avoiding use of low fracture toughness materials as defined by NASA-STD-5019A, section 3.2.
- Employing fasteners with rolled threads which meet fatigue requirements of NASA-STD-5001.
- Fasteners fabricated, procured, and inspected according to a military, NAS, or equivalent, approved commercial aerospace specification.
- Not be reworked or custom made without prior RFCB approval.

But several other requirements have been added, unique to NASA-STD-5019A, to improve the integrity and reliability of fasteners classified as low-risk. Following details outlined in NASA-STD-5020, low-risk fasteners now are required to have preload control per section 6.1, and positive joint separation margins under nominal loading conditions per sections 4.3 and 6.5 of NASA-STD-5020. This ensures a good understanding of the operating preload range and prevents joint gapping which could lead to fastener fatigue and/or dynamic response issues. In addition, full traceability is required for delivered flight fasteners, including both (a) raw material heat-treat certifications and (b) fastener lot testing information, such as tensile, shear, and fatigue results as part of a Material Test Report.

NASA-STD-5019A, item 6.1.1.4.b.(2)B, provides a list of fasteners typically accepted as low risk due to their ductility and high tolerance against defects and flaws. A reformatted copy of the list is reproduced here for completeness:

- <u>Iron-based superalloy A286</u>:
  - NAS4003: Fastener, A286 Corrosion Resistant Alloy, Externally Threaded, 160 ksi F_{tu}, 95 ksi F_{su}, 1000 °F
  - NA0026: Procurement Specification Metric Fasteners, A-286 CRES Externally Threaded, 1100 MPa Tensile, 660 MPa Shear
- <u>Nickel-based superalloy Inconel™ 718</u>:
  - NASM85604: Bolt, Nickel Alloy 718, Tension, High Strength, 125 ksi F_{su} and 220 ksi F_{tu}, High Temperature, Spline Drive
- <u>Cobalt-Chromium-Nickel-based superalloy MP35N</u>:
  - SAE AS7468: Bolts, Cobalt-Chromium-Nickel Alloy, UNS R30035, Tensile Strength 260 ksi, Procurement Specification
- <u>Austenitic Stainless Steel 300 Series CRES</u>:

  - NA0271: Metric Fasteners, CRES 300 Series, Externally Threaded, MJ Thread, 500 MPa F_{tu} and 700 MPa F_{tu}

If fatigue test data from the fastener manufacturer is not available, testing is required in accordance with NASM1312-11 for standard (English) fasteners, or NASM1312-111 for metric fasteners. This may be the case with small fasteners (i.e., sizes less than 0.19 in or 5 mm), so additional tension fatigue performance will need to be documented to satisfy 6.1.1.4.b.(2) in NASA-STD-5019A. The following provides a list of general NAS fastener testing specifications:

- NASM1312-6: Fastener Test Methods, Method 6, Hardness.
- NASM1312-8: Fastener Test Methods, Method 8, Tensile Strength.
- NASM1312-11: Fastener Test Methods, Method 11, Tension Fatigue.
- NASM1312-20: Fastener Test Methods, Method 20, Single Shear.
- NASM1312-108: Fastener Test Methods, Metric, Method 108, Tensile Strength.
- NASM1312-111: Fastener Test Methods, Metric, Method 111, Tension Fatigue.
- NASM1312-113: Fastener Test Methods, Metric, Method 113, Double Shear.

One must note that fasteners made from *any* form of titanium alloy cannot be classified as NFC low risk under any circumstances. Alloys such as Ti-6Al-4V and cp-Ti possess low-fracture toughness and increased susceptibility to environmentally assisted cracking (EAC) or sustained load cracking (SLC) failure modes. An example is available in published literature (Lewis and Kenny, 1976) on EAC, while another publication describes testing of the effects of hydrogen content and temperature on SLC in Ti-6Al-4V (Boyer and Spurr, 1978).

A general point to consider is that toughness tends to decrease with increase in strength and tends to increase with an increase in ductility. If a fastener is steel and the K_{Ic} value is not known, low fracture toughness has to be assumed when the A-basis ultimate strength is greater than 180 ksi (1241 MPa).

6.1.1.5 NFC Fail-Safe Fasteners (NASA-STD-5019A, Section 6.1.1.5)

NASA-STD-5019A:
6.1.1.5 NFC Fail Safe Fasteners

To classify metallic fasteners as NFC fail-safe, meet the following:

a. The fasteners meet the fail-safe requirements in section 6.2.3 in this NASA Technical Standard.

b. The fastener satisfies all of the following general fastener attributes:

(1) Fasteners are fabricated from a metal with high resistance to stress corrosion cracking as defined in MSFC-STD-3029.

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

(3) The fastened joint complies with NASA-STD-5020 without joint separation in the nominal configuration

(4) Fasteners have rolled threads and are assessed to establish that they meet the fatigue requirements in NASA-STD-5001.

(5) The fasteners are not made from a low fracture toughness alloy as defined in section 3.2 in this NASA Technical Standard.

(6) Fasteners are not reworked or custom made unless the application is approved by the RFCB.

(7) Fasteners manufactured from titanium alloys require additional considerations for this classification, including risk mitigation and assessment that are approved by the RFCB

Titanium alloys, such as Ti-6Al-4V (including annealed and STA conditions), cp-Ti, and other titanium alloys, have potential generic EAC or SLC failure modes that are not mitigated by the fail-safe requirements. Additional risk mitigation is needed for their use in this classification with an assessment that establishes that there is no credible risk of generic fastener failures related to flaws or under applied load. The assessment should include credible initial fastener defects/crack size, the largest credible preload, and maximum service life loading and should compare the Critical Stress Intensity Factor to K_{SLC} *and* K_{EAC} *lower bound values determined from tests of flawed fasteners in applicable service life environments.*

NFC fail-safe fasteners have to satisfy the general requirements for all NFC fail-safe components per NASA-STD-5019A, section 6.2.3. This normally entails performing a structural analysis whereby the most highly loaded fastener in a local pattern is fully removed from the load path (i.e., to simulate a complete failure of the part). Multiple analyses may be required to investigate all mission phases. Further, identification of the “most highly loaded” fastener may be difficult when both shear and tensile loads are involved. For these cases, it is recommended that two separate analyses be performed where the most highly loaded fastener in tension *or* shear is removed. The fastener with the lowest margin (if not one of the above cases) should also be a candidate for removal. It has to be demonstrated that all structural margins remain positive under the new load path distribution; this includes the remaining fasteners as well as the surrounding structure. Dynamic response of the structure should also be considered in this assessment to ensure that primary launch frequencies are not altered so greatly as to effect load input amplification. Conversely, a joint separation assessment is not required under this special analysis. Typically, it is acceptable to perform the margin calculations for this scenario using an FS = 1.0, but each project could approve varying approaches; so, consultation is necessary with the delegated Technical Authority. It is also recommended that one use the analysis approaches outlined in NASA-STD-5020 (sections 4 and 6) if not specifically required by the responsible Technical Authority. This exercise also has to show that no resulting catastrophic hazard is created under load path re-distribution, and/or fatigue damage is not present due to the NFC fail-safe scenario.

Keep in mind that fail-safe analysis has to continue to show that failure of the fastener does not create debris that would violate the NFC low-release mass requirements of NASA-STD-5019A, section 6.2.1

In the case of NFC composite components, one is required to demonstrate the composite material still has positive structural margins under design ultimate loads combined with the assumed worst-case impact damage from the NFC fail-safe fastener. An approach many may be familiar with includes using the "punch equation" to assess containment as outlined in section 6.2.2 of Volume 2 of this Handbook. But this type of assessment focuses on ductile materials with defined yield strength values, and extreme caution should be used in applying this to brittle composite structure. Because of the brittle nature of composite materials, a more appropriate path should be undertaken through a validated analysis approach (employing software such as LS-DYNA® or Marc™) in combination with appropriate test data, such as coupon or component impact testing. Note that the liberated debris from an NFC part needs to be accounted for potential impact to a fracture critical part. For fracture critical composite materials, the NFC fail-safe impact damage has to be included in the Damage Threat Assessment and Residual Threat Determination as detailed in NASA-STD-5019A, section 7.4.

Unlike fail-safe rivets, fail-safe fasteners must also comply with additional general requirements per NASA-STD-5019A, section 6.1.1.5. These have been detailed in other standards and include:

- Using materials not sensitive to stress corrosion cracking (see MSFC-STD-3029).

- Avoiding use of low fracture toughness materials as defined by NASA-STD-5019A, section 3.2.
- Employing fasteners with rolled threads which meet fatigue requirements of NASA-STD-5001.
- Fasteners fabricated, procured, and inspected according to a military, NAS, or equivalent approved commercial aerospace specification.
- Not be reworked or custom made without prior RFCB approval.

In addition, following details outlined in NASA-STD-5020, fail-safe fasteners are required to possess positive joint separation margins under nominal loading conditions per sections 4.3 and 6.5 of NASA-STD-5020.

While titanium alloys are not specifically excluded from the fail-safe category (as they are with low risk), additional assessment and an approved approach for use have to be provided to the RFCB. This could include lot-specific testing of the candidate Ti fasteners (e.g., fatigue under environmental conditions), joint preload evaluation, etc. Alloys such as Ti-6Al-4V and cp-Ti possess low-fracture toughness and increased susceptibility to EAC or SLC failure modes. An example is available in published literature (Lewis and Kenny, 1976) on EAC, while another publication describes testing of the effects of hydrogen content and temperature on SLC in Ti-6Al-4V (Boyer and Spurr, 1978).

6.1.1.6 NFC Locking Devices (NASA-STD-5019A, Section 6.1.1.6)

NASA-STD-5019A:
6.1.1.6 NFC Locking Devices

To classify metallic locking devices to prevent fastener or connector backout, including wires, tangs, or other methods, as NFC locking devices, NFC hardware is to meet the requirements of section 6.2.1 in this NASA Technical Standard.

Locking devices to prevent fastener or connector back-out include wires, tangs, adhesives, and other methods. All these components should satisfy the requirements of NASA-STD-5019A, section 6.2.1, for a low-release mass classification as described above in section 6.1.1.1.

6.1.2 NFC Shatterable Components and Structures (NASA-STD-5019A, Section 6.1.2)

NASA-STD-5019A:
6.1.2 NFC Shatterable Components and Structures

To classify parts as NFC shatterable components or structures, satisfy one of the items listed below in section 6.1.2.1 or section 6.1.2.2 in this NASA Technical Standard, depending on application and hardware type, to meet requirement [FCR 7], section 6.1.b in this NASA Technical Standard.

6.1.2.1 NFC Internal Shatterable Components

Shatterable components and structures are classified as NFC by one of the following:

a. For shatterable components and structures inside habitable volumes, meet the following:

(1) Requirements in section 6.2.2 in this NASA Technical Standard.

(2) The particulate containment requirements in NASA-STD-5018, Strength Design and Verification Criteria for Glass, Ceramics, and Windows in Human Space Flight Applications.

b. For shatterable components and structures inside non-habitable volumes, meet the requirements in sections 6.2.1, 6.2.2, 6.2.3, 6.2.4, or 6.2.6 in this NASA Technical Standard.

6.1.2.2 NFC External Shatterable Components

[Note: it is assumed the NASA Technical Standard section 6.1.2.2 will be modified by an administrative change to correct errors as shown by the strikeout of "either" and "or" and inserting "and" as shown below.]

To classify parts as NFC shatterable components or structures located on the external surface of a spacecraft that are manufactured from a material with limited ductility such that it is prone to brittle failures when cracked and/or subjected to impact, meet 6.1.2.2.a, 6.1.2.2.b, and 6.1.2.2.c below:

a. A DTA and IDMP are developed to mitigate credible catastrophic impacts from vehicle loss of external surface mass, crew exposure, micrometeoroid and orbital debris (MMOD), extravehicular activity (EVA), inadvertent contacts, and EVA tool impact hazards.

b. The design has sufficient structural integrity such that the loss of a primary member does not result in catastrophic loss of spaceflight hardware function or required strength that prevents the hardware from safely completing the mission.

c. Any mass released from these components meets the low-released mass requirements of section 6.2.1 in this NASA Technical Standard.

Refer to section 7.4.1 for DTA and 7.4.2 for IDMP.

The title of this section uses the terms "shatterable," "components," and "structures." Before discussing “shatterable,” a clarification of the definition of “part” is being offered. NASA-STD-5019A, section 3.2, describes a component as "a hardware unit considered a single entity for the purpose of fracture control" and states "a component contains at least one part." Section 3.2 also states "part: hardware item considered a single entity for the purpose of fracture control." In this Handbook section, the terms "component" and "structure" and "hardware" will be treated for fracture control as synonymous to the definition of "part."

Note the requirements in this section are targeted specifically to Shatterable Components and Structures. To define these, the term "Shatterable Materials" is helpful, which is defined in the NASA-STD-5019A, section 3.2, as "any material that is prone to brittle failures during operation that could release many small pieces into the surrounding environment." There are two unique aspects of shatterable components and structures that need to be considered:

1. What is the consequence of the brittle failure of the component or structure, meaning a loss of structural capability? and
2. What is the consequence of the failure producing "many small pieces into the surrounding environment?”

Both aspects are addressed in the requirements trail through sections 6.1.2.1 and 6.1.2.2 in NASA-STD-5019A that are used when classifying parts as NFC shatterable components or structures. The two highest level divisions depend upon whether the parts are inside a surrounding volume in the flight vehicle, in which case section 6.1.2.1 applies, or if they are on an external surface of the flight vehicle, then section 6.1.2.2 applies.

NASA-STD-5019A, Section 6.1.2.1

In this section of NASA-STD-5019A for internal shatterable components, there are two requirement paths: a and b, depending upon whether the part is inside a habitable volume or a non-habitable volume.

NASA-STD-5019A, Item 6.1.2.1.a

This item addresses shatterable components inside a habitable volume and imposes two requirements. To classify hardware as NFC Internal Shatterable Component inside a habitable volume per section 6.1.2.1.a in NASA-STD-5019A, an assessment has to demonstrate compliance with both requirements 6.1.2.1.a(1) and 6.1.2.1. a(2) that are described below.

NASA-STD-5019A, Item 6.1.2.1.a(1)

This item requires the hardware to satisfy section 6.2.2, NFC Contained Hardware, in NASA-STD-5019A.

Section 6.2.2 requires targeted hardware to remain in a restricted space defined by a containment structure. The surrounding volume boundary of the internal shatterable components and structures could be the containment structure if it satisfies the requirements. Alternatively, a separate local containment structure may be provided. The containment requirements are specified in items a through d and are discussed in section 6.2.2 in this Handbook.

NASA-STD-5019A, Item 6.1.2.1.a(2)

This item addresses the hazard from the shatterable component and/or structures' brittle fracture introducing small fragments into a surrounding habitable environment by imposing the particulate containment requirements specified in NASA-STD-5018, Strength Design and Verification Criteria for Glass, Ceramics, and Windows in Human Space Flight Applications.

Section 4.8.5, Containment, in NASA-STD-5018 states:

> "Materials that can shatter shall not be used in inhabited compartments unless positive protection is provided to prevent fragments greater than 50 μm (0.0020 in) maximum dimension from entering the cabin environment."

Imposing these particulate containment requirements also means the container has to ensure fragments of the hardware exceeding 50 μm (0.0020 inches) in size cannot escape from the containment. If the container has any openings, they will need screens that prevent escape of larger fragments.

Shatterable parts that are adequately contained in a habitable environment may be acceptable if the containment ensures that the requirements of both sections 6.2.2 and 4.8.5 in NASA-STD-5018 are met. For example, glass tablet screens and fiber optic cables that are encased in shatter-resistant polymeric films with sealed edges may be classified as meeting both these containment requirements as an item 6.1.2.1.a, NFC Shatterable Components and Structures part.

NASA-STD-5019A, Item 6.1.2.1.b

This item permits shatterable components and structures <u>inside a non-habitable volume</u> to meet the requirements in either section 6.2.1, 6.2.2, 6.2.3, 6.2.4, or 6.2.6 in NASA-STD-5019A. Each of these five sections were evaluated for applicability to hardware that is addressed by this section. A summary of findings for each one is provided next.

> Section 6.2.1 on NFC Low-Released Mass in NASA-STD-5019A has two requirements, a and b. Both items must be satisfied to use this classification.
>
> > Item 6.2.1.a addresses whether the failure of the shatterable component or structure results in a catastrophic hazard; if it does, the hardware cannot satisfy this requirement.
> >
> > Item 6.2.1.b requires the release of the mass to not cause a catastrophic hazard. There are four subsidiary parts. All the first three are applicable and must be satisfied. The

fourth item, 6.2.1.b(4), is not applicable since it is addressing effects of external released mass; but this item 6.1.2.1.b is addressing only internal components.

Section 6.2.2 on NFC Contained in NASA-STD-5019A has four requirement items. Their review shows that all four items are applicable and have to be satisfied.

Section 6.2.3 on NFC Fail-Safe in NASA-STD-5019A has four requirement items. Review shows all four items are applicable and have to be satisfied.

Section 6.2.4 on NFC NHLBB Pressurized Components in NASA-STD-5019A has introductory guidance that states "this classification is intended for metallic pressure-bearing walls of containers, trapped volumes, lines, ..., or other pressurized hardware that transfer non-hazardous fluid under pressure and that would leak down in the presence of a flaw rather than burst when used as intended . . .. Also, this classification is intended for hardware designed to carry primarily pressure loads." None of the described hardware, material, or functions in the quoted guidance are likely to be applicable. It is concluded that section 6.2.4 is not likely to be applicable for assessments of item 6.1.2.1.b hardware.

Section 6.2.6 on NFC Documented Non-Hazardous Failure Mode in NASA-STD-5019A has only one requirement which states (in part):

> "Provide documentation establishing that a hazard assessment has been performed and that there are no credible catastrophic hazards resulting from failure of the part caused by a flaw ... ."

To utilize this section, a hardware failure assessment would have to demonstrate that no credible catastrophic consequence resulted from the part failure. Due to the susceptible nature of shatterable components or structures to failure from impacts, this appears to be a difficult or impossible task if the part provides structural support or interacts with other critical hardware.

If the component has no structural or other critical functions, and if failure of the part does not lead to collateral damage causing a catastrophic hazard, an assessment may be able to demonstrate no credible catastrophic hazards result from the part failure. In that situation, section 6.2.6 could be applicable to the shatterable component.

An example could be an optical part, such as a camera lens, provided that debris from fracture of the lens did not constitute a catastrophic hazard in the non-habitable volume. NASA-STD-5018 defines Non-Structural Glass as:

> "Any glass component that is not a part of a structural load path or a part of a pressure vessel. The only loads non-structural glass carries are inertial. Failure of this type of hardware does not violate redundancy requirements for crew safety but could cause the loss of an important function and could present a significant hazard. An example of nonstructural glass is a camera lens that is not subjected to pressure loading."

> NASA-STD-5018, section 4.11, Non-Structural Glass, specifies the overarching requirements for this category. Section 4.11.1, Requirements Applicable to Non-Structural Glass, lists detail requirement sections. Some of these, such as section 4.4.2, Minimum Factor of Safety for Tempered Glass, may not be relevant for the hardware being addressed if the hardware does not have tempered glass. Others, such as section 4.3.3, Inadvertent Content, that specifies the contact loading for strength evaluation of the glass would likely always be relevant.

In summary, the assessment required by item 6.1.2.1.b in NASA-STD-5019A for classification of hardware as NFC Internal Shatterable Component inside a non-habitable volume can demonstrate compliance by satisfying all the cited requirements in any one of the following four sections in NASA-STD-5019A:

> Section 6.2.1 on NFC Low-Released Mass to be applicable the hardware assessment needs to show all the sections are satisfied except 6.2.1.b.(4), which is not applicable for hardware inside a surrounding volume.
>
> Section 6.2.2 on NFC Contained requires the hardware to satisfy all four section 6.2.2 items.
>
> Section 6.2.3 on NFC Fail-Safe requires the hardware to satisfy all four section 6.2.3 items.
>
> Section 6.2.6 on NFC Documented Non-Hazardous Failure Mode may be applicable if all aspects and consequences of failure of the part satisfies the section 6.2.6 requirement.

Section 6.2.4 is not included in the above summary because the evaluation reported above concluded it is not likely applicable for assessment of shatterable components and structures.

NASA-STD-5019A, Section 6.1.2.2

In this section of NASA-STD-5019A for external shatterable components, three requirements are imposed on shatterable components or structures. To achieve compliance with this section, an assessment has to demonstrate that all three items are satisfied.

As discussed in the introduction to section 6.1.2 in this Handbook, these shatterable components have low tolerance for impacts; and their brittle failure mode presents a risk they may fail and disperse "many small pieces" into the surrounding environment.

NASA-STD-5019A, Item 6.1.2.2.a

This item requires a DTA and IDMP be developed to mitigate the severity of credible catastrophic impacts to the shatterable component. The DTA and IDMP are described in sections 7.4.1, Damage Threat Assessment, and 7.4.2, Impact Damage Mitigation Plan, in

NASA-STD-5019A. Discussions of these sections are also provided in this Handbook.

This section also supplies the following list of possible impact sources to be considered: vehicle loss of external surface mass, crew exposure, micrometeoroid and orbital debris (MMOD), extravehicular activity (EVA), inadvertent contacts, and EVA tool impact hazards. These sources are supplemented by the requirement in item 7.4.1.b DTA to "Define and quantify flaws from any source that may occur to the hardware during its service life."

In addition, item 7.4.1.a states the requirement: "Provide information for residual strength sensitivity to impact damage and manufacturing flaws based on test data." The test data are needed as described in detail by guidance in section 7.4 in both NASA-STD-5019A and in this Handbook that addresses the Building Block Approach (BBA). The requirements in items 7.4.1.a and 7.4.1.b affect and support each other. To quantify the risk of loss of structural capability from a particular impact damage or flaw source, the effect of the impact or flaw upon the hardware has to be known to determine the hazard severity.

The IDMP described in item 7.4.2.a requires strategies be defined, documented, and implemented to diminish selected damage threats identified in the DTA. The strategies could involve protections to diminish or prevent impact damage or could involve inspection/detection methods to identify damage or flaws in the hardware that could result in catastrophic hazards. Item 7.4.2.b requires a prescription of when and how the strategies are to be used during the hardware mission to mitigate credible damage or threats.

NASA-STD-5019A, Item 6.1.2.2.b

This item requires the hardware design to have sufficient structural integrity such that the loss of a primary member does not result in catastrophic loss of spaceflight hardware function or required strength that prevents the hardware from safely completing the mission.

For some types of shatterable components, evaluation of this structural integrity requirement may be similar to a "fail-safe" structural analysis requirement. For other types of shatterable components, the "fail-safe" evaluation may not be relevant. For example, the shatterable component could be protecting sensitive structures or mechanisms during the mission. In that case, the assessment needs to determine whether the shatterable hardware can complete this required function during the mission after loss of a part or a primary member of the structure. Also, the nature of shatterable material may present a risk of failure of adjacent shatterable structural members as a consequence of the failure of one member due to debris impacts. If the secondary damage results in a catastrophic hazard, the component may not qualify to be classified as an NFC External Shatterable Component.

NASA-STD-5019A, Item 6.1.2.2.c

This item addresses risks from loss of mass of the shatterable components, which could happen if the shatterable component fails as noted in the introduction to this section. The requirement is to assess the effect of lost mass on other flight hardware by imposing the low release mass requirements of section 6.2.1 in NASA-STD-5019A. For the low-released mass assessment under item 6.1.2.2.c, the assessed structure is external; so, all the section 6.2.1 items are applicable, including 6.2.1.b.(4).

6.1.3 NFC Rotating Hardware (NASA-STD-5019A, Section 6.1.3)

NASA-STD-5019A:
6.1.3 NFC Rotating Hardware

Satisfy one of the following items to classify a part as NFC rotating hardware to meet requirement [FCR 7], section 6.1.c in this NASA Technical Standard:

a. The rotating hardware is computer equipment, such as computer data storage disks and computer cooling fans.

b. The rotating hardware meets the conditions in section 6.2.5 in this NASA Technical Standard.

c. The rotating hardware is within an enclosure and meets the following:

  (1) In the event of a rotor fracture caused by flaws, a conservative assessment of credible rotor fragments shows the fragments are contained within the enclosure in accordance with section 6.2.2 in this NASA Technical Standard.

  (2) The structural mounts for the rotating hardware and the enclosure are evaluated as standard structure and meet fracture control requirements.

  (3) The mount assessments include credible loads from a sudden stop of the rotor, unless it is established that either of the following are satisfied:

    A. The rotating hardware does not have a credible sudden stop catastrophic hazard during the service life that has resulted from a structural failure of the rotating hardware or adjacent structure caused by flaws.

    B. The rotating hardware has design features and monitoring with safety controls that make a sudden stop a non-credible event.

In this section of NASA-STD-5019A, there are three top-level items describing ways rotating hardware may be shown to qualify for classification as NFC Rotating Hardware.

NASA-STD-5019A, Item 6.1.3.a

This item in NASA-STD-5019A specifies generic rotating hardware types that may be placed in this classification based on the nature of the hardware; namely, that it is computer equipment with rotating parts such as "hard drives," i.e., data storage disk drives where the rotating parts are inside metallic cases. Studies and photos of reported mechanical failures of disk drives available on the internet shows that although the drives fail mechanically, the failure is contained within the device itself, and therefore does not present a risk of affecting other structure. Note that loss of the function may be a catastrophic risk for completing a spacecraft mission, but that is not a fracture control concern. It could be addressed by adding a backup function. Other computer hardware such as small cooling fans also may fail by blade loss or bearing seizure. These parts have very small energy and are very unlikely to affect hardware outside of the computer case, so they also are not a fracture control concern.

NASA-STD-5019A, Item 6.1.3.b

This item in NASA-STD-5019A permits rotating hardware to be classified as NFC Rotating Hardware provided the hardware meets the conditions in section 6.2.5, NFC Low-Risk Parts. The rationale for this approach is if there is negligible risk of a critical size crack developing in the rotating hardware, fracture of the rotating hardware is unlikely. The introductory guidance in section 6.2.5 describes the hardware qualities and conditions that are to be established in the fracture control assessment for hardware to be classified as NFC Low-Risk Parts.

The detailed requirements to be satisfied for fracture control assessment of metallic parts are specified in 6.2.5.a, items (1) through (5). Composite or bonded hardware has to satisfy the requirements in 6.2.5.b with items (1), (2), and (3). There is also guidance provided at the bottom of section 6.2.5 providing examples of manufacturing processes that do not qualify as Low-Risk Parts, and other useful guidance citing the NASGRO® User's Manual, Appendix B, where the net-section stress calculation method is described.

This requirement does not specifically address the non-rotating structures that are supporting the rotating hardware. The non-rotating supporting structures also have to satisfy fracture control requirements as the rotating hardware would have a failure mode due to inadequate supporting structure if not included.

The assessment of rotating hardware that is to be classified under section 6.2.5 in NASA-STD-5019A should include all anticipated significant loadings. There is a possible loading that is unique to rotating hardware that has to be included in the assessment loads if it is a credible loading event. Rotating hardware may experience a sudden stop that could potentially cause very large impulsive loads on the structures. The sudden stop loading is described below in item 6.1.3.c(3) in this Handbook. Additionally, item 6.1.3.c(3), including items A and B under that section in this Handbook, describe approaches that could be utilized to make the sudden stop scenario a non-credible event. If that condition is achieved, the sudden stop loadings would be non-credible and would not be included in the lifetime loads used for the structure fracture control assessments.

Bearings supporting rotating hardware are a special case for fracture control assessment. It may be possible for some bearings, as designed and installed in the flight hardware could be low risk structure if they satisfied the requirements discussed below in item 6.1.3.c(3)B in this Handbook.

NASA-STD-5019A, Item 6.1.3.c

This item in NASA-STD-5019A states the rotating hardware has to be located within an enclosure, and the hardware has to satisfy all three of the items discussed next.

NASA-STD-5019A, Item 6.1.3.c(1)

This item in NASA-STD-5019A requires a conservative assessment showing that, in the event the rotor fractures, the enclosure is able to satisfy the containment requirements in section 6.2.2, NFC Contained, for credible size rotor fragments. Refer to that section for the detailed requirements to be met.

NASA-STD-5019A, Item 6.1.3.c(2)

This item in NASA-STD-5019A requires the structural mounts of the rotating hardware and the enclosure structural mounts to satisfy fracture control requirements. The fracture control categories that could be used for the structural mounts include: 6.2.3, NFC Fail-Safe; 6.2.5, NFC Low-Risk Parts, or treat the hardware as fracture critical using section 7.3, General Approaches for Fracture Critical Metallic Parts Assessment, or section 7.4, General Approaches for Fracture Critical Composite or Bonded Hardware Assessment. Note the rotor structural mounts requirement also applies to all the supporting structures up to the interface where other structures provide loading support. They, in turn, also have to satisfy damage tolerance requirements.

NASA-STD-5019A, Item 6.1.3.c(3)

This item in NASA-STD-5019A requires the assessment of the rotating hardware mounts (and thereby, also the structure which supports the mounts) to include credible loads from a sudden stop of the rotor unless sudden stop becomes a non-credible catastrophic hazard by implementing the requirements in this section, including items 6.1.3c(3)A and B.

A brief description of rotor sudden stop is provided below. An example is provided in section 6.1.3 of Volume 2 of this Handbook.

A rotating structure acquires rotational kinetic energy as rotational speed is increased. When the rotor speed is decreased at the usual rates under motor control, the rotational kinetic energy is dispersed into the rotor system supports as reaction forces. These loadings are small compared to the forces resulting from the large deceleration rates that can occur due to sudden stop failure conditions. Some of the possible failure condition types that could cause sudden stop include fracture and jamming of the rotor bearing, a structural member fracture that positions the member between the rotor and stator causing jamming of the rotor, or foreign objects jamming spaces between the rotor and stator. The common nature of these failures is the rotor speed is rapidly decelerated by a jamming action upon the rotor causing the rotation to stop in a very short time span. The rotor stop duration is dependent upon the stiffness and strength of the jamming object and the compliance and strengths of the jamming points. The average torque from a sudden stop can be estimated given the time duration **t** as follows: Compute the rotor angular momentum, **H**, as the product **Iω** where **I** is the rotor mass moment of rotational inertia at rotational speed, **ω**. The torque **T** resulting from a jamming force on the rotor is:

$$T = H / t$$

The duration **t** of the sudden stop event is a major factor determining the magnitude of the torque (and reaction forces) for a particular situation. If the sudden stop is due to a ball or roller bearing binding with the bearing races, there may be an initial failure mode where damage of the bearing parts occurs over a number of rotations before a final seizure of the bearing. In this case, the rotor speed may be decreased before the bearing seizure event. However, if a structural member fractures due to a crack in such a way that pieces become jammed between the rotor and non-rotating parts, the sudden stop torque could quickly rise to catastrophic levels where it could fail structures not designed to accommodate these sudden stop conditions. Also, the reaction forces will be transmitted into the rotor base support and throughout the enclosure structures until they are equilibrated; so, they could affect remote structures.

Item 6.1.3.c(3), A and B in NASA-STD-5019A, provides two types of approaches to avoid a catastrophic sudden stop hazard. If either one of these is pursued, the requirement for each of them remains the same, i.e., the rotating hardware does not have a credible sudden stop catastrophic hazard. This means the suggestions listed below for item A for the rotating hardware also have to control sudden stop risk due to flaws in adjacent structures, including the non-rotating hardware. Similarly, if the approaches for item B are followed, the situation has to ensure any possibility of a sudden stop catastrophic hazard is non-credible.

Note also that whatever approaches are utilized to satisfy item A and/or B, the assessment of the hardware has to include loadings from expected events. For example, if debris shields are used to prevent jamming due to debris between a rotor and stationary structure, the shields should be designed to resist probable debris loadings on the shields. Another example is if bearing housing tolerances are designed to permit the outer race to rotate within the housing with friction in the event of a bearing jamming, the torque required to rotate in the housing is an applicable load for the structural assessments.

The approaches discussed for items A and B could be utilized in a combined manner, such that the net result is the sudden stop scenario becomes a non-credible event. If that condition is assured, the sudden stop loadings would not be included in the lifetime credible loads applied to the structures.

NASA-STD-5019A, Item 6.1.3.c(3)A

This item in NASA-STD-5019A required the rotating hardware not to have a credible sudden stop catastrophic hazard from a structural failure caused by flaws of either the rotating hardware or adjacent structure. This may be satisfied if the rotating and adjacent structures meet section 6.2.5, NFC Low-Risk Parts, for the sudden stop load case.

NASA-STD-5019A, Item 6.1.3.c.(3)B

This item in NASA-STD-5019A requires the rotating hardware to have design features and monitoring with safety controls that make a sudden stop a non-credible event.

An example of what could be provided is specified in the mechanical system safety requirements that are imposed on all SSP and ISS program payloads as described in letter number MA-2-00-057 dated 9/28/2000 in reference.[8] This letter describes the design for the minimum risk (DFMR) approach. Representative portions of some of the sections in the letter are shown below to illustrate the content; all the content of all the relevant sections of the letter could be applicable.

> "... This letter is intended to consolidate and clarify the major PSRP [*Payload Safety Review Panel*] policy decisions on matters related to the safety requirements for the design and verification of mechanisms (movable mechanical systems) used in safety critical applications. ..."
>
> "1.0 Binding/Jamming/Seizing. Designs shall include provisions to prevent binding/jamming/seizing. Appropriate design provisions include, but are not limited to, dual rotating surfaces or other mechanical redundancies, robust strength margins such that self-generated internal particles are precluded, shrouding and debris shielding, proper selection of materials and lubrication design to prevent friction welding or galling, etc. ..."
>
> "5.0 Strength and Fracture Control. Structural design of safety critical mechanical system components shall adhere to paragraphs 208.1, 208.2, and 208.3 of NSTS 1700.7, Safety Policy and Requirements for Payloads Using the Space Transportation System. Movable mechanical assemblies used in safety critical applications shall be included in an acceptable fracture control program (reference NASA-STD-5003). ..."
>
> "11.0 Design Life Verification Test. For applications where design life might be a concern due to endurance or fatigue limits being exceeded, potential deterioration of lubrication, or excessive wear, design life verification testing shall be conducted to verify that design life requirements have been complied with. Design life testing for mechanisms that pose a catastrophic hazard potential shall assure at least four times the number of operational cycles, plus four times the number of component and vehicle functional and environmental test cycles. ..."
>
> "A comprehensive Mechanical Systems Verification Plan that describes the verification approach for safety critical movable mechanical systems must be submitted for review and approval by the MSWG. ..."

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[8] NSTS/ISS 18798, Revision B, Interpretations of NSTS/ISS Payload Safety Requirements, section 7.3, Mechanical Systems Safety (MA2-00-057), MA2/Manager, Space Shuttle Program Integration, OA/Deputy Manager, International Space Station Program, 9/28/2000.

6.1.4 NFC Sealed Containers (NASA-STD-5019A, Section 6.1.4)

NASA-STD-5019A:
6.1.4 NFC Sealed Containers

Satisfy all of the following to classify a part as an NFC sealed container, e.g., a sealed electronics box that is not part of a pressure system and is not a pressure vessel, to meet requirement [FCR 7] section 6.1.d in this NASA Technical Standard:

a. The container meets the following:

(1) Does not contain a hazardous material.

(2) Loss of pressure or fluid from the container does not result in a catastrophic hazard.

(3) Container supports meet fracture control requirements.

Note that supports may either be integral to the container or separate parts, such as brackets. If the supports are integral to the container and are fracture critical, further discussion with the RFCB is necessary for classification of the container. Separate support parts should be classified independent of the container.

b. The part is manufactured from metal alloys typically used for commercially available sealed containers procured to an aerospace standard or equivalent that are not susceptible to crack extension related to EAC or SLC.

c. The container satisfies the LBB definition in this document at MDP.

d. The container does not have an impervious barrier or coating that inhibits leakage on either the interior or exterior surfaces.

e. A container is subject to the following:

(1) Inspected for leaks before repressurization.

(2) Re–flight containers are inspected for leaks before being reflown.

f. The container stored fluid energy is less than 19,307 J (14,240 ft-lb) based on adiabatic expansion of a perfect gas.

g. If the MDP of the container is 152 kPa (22 psi, 1.5 atm) or less, no additional assessment for items h and i below is required.

h. If the MDP of the container is greater than 152 kPa (22 psi, 1.5 atm) and no more than 304 kPa (44 psi, 3 atm), satisfy one of the following:

(1) An analysis shows that the container has a positive margin against burst when a factor of 2.5 on MDP is used.

(2) The container is proof tested to a minimum of 1.5 times the MDP.

i. If MDP is greater than 304 kPa (44 psi, 3 atm), the sealed container may not be classified in this category.

The container portion of an NFC sealed container does not require NDE to screen for flaws. The container supports may require NDE, depending on their individual fracture control classification.

The guidance on LBB assessment provided in section 6.2.4 in this NASA Technical Standard is also applicable to this section. Proof tests are usually performed in the operational environment, or the test levels are adjusted via an ECF.

Inertial load effects (including attach points) may necessitate additional assessments beyond the items in this category.

A sealed container is defined in NASA-STD-5019A as "Any single, independent container (not part of a pressurized system), component, or housing that is sealed to maintain an internal non-hazardous environment and that does not meet the definition of a pressure vessel."

In addition, section 6.1.6, NFC Batteries, in NASA-STD-5019A has two possible requirement paths, and item "b" directs the user toward this section 6.1.4 sealed container requirements.

This classification is intended for sealed containers as cited in the definition. The contents are specified to be non-hazardous so that expected leakage, since this part uses LBB to avoid fracture, does not result in a catastrophic hazard.

NASA-STD-5019A, Item 6.1.4.a

This item in NASA-STD-5019A requires the container to satisfy the following three requirements.

NASA-STD-5019A, Item 6.1.4.a(1)

The first requirement is the contents cannot be a hazardous material. The definition of "Hazardous Material" in NASA-STD-5019A is: "For fracture control, a material the release of which would create a catastrophic hazard." If hardware being evaluated for this category contains hazardous materials, this classification is not applicable. In that case, if the hardware is a payload or experiment, section 7.5.5, Hazardous Fluid Containers for Payloads and Experiments, in this Standard may be applicable.

NASA-STD-5019A, Item 6.1.4.a(2)

The second requirement states the loss of pressure or fluid from the container and leakage to the surroundings cannot result in a catastrophic hazard. This calls for a hazard assessment to be evaluated for effects of both the loss of pressure or fluid on the container and its contents and the effects of possible leakage of fluids to the exterior surroundings.

NASA-STD-5019A, Item 6.1.4.a(3)

This requirement imposes fracture control on the container supports. The guidance provided after items 6.1.4.a(3) and after 6.1.4.i in NASA-STD-5019A addresses the structural assessment of the container supports. They are copied below:

> *"Note that supports may either be integral to the container or separate parts, such as brackets. If the supports are integral to the container and are fracture critical, further discussion with the RFCB is necessary for classification of the container. Separate support parts should be classified independent of the container."*
>
> *"The container portion of an NFC sealed container does not require NDE to screen for flaws. The container supports may require NDE, depending on their individual fracture control classification."*

Separate support parts may be fracture critical hardware or they may satisfy an NFC category such as section 6.2.3, NFC Fail-Safe, or 6.2.5, NFC Low-Risk Parts. The guidance at the end of section 6.1.4 is copied below as it also relates to these structural assessments.

> *"Inertial load effects (including attach points) may necessitate additional assessments beyond the items in this category."*

The above guidance is addressing the container, the supports, and the need to assess all loading effects, including dynamic and inertial loadings and interactions between the container and the supports. For example, a crack in the container could result in fracture of an integral bracket leading to complex failure scenarios. Similarly, a crack in a bracket that is integral to the container may affect the container structural integrity.

There may be instances where integral parts of the support, or integral regions significantly affected by support loads, may fulfill the NFC low-risk requirements.

NASA-STD-5019A, Item 6.1.4.b

This sets requirements on the metal used to manufacture the container. The purpose is to assure the container does not have crack failure modes due to environmental influence (i.e., EAC) nor sustained loadings (i.e., SLC) that would invalidate the presumption of a LBB failure mode.

The determination of metal susceptibility to crack extension by EAC is a concern for containers of hazardous fluids such as propellants. (For an example, see the reference by Lewis, et al., that is cited in NASA-STD-5019A, Appendix B.4). Containers meeting requirements in this section encounter only non-hazardous materials. For containers made from common aerospace materials, with exposure to common, non-hazardous fluids, EAC may not be a concern, but it depends upon the fluids. Also, some metals, such as titanium, may be susceptible to SLC, depending on the hydrogen content, and may not be a good choice for a container. If titanium is used, an assessment would need to demonstrate the container would not fail due to SLC. (For information on SLC and titanium, see the reference by Boyer, et al., that is cited in NASA-STD-5019A, Appendix B.4). Credible defects and acceptance criteria should be taken into account in the EAC and SLC assessment.

NASA-STD-5019A, Item 6.1.4.c

This requires the container to satisfy the LBB criteria at MDP. The purpose of this requirement, along with other related requirements in this section, is to protect against a fracture event by requiring the container to satisfy LBB criteria making a leak the credible failure mode as opposed to a fracture (i.e., sudden release of energy).

The definition of LBB in section 3.2, Definitions, in NASA-STD-5019A is:

> "Leak-Before-Burst (LBB): Characteristic of pressurized hardware whose only credible failure mode at or below maximum design pressure (MDP) with service life loads resulting from the presence of a potential flaw is a pressure-relieving leak at the flaw as opposed to burst or rupture at the critical stress intensity factor. As the hardware item leaks down, there is no re-pressurization or continued pressure cycles that could lead to continued crack growth. In this failure mode, the hardware will not fail in a fragmentary, catastrophic manner. Instead, only small, slow-growing leaks would develop, leaking in a controlled manner. Additional aspects of LBB assessments are described in section 6.2.4 in this NASA Technical Standard. "

MDP is Maximum Design Pressure, which is defined in section 3.2, Definitions, in NASA-STD-5019A.

The guidance at the end of section 6.1.4 in NASA-STD-5019A is relevant and is copied below:

> *"The guidance on LBB assessment provided in section 6.2.4 in this NASA Technical Standard is also applicable to this section."*

The purpose of ensuring the container satisfies this LBB criteria, the other requirements b, d, and e, and the aspects cited in guidance at the end of section 6.2.4 in NASA-STD-5019A, is to ensure fracture of the container is a non-credible event. The question then arises, how is the demonstration the container satisfies this LBB criteria to be performed? Usual assessment methods for damage tolerance begin with the NDE detectable crack size, but NDE is not a requirement imposed by fracture control for this classification.

Two possible examples for performing the assessments are provided below. The objective of these example assessments is to demonstrate there is sufficient separation between the condition where the crack leaks and when the FAD criteria predict fracture. There is not a required amount of separation in these events. The assessment variability for different crack sizes should be small relative to the separation of the leak and fracture events to achieve a credible result that demonstrates the hardware satisfies the LBB definition and requirement 6.1.4c in NASA-STD-5019A.

Example 1 for satisfying the LBB definition: a matrix of NASFLA crack analyses:
In this example, damage tolerance assessments using the NASGRO® tool, NASFLA could be performed using an assumed initial surface crack of various sizes and aspect ratios in a particular container design. This example method needs to assess a significant matrix of possible cracks. The purpose of these analyses would be to determine if the container can develop a leaking crack, while avoiding a catastrophic burst, as required by the LBB definition in NASA-STD-5019A.

To perform this analysis, the container stresses and geometry are needed. In this example, the maximum pressure and energy permitted in this classification are assumed, resulting in the container size described in item 6.1.4.f in this Handbook. The container membrane wall stress is used in this example, but for a particular container, all highly stressed regions would need to be assessed, as well as relatively thick regions (including stiffeners if present). The wall membrane hoop stress is computed as pressure times radius divided by wall thickness for a range of wall thicknesses. An initial assessment may be made for a leaking through crack to determine the fracture sensitivity of the container to through crack lengths at MDP.

Next, a range of surface crack sizes and aspect ratios are assessed using the NASFLA solution SC30, which has a number of possible failure criteria available on the "Material" tab. It is recommended to utilize the defaults, Fracture toughness and Net section stress, plus the "Plastic limit load" and the "FAD: Fitnet Option 1" criteria. For the FAD, input the minimum yield strength and the mean "E" Young's modulus of the container material. If these are not known, use the nominal yield strength in the NASGRO® material database, and a nominal Young's modulus. If the material stress strain response is known, the more advanced "FAD: Fitnet Option 3" may be used. Compute for the range of initial crack sizes and shapes using the NASFLA "Computations" tab option to "Do parameter analyses by varying initial geometry and loading." Evaluate the results, and search for the message "WARNING (detected by Plastic Limit Load Failure Criterion)]: Applied load is larger than the local limit load." The meaning of this message is defined in the NASGRO® Manual, Appendix X, pgs. X-4 to X-5, as copied below:

> "The 'local' limit load is associated with plastic collapse of the local ligament between the deepest point of the surface crack and the back face of the rectangular cross-section. This local plastic collapse essentially creates a through crack but does not necessarily cause failure of the entire structure."

It is assumed this message means the crack local ligament is about to rupture and permit leaking of the fluid. To determine the fracture failure condition, the assessment needs to compute for more cycles and/or deeper, longer surface cracks, until a message appears similar to the following one reporting the crack has exceeded the FAD criteria, and fracture is predicted:

```
"[OPTION 1 FAD CRITERION (used) ]:              >>> FAILURE IS IMMINENT <<<
        RESULTS BASED ON LOAD BLOCKS
          Computed FAD parameters at failure LARGER THAN FAL:
          * Normal tension is more dominant
          * Global solutions are used
          Computed FAD parameters (Lr,Kr) at failure  : Lr=    0.2868
              Computed Kr at a-tip  =    1.0382, Kr at FAL =    0.9800
              Computed Kr at c-tip  =    0.0687, Kr at FAL =    0.9800"
```

The objective of the assessment analysis is to demonstrate there is sufficient separation between the condition where the "Plastic Limit Load" message appears indicating leakage and when the FAD criteria is exceeded, resulting in fracture prediction.

Note that even though SC30 was selected for this example problem, depending on the geometry and dominant load case, other crack models such as SC03, SC04, or SC05 may be more appropriate. In addition, the FAD option is exercised in this example, although not all crack models in NASGRO® currently have that option.

In this example, it is recommended to perform the assessment for a range of surface crack sizes and aspect ratios. However, careful consideration needs to be made for the range and aspect ratios. For example, at a constant depth, a low aspect ratio would envelope the higher aspect ratios; and there would be no need to conduct the analysis for higher aspect ratios. It is likely that a very low aspect ratio shows the crack would propagate circumferentially and not through the depth.

<u>Example 2 for satisfying the LBB definition: using API 579-1/ASME FFS-1 Fitness-for-Service methods for NDE size crack with NASFLA crack analyses:</u>

The guidance at the end of section 6.1.4 in NASA-STD-5019A is relevant and is copied below:

> *"The guidance on LBB assessment provided in section 6.2.4 in this NASA Technical Standard is also applicable to this section."*

The example 2 method is discussed in section 6.2.4 in this Handbook. The discussion will not be repeated here to avoid duplication. However, it is noted the method requires NDE to define a portion of the initial crack size used in the assessment. Although NDE is not required for hardware meeting this 6.1.4 classification, there is nothing preventing its use if that is a simpler way to demonstrate the LBB definition and requirement 6.1.4.c in NASA-STD-5019A are satisfied.

Section 6.1.4 in Volume 2 of this Handbook contains a checklist and examples of applicability for performing assessments for these types of hardware.

Demonstration that a through flaw on ten times thickness (10t) remains stable is a commonly acceptable applied approach. This approach would require RFCB approval. The 10t requirement for LBB verification was introduced in NASA fracture control requirements for Space Station (NASA-SSP-30558, Rev. B, 1994).

NASA-STD-5019A, Item 6.1.4.d

The container cannot have an impervious barrier or coating because it would prevent fluid leaks, especially at the low pressures typical of sealed containers, and that would invalidate the LBB characteristic of the system.

NASA-STD-5019A, Items 6.1.4.e, e(1), e(2)

These items impose two additional requirements as items e(1) and e(2) to ensure the conditions at the beginning of the service life are consistent with the basis for establishing the container as a LBB part. Repeated pressurization could cause crack growth beyond the critical size and cause catastrophic failure during or after pressurization.

NASA-STD-5019A, Item 6.1.4.f

This requirement ensures the container is not a pressure vessel which has more stringent controls upon it due to high energy content. By imposing this requirement, a size and pressure limit is established for a container that ensures it is less than the quantity used in the pressure vessel definition. The calculation of this energy is performed with the equation for energy release of a reversible adiabatic (isentropic) expansion of an ideal gas. The equations and sample calculation are provided in Volume 2, section 4.3.2.2, of this Handbook.

An example container volume could be computed to be 0.0254 cubic m (1550 cubic in) for a maximum absolute pressure of 3 atm (per the requirement 6.1.4.i) for a vacuum external pressure. If the container is assumed to be a cylinder, it could have a diameter of 0.508 m (20 in), and the length would then be limited to 0.500 m (19.7 in.).

NASA-STD-5019A, Item 6.1.4.g

This requirement sets an upper limit for the container MDP to limit damage risks if the container fails. If the MDP of the container is 152 kPa (22 psi, 1.5 atm) or less, no additional assessments per items h and i are required. The strength is, in this case, guaranteed by LBB assessment per 6.1.4c, as a minimum.

NASA-STD-5019A, Item 6.1.4.h

The additional requirements imposed in item "h" reduce risk of failure of the container for the operating situation at pressures above 152 kPa. These apply if the MDP of the container is greater than 152 kPa (22 psi, 1.5 atm) and no more than 304 kPa (44 psi, 3 atm). In this situation, item 6.1.4.h requires one of the following to be satisfied:

(1) An analysis shows that the container has a positive margin against burst when a factor of 2.5 on MDP is used.
(2) The container is proof tested to a minimum of 1.5 times the MDP.

NASA-STD-5019A, Item 6.1.4.i

This requirement sets an upper bound of 304 kPa (44 psi, 3 atm) on the allowable pressure for this classification. The upper bound reduces risks in the event of an NFC sealed container failure. A complex container failure remains a concern because NDE of the container is not required, so it could have flaws. Apart from pressure vessel classification of such containers, other classifications may be explored as well, e.g., NHLBB pressurized component (section 6.2.4), NFC low risk (section 6.2.5), subject to approval by RFCB.

6.1.5 NFC Tools, Mechanisms, and Tethers (NASA-STD-5019A, Section 6.1.5)

NASA-STD-5019A:
6.1.5 NFC Tools, Mechanisms, and Tethers

Satisfy either of the following to classify a part as an NFC tool, mechanism, or tether to meet requirement [FCR 7] section 6.1.e in this NASA Technical Standard:

a. To classify tools, mechanisms, and tethers as NFC during storage and usage, meet the requirements in sections 6.2.1 or 6.2.5 in this NASA Technical Standard.

b. To classify tools, mechanisms, and tethers as NFC during storage, meet the requirements in sections 6.2.2 or 6.2.3 in this NASA Technical Standard.

NASA-STD-5019A, Items 6.1.5.a, b

This section of NASA-STD-5019A classifies and assesses tools, mechanisms, and tethers for fracture control. They are classified and assessed with the same methodology as used for other flight hardware. Tools, mechanisms, and tethers may have storage, use, and other phases during their service lifetime which makes their classification complex.

Tools are devices that are manually manipulated by a crew member to perform some activity with another object or perform a structural function. Mechanisms are defined in section 3.2 in NASA-STD-5019A as "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." Tethers provide a restraining action upon other parts.

A hypothetical example of flight hardware that may be a tool, mechanism, or tether may have the following sequence of events, i.e., phases, during its service lifetime:

1. Processing such as: qualification, testing, inspection, packaging for launch, and transportation followed by either storage in a compartment or otherwise secured for launch,

2. The launch, ascent, and on-orbit maneuvers with the part in the storage or secured condition,

3. On-orbit use, including possible repetitive sequences of removing the part from storage or secured status for use providing a possibly critical function, followed by re-storing or re-securing while on-orbit in the original or alternate locations, and

4. Finally, some re-packaging or storing or securing for re-entry in a vehicle, experiencing the re-entry and landing, and subsequent ground operations, or

5. Alternatively, in some cases, on-orbit storage within a container for disposal by re-entry burn.

The assessment of a part with such a lifetime sequence may determine the part satisfies a combination of the possible NFC classifications during the five phases of its lifetime. For example, the hardware may qualify during phases 1 and 2, and possibly also phases 4 and 5, for classification under NASA-STD-5019A, section 6.2.2, NFC Contained, when in storage, or as section 6.2.3, NFC Fail-Safe, while secured, which are also item 6.1.5.b in NASA-STD-5019A.

For the phase 3 service life, with on-orbit use and sequences of storage/securing occurring, possible NFC classifications are section 6.2.1, NFC Low-Released Mass, and/or section 6.2.5, NFC Low-Risk Parts, which are item 6.1.5.a in NASA-STD-5019A.

In summary, if the part qualifies during all the mission phases for classification as one or more of these four NFC categories, the hardware could be classified as section 6.1.5, NFC Tools, Mechanisms, and Tethers.

Parts with both NFC phases and a fracture critical phase:
Another consideration is when an astronaut may be in contact with the hardware. In that situation, the NFC Fail-Safe classification may not be an option if fracture of part of the fail-safe hardware could expose the astronaut to a fractured sharp edge which could be a catastrophic hazard. If no other NFC classification is applicable, the part has to be classified as a fracture critical part in accordance with FCR 10 in section 7.1 in NASA-STD-5019A.

If this situation occurred during the third phase of the above example, the part has to be classified as a fracture critical part. Note the earlier two phases are not changed, but the part is no longer an NFC part. The fracture control assessment of the part has to satisfy the applicable requirements of sections 7, 8, and 9. Note the assessment also has to include the loadings and environments acting upon the part from the beginning, i.e., from the initial flaw screening per section 8.1, which could occur during phase 1 in the example, and the loadings and environment acting upon the part during the remainder of phase 1, including phase 2, and phase 3 where the part became fracture critical.

Parts with a potential NFC phase after a fracture critical phase:
Note that although the later phases 4 to 5 could possibly satisfy an NFC classification, the part remains classified as a fracture critical part. Also, the assessment of these later phases 4 to 5 to determine the part classification during those phases would have to include effects of crack growth during the previous phases of the service life. However, if the part is demonstrated to be in an NFC risk classification in phases 4 to 5, then the loadings and environments of these latter phases should not be included in the assessment for the earlier fracture critical phase of the service life. The reasoning in that situation would be the crack growth analysis that is repeated four times to obtain the factor of four on life for the fracture critical phase should not include the latter NFC phases because a fracture event during phases 4 to 5 would not be credible.

Re-flight of a part with NFC phase after a fracture critical phase:
If the part is to be re-flown, the effects of all the phases, including 4 to 5 of the first flight, would have to be included in the evaluation used to establish the beginning condition for the re-flight service life phases.

The aspects of NFC and fracture critical classification during phases of the service life of a part are also addressed in section 4.3 in this Handbook.

Fracture critical tools, mechanisms, and tethers:
One more consideration is the part classification evaluation should consider the guidance in section 7.2.10 in NASA-STD-5019A for classification of fracture critical tools, mechanisms, and tethers. The guidance is copied below:

> *"The following are to be applied to fracture critical tools or mechanisms that are the only (no backup) means for performing a function where failure to perform the function would result in a catastrophic hazard or a tool or mechanism whose failure during use would, in itself, result in a catastrophic hazard. This classification includes safety-critical tethers."*

Hardware with the above-described attributes is classified as fracture critical parts in section 7.2.10 in NASA-STD-5019A and therefore are excluded from being classified as NFC under section 6.1.5 in NASA-STD-5019A.

6.1.6 NFC Batteries (NASA-STD-5019A, Section 6.1.6)

NASA-STD-5019A:
6.1.6 NFC Batteries

Satisfy one of the following to classify parts as NFC battery cells/cases to meet requirement [FCR 7] section 6.1.f in this NASA Technical Standard:

a. Meet the NHLBB requirements in section 6.2.4 in this NASA Technical Standard.

b. Meet the sealed container requirements in section 6.1.4 in this NASA Technical Standard.

Small batteries in common use, such as button cells of 200 mA-hr or less and carbon-zinc or zinc-air batteries of size F or smaller are exempt from fracture control.

Batteries are widely used in spaceflight systems and accessories utilized by astronauts. They may contain toxic materials and are subject to pressure and thermal cycling as they are charged and discharged. They present safety concerns and controls are in place for NFC batteries as discussed in this section. Fracture critical batteries are discussed in section 7.2.11 in this Handbook.

The guidance in section 6.1.6 in NASA-STD-5019A defines a category of small batteries that are exempt from fracture control. It states:

> *"Small batteries in common use, such as button cells of 200 mA-hr or less, and carbon-zinc or zinc-air batteries of size F or smaller are exempt from fracture control."*

The process of classifying exempt parts is described in section 5 in NASA-STD-5019A which states:

> *"Parts that are identified and shown to meet the exempt classification criteria in documentation cited in the Fracture Control Summary Report (FCSR) in accordance with the requirements listed in section 9 of this NASA Technical Standard comply with fracture control requirements without further activity beyond conventional aerospace verification and quality assurance procedures, unless otherwise indicated in this document."*

JSC 20793, Crewed Space Vehicle Battery Safety Requirements, has detailed descriptions and assessments of batteries in use for NASA missions. JSC 20793 is not imposed in this section; it is imposed by item a in section 7.2.11 where it is discussed in this Handbook. In the JSC 20793 March 2017 version D, section 5 addresses general battery hazards and controls. Item 5.1.1.1g item 3 states: "*Small batteries that fall under the non-critical category (see 4.1.3) are exempt from fracture control.*" Section 4.1.3 in that document provides a list of non-critical "low energy cells and battery designs for which standard emergency procedures are written and practiced." The document requires safety controls for non-critical batteries in other sections. For example, section 4.2.2 describes a "Unique Hazard Report" that provides verification evidence for the battery system.

NASA-STD-5019A, Items 6.1.6.a, b

This section in NASA-STD-5019A specifies that either item "a" or "b" is to be satisfied. The "a" item imposes the requirements in section 6.2.4, while the "b" item imposes the requirements in section 6.1.4 in NASA-STD-5019A.

To qualify hardware under either the "a" or "b" item, all the requirements in the selected section have to be demonstrated to be satisfied.

To assist in evaluating whether either of these two items are applicable for the particular NFC Battery hardware being assessed, a summary of the common requirements that have to be satisfied in both of these two sections is provided below:

- Satisfy the LBB definition in NASA-STD-5019A at MDP (also refer to the LBB guidance in section 6.2.4)
- Loss of fluid from the battery does not cause a catastrophic hazard or release a hazardous material.
- The structural supports satisfy fracture control requirements.
- The battery is manufactured from metal alloys typically used for commercially available hardware procured to an aerospace standard or equivalent that are not susceptible to crack growth related to EAC or SLC as defined in NASA-STD-5019A in the applicable environment.
- The battery does not have an impervious barrier or coating that inhibits leakage on either the interior or exterior surfaces.
- Re-flight batteries are inspected for leaks before repressurization and/or before being re-flown.

Next, summaries of the <u>different requirements in the two sections</u> are provided.

<u>6.2.4 additionally requires the following</u>:

c. As the hardware leaks down, there is no re-pressurization or continued pressure cycles that could lead to continued fatigue or crack growth related to EAC or SLC. (Comment: This could be an issue for batteries if venting was somehow prevented.)

d. The hardware is manufactured from metal alloys . . . using processes that have been established by reliability or inspections of many similar parts to be extremely unlikely to produce parts with a flaw exceeding process specifications.

6.1.4 additionally requires the following:

Section guidance notes the structural design is to be discussed with the RFCB if the hardware structural supports are integral to the container (i.e., the battery) and are fracture critical.

f. The hardware stored fluid energy is less than 19,307 J (14,240 ft-lb) based on adiabatic expansion of a perfect gas.

g. If the MDP of the hardware is 152 kPa (i.e., 22 psi, 1.5 atm) or less, no additional assessment per items "h" and "i" in section 6.1.4 in NASA-STD-5019A is required; otherwise, they are imposed.

h. This item imposes either one of the following additional requirements if the MDP is greater than 152 kPa (i.e., 22 psi, 1.5 atm) and no more than 304 kPa (i.e., 44 psi, 3 atm):

(1) Analysis shows positive margin against burst using a factor of 2.5 on MDP,

(2) The hardware is proof tested to a minimum of 1.5 times the MDP.

i. States if the MDP is greater than 304 kPa (i.e., 44 psi, 3 atm), the hardware may not be classified in this category.

6.2 General Approaches for NFC Parts (NASA-STD-5019A, Section 6.2)

NASA-STD-5019A:
6.2 General Approach for NFC Parts

Parts in this category may be classified NFC if documented assessment cited in the FCSR shows that they do not present a credible catastrophic hazard resulting from failure of the part caused by a flaw or that they do not have a credible possibility for a flaw to cause failure of the part. Both composite and bonded hardware are to satisfy section 6.3 in addition to the items in this section.

[FCR 8] Each part classified as NFC that is not of a specific hardware type as described in section 6.1 in this NASA Technical Standard shall comply with one of the following items:

a. NFC low-released mass complies with section 6.2.1 in this NASA Technical Standard.

b. NFC contained complies with section 6.2.2 in this NASA Technical Standard.

c. NFC fail-safe complies with section 6.2.3 in this NASA Technical Standard.

d. NFC NHLBB pressurized components comply with section 6.2.4 in this NASA Technical Standard.

e. NFC low-risk part complies with section 6.2.5 in this NASA Technical Standard.

f. NFC documented non-hazardous failure mode complies with section 6.2.6 in this NASA Technical Standard.

[Rationale: Parts that can be shown to have no credible catastrophic hazard resulting from a failure of the part caused by a flaw or to have no credible possibility for flaws to cause failure are not fracture critical. These parts can be classified as NFC.]

Use of an alternative approach requires unique rationale and approval by the RFCB as described in section 10 [FCR 26] in this NASA Technical Standard.

Sections 6.2.1 through 6.2.4 in this NASA Technical Standard provide approaches to establish that a part does not present a credible catastrophic hazard because of part failure. Section 6.2.5 in this NASA Technical Standard provides an approach to show that a part does not have a credible possibility for a flaw to cause failure in the part.

There are three different types of approaches within this section for classification of NFC parts:

1. Failure of the part does not cause a catastrophic hazard as described by the specific classifications in sections 6.2.1 – 6.2.4.

2. Failure of the part due to a flaw is unlikely as described by the low-risk classification in section 6.2.5.

3. The part has no catastrophic failure modes from failure due to a flaw as described by section 6.2.6.

Classifications for item 1 rely on activities performed to show that even if the part fails due to a flaw, no catastrophic failure occurs. Considerations for more than one failure mode of concern are included in some of the corresponding sections such as debris considerations for an NFC Fail-Safe classification. Examples of activities performed include providing assurance that leakage does not represent a catastrophic hazard and that a pressurized part is leak-before-burst so that no structural rupture occurs for NFC NHLBB.

The low-risk approach for item 2 provides activities to assess the likelihood of failure due to the presence of a flaw. Risk is not assessed directly, but through meeting a list of conditions; the part is judged to be “low-risk.”. The activities or conditions are intended to show that the part is unlikely to have a preexisting flaw and is unlikely to propagate a flaw if present.

Item 3 represents the classification where a documented hazard analysis report establishes that no catastrophic failure modes exist for failure due to a flaw.

6.2.1 NFC Low-Released Mass (NASA-STD-5019A, Section 6.2.1)

NASA-STD-5019A:
6.2.1 NFC Low-Released Mass

Small parts or masses that are released (because of structural failure caused by a flaw) may be designated NFC via the low-released mass category.

Satisfy all of the following items to classify a part as an NFC low-released mass to meet requirement [FCR 8] section 6.2.a in this NASA Technical Standard.

a. The fracture of the part does not cause a catastrophic hazard.

b. The release of the mass does not cause a catastrophic hazard.

  (1) For NFC composite or bonded parts that may be impacted by an NFC low-released mass part, establish that the impacted NFC composite or bonded parts can sustain DUL. This is verified by analysis combined with coupon or hardware element test data while subject to the worst-case impact damage from the released mass.

  (2) For fracture critical composite or bonded parts that may be impacted by an NFC low-released mass part, include the worst-case impact damage from the released mass in the DTA and RTD during evaluation of the fracture critical part, described in section 7.4 in this NASA Technical Standard.

  (3) Loss of function and impact with other hardware, equipment, spacecraft, and personnel are addressed in the evaluation.

  (4) External released mass or parts, including those that would be subjected to aerodynamic flow, may only be classified low-released mass when the program has established an acceptable debris field criterion and the parts fall within it.

The program should provide the launch vehicle acceptable debris field criteria. The program or launch payload integrator has to address concerns of impact on adjacent payloads and other spacecraft.

This NFC low-released mass section imposes requirements that ensure the small part or mass released because of a structural failure caused by a flaw does not cause a catastrophic hazard during the mission service life. To achieve this purpose, comprehensive requirements are imposed that address risks due to fracture or loss of the part and the effects of the released part or part fragments upon other hardware or personnel, including vehicle structures.

NASA-STD-5019A, Item 6.2.1.a

This item in NASA-STD-5019A requires the part fracture and release not to cause a catastrophic hazard. This is a very broad requirement, and all aspects of consequences due to the fracture of the part are to be assessed. The part does not qualify for this classification if fracture of the part results in a catastrophic hazard.

NFC low-released mass fasteners, rivets, or shear pins have to satisfy the requirements in section 6.1.1.1 which points to this section 6.2.1 in NASA-STD-5019A. Details specific to NFC low-released mass are discussed in section 6.1.1.1 in this Handbook.

In some programs, such as the Space Shuttle, specific limits on parts qualifying under this type of NFC classification in the program fracture control requirement documents were imposed. Those requirements were derived to address particular catastrophic hazards that existed in that program. For example, the Space Shuttle program set requirements to prevent penetration of the shuttle bay bulkhead by a small-released mass. The basis for the requirement details were set by the maximum travel distance from release to impact with the bulkhead, the acceleration of the vehicle, and the ability of the bulkhead to resist penetration. The requirements for that program are not transferrable to other programs. However, a particular vehicle program may use similar methods to set the maximum mass, speed, and momentum limits, or other relevant aspects, for released small mass parts to address catastrophic hazards affecting the program hardware or vehicle. In this event, the program defined criteria for an NFC low-released mass would be applicable to hardware utilizing that program under this category in NASA-STD-5019A. Also, if a program imposed additional requirements on NFC low-released mass parts, such as conditions requiring RFCB approvals, those additional requirements would be applicable to parts qualifying as NFC parts under this classification.

NASA-STD-5019A, Item 6.2.1.b

This item in NASA-STD-5019A requires the consequences of the release of the mass not to cause a catastrophic hazard. This is also a very broad requirement. All aspects and consequences of the release of the part are to be assessed, including the topics in the following four items.

NASA-STD-5019A, Item 6.2.1.b(1)

This item in NASA-STD-5019A requires assessments if there are NFC composite or bonded parts that may be impacted by the NFC low-released mass or part. NFC composite or bonded parts are already subject to the requirements in section 6.3 in NASA-STD-5019A, which include a DTA, an IDMP, and determination of the RTD. This item additionally requires the effect of the release and worst-case impact of the NFC low-released mass to be included in these assessments. This section also requires the strength of these hardware types after impact by the released mass to be sufficient to sustain DUL. Additionally, the strength assessment has to be verified by analysis combined with coupon or hardware element test data. The DTA, IDMP, and RTD requirements are specified in sections 7.4.1, 7.4.2, and 7.4.3 in NASA-STD-5019A, and are discussed in these sections in this Handbook.

NASA-STD-5019A, Item 6.2.1.b(2)

This item in NASA-STD-5019A requires assessments of fracture critical composite or bonded parts that may be impacted by an NFC low-released mass part to include the worst-case impact damage from the NFC low-released mass part. The DTA and RTD assessment requirements are specified in sections 7.4.1 and 7.4.3 in NASA-STD-5019A and are discussed in these sections in this Handbook.

NASA-STD-5019A, Item 6.2.1.b(3)

This item in NASA-STD-5019A lists additional aspects to be addressed in the assessment evaluation. These include loss of the functions the part was providing, and risks and effects from impact of the NFC low-released mass with other hardware, equipment, spacecraft and personnel. The effects to be assessed include structural strength evaluations of the impacted hardware and any secondary effects such as debris from the newly impacted hardware.

NASA-STD-5019A, Item 6.2.1.b(4)

This item in NASA-STD-5019A addresses parts that are external to a vehicle, such as those with a release trajectory that places them into the aerodynamics flow field. The requirement is the released mass or part is not allowed to violate the program-established limitations on loose mass in the vehicle external aerodynamic flow field. Classification of released mass under this section is possible only when the vehicle program has established an acceptable debris field criterion, and the released mass or parts do not violate the limitations on loose mass in the vehicle external aerodynamic flow field. If the program has not established an acceptable debris field criterion, this section cannot be applied; in that event, no released mass that enters the external aerodynamic flow field can be classified as an NFC low-released mass part. There is guidance in this section relevant to this requirement that is copied below:

> *"The program should provide the launch vehicle acceptable debris field criteria. The program or launch payload integrator has to address concerns of impact on adjacent payloads and other spacecraft."*

6.2.2 NFC Contained (NASA-STD-5019A, Section 6.2.2)

NASA-STD-5019A:
6.2.2 NFC Contained

Parts that would be safely confined to an enclosed volume should they become loose because of the presence of a flaw may be designated NFC via the contained category.

Satisfy all of the following items to classify a part as NFC contained to meet requirement [FCR 8] section 6.2.b in this NASA Technical Standard:

a. A containment assessment conservatively establishes that the contained part does not penetrate, fracture, or otherwise escape the enclosure.

(1) Metallic containers are shown to meet the penetration criterion by a validated analysis method that includes uncertainty factors on the container thickness or by test.

(2) Composite containers are shown to meet this criterion by establishing that the composite container can sustain DUL (verified by analysis combined with coupon or hardware element test data) with the worst-case impact damage from the released part.

b. Release or failure of the contained part because of a flaw does not result in a catastrophic hazard.

c. The enclosure structure and supports meet the following:

(1) Fracture control requirements listed in this NASA Technical Standard.

(2) Perform their intended functions if impacted by the loose part, fragments, or contents of the part.

d. Assessment of containers with mechanically secured closures shows the design is at least one fault tolerant against release of the contents.

Consider all sources of energy available to a contained part during a containment analysis.

If the part contains hazardous materials or fluids, to satisfy item 6.2.2.b (above), the containment assessment also establishes that no hazardous materials or part fragments are released that result in a catastrophic hazard. Also note that impact with a composite enclosure is to be considered during fracture control classification and assessment of the enclosure.

This NFC section imposes containment requirements that ensure parts in this classification are confined to an enclosed volume where they cannot cause a catastrophic hazard. The guidance at the beginning and end of this classification is copied below as an introduction that describes the function and objectives of this classification:

> *"Parts that would be safely confined to an enclosed volume should they become loose because of the presence of a flaw may be designated NFC via the contained category."*
>
> *"Consider all sources of energy available to a contained part during a containment analysis."*
>
> *"If the part contains hazardous materials or fluids, to satisfy item 6.2.2.b (above), the containment assessment also establishes that no hazardous materials or part fragments are released that result in a catastrophic hazard. Also note that impact with a composite enclosure is to be considered during fracture control classification and assessment of the enclosure."*

NASA-STD-5019A, Item 6.2.2.a

This item in NASA-STD-5019A imposes the broad requirement that "a containment assessment conservatively establishes that the contained part does not penetrate, fracture, or otherwise escape the enclosure." If enclosures have openings, they can only provide containment of parts larger than the openings.

NFC contained fasteners, rivets, and shear pins have to satisfy the requirements in section 6.1.1.2 which points to this section 6.2.2 in NASA-STD-5019A. Details specific to NFC contained fasteners, rivets, and shear pins are discussed in section 6.1.1.2 in this Handbook.

Notice there is no limit on when requirements in this section are applied. The requirements are active throughout the mission lifetime of the enclosure and the contained hardware. This means the enclosure has to continue to perform its intended function throughout its mission lifetime after impact from a contained part. And, since the contained part may be damaged or in fragments after impact with the enclosure, depending on the part and the enclosure types of materials, the enclosure may have to prevent different sizes and shapes from escaping after an initial containment of the part.

Alternatively, if the enclosure cannot sustain the containment impacts throughout the mission lifetime, the mission may need to include capabilities and opportunities to inspect, repair, or replace the enclosure once a containment impact has been determined to have occurred by suitable inspection or monitoring devices.

The worst-case condition (heaviest piece/greatest travel distance/thinnest wall that could be penetrated, etc.) have to be assessed in the containment assessments for the hardware in question. If the worst-case is not clear due to varying combinations of part conditions, the assessment should evaluate the parts with the worst case for each condition.

In some programs, such as the Space Shuttle, the vehicle provided stowage compartments such as "mid-deck lockers," and other devices such as "get-away-special (GAS)" canisters, and soft stowage bags called "Cargo Transfer Bags." The requirements for "stowage" or containment developed for the Space Shuttle program are not transferrable to other programs because the vehicle structures and characteristics are not the same. However, a particular program may provide similar standardized containment devices. In that event, the program would be expected to define the screening criteria for parts to be classified as NFC Contained parts if they are placed in program-provided containment devices. Also, the program could impose additional requirements on parts such as requiring RFCB approval.

NASA-STD-5019A, Item 6.2.2.a(1)

This item in NASA-STD-5019A requires metallic containers to satisfy the penetration containment criteria by a validated analysis method that includes uncertainty factors or by test.

Volume 2I, section 6.2.2 in the Handbook, discusses analyses to demonstrate containment of a metallic rotor fragment by a metallic enclosure. The assessment variables are the mass, velocity, and diameter of the projectile, and the tensile yield strength and thickness of the enclosure. The same type of assessment can be applied for containment assessment of non-metallic parts in a metallic enclosure, since a non-metallic part is less likely to penetrate a metallic enclosure. A recommended modification of the well-known "punch" equation formulation is provided in Volume 2, section 6.2.2 in the Handbook, that minimizes non-conservative predictions based on comparisons with reported test data. The section of the Handbook also shows predictions using the recommended equation with data from other references that reported tests for metallic projectiles impacting metallic enclosures. Analyzing these other data references shows predictions are mostly conservative, except for a few data points. To be conservative for these outlier data points, an uncertainty factor of 1.25 is needed.

It may be possible for the structure to satisfy the NFC low-risk parts classification. The enclosure supports may be able to satisfy either the NFC low-risk parts or fail-safe classifications. Alternatively, the enclosure structure, and/or its supports, will be fracture critical structures. In that case, they would need to satisfy the fracture critical sections 7.3 or 7.4 in NASA-STD-5019A as described in those sections in this Handbook.

NASA-STD-5019A, Item 6.2.2.a(2)

This item in NASA-STD-5019A requires composite containers to demonstrate the enclosure can withstand DUL that is verified by analysis combined with coupon or hardware element test data for worst-case impact damage from the released part.

NASA-STD-5019A, Item 6.2.2.b

This item in NASA-STD-5019A requires assessments on risks of catastrophic hazards caused by either release of the contained part or failure of the contained part. Addressing them will vary depending on the nature of the contained part and the way it is restrained in the enclosure.

If the contained part and the method of securing it satisfy fracture control classifications, the risk of failure caused by a flaw would be non-credible. If this was not the situation, assessments would have to demonstrate by other means that the risk of release and failure of the part was controlled and non-credible.

NASA-STD-5019A, Item 6.2.2.c

This item in NASA-STD-5019A imposes the following two requirements on the enclosure structure and on its supports.

NASA-STD-5019A, Item 6.2.2c(1)

This item in NASA-STD-5019A requires the enclosure structure and its supports to satisfy fracture control requirements in the Standard. Notice this does not mean the enclosure structure and supports have to be fracture critical structures. It may be possible for the structure to satisfy the NFC low-risk parts classification. The enclosure supports may be able to satisfy either the NFC low-risk parts or fail-safe classifications. Alternatively, the enclosure structure, and/or its supports, may be fracture critical structures. In that case, they would need to satisfy the fracture critical section 7.3 or 7.4 in NASA-STD-5019A as described in those sections in this Handbook.

NASA-STD-5019A, Item 6.2.2c(2)

This item in NASA-STD-5019A requires both the enclosure structure and its supports to perform their intended functions if impacted by the loose part, fragments of the part, or the contents (if any) of the part. This requirement is similar to the aspects discussed in item 6.2.2.a in this Handbook relating to the enclosure structure and supports being able to perform their intended function throughout their mission lifetime after impact from a loose part, fragments of the part, or the contents (if any) of the part.

Similar to item 6.2.2.a, if the enclosure structure and supports cannot perform their intended functions throughout their mission lifetime, the mission may need to include capabilities and opportunities to inspect, repair, or replace the enclosure structure once a containment impact has been determined to have occurred by suitable inspection or monitoring devices.

NASA-STD-5019A, Item 6.2.2.d

This item in NASA-STD-5019A addresses containers with mechanically secured closures, such as the lockers, etc., described above that were used in the Space Shuttle program. This item requires the closure mechanisms to be at least one fault tolerant against release of the contents.

6.2.3 NFC Fail Safe (NASA-STD-5019A, Section 6.2.3)

NASA-STD-5019A:
6.2.3 NFC Fail Safe

Parts with sufficient structural redundancy that may fail because of the presence of a flaw may be designated NFC via the fail-safe category.

Satisfy all of the following items to classify a part as NFC fail-safe to meet requirement [FCR 8] section 6.2.c in this NASA Technical Standard:

a. Documented assessment establishes that loss of any load path does not result in a catastrophic hazard and that risk of loss of the structural redundancy because of multi-site fatigue or damage of redundant load path structures from any source during the service life of the structure is not a credible concern.

b. Failure of the part does not generate pieces or debris that would violate the NFC low-released mass requirements in section 6.2.1 in this NASA Technical Standard.

c. After the loss of any load path, there is sufficient remaining structural capability to safely sustain all resulting redistributed loads and environments (including dynamic response changes) until termination of the mission or until such time as the part is inspected and refurbished.

(1) For NFC composite or bonded parts that may be impacted by an NFC fail-safe part, establish that the impacted NFC composite or bonded parts can sustain DUL verified by analysis combined with coupon or hardware element test data, while being subjected to the worst-case impact damage from the NFC fail-safe part.

(2) For any remaining NFC composite or bonded structure of this fail-safe part, establish that the remaining structure can sustain DLL. This is verified by analysis combined with coupon or hardware element test data with the worst-case impact damage from the NFC fail-safe part.

(3) For fracture critical composite or bonded parts that may be impacted by an NFC fail-safe part, include the worst-case impact damage caused by the NFC fail-safe part in the DTA and RTD during evaluation of the fracture critical parts as described in section 7.4 in this NASA Technical Standard.

For metallic structures, verification by analysis is sufficient.

d. Re-flight hardware is verified by visual inspection or other means to be intact and free of structural anomalies before being re-flown.

The possible consequences of the release of redundant parts need to be assessed. Failure of a redundant part may create impact with an adjacent part and is to be considered during fracture control classification and assessment of the adjacent part.

The guidance at the beginning of this section states:

> *"Parts with sufficient structural redundancy that may fail because of the presence of a flaw may be designated NFC via the fail-safe category."*

The guidance may be more understandable if it is rephrased as: "fail-safe hardware with redundant members that can survive the loss of any one member due to the presence of a flaw and still meet structural performance requirements and not cause a catastrophic hazard may be suitable for classification as an NFC fail-safe part."

To further explain this situation, first note that fracture control assesses the risk of failure due to a single critical crack in a structure, which is assumed to be located in the worst material at the highest stressed location. Next, observe that the presumed loss of a member in a redundant structure due to a crack in that member eliminates the need to assume a crack occurring at the same time in the remaining redundant structure members. It is necessary to ensure the remaining structure satisfies all performance requirements and does not cause a catastrophic hazard. It is also necessary to confirm whether it is true that if any of the other redundant structure members were assumed to fail, that remaining structure would also meet all requirements and not cause a catastrophic hazard.

Note that generic failure modes that could affect more than the one member assumed to have a crack have to be removed from the realm of possibilities by control of the processes used to make the members and verified by process control inspections of all the members during and after manufacturing.

This classification only applies for structures with redundant members, i.e., the remaining members can carry the redistributed load changes due to the loss of one member without loss of structural capabilities or causing a catastrophic hazard during the mission lifetime.

NASA-STD-5019A, Item 6.2.3.a

This item in NASA-STD-5019A requires assessments that demonstrate the structure is sufficiently robust and redundant that it qualifies as NFC fail-safe structure. This item requires two aspects be satisfied: first, that the structure is sufficiently redundant, and second that failure of the remaining structure elements due to multi-site fatigue or any other source is not a credible concern.

The demonstration that the structure is sufficiently redundant involves structural analyses wherein one of the structural members is presumed to be defective. The load capability and stiffness of that member is changed to simulate a fracture of that member, followed by assessment of all the remaining redundant members. The assessment has to demonstrate all the remaining members, including the remnants of the fractured member, have adequate capability to withstand all loadings, including static and acceleration loads and redistributed dynamic loads, i.e., considering dynamic load amplification. Also, the assessment has to demonstrate the members have sufficient fatigue strength and any other relevant structural qualities needed to resist possible failure modes, such as stiffness to resist buckling. The only failure modes that are not assessed are those caused by growth of a crack resulting in fracture. These are not assessed because crack growth and fracture is presumed to have caused the failure of the member selected to be defective during this assessment phase, and only one crack is presumed to be affecting the structure.

The choice of which structural member is to be presumed to have failed and is removed from the structure support may be complex. The best approach for finite element analyses is to try removing each of them in turn, as the process is quick. If this choice is not available, the minimum is to remove the highest loaded member, and then remove the member with the lowest structural margin (which may not be the same one). Where dynamic amplifications could make significant contributions to member loadings, the dynamic amplified member loadings have to be assessed for the two members selected for removal as described above. For completeness, evaluate the removal of one more member that is not expected to produce significantly different results. If the "one more" member has significantly different loading redistribution into the other remaining members causing other members to be at risk of failing, the situation has not been adequately assessed; additional analyses are needed with removal of other different members.

The required demonstration that multi-site fatigue or damage from any other source is not a credible concern has to evaluate the initial state of the structure members after manufacturing. If the manufacturing process is likely to cause small defects in multiple structural members, those small defects have to be assessed and shown to be small enough so they are not predicted to grow due to loadings the structure experiences during the mission service life. If small initial defects are found to grow during the mission service life, or any other generic source of damage is found that reduces the member structure strength during the mission service life, the structure cannot be classified NFC fail-safe. For metallic hardware, fracture mechanics methods may be applied to assess initial defects for susceptibility to multi-site fatigue damage risk. For composite or bonded structures, coupon test data are needed that establish initial manufacturing defects do not present a risk of failure of the structure members.

NASA-STD-5019A, Item 6.2.3.b

This item in NASA-STD-5019A requires a failure of any one loaded member not to generate pieces or debris that would violate the NFC low-released mass section 6.2.1 requirements in NASA-STD-5019A, which are discussed in the same sections in this Handbook. Note that the requirement in item 6.2.1.a is not applicable, because the fracture of a loaded member in an NFC fail-safe structure was already addressed by item 6.2.3.a. However, all four of the items under i 6.2.1.b are relevant. Documented assessments are required that show none of these four items cause a catastrophic hazard. These assessments are discussed in the items under 6.2.1.b in this

Handbook but may have an additional concern because the redundant structure elements may be in close proximity to each other, presenting a greater-than-usual risk for collateral damage from the failed member. Item 6.2.1.b(3) includes a required assessment for loss of function, but that "loss of function" aspect can be skipped because loss of function has already been addressed by item 6.2.3.a requirements. The remaining item 6.2.1.b.(3) aspects are relevant and have to be assessed.

NASA-STD-5019A, Item 6.2.3.c

This item in NASA-STD-5019A imposes requirements that are the same as those addressed per item 6.2.3.a, except this one additionally permits the structure assessment to span the mission lifetime "until such time as the part is inspected and refurbished." This addition gives an option for the mission to include planned inspection and refurbishments of the hardware. If the mission includes planned inspection and refurbishments of the hardware, it reduces the extent of the exposure of the structures to mission loadings and environments.

NASA-STD-5019A, Item 6.2.3.c(1)

This item in NASA-STD-5019A requires that any NFC composite or bonded parts that may be impacted by a failed structural member of the fail-safe structure include the worst-case impact damage from this source in the DUL strength assessment of the NFC composite or bonded part. It is further required that the assessment be verified by analysis combined with coupon or hardware element test data.

NASA-STD-5019A, Item 6.2.3.c(2)

This item in NASA-STD-5019A applies to any NFC composite or bonded structures that are part of the fail-safe structure that remain after one member is removed. The requirement is to demonstrate this remaining structure can sustain DLL, and it is to be verified by analysis combined with coupon or hardware element test data for the worst-case impact damage from the NFC failed structural member.

NASA-STD-5019A, Item 6.2.3.c(3)

This item in NASA-STD-5019A applies to any fracture critical composite or bonded structures that may be impacted by an NFC fail-safe part. The requirement is to include the worst-case impact damage caused by the NFC fail-safe part in the DTA and RTD evaluations that are required in section 7.4 for the impacted fracture critical composite or bonded structures.

There is guidance that appears after item 6.2.3.c.(3) that states:

> "*For metallic structures, verification by analysis is sufficient.*"

It is presumed the guidance applies to any metallic fracture critical parts that may be impacted by a failed member of an NFC fail-safe part. Analysis would be needed to address the worst-case impact from the failed member of the fail-safe structure as part of the required evaluations supporting the fail-safe structure assessments.

NASA-STD-5019A, Item 6.2.3.d

This item in NASA-STD-5019A requires NFC fail-safe hardware that is to be re-flown first pass an inspection which may be a visual or other means that verifies the hardware is intact and free of structural anomalies before it is re-flown. Examples of inspection methods may include visual inspection aided by magnified lens or other equipment such as cameras or borescopes or more advanced methods such as built-in sensors in composite structures.

Guidance appearing at the end of this section in NASA-STD-5019A states:

> *"The possible consequences of the release of redundant parts need to be assessed. Failure of a redundant part may create impact with an adjacent part and is to be considered during fracture control classification and assessment of the adjacent part"*.

This guidance is addressed by the requirements in items 6.2.3.c(1), 6.2.3.c(2), and 6.2.3.c(3) in NASA-STD-5019A as discussed in these sections in this Handbook.

6.2.4 NFC Non-Hazardous-Leak-Before-Burst (NHLBB) Pressurized Components (NASA-STD-5019A, Section 6.2.4)

NASA-STD-5019A:
6.2.4 NFC NHLBB Pressurized Components

This classification is intended for metallic pressure-bearing walls of containers, trapped volumes, lines, fittings, valves, regulators, filters, bellows, or other pressurized hardware that transfer non-hazardous fluid under pressure and that would leak down in the presence of a flaw rather than burst when used as intended. Typically, these parts are produced under process control in large quantities, are identical parts, and are subjected to NDE and qualification testing to ensure the parts are reliable and present a low risk of containing detectable flaws that result in crack growth related to environmental, loading, or other conditions. Also, this classification is intended for hardware designed to carry primarily pressure loads. This hardware is usually designed with appropriate supports, brackets, or relief loops such that the hardware is not subject to significant structural loads. In this classification, the leakage of the fluid is not allowed to create a catastrophic hazard. This section does not apply to the hardware types addressed in section 7.2 in this NASA Technical Standard.

Satisfy all of the following items to classify a part as an NFC NHLBB component to meet requirement [FCR 8] section 6.2.d in this NASA Technical Standard:

a. The pressurized item satisfies the LBB definition in this document at MDP.

b. The leak does not cause a catastrophic hazard nor release hazardous fluid.

c. As the hardware item leaks down, there is no repressurization or continued pressure cycles that could lead to continued fatigue or crack growth related to EAC or SLC.

d. The hardware is manufactured from metal alloys that are not susceptible to crack growth related to EAC or SLC in the applicable environment and that are typically used for pressurized systems, using processes that have been established by reliability or inspections of many similar parts to be extremely unlikely to produce parts with a flaw exceeding process specifications.

e. Associated structure supporting the pressurized hardware also meets fracture control requirements.

f. Hardware does not have an impervious barrier, coating, etc., on either the interior or exterior surfaces that inhibits leakage.

g. Re-flight hardware is inspected for leaks before repressurization and/or before being re-flown.

Note that leaking hardware may present unacceptable impacts on program mission success. 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.

When LEFM is applicable, an acceptable approach to LBB for metallic alloys is to show by analysis that a worst-case surface crack will grow into a through-the-thickness crack without unstable crack propagation. This presumes the hardware manufacturing process has no credible risk of producing initial flaws longer than the crack, and leakage through the crack is shown to reduce pressure before loadings could grow the crack to cause fracture. The analysis, taking into account applied loads and residual stress effects, shows that the crack will leak and not be unstable. Additional guidance on analysis and leakage is available in API 579-1/ASME FFS-1, Fitness-for-Service.

The introductory guidance in section 6.2.4 in NASA-STD-5019A is repeated below in a modified and re-arranged format to assist the users of this Handbook.

In this classification, the fluid is non-hazardous so that leakage of the fluid does not create a catastrophic hazard. Also, this section does not apply to the hardware types addressed in the fracture critical section 7.2 in NASA-STD-5019A.

This classification is intended for metallic pressure-bearing walls of containers, trapped volumes, lines, fittings, valves, regulators, filters, bellows, or other pressurized hardware that transfer non-hazardous fluid under pressure and that would leak down in the presence of a flaw rather than burst when used as intended.

Typically, these parts are produced under process control in large quantities, are identical parts, and are subjected to NDE and qualification testing to ensure the parts are reliable and present a low risk of containing detectable flaws that result in crack growth related to environmental, loading, or other conditions.

Also, this classification is intended for hardware designed to carry primarily pressure loads for pressurized components as defined in section 3.2 in NASA-STD-5019A. This hardware is usually designed with appropriate supports, brackets, or relief loops such that the hardware is not subject to other significant structural loads.

The detailed requirements in section 6.2.4 of NASA-STD-5019A are discussed next.

NASA-STD-5019A, Item 6.2.4.a

Item 6.2.4.a of NASA-STD-5019A requires the container to satisfy the LBB criteria at MDP. The purpose of this requirement, along with other related requirements in this section, is to protect against a fracture event by requiring the container to satisfy LBB criteria making a leak the credible failure mode as opposed to a fracture. The definition of LBB in section 3.2 Definitions in NASA-STD-5019A is:

> "Leak-Before-Burst (LBB): Characteristic of pressurized hardware whose only credible failure mode at or below maximum design pressure (MDP) with service life loads resulting from the presence of a potential flaw is a pressure-relieving leak at the flaw as opposed to burst or rupture at the critical stress intensity factor. As the hardware item leaks down, there is no re-pressurization or continued pressure cycles that could lead to continued crack growth. In this failure mode, the hardware will not fail in a fragmentary, catastrophic manner. Instead, only small, slow-growing leaks would develop, leaking in a controlled manner. Additional aspects of LBB assessments are described in section 6.2.4 in this NASA Technical Standard."

MDP is maximum design pressure, defined in section 3.2, Definitions, in NASA-STD-5019A.

The purpose of ensuring the hardware satisfies this LBB criteria, the other requirements c, d, and f, and the aspects cited in guidance at the end of section 6.2.4 in NASA-STD-5019A is to ensure fracture of the hardware is a non-credible event. The question then arises, how is the demonstration the container satisfies this LBB criteria to be performed? Usual assessment methods for damage tolerance begin with the NDE detectable crack size, but NDE is not a requirement imposed by fracture control for this classification.

Two possible examples for performing the assessments are provided below. The objective of these example assessments is to demonstrate that there is sufficient separation between the condition where the crack leaks and when the FAD criteria predict fracture. There is not a required amount of separation in these events. The assessment variability for different crack sizes should be small relative to the separation of the leak and fracture events to achieve a credible result that demonstrates the hardware satisfies the LBB definition and requirement 6.2.4a in NASA-STD-5019A.

Example 1 for satisfying the LBB definition: a matrix of NASFLA crack analyses:
The example 1 method is discussed in section 6.1.4 in this Handbook. The complete discussion will not be repeated here to avoid duplication. In brief, it is noted the method follows the guidance at the end of section 6.2.4 in NASA-STD-5019A by applying LEFM assessment methods. The example utilizes the NASGRO® NASFLA program capabilities to assess a range of surface crack sizes and aspect ratios to determine when the remaining ligament below the surface crack is predicted to be plastic, which is assumed to be the condition for the crack to leak fluid. This example method needs to assess a significant matrix of possible cracks. The same analyses also apply the fracture criteria "FAD: Fitnet Option 1" to determine if and when the surface crack fractures. The assessments are to determine if a surface crack in the hardware will leak before fracturing, and how many pressurization cycles are needed for this crack growth progression. If possible, if crack sizes are shown to leak before breaking, the assessment validates a LBB condition. If cracks are more likely to break than leak, the hardware fails to achieve the LBB condition.

Example 2 for satisfying the LBB definition: using API 579-1/ASME FFS-1 Fitness-for-Service methods for NDE size crack with NASFLA crack analyses:

This example 2 method is described in this section. The assessment is defined by the guidance provided at the end of section 6.2.4 in NASA-STD-5019A, which is copied below:

> *"When LEFM is applicable, an acceptable approach to LBB for metallic alloys is to show by analysis that a worst-case surface crack will grow into a through-the-thickness crack without unstable crack propagation. This presumes the hardware manufacturing process has no credible risk of producing initial flaws longer than the crack, and leakage through the crack is shown to reduce pressure before loadings could grow the crack to cause fracture. The analysis, taking into account applied loads and residual stress effects, shows that the crack will leak and not be unstable. Additional guidance on analysis and leakage is available in API 579-1/ASME FFS-1, Fitness-for-Service."*

The methodology in API 579-1/ASME FFS-1, Fitness-for-Service, for a "Level 3 Assessment" is stated in section 3.4.4.5 in API 579-1/ASME FFS-1 and is copied below:

> "A Level 3 assessment normally relies on a determination of maximum expected flaw sizes at locations of high stresses. In general, these postulated flaws should be assumed to be surface breaking, and to be oriented transverse to the maximum stress. For welded structures, this often implies that the flaw is located within the residual stress field parallel to a longitudinal weld or transverse to a circumferential weld. The maximum expected flaw size should be detectable with standard NDE techniques. The detectable flaw size will depend on factors such as surface condition, location, accessibility, operator competence, and NDE technique... In this assessment, the aspect ratio of the assumed flaw should be large enough to ensure that the calculations are not highly sensitive to small variations in flaw depth in the through thickness direction. To reduce this sensitivity, a minimum crack-like flaw aspect ratio of 6:1 is recommended."

It is clear from the above excerpt that NDE is required to apply the API 579-1/ASME FFS-1 Fitness-for-Service methodology. While NDE is not required in this 6.2.4 NFC classification, there is nothing preventing its use if it is simpler or more effective way to demonstrate the hardware satisfies the LLB definition and requirement 6.2.4a in NASA-STD-5019A.

There is additional guidance in API 579-1/ASME FFS-1, section 9.5.2.2, Limitations of LBB, that notes LBB methodology may not be suitable for the following situations:

- Flaws near stress concentrations or regions of high residual stress, and
- When the stresses are higher on the surface than the interior of the pressure wall causing the flaw to grow faster in the surface direction than in the depth direction.

If the above cited Limitations of LBB are not applicable for the hardware being assessed, the next step is to determine the initial crack size defined by the NDE. Section 9.5.2.4, Flaw Dimensions for LBB, in NASA-STD-5019A specifies the surface crack length to be used as shown in Equation 1:

$$2C_{LBB} = 2C + 2t \qquad \text{Equation 1}$$

where $2C_{LBB}$ is the crack surface length used in the assessment, which is computed as the 2C from NDE plus 2 times the wall thickness. This surface length is used with the NDE determined crack depth in a crack growth analysis to determine if the crack will grow through the thickness or, alternatively, develop a plastic ligament in the crack depth that is presumed to result in leakage. See the discussion of Example 1 in section 6.1.4 in this Handbook for more details on NASFLA analyses to determine the Plastic Limit Load assessment that suggests crack leakage and the FAD assessment that predicts crack fracture.

It is also noted that Volume 2 of NASA-HDBK-5010 may be helpful for LBB assessment as well as assessment of pressurized hardware. If there is a need to assess leak rates from a through crack, section 9.5.2.5 in API 579-1/ASME FFS-1 points to the following reference:

> Ewing, D.J.F., "Simple Methods For Predicting Gas Leakage Flows Through Cracks," Paper C376/047 In Proceedings of International Conference on Pipework Engineering And Operation, I. Mech. E., London, 21-22, Pp. 307-314, February, 1989.

Appendix B contains report MPFR-14-031, Leak Before Break Evaluation of MSFC/MAF Steam Pipes, that illustrates an LBB demonstration using API 579-1/ASME FFS-1 Fitness-for-Service methodology.

NASA-STD-5019A, Item 6.2.4.b

The definition of "Hazardous Fluid" in NASA-STD-5019A is copied below:

> "Hazardous Fluid: For fracture control, a fluid the release of which would create a catastrophic hazard. These types of fluids may include liquid chemical propellants, liquid metals, biohazards, and other highly toxic liquids or gases. The release of such fluids 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."

This requirement has several effects. First, it ensures the hardware conveys only non-hazardous fluids, so that leaked fluid is not hazardous. Second, the leak of fluid from the system cannot cause a catastrophic hazard in the components or associated systems due to leakage of fluid from the component. Third, it ensures the leak does not occur in a hazardous manner such as release during a sudden fracture of the component.

NASA-STD-5019A, Item 6.2.4.c

This requirement within NASA-STD-5019A means these components are not pressurized by continuous or intermittent pumping from a fluid reservoir that could cause fatigue crack growth. Also, re-pressurization from a pressure vessel could cause extended duration of sustained stresses causing more leakage through a crack, and worst, crack growth if the component material had unknown EAC or SLC vulnerability.

NASA-STD-5019A, Item 6.2.4.d

There are two important aspects imposed in this requirement: (1) the material is not susceptible to EAC or SLC in the fluid and surrounding environment, and (2) the manufacturing process has to reliably produce parts without flaws exceeding the process specifications.

The determination of metal susceptibility to crack extension by EAC is a concern for hardware used with hazardous fluids such as propellants. (For an example, see the reference by Lewis and Kenny (1976) cited in NASA-STD-5019A, Appendix B.4). Hardware meeting requirements in this item encounter only non-hazardous materials. For hardware made from common aerospace materials, with exposure to common, non-hazardous fluids, EAC may not likely be a concern, but it depends upon the fluids. Also, some metals, such as titanium, may be susceptible to SLC, depending on the hydrogen content, and may not be a good choice for this hardware. If titanium is used, an assessment would need to demonstrate the hardware would not fail due to SLC. (For information on SLC and titanium, see the reference by Boyer, et al. (1978) cited in NASA-STD-5019A, Appendix B.4).

The second part of this requirement is critical and key to ensuring the reliability of this hardware as NFC hardware suitable for this classification. This part of the requirement is cited below:

> "The hardware is manufactured ... using processes that have been established by reliability or inspections of many similar parts to be extremely unlikely to produce parts with a flaw exceeding process specifications."

This hardware aspect is important because NDE is not required for this hardware. The control of flaws that present a risk of any type of failure rests upon the presumption the hardware satisfies this requirement. Credible defects and acceptance criteria should be taken into account in the EAC and SLC assessment.

NASA-STD-5019A, Item 6.2.4.e

This means the components and piping bracket structures that carry most of the non-pressure loadings are themselves attached and supported by hardware that satisfies NFC or fracture critical hardware requirements.

NASA-STD-5019A, Item 6.2.4.f

The concern here is any protective covering for corrosion protection or other purpose cannot have an ability to prevent fluid leaks that would invalidate the LBB characteristic of the system.

NASA-STD-5019A, Item 6.2.4.g

This item imposes requirements before hardware is re-pressurized and/or being re-flown to ensure the conditions at the beginning of the service life are consistent with the basis for qualifying the hardware as LBB. An example is if the container developed leaks in previous use that were not detected by this required inspection before re-pressurization or re-flight resulting in unacceptable dilution or toxicity of breathing environments if the container is in a habitable module or increases in oxygen or flammable material beyond flammability limits, or loss of a safety-critical function.

Observation on proof testing and NDE of this hardware:
It is noted the hardware addressed in this section is often proof tested for acceptance irrespective of fracture control. If weld joints receive pre- and post-proof NDE that detects a crack, the assessment methods described in item 6.2.4.a of NASA-STD-5019A as examples 1 and 2 could be used to evaluate the crack.

6.2.5 NFC Low Risk Parts (NASA-STD-5019A, Section 6.2.5)

NASA-STD-5019A:
6.2.5 NFC Low-Risk Parts

The low-risk classification is intended for parts that are extremely unlikely to contain or develop critical flaws because of (1) extremely low likelihood of flaws being induced by manufacturing processes, environmental effects, or service events and (2) large structural margins.

Satisfy all of the items in section 6.2.5.a for metallic parts or all of the items in section 6.2.5.b for composite or bonded hardware to classify a part as an NFC low-risk part to meet [FCR 8] section in this NASA Technical Standard:

a. Metallic parts are classified as low risk, provided the documented assessment shows they meet the following:

(1) The part is manufactured from materials with well-characterized strength and ductility properties using processes that have been established by inspections to be extremely unlikely to produce parts with flaws and that have been shown not to fail because of brittle fracture.

(2) Metallic parts have a material property ratio of $K_{Ic}/Fty \geq 1.66 \sqrt{\text{mm}}$ $(0.33 \sqrt{\text{in}})$ and do not have sensitivity to EAC, SLC, or stress corrosion cracking as defined in NASA-STD-6016.

(3) Aluminum parts are not loaded in the short transverse direction if this dimension (from the raw stock part) is greater than 7.62 cm (3 in).

(4) Parts have total net-section stresses, e.g., maximum principal or von Mises, whichever is larger, at limit load that are less than 30 percent of the ultimate strength.

(5) One of the following is satisfied:

A. Perform a fatigue analysis that results in a minimum service life factor of 4 with a factor of 1.5 on local cyclic stresses.

For metallic parts addressed in 6.2.5.a.5.A in this NASA Technical Standard, the part should meet conventional fatigue, accounting for notch and mean stresses, with 4 lifetimes and 1.5 on alternating stress.

B. Perform a damage tolerance analysis that results in a minimum of 4 complete service lives with a factor of 1.5 on alternating stress using a

0.127-mm (0.005-in) initial crack that conservatively accounts for the effects of notches and mean stress.

b. Composite or bonded hardware is classified as low risk, provided the documented assessment shows it meets the following, based on the flaws identified by the RTD performed in accordance with section 7.4.3 in this NASA Technical Standard:

(1) The part residual strength with the largest RTD flaw can sustain DUL verified by analysis combined with coupon or hardware element test data.

(2) The part limit strain with the RTD established flaw size is below the no-growth threshold strain established by test.

(3) Re-flight hardware is verified by visual inspection or other means to show the hardware is intact and free of structural anomalies before being reflown.

Note that metallic welds and castings are manufacturing processes that may be likely to contain critical flaws, and therefore, they do not qualify as low-risk parts unless inspection data establish they have no flaws that can grow, i.e., the crack stress intensity factor is below threshold, including environment and residual stress effects.

For metallic parts addressed in item 6.2.5.a (above), the net-section stresses are to be computed based on strength-of-materials theory. An example of the net-section stress calculation for combined tension and bending stress is detailed in the NASGRO® User's Manual, Appendix B, in the beginning pages, except no crack or epsilon factor is used for this NFC low-risk application. For complex parts where finite element results are obtained that may include stress concentrations and stress gradients, the net-section stresses are to be computed by integrating the stress distribution and dividing by the area for the sectional area being assessed.

The low-risk classification is intended for parts that are extremely unlikely to contain or develop critical flaws. Critical flaws are those that could cause fracture before the end of the required damage tolerance lifetime. The requirements for classification of hardware in this category are different for metallic versus composite or bonded materials as detailed in items 6.2.5.a and 6.2.5.b in NASA-STD-5019A.

Some hardware types such as pressure vessels, habitable modules, and pressure components with hazardous materials typically fall in the fracture critical classification and do not fit in this category because construction or manufacturing processes are likely to produce inherent defects in the part. The use of the NFC Low Risk approach is not recommended for these hardware types.

The NFC Low Risk approach has typically been reserved for non-load carrying hardware such as payloads. This approach relies on well characterized aerospace materials that are process-insensitive where the likelihood of a presence of a flaw is extremely low. Since the risk assurance is provided by predictable material behavior, no damage tolerance analyses nor NDE are required for this category of hardware. However, caution should be exercised in using the NFC Low Risk category for primary and secondary load-carrying members and structures for human-rated vehicles which are subject to high energy flight environments. A durability assessment based on the assumption that there is no pre-existing flaw may show more than four lifetimes. However, in some standard aerospace materials a damage tolerance analysis assuming an initial crack size according to NASA-STD-5009 subject to service life loads, may show less than four lifetimes, and in some cases less than one. It is therefore recommended that the fracture control practitioner use caution in utilizing the NFC Low Risk approach on a vehicle primary and secondary structure or hardware. A fracture fatigue assessment can be performed to determine if that particular case falls short of the four lifetimes. If that is the case, ample evidence needs to exist that the material, product form, and manufacturing (e.g., machining) has extensive process controls and monitoring in place to ensure the final product is free from defects.

Note that due to the nature of additive manufacturing (AM), which is process-dependent and likely to produce parts with defects, AM parts are precluded from the NFC Low Risk category.

NASA-STD-5019A, Item 6.2.5.a

There are two aspects to be addressed to qualify metallic parts for an NFC Low-Risk Parts classification. The first aspect addresses the manufacturing and material characteristics. To qualify metallic hardware as low risk parts, it is necessary to demonstrate they have an extremely low likelihood of occurrence of critical flaws that are induced by manufacturing processes, environmental effects, or service events by satisfying each of the three items (1), (2), and (3).

NASA-STD-5019A, Item 6.2.5.a(1)

Item 6.2.5.a(1) of NASA-STD-5019A requires metallic parts classified in this category to be made of ductile metals that also satisfy the items (2) and (3) requirements listed below. They are to be manufactured using processes that have been demonstrated to be extremely unlikely to cause critical flaws. A classic example of parts meeting these criteria are those made from extruded shapes of a ductile material such as 2024-T351 aluminum. In this example, the manufacturing and extrusion processes have been demonstrated by a significant experience base to be unlikely to cause critical flaws in the extrusions. Also, the subsequent processing of parts such as these cannot involve manufacturing methods that are likely sources of critical flaws such as welding. Additional guidance is provided at the end of section 6.2.5 in NASA-STD-5019A, which is copied below:

> *"Note that metallic welds and castings are manufacturing processes that may be likely to contain critical flaws, and therefore, they do not qualify as low-risk parts unless inspection data establish they have no flaws that can grow, i.e., the crack stress intensity factor is below threshold, including environment and residual stress effects."*

Parts manufactured using other methods with an unknown probability of containing critical internal or surface flaws are not suitable for this classification unless the process has been demonstrated to reliably satisfy the guidance cited above. Examples include newly developed manufacturing or processing methods such as AM parts. AM parts are explicitly excluded from the low-risk part classification in MSFC-STD-3716, Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals.

NASA-STD-5019A, Item 6.2.5.a(2)

Item 6.2.5.a(2) of NASA-STD-5019A imposes the above cited material property ratio on prospective flight hardware metallic materials that are to be classified under this section. In addition, the hardware material has to be shown by fracture specimen test data or approved data by RFCB that it is not susceptible to failure caused by EAC, SLC, or stress corrosion cracking when exposed to the environments the hardware experiences throughout its lifetime. The test data have to be applicable for the particular hardware material metallurgical condition and the flight environments. Credible defects and acceptance criteria should be considered in the EAC and SLC assessment.

NASA-STD-5019A, Item 6.2.5.a(3)

Item 6.2.5.a(3) of NASA-STD-5019A is a straightforward limitation on aluminum hardware part thicknesses. The purpose is to avoid this failure mode in aluminum parts. For example, MIL-HDBK-5H, Metallic Materials and Elements for Aerospace Vehicle Structures, property data for aluminum 2024-T351 plate in Table 3.2.3.0(b1) and 7075-T651 plate in Table 3.7.4.0(b1) shows reduced ultimate and yield strengths in the short transverse direction. Additionally, notes in this reference state these specific alloy, temper, and product forms exhibit poor stress-corrosion cracking resistance in this grain direction, which corresponds to an "SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a)." This would invalidate parts made of these materials per the above paragraph (2) from use in flight environments where stress corrosion cracking (SCC) occurs.

The second aspect to be demonstrated for metallic hardware to be classified as a low-risk part addresses the stress state and fatigue capability by establishing it meets both items (4) and (5) as discussed below.

NASA-STD-5019A, Items 6.2.5.a(4) a(5)

To demonstrate this item (4) requirement is met, the net section stresses should be computed. For uniform tension and simple bending loadings, this is a strength-of-materials theory calculation using Equation 2 that also is described in the NASGRO® version 8 program Main Reference Manual in section 2.1.6:

$$S_n = P/A_n + Mc/I_n \qquad \text{Equation 2}$$

In the above equation, S_n is the net-section stress, P is the applied load, A_n is the net area, M is the resultant moment, c is the distance to the outer fibers, and I_n is the moment of inertia of the net section. This formula also is more fully described in the NASGRO® User Manual, Appendix

B. The NASGRO® programs NASFLA and NASSIF compute and report a "net section yield" ratio, which is the ratio of S_n to the material yield strength. The NASFLA program checks this quantity and can provide a warning message if yielding is imminent anywhere in the net section. The methodology is documented for all the available geometries and stress distributions in the NASGRO® User Manual, Appendix B. This application tool is specialized for calculations involving cracks. The net section stress calculation equations provided in this reference could be utilized for approximately computing the net section stresses of complex geometries and loadings for comparison to the material ultimate strength. The computation is not exact because these NASGRO® programs utilize an epsilon factor to compute bending stress that is near, but not at the outer fiber of the net section, as explained on pages B-1 and B-109 in Appendix B in the NASGRO® User Manual. Because the bending stress is reduced by this factor, the calculation reports a smaller value of the ratio to the yield stress. If the factor is computed, it will provide a lower bound check of the net section stress for the many complex geometry and loading cases that are available in these programs. To get the appropriate stress ratio with this tool, input 30% of the ultimate stress as the "yield stress" and compute for a very small crack, barely larger than the particular solution accuracy limits. The outputs relating to Stress Intensity Factors are ignored when using these programs for this purpose.

In addition, at the end of section 6.2.5 in NASA-STD-5019A, notes in italics provide guidance for computing net section stress for complex parts where finite element results are obtained that may involve stress concentrations and stress gradients. In this situation, the guidance states the net-section stresses may be computed by integrating the stress distribution and dividing by the area for the sectional area being evaluated.

Other equivalent methods for determining net section stress may be employed.[9]

NASA-STD-5019A, Item 6.2.5.a(5)A

Per the guidance in item 6.2.5.a(5)A in NASA-STD-5019A, this analysis is to be a conventional fatigue assessment. The assessment has to account for effects of notches and mean stress effects and is to demonstrate the part survives 4 lifetimes with a factor of 1.5 on the alternating stress.

NASA-STD-5019A, Item 6.2.5.a(5)B

This type of damage tolerance analysis is sometimes known as a "durability" damage tolerance analysis. It has been used for spaceflight hardware as an alternative to perform the conventional fatigue assessment. The damage tolerance analysis is to utilize the specified initial crack size and should satisfy all the technical assessment requirements in section 7.3 in NASA-STD-5019A. The analysis should use crack growth models that represent effects of notches and apply flight loadings that include mean stress effects. It is expected the user will utilize the NASGRO® NASFLA program for the analysis. In addition, the analysis should set the crack growth rate

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[9] Some programs or RFCBs have approved methods such as dividing the peak stress by the concentration factor of the geometry or staying away a distance of 2 diameters for holes. Although these are practical methods, they may not apply universally to all hardware; and the analyst should use these methods with understanding and care and seek RFCB approval.

equation exponent "p" to zero in the NASFLA "Material" table. The reasons are because this initial crack size is so small that the threshold crack growth rate parameters resulting from fitting data for large cracks are not selected to simulate this small crack. If the exponent "p" is not set to zero, specialized testing and crack growth modeling would be needed that simulates small crack growth plasticity[10] and residual stress effects.

If there is no data available in the threshold region, setting p = 0 yields a conservative approach.

NASA-STD-5019A, Item 6.2.5.b

Specific requirements imposed by NASA-STD-5019A upon composite or bonded hardware to be classified as low risk are detailed in item 6.2.5.b, items (1), (2), and (3) that are discussed below. Additional guidance is provided next on development of a plan and then on the aspects of section 6.3 in NASA-STD-5019A that are applicable to NFC Low Risk Parts.

Development of a design, inspection, and manufacturing plan for composite or bonded hardware being considered for this classification should begin by recognizing that care should be taken to reduce the likelihood of a part containing or developing a critical flaw. Material production processes should use documented quality control and protection methods to prevent introducing defects into the material system or opportunity for any sources of damage to the hardware throughout the manufacturing process. The part should be manufactured from a material system that is well characterized and understood in terms of storage requirements, shelf life, rheology (proper cure schedule), and details related to multi-step cure/pressure sequencing for higher complexity material systems such as sandwiches or structural features.

As described in section 6.3 in NASA-STD-5019A, in addition to the requirements stated in section 6.2.5, all NFC low risk composite parts should be included in a DTA, an IDMP, and a RTD that have been documented in the FCSR and has been approved by the RFCB. Guidance for developing a DTA, IDMP, and a RTD can be found in this Handbook in sections 7.4.1, 7.4.2, and 7.4.3, respectively. Details of the fabrication procedure used to control potential sources for damage or flaws to be introduced into the parts should be accounted for in the DTA. Mitigation strategies for avoiding fabrication and pre-flight damage should be included in the IDMP. All personnel that may come into the proximity of production or storage of flight parts for any reason should be trained according to procedures outlined in the IDMP, especially those related to inadvertent damage occurring during production or preflight activities.

NASA-STD-5019A, Item 6.2.5.b(1)

Potential methodologies to demonstrate residual strength may vary in their utilization of analysis verification to differing degrees. The nature of such methodologies may range from demonstration of residual strength by test only to demonstration based on a test-validated model. If a test-only approach is desired, note that NASA-STD-5019A still requires verification by

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[10] Refer to references on growth of small cracks such as "The Significance of Small Cracks in Fatigue Design Concepts as Related to Rotorcraft metallic Dynamic Components," by R.A. Everett, Jr., and W. Elber, DTIC Accession Number ADP010634, available at https://apps.dtic.mil/sti/citations/ADP010634 .

analysis (in this scenario, simple predictive methods could be used minimally just to demonstrate that the test results are within expectations). See section 7.4 for discussion on use of a test-verified analysis approach. See section 7.4.3 for further discussion on use of a test only approach. Whatever exact methodology for demonstrating strength is used, the part should be loaded until failure (onset of flaw growth) or until the required design envelope has been reached. If the failure load is less than the required design load, low risk cannot be used.

NASA-STD-5019A, Item 6.2.5.b(2)

The part limit strain criterion is based on comparison of strain against the no-growth threshold strain value. Note that "no-growth threshold strain" is material and layup specific for composites and refers to the maximum absolute strain value in load cycling for which no-growth of a RTD determined flaw is observed after 1 million cycles. In this context, strain corresponds to levels on the "outer surface" of a laminate similar to where strain data would have been gathered using bonded gauges or digital image correlation in the testing that determined the threshold value. In sandwich structures, strain should be assessed individually for each face sheet.

The part limit strain (i.e., the maximum strain in a part at limit load) should be determined by analysis or test. If analysis is used, no damage simulation capability in the model is necessary since the criteria for failure, no-growth threshold strain, is seen at the end of (but still within) the linear elastic range. The model of a part should include the worst-case RTD flaw (modeled with contact behavior on the crack surfaces). Maximum strain should not be taken from node/elements in the model that exist at location where a stress singularity exists and unrealistically high values are predicted (i.e., at a geometric discontinuity, etc.).

If a test is used to determine part limit strain and strain gauges are planned, some knowledge is required about where the maximum strain is expected to place the gauges at that location. A model may also be useful for this purpose. Another option for determining maximum part strain at limit load if a test is employed is to use digital image correlation.

NASA-STD-5019A, Item 6.2.5.b(3)

Visual inspection should be performed between flights according to procedures outlined in the IDMP. This should include specific screening for both obvious damage and also barely visible damage. Barely visible damage may indicate internal damage that could cause a reduction in strength. The DTA should include consideration of scenarios where damage may be introduced specific to re-flight activities such as reentry, recovery, refurbishing, etc. See section 8.1.2 in NASA-STD-5019A for more information on visual inspection and NDE.

Section 6.2.5 of Volume 2 of NASA-HDBK-5010 contains checklists for assessing and categorizing metallic hardware and composite or bonded hardware as NFC low risk.

Note that BVID as defined in the aircraft industry may be inappropriately large for spaceflight applications. Barely visible damage and critical defect size need to be established by means of IDMP and RTD. Appropriate inspection for re-flight needs to be established as well.

6.2.6 NFC Documented Non-Hazardous Failure Mode (NASA-STD-5019A, Section 6.2.6)

NASA-STD-5019A:
6.2.6 NFC Documented Non-Hazardous Failure Mode

Provide documentation establishing that a hazard assessment has been performed and that there are no credible catastrophic hazards resulting from failure of the part caused by a flaw to classify a part as NFC Documented Non-Hazardous Failure Mode to meet requirement [FCR 8] section 6.2.f in this NASA Technical Standard.

Note that this category is significantly different from the Exempt classification in section 5. Exempt parts are nonstructural and have no hazardous concerns or failure modes. This category may have structural or non-structural parts that are to be addressed by a documented hazard assessment that establishes no credible catastrophic hazards exist for the failure modes identified.

For composite or bonded parts classified as NFC Documented Non-Hazardous Failure Mode according to this section may not be required to meet all the requirements in section 6.3 in this NASA Technical Standard. Guidance from the RFCB may be necessary.

The classification requires that a documented hazard analysis report assures that no catastrophic failure mode exists for failure of the part due to a flaw.

Section 6.1, Established Approaches for Specific NFC Hardware Types, and section 6.2, General Approaches for NFC Parts, in NASA-STD-5019A include many situations where the prescribed approach results in a controlled condition where the structure is unlikely to fail and cause a catastrophic hazard. None of the situations addressed elsewhere in section 6 are acceptable subjects for assessments based on this section.

An example of a situation that could be addressed by this section could be a case where a structure member experiences a crack and fails to some degree to support load, but the consequence of the member condition is either minor or controlled such that no catastrophic hazard event could occur; and that condition is documented by engineering and safety evaluations.

Another example of a situation that may be applicable for this section may be a structure that experiences a displacement-controlled loading in a manner such that the structure/material has capability to sustain a flaw/crack that causes the loading to relax so that a critical crack size resulting in fracture cannot be achieved. Examples of this situation occur in the test specimen described in the following ASTM standards:

- ASTM E1221, Standard Test Method for Determining Plane-Strain Crack-Arrest Fracture toughness, K_{Ia}, of Ferritic Steels, shows a wedge-loaded double cantilever beam specimen.

- ASTM E1681, Figure 3, describes a Modified Bolt-Load Compact Specimen.

It is important to perform a complete system/structural analysis of a situation where one structural member may not fail due to compliance reduction of a displacement-controlled load. For example, consider a structure with redundant elements that together resist applied loads. If one element experiences a change in compliance due to a crack or local uncontrolled deformation, the loads that are diminished in that element may transfer into adjacent elements, which may then be at risk of failing or deforming such that portions of their loads are transferred further into the structure until finally a catastrophic hazard event is encountered.

A similar condition as described above caused the catastrophic failure in 1982 of the drive system of a major NASA wind tunnel facility, the National Full-Scale Aerodynamics Complex’s 80-foot by 120-foot Wind Tunnel. The failure began when several structural elements loaded in parallel deformed unexpectedly due to joint failure during an increasing wind load test. The consequence of a few elements shedding loads into adjacent members caused the aerodynamic control structure to change in a manner that increased structure loads. This resulted in failure of the aerodynamics control structure, causing a huge aerodynamic overload that collapsed the structure. The failed structure debris was blown into and destroyed the wind tunnel drive system blades.

6.3 Additional Activities for Composite or Bonded NFC Hardware (NASA-STD-5019A, Section 6.3)

NASA-STD-5019A:
6.3 Additional Activities for Composite or Bonded NFC Hardware

Composite or bonded hardware classified as NFC require activities (detailed below) to be performed and then documented in the FCSR in addition to the other activities for the specific NFC category.

[FCR 9] NFC composite or bonded parts that satisfy requirements for classification in a specific category in sections 6.1 and 6.2 in this NASA Technical Standard shall also comply with all of the following items:

a. For parts classified as NFC low risk, develop the following:

(1) A DTA in accordance with section 7.4.1 in this NASA Technical Standard.
(2) An IDMP in accordance with section 7.4.2 in this NASA Technical Standard.
(3) An RTD in accordance with section 7.4.3 in this NASA Technical Standard.

b. For NFC parts not classified as low risk, perform the following:

(1) Define and quantify the flaws from any source that may occur to the hardware during its service life, considering all applicable flaw detection and mitigation strategies that are implemented for the flight hardware.

(2) Develop an IDMP in accordance with section 7.4.2 in this NASA Technical Standard.

c. Perform NDE after completion of all manufacturing processes (or after proof test, if a proof test is performed) in accordance with section 8.1.2 in this NASA Technical Standard, with the following clarifications:

(1) No NDE is required for NFC low-released mass parts.

(2) No NDE is required for NFC contained parts.

No NDE is required because there is no credible catastrophic hazard for these two specific categories.

d. Meet the traceability requirement of section 8.2 in this NASA Technical Standard [FCR 21].

e. Meet the material selection and usage requirement of section 8.3 in this NASA Technical Standard [FCR 22].

[Rationale: Parts classified as NFC that also contain composite or bonded materials need additional precautions to provide mitigation for undetected damage. These parts can be classified as NFC.]

Use of an alternative approach requires unique rationale and approval by the RFCB as described in section 10 [FCR 26] in this NASA Technical Standard.

The assessments in sections 7.4.1 and 7.4.2 in this NASA Technical Standard rely on NDE and material controls, including traceability requirements as prescribed in section 8 in this NASA Technical Standard to address hazards.

Traceability for NFC composite or bonded parts is somewhat unique relative to NFC metallic parts. While metallic parts usually have a specification for providing minimum properties throughout the part, composite or bonded parts are composed of elements that may have specifications, but the properties after combination of these elements are often unique to the hardware being produced.

NASA-STD-5001 requires a proof test for all composite or bonded structures.

NASA-STD-5019A, Item 6.3.a

Item 6.3.a in NASA-STD-5019A imposes additional requirements on composite and bonded hardware classified under section 6.2.5, NFC Low Risk in NASA-STD-5019A. Composites are treated differently from most other material because with most materials the strength (and critical flaws) in the material is generated as the material is manufactured. Section 2.5 requires the material be created with “well-characterized strength and ductility properties” so adequate process control limits the risk that a part will have flaws severe enough to reduce the part to a low delivered strength (e.g., below 30 percent of DUL). With composite and bonded parts, the strength of the part is generated as the part is manufactured; history has shown that when these processes fail, the effect on delivered strength can be severe. In addition, for composite and bonded joints, damage after manufacturing which may not be readily detectible, can severely limit its load carrying capacity. For these reasons, extra controls of the part manufacturing process and protection against subsequent damage are required. Item 6.2.5.b(1) in NASA-STD-5019A requires the hardware residual strength with the largest flaw from an RTD to be able to sustain the DUL. The three additional requirements imposed by item 6.3.a in NASA-STD-5019A are needed to define the process for assessing risk of damage that could degrade the hardware strength below DUL during its service life. Both a DTA and an IDMP are needed to determine and validate the RTD flaw(s) used in assessing the hardware's ability to support the DUL.

NASA-STD-5019A, Item 6.3.a(1)

Per requirement 6.3.a(1) in NASA-STD-5019A, a DTA also needs to be developed for NFC low-risk composite parts. The DTA should identify and quantify any potential source of damage that may occur during hardware service life. See section 7.4.1 in this Handbook for further guidance on developing a DTA.

NASA-STD-5019A, Item 6.3.a(2)

Section 7.4.2 in NASA-STD-5019A requires an IDMP be developed for composite or bonded fracture critical parts. Per requirement 6.3.a(2), an IDMP also needs to be developed for NFC low-risk composite parts. The IDMP should prescribe protection and detection strategies for threats that are identified in the DTA. See section 7.4.2 in this Handbook for further guidance on developing an IDMP.

NASA-STD-5019A, Item 6.3.a(3)

Section 7.4.3 in NASA-STD-5019A requires that an RTD be developed for composite or bonded fracture critical parts. Per requirement 6.3.a(3), a RTD also needs to be developed for NFC low-risk composite parts. This involves defining the worst-case credible flaw that could (1) be expected to occur and (2) be tolerated by the hardware. See section 7.4.3 in this Handbook for further guidance on developing an RTD.

NASA-STD-5019A, Item 6.3.b

Item 6.3.b in NASA-STD-5019A imposes two requirements 6.3.b(1) and 6.3.b(2) on NFC composite or bonded hardware that is not classified as section 6.2.5, NFC Low-Risk, in NASA-STD-5019A. Review of all the NFC categories for composite or bonded hardware shows that NFC composite or bonded hardware that is assessed under the first four of the following five NFC classifications <u>have to</u> also <u>satisfy</u> items 6.3.b(1) and 6.3.b(2) additional requirements. The fifth item may or may not be an exception as explained below:

1. Item 6.1.2.1.b, NFC Internal Shatterable Components: for hardware inside a non-habitable volume which may utilize the requirements in section 6.2.3, Fail-Safe (also see the 6.2.3 comment below).

2. Section 6.1.3, NFC Rotating Hardware: included because 6.1.1.3b applies section 6.2.5 requirements.

3. Section 6.1.5, NFC Tools, Mechanisms, and Tethers: included because item 6.3.a applies section 6.2.5 requirements.

4. Section 6.2.3, NFC Fail-Safe: included due to risk of generic damage to more than one of the redundant structures.

5. Section 6.2.6, NFC Documented Non-Hazardous Failure Mode: hardware in this

category may or may not be required to satisfy all the additional requirements. This requirement in NASA-STD-5019A has guidance stating the hardware may not be required to meet all the additional requirements and that guidance from the RFCB may be needed.

The above review also determined that requirements 6.3.b(1) and 6.3.b(2) are not applicable to other NFC hardware classifications as a result of the intrinsic requirements imposed by the other classifications. Examples of excluded sections with explanations are the following:

- Section 6.1.1.4, NFC Low-Risk Fasteners: is excluded because the parts are metallic.
- Item 6.1.2.1.a, NFC Internal Shatterable Components for hardware inside a habitable volume is excluded because it has to meet section 6.2.2, NFC Contained requirements. The containment requirements are not affected by the strength of the contained hardware.
- Section 6.1.2.2, NFC External Shatterable Components: is excluded because this section imposes requirements that include development of a DTA and IDMP in addition to other specialized requirements.
- Section 6.2.1, NFC Low-Released Mass: is excluded because item 6.2.1.a requires that fracture of the part does not cause a catastrophic hazard.

NASA-STD-5019A, Item 6.3.b(1)

Requirements 6.3.b(1) and 6.3.b(2) in NASA-STD-5019A apply to composite or bonded parts classified under section 6.2.5, NFC Low-Risk Parts in NASA-STD-5019A. These requirements also apply to composite or bonded parts classified under the other applicable NFC sections that are identified in the above list in item 6.3.b in this Handbook.

Requirement 6.3.b(1) in NASA-STD-5019A is similar to development of a DTA for fracture critical hardware. A DTA should identify and quantify any potential source of damage that may occur during the hardware service life. In addition, this requirement recognizes that NDE and any other mitigation strategies may diminish the probability of occurrence of some flaws in the hardware. See section 7.4.1 in this Handbook for further guidance on developing a DTA.

NASA-STD-5019A, Item 6.3.b(2)

Section 7.4.2 in this Handbook provides guidance on development of an IDMP for composite or bonded fracture critical parts. The IDMP should prescribe flaw mitigation strategies for threats that are identified in item 6.3.a(1). See section 7.4 in this Handbook for further guidance on developing both a DTA and an IDMP.

NASA-STD-5019A, Item 6.3.c

NDE should be performed after a proof test since flaws may have experienced growth or opened up. (Note: NASA-STD-5001B, section 4.2.3, specifies design and proof test factors in Table 2 for all composite/bonded structures, including bonded sandwich structures and bonded inserts but excluding glass). See section 8.1.2 in this Handbook for further information and guidance on NDE requirements. Common flaw types resulting from manufacturing process-related deficiencies are embedded delaminations in monolithic laminates, sandwich core-facesheet disbonds, porosity, poor bonding between different materials (e.g., polymer-to-metal), and voids in potted areas such as core splices. Inadvertent impact damage may result in delamination, matrix crushing, and/or fiber breakage depending on the nature of the impact. See section 7.4.1 for a more detailed discussion on flaws that can arise during manufacturing.

NASA-STD-5019A, Item 6.3.d

Traceability requirements defined in section 8.2 of NASA-STD-5019A are such that the complete history for any fracture critical or NFC composite/bonded part is kept. This includes applied loads, damage, repair, manufacturing processes, and environmental exposure. See section 8.2 for further detail on traceability for composite parts.

NASA-STD-5019A, Item 6.3.e

All fracture critical and NFC composite/bonded hardware has to meet selection and processing requirements outlined in section 8.3 in NASA-STD-5019A. See section 8.3 in this Handbook for more information and guidance on these requirements. Note that NASA-STD-5001B, section 4.2.3, specifies design and proof test factors in Table 2 for all composite/bonded structures, including bonded sandwich structures and bonded inserts but excluding glass.

7. ASSESSMENT OF FRACTURE CRITICAL PARTS

This section provides guidance and interpretations of numbered and titled material from NASA-STD-5019A.

7.1 Fracture Critical Parts (NASA-STD-5019A, Section 7.1)

NASA-STD-5019A:
7.1 Fracture Critical Parts

[FCR 10] Parts shall be classified as fracture critical unless one of the following is met:

a. There is no credible possibility for a flaw in the part to cause failure during the lifetime of the part.

b. Part failure does not result in a credible catastrophic hazard.

[Rationale: Parts that do not meet one of the above criteria require mitigation to preclude catastrophic failure. Classification as fracture critical denotes the need for knowledge of the sensitivity of the part to flaws or damage, an adequate screening of parts for flaws or damage and protection from damage, and traceability to assure a high-quality aerospace part is produced.]

Parts that are fracture critical require risk mitigation activities to provide assurance that flaw or damage sensitivity is understood relative to flaw screening or qualification and acceptance testing and material processing parameters.

The methods in this section are based on NASA's experience base, established approaches, industry standards, or aerospace standards. Any deviations or omissions of elements in the activities or approaches described in this section constitute an alternative approach that is to satisfy the requirements in section 10 [FCR 26] in this NASA Technical Standard.

In addition to assessments discussed in the subsequent subsections, fracture critical parts are subject to flaw screening, traceability, and material selection requirements in accordance with section 8 in this NASA Technical Standard. Documentation of the approaches to implementation and the results of implementation activities are discussed in section 9 of this NASA Technical Standard for the FCP and FCSR requirements.

a. Parts are fracture critical unless one of the following is met:

  (1) The part is exempt in accordance with section 5 in this NASA Technical Standard.
  (2) The part is NFC in accordance with section 6 in this NASA Technical Standard.

b. Fracture critical parts are to comply with one of the following applicable items:

(1) Established approaches for the specific hardware types in accordance with section 7.2 in this NASA Technical Standard.

(2) General approach for fracture critical metallic parts assessment in accordance with section 7.3 in this NASA Technical Standard.

(3) General approach for fracture critical composite or bonded hardware assessment in accordance with section 7.4 in this NASA Technical Standard.

(4) Optional approaches for fracture critical parts in accordance with section 7.5 in this NASA Technical Standard.

(5) Satisfy requirements in section 10 in this NASA Technical Standard for an alternative approach.

c. Fracture critical parts are also to comply with the following items:

(1) Satisfy flaw screening, traceability, and material requirements in section 8 in this NASA Technical Standard.

(2) Satisfy documentation requirements in section 9.1 in this NASA Technical Standard.

d. A part should always be classified as fracture critical if there is doubt or concern to establish that it is not fracture critical.

e. Parts that are often determined to be fracture critical include but are not limited to: rotating hardware that does not satisfy this NASA Technical Standard's section 6.1.3 requirements, hazardous fluid containers, pressure systems that contain hazardous fluids (such as liquid rocket engine systems), and pressurized structures (such as propellant tank structures), primary thrust structure (unpressurized), solid rocket motor cases and nozzles, and habitable modules.

f. Pressure vessels, as defined in section 3.2 of this NASA Technical Standard, are fracture critical.

g. Fracture critical parts receive additional attention beyond the standard structural and quality assurance assessments normally given to spaceflight hardware. These additional activities include the following:

(1) Either an approved set of prescribed activities deemed to be sufficient to mitigate the risk of failure because of a flaw (established approaches and

optional approaches) or a damage tolerance assessment (analysis, test, or both) to show life requirements are met in the presence of flaws.

(2) Screening of parts for flaws.

(3) Traceability of the parts.

(4) Material requirements.

(5) Documentation of the assessment and hardware implementation process.

Section 7 in NASA-STD-5019A describes assessment requirements imposed upon parts classified as fracture critical parts.

FCR 5 in item 4.3.a in NASA-STD-5019A requires ". . . fracture control classification of each part as either exempt, NFC, or fracture critical." For parts to be classified as exempt or NFC, they have to satisfy the applicable requirements in sections 5 or 6 in NASA-STD-5019A.

NASA-STD-5019A, Items 7.1.a and 7.1.b

FCR 10 in section 7.1 in NASA-STD-5019A specifies the conditions when parts have to be classified as fracture critical. Parts are classified fracture critical unless either "a" there is no credible possibility for a flaw in the part to cause failure during the lifetime of the part, or "b" failure of the part does not result in a credible catastrophic hazard. If neither condition "a" nor "b" is applicable, the part has a credible risk of a catastrophic hazard caused by a flaw and should be classified fracture critical.

As stated in this section's guidance paragraph "a," parts should be presumed to be fracture critical unless they are demonstrated to satisfy applicable requirements in section 5 or 6 in NASA-STD-5019A for classification as exempt or NFC parts. In addition, this section's guidance paragraph "d" states a part should always be classified as fracture critical if there is doubt or concern about establishing a part as not fracture critical.

NASA-STD-5019A, section 7.1 rationale states fracture critical parts require mitigation activities to avoid catastrophic failure caused by a flaw. The material specification and manufacturing processing used to produce the part affect the risk of flaws in the part. To evaluate the risk of failure due to a flaw, the part's sensitivity to flaws has to be known. Then inspections may be used to exclude parts with critical size flaws. Knowledge of the part's sensitivity to loadings and damage sources that cause creation or growth of flaws is needed to assess the risk of a critical flaw developing during the part's service lifetime. Protection and redundant design strategies may help avoid risks of damage resulting in catastrophic failure due to a flaw during the part's service lifetime.

The flaw screening, traceability, and material selection aspects cited in the above paragraph are specified by requirements in NASA-STD-5019A in section 8, "Flaw screening, traceability, and material selection." Required fracture control documentation, including the approaches used for fracture control implementation and results of these activities, including requirements on the FCP and FCSR, are specified in NASA-STD-5019A in section 9, "Fracture control documentation and verification."

The section 7.1 guidance in NASA-STD-5019A also explains the methods described in section 7 are based on NASA flight hardware experience base, established approaches for particular types of hardware, and industry or aerospace standards. Some of these are tailored based on NASA flight hardware experience. Any deviation from the requirements in section 7 constitutes an alternative approach that should satisfy section 10, FCR 26, in NASA-STD-5019A.

Section 7 includes the following major topic section headings. As stated in this section's guidance paragraph "b," fracture critical parts are expected to comply with one of the following five applicable major categories in NASA-STD-5019A, section 7:

1. Section 7.2, Established approaches for the specific fracture critical hardware types, which includes the following:

    7.1.1 Fracture critical metallic pressure vessels
    7.1.2 Fracture critical COPVs and composite overwrapped pressurized fluid containers
    7.2.3 Other fracture critical pressure vessels and pressurized fluid containers
    7.2.4 Fracture critical lines, fittings, and other pressurized components
    7.2.5 Fracture critical habitable modules and volumes
    7.2.6 Fracture critical pressurized structures
    7.2.7 Fracture critical rotating hardware
    7.2.8 Fracture critical fasteners
    7.2.9 Fracture critical shatterable components and structures
    7.2.10 Fracture critical tools, mechanisms, and tethers
    7.2.11 Fracture critical batteries

2. Section 7.3, General approach for fracture critical metallic parts assessment, which includes the following:

    7.3.1 Loading spectra
    7.3.2 Assessment by analysis
    7.3.3 Assessment by test

3. Section 7.4, General approach for fracture critical composite or bonded hardware assessment, which includes the following:

    7.4.1 Damage threat assessment
    7.4.2 Impact damage mitigation plan

7.4.3 Residual threat determination
7.4.4 Loading spectra
7.4.5 Damage tolerance tests of coupons
7.4.6 Damage tolerance tests of hardware elements
7.4.7 Strength and life assessments
7.4.8 Damage tolerance tests full-scale flight-like hardware
7.4.9 Evaluate flaws or damage that occurs during BBA testing

4. Section 7.5, Optional approaches for fracture critical parts, which includes the following:

7.5.1 Single-event fracture critical components
7.5.2 High-cycle fatigue components
7.5.3 Proof test approach for composite or bonded hardware
7.5.4 Fleet leader testing
7.5.5 Hazardous fluid containers for payloads and experiments

5. Section 10, Alternatives, contains FCR (26) that prescribes requirements for use of an alternative approach instead of meeting any portion of the accepted approaches in sections 5, 6, 7, or 8 in NASA-STD-5019A.

Fracture critical parts should also be shown to satisfy the pertinent requirements in the two following major section headings:

Section 8, Flaw screening, traceability, and material selection

> Detail requirements are in the sections under this heading on NDE for metallic parts, NDE for composite or bonded parts, proof test, process control, detected flaws, traceability for fracture control, and material selection and usage for fracture critical parts.

Section 9, Fracture control documentation and verification

> Detail requirements are in the sections under this heading on fracture control documentation, fracture control plan, engineering drawings, fracture control summary report, detailed information for the FCSR, other documentation, and verification.

This section in NASA-STD-5019A includes three guidance paragraphs: e, f, and g.

Guidance paragraph "e" identifies types of parts that are often determined to be fracture critical. These include, but are not limited to, rotating hardware that does not satisfy section 6.1.3 requirements in NASA-STD-5019A, hazardous fluid containers, pressure systems that contain hazardous fluids (such as liquid rocket engine systems), and pressurized structures (such as propellant tank structures), primary thrust structure (unpressurized), solid rocket motor cases and nozzles, and habitable modules.

Guidance paragraph "f" states pressure vessels, as defined in section 3.2 of this Handbook, are fracture critical.

Guidance paragraph "g" states that fracture critical parts receive additional attention beyond the standard structural and quality assurance assessments normally given to spaceflight hardware. These additional activities include the following three items:

1. Either an approved set of prescribed activities deemed to be sufficient to mitigate the risk of failure because of a flaw (established approaches and optional approaches) or a damage tolerance assessment (analysis, test, or both) to show life requirements are met in the presence of flaws.

2. Screening of parts for flaws.

3. Traceability of the parts.

7.2 Established Approaches for Specific Fracture Critical Hardware Types (NASA-STD-5019A, Section 7.2)

NASA-STD-5019A:
7.2 Established Approaches for Specific Fracture Critical Hardware Types

[FCR 11] Each fracture critical part that is described by a specific hardware type in the following list shall comply with the established approach given in one of the following items:

a. Fracture critical metallic pressure vessels comply with section 7.2.1 in this NASA Technical Standard.

b. Fracture critical COPVs and composite overwrapped pressurized fluid containers comply with section 7.2.2 in this NASA Technical Standard.

c. Other fracture critical pressure vessels and pressurized fluid containers comply with section 7.2.3 in this NASA Technical Standard.

d. Fracture critical lines, fittings, and other pressurized components comply with section 7.2.4 in this NASA Technical Standard.

e. Fracture critical habitable structures and volumes comply with section 7.2.5 in this NASA Technical Standard.

f. Fracture critical pressurized structures comply with section 7.2.6 in this NASA Technical Standard.

g. Fracture critical rotating hardware complies with section 7.2.7 in this NASA Technical Standard.

h. Fracture critical fasteners comply with section 7.2.8 in this NASA Technical Standard.

i. Fracture critical shatterable components and structures comply with section 7.2.9 in this NASA Technical Standard.

j. Fracture critical tools, mechanisms, and tethers comply with section 7.2.10 in this NASA Technical Standard.

k. Fracture critical batteries comply with section 7.2.11 in this NASA Technical Standard.

[Rationale: Parts that comply with this requirement have had sufficient activities performed to establish adequate risk mitigation of failure caused by the presence of a flaw or crack-like defect.]

There are currently no predefined approaches for pressure vessels or pressurized fluid containers that are qualified under a different code/standard than ANSI/AIAA S-080 or ANSI/AIAA S-081, such as the ASME Boiler and Pressure Vessel Code, Section VIII, Divisions 1 or 2, or the United States Department of Transportation (DOT) Code of Federal Regulations Title 49, Transportation. These codes/standards do not impose the structural integrity activities needed for damage tolerance that are specified in ANSI/AIAA S-080 and ANSI/AIAA S-081. The approaches used by these ASME, DOT, and other industrial codes/standards to certify vessels do not include damage tolerance. In addition, service fluid, temperature, mounting, vibration, or vacuum requirements consistent with aerospace environments are not addressed in these codes/standards. Damage tolerance is required for commercially available off-the-shelf (COTS) pressure vessels. Pressure vessels certified to ASME, DOT, and other industrial codes/standards with failure modes where leakage would not result in a catastrophic hazard (some examples of leakage resulting in catastrophic hazards are: toxic release, asphyxiation hazards, flammable mixture release, thrust loading on the pressure vessel mounting or surrounding structure that results in loss of structural margin or the need for operational modifications, or loss of critical system function) may be proposed for acceptance without damage tolerance assessment (in combination with other activities) by developing an alternative approach as required in FCR [26], section 10 of this NASA Technical Standard.

Equivalence means that damage tolerance life analysis or test requirements in sections 7.2.1 or 7.2.2 in this NASA Technical Standard are also applied in modified form for a vessel meeting section 7.2.3 in this NASA Technical Standard. Equivalence does not mean other types of assessment, such as fatigue calculations or cycle test, can be substituted for the damage tolerance methodology detailed in sections 7.2.1 and 7.2.2 in this NASA Technical Standard.

Section 7.2 in NASA-STD-5019A lists eleven established approaches for assessment of fracture critical hardware. The sections are based on NASA experience for each hardware type. The FCR 11 "shall" requirement in NASA-STD-5019A imposes all the details of a selected section 7.2 classification upon the flight hardware. Fracture critical parts that comply with these requirements have established adequate risk mitigation from failure caused by the presence of a flaw or crack-like defect and are the preferred approaches if completely implemented. An alternative approach may be feasible if it satisfies all the requirements in section 10 in NASA-STD-5019A.

The extensive guidance at the end of this section on "pressure vessels or pressurized fluid containers that are qualified under a different code/standard than ANSI/AIAA S-080 or ANSI/AIAA S-081" was extracted from section 7.2.3 in NASA-STD-5019A, which is discussed in section 7.2.3 in this Handbook.

NASA-STD-5019A, Item 7.2.a

Item 7.2.a in NASA-STD-5019A imposes section 7.2.1 requirements upon fracture critical metallic pressure vessels designed to meet ANSI/AIAA S-080-1998, Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components. Fracture critical metallic pressure vessels meeting other codes/standards are addressed in section 7.2.3 in NASA-STD-5019A.

The definition of a pressure vessel is in section 3.2, Definitions, and is also stated in the beginning of section 7.2.1 in NASA-STD-5019A. Metallic pressurized vessels which have less stored energy, less MDP pressure, and contain a non-hazardous fluid or a hazardous fluid at less than 103 kPa (15 psia), do not satisfy the definition of a pressure vessel and are not necessarily candidates for assessment under section 7.2.1. If such a pressure vessel is designed to meet ANSI/AIAA S-080-1998 but does not meet the definition of a pressure vessel, it may still be classified under section 7.2.1 if following these requirements is the best way to demonstrate compliance with NASA-STD-5019A.

Metallic containers that do not meet the definition of a pressure vessel may qualify under other sections in NASA-STD-5019A. A sealed container may be classified as an NFC Sealed Container if it satisfies all the requirements for section 6.1.4 in NASA-STD-5019A. A container of hazardous fluids for a payload or experiment may be able to satisfy the requirements under section 7.5.5, Hazardous Fluid Containers for Payloads and Experiments, in NASA-STD-5019A. It may also be possible to classify other pressurized metallic vessels under section 7.2.3 for fracture critical pressure vessels and pressurized fluid containers that do not satisfy requirements for assessment under section 7.2.1 in NASA-STD-5019A. Depending on the fracture classification, other categories may be explored as well, such as NHLBB pressurized component (section 6.2.4) and NFC low risk (section 6.2.5), subject to approval by the RFCB.

NASA-STD-5019A, Item 7.2.b

Item 7.2.b in NASA-STD-5019A imposes section 7.2.2 requirements upon fracture critical composite overwrapped pressure vessels (COPVs) which are designed to meet ANSI/AIAA S-081-2000, Space Systems – Composite Overwrapped Pressure Vessels (COPVs). This section also applies to composite overwrapped pressurized fluid containers which are pressurized parts and do not meet the definition of a pressure vessel but otherwise satisfy requirements of section 7.2.2. Fracture critical COPVs meeting other codes/standards are to satisfy requirements in section 7.2.3 in NASA-STD-5019A.

NASA-STD-5019A, Item 7.2.c

Item 7.2.c in NASA-STD-5019A imposes section 7.2.3 requirements upon other fracture critical pressure vessels and pressurized fluid containers that do not satisfy the requirements in neither section 7.2.1 nor 7.2.2 in NASA-STD-5019A. This section does not prescribe a detailed approach because there is none for this category. Instead, this section requires an approach to be developed and documented that satisfies the requirements in section 7.2.3 in NASA-STD-5019A. Detailed guidance is provided in section 7.2.3 in NASA-STD-5019A.

NASA-STD-5019A, Item 7.2.d

Item 7.2.d in NASA-STD-5019A imposes section 7.2.4 requirements upon fracture critical lines, fittings, and other pressurized components that are part of a pressurized system such as valves, filters, regulators, heat pipes, and heat exchangers that transfer hazardous fluids. The guidance at the end of this section describes these parts as typically produced under process control that ensures the parts are reliable and have a low risk of containing detectable flaws that result in crack growth.

NASA-STD-5019A, Item 7.2.e

Item 7.2.e in NASA-STD-5019A imposes section 7.2.5 requirements upon fracture critical habitable modules and volumes. The requirements include demonstrating damage tolerance, a proof test, post-proof test NDE of pressure shell welds, and monitoring with documentation that ensures the certification is not invalidated.

NASA-STD-5019A, Item 7.2.f

Item 7.2.f in NASA-STD-5019A imposes section 7.2.6 requirements upon fracture critical pressurized structures. Guidance in section 7.2.6 clarifies that:

> "*This section is intended for pressurized structures such as launch vehicle main propellant tanks that carry internal pressure and vehicle structural loads.*"

NASA-STD-5019A, Item 7.2.g

Item 7.2.g in NASA-STD-5019A imposes section 7.2.7 requirements upon fracture critical rotating hardware. These requirements impose the appropriate section 7.3 or section 7.4 fracture control requirements according to the material type. A spin proof test is imposed. In addition, since item 7.3.a states: "Include all anticipated significant loadings, both cyclic and sustained, for each fracture critical part throughout its service life," and section 7.4.4 imposes a similar loads assessment, loads unique to rotating hardware, namely rotor sudden stop loadings, may need to be addressed as discussed in sections 7.2.7 and 6.1.3 in this Handbook.

NASA-STD-5019A, Item 7.2.h

Item 7.2.h in NASA-STD-5019A imposes section 7.2.8 requirements upon fracture critical fasteners. These requirements include design, fabrication, purchase, and implementation attributes as specified in item 7.2.8.a. Other aspects are also addressed, including preload, inspection methods, initial flaw size, proof loading, traceability, and controls on storage of fracture critical fasteners.

NASA-STD-5019A, Item 7.2.i

Item 7.2.i in NASA-STD-5019A imposes section 7.2.9 requirements upon fracture critical shatterable components and structures.

NASA-STD-5019A, Item 7.2.j

Item 7.2.j in NASA-STD-5019A imposes section 7.2.10 requirements upon fracture critical tools, mechanisms, and tethers.

NASA-STD-5019A, Item 7.2.k

Item 7.2.k in NASA-STD-5019A imposes section 7.2.11 requirements upon fracture critical batteries.

7.2.1 Fracture Critical Metallic Pressure Vessels (NASA-STD-5019A, Section 7.2.1)

NASA-STD-5019A:
7.2.1 Fracture Critical Metallic Pressure Vessels

This category pertains to pressure vessels that are designed to meet ANSI/AIAA S-080-1998, Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components. Fracture critical metallic pressure vessels meeting other codes/standards are addressed in section 7.2.3 in this NASA Technical Standard.

Pressure vessels as defined by NASA are always fracture critical. For reference only, the definition of pressure vessels is repeated as guidance below.

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

- *Contains stored energy of 19,307 J (14,240 ft-lb) or greater based on adiabatic expansion of a perfect gas.*
- *Stores a gas that will experience an MDP greater than 690 kPa (100 psia).*
- *Contains a fluid (gas and/or liquid) in excess of 103 kPa (15 psia) that will create a hazard if released.*

Fracture critical metallic pressure vessels are to comply with ANSI/AIAA S-080-1998, with tailoring as specified below in items a through k to meet requirement [FCR 11] section 7.2.a in this NASA Technical Standard.

Subsequent versions of ANSI/AIAA S-080 with modifications that implement the technical content as mandated in this section may be used with the approval of the RFCB.

a. Describe the damage tolerance assessment approach in the FCP in accordance with section 4.1 [FCR 1] in this NASA Technical Standard.

b. All occurrences of the following terms in ANSI/AIAA S-080-1998 are replaced with the terms having meanings as specified below:

(1) All occurrences of "maximum expected operating pressure" and "MEOP" are substituted with “maximum design pressure” and "MDP" as terms in this NASA Technical Standard in section 3.2.

(2) The word "nominal" is replaced with the word "average" in all ANSI/AIAA S-080-1998 sections except 4.7.2.

(3) All occurrences of the term “service life” have the meaning defined in this NASA Technical Standard in section 3.2 for “service life.”

c. The ANSI/AIAA S-080-1998 requirements in section 5.1, Approach A, Path 2, as detailed in section 5.1.2 of that document are followed for all the metallic pressure vessels addressed by that section with the modifications specified in this section of this NASA Technical Standard.

d. ANSI/AIAA S-080-1998 section 4.2.7 safe-life requirements are met with the following modifications:

(1) The safe-life assessment analysis and test assessments are to encompass and represent the worst-case flaw location, shape, aspect ratio, and orientation.

(2) The process for selecting the worst-case flaw location, shape, aspect ratio, and orientation is based on vessel stress/strain response, material strength, and crack growth properties and documented in the analysis report.

(3) The assessment determining the worst-case flaw location, shape, aspect ratio, and orientation includes all regions of the pressure vessel, including the boss and any internal and external attachments.

(4) The safe-life assessment analysis and test loading spectra are to include all loadings experienced during the service life, including those specified in this NASA Technical Standard in section 7.3.1, unless the RFCB approves the exclusion of specific loadings as insignificant for a component assessment.

For example, with approval of the RFCB, service life loadings that affect the safe-life of a particular region of the vessel by less than 5 percent may be excluded from the safe-life assessment of these regions.

(5) The assessments are to show that all safe-life requirements are met for the entire mission service life.

The mission service life includes all of the hardware activities included in the hardware mission as defined in NPR 7120.5, for the duration of the service life as defined in section 3.2 in this NASA Technical Standard. If the mission service life includes periodic "depot" intervals (opportunities for inspection) with fully qualified screening inspections that ensure that acceptable hardware has sufficient life, including the service life factor, to reach the next "depot" evaluation, this "depot" interval-based service-life approach may be proposed as an alternative approach by meeting the requirements in section 10 of this NASA Technical Standard.

e. If the AIAA S-080-1998 section 4.2.7 analysis option to show safe-life is planned, apply the following modifications to the requirements:

(1) Obtain pre-approval by the RFCB for all crack growth computer analysis programs other than NASGRO®.

(2) If the analysis ability to simulate crack growth is invalidated by plasticity or other effects, the assessment is performed by test.

(3) If NASGRO® is used, either set B_k to zero, or set B_k such that the stress intensity factor for the part thickness is less than or equal to the critical stress intensity value with approval of the Technical Authority or the RFCB.

(4) Establish that the assessed parts survive 4 lifetimes without failure (hazardous leak or fracture instability) by analyses that assess all applicable effects causing crack growth as a result of cyclic loadings.

A. If the loading sequence of high/low loads is unknown, then damage tolerance analysis is to show that the stress intensity factor at limit load is less than the critical stress intensity factor or residual strength at the end of 4 lifetimes.

B. If the service lifetime is a single event or the fatigue crack growth is small relative to the critical crack size (initial and critical cracks are of similar size), the analysis is to establish one of the following:

i. Reserve capability against fracture by meeting either a lower bound critical stress intensity factor or residual strength at the end of 4 lifetimes.

ii. A factor of 1.4 on critical stress intensity factor or residual strength after 1 lifetime.

Assessments of metallic alloys that are susceptible to crack growth related to SLC or EAC during the service life are addressed in item (6) below.

(5) Use critical stress intensity factor and cyclic threshold stress intensity range (ΔK_{th}) values that are less than or equal to the average values.

(6) For metallic alloys susceptible to EAC or SLC or both, satisfy all of the following:

A. Use the lower bound value of stress intensity factor threshold for assessment of EAC (K_{EAC} or K_{IEAC} as appropriate) and SLC if the material exhibits these behaviors in the application conditions.

B. Show that the applied stress intensity factor related to the largest service load is smaller than the lower bound stress intensity factor thresholds determined in item A above at the end of 4 lifetimes.

f. When performing proof testing in accordance with ANSI/AIAA S-080-1998 sections 4.2.7, 4.6.4, and/or 5.1.2.4, the duration of the proof test loading is minimized while also meeting the requirement to verify the pressure stability.

g. If the AIAA S-080-1998 section 4.2.7 testing option to show safe-life is planned, requirements are to include the following items:

(1) The testing approach and rationale are subject to both of the following:

A. RFCB approval before implementation.
B. Documentation in the FCP.

(2) The testing is to show that the hardware meets the damage tolerance lifetime and failure condition requirements in ANSI/AIAA S-080-1998 as modified in this NASA Technical Standard for initial flaws in the worst location, aspect ratio, and orientation in conditions that account for the service environments.

(3) Testing reports showing that the testing objectives have been achieved are documented in accordance with section 9.1 in this NASA Technical Standard and cited in the FCSR.

h. The ANSI/AIAA S-080-1998 section 5.1.2.6 Special Provision is not allowed.

Pressure vessels as defined by NASA are always fracture critical.

i. Vessels with crack-like flaws that are induced during the manufacturing process are not accepted as flight hardware unless a process for remediation repair has been established and the Technical Authority approves the part and process.

Refer to section 8.1.5 of this NASA Technical Standard for further requirements and guidance.

j. The ANSI/AIAA S-080-1998 requirements are subject to the following:

(1) Quality assurance in section 4.6 of that document is supplemented by requirements in section 8 (and its subsections) in this NASA Technical Standard.

(2) If there is a conflict with ANSI/AIAA S-080-1998, the ANSI/AIAA S-080-1998 requirements for quality assurance in section 4.6 of that document are

superseded by requirements in section 8 (and its subsections) of this NASA Technical Standard.

k. The ANSI/AIAA S-080-1998 requirements for fracture critical part documentation and reporting are subject to the following:

(1) Supplemented by requirements in section 9 (and its subsections) of this NASA Technical Standard.

(2) If there is a conflict with ANSI/AIAA S-080-1998, the ANSI/AIAA S-080-1998 requirements for fracture critical part documentation and reporting of that document are superseded by requirements in section 9 (and its subsections) of this NASA Technical Standard.

(3) The ANSI/AIAA S-080-1998 section 4.2.5 required stress analysis report and the section 4.2.7 safe-life analysis report are provided as part of the FCSR documentation.

Note that ANSI/AIAA S-080-1998 also addresses other hardware types, but only the metallic pressure vessel requirements as tailored in this section are applicable for this NASA Technical Standard.

Section 7.2.1 in this Handbook describes application of the requirements in section 7.2.1 in NASA-STD-5019A upon fracture critical metallic pressure vessels that are designed and built to the ANSI/AIAA S-080-1998 standard. These vessels are pressurized metallic containers whose contents meet the definition of a pressure vessel in section 3.2, Definitions, in NASA-STD-5019A, which is also repeated as guidance at the beginning of section 7.2.1 and summarized below.

A metallic pressurized fluid container is a fracture critical metallic pressure vessel if it has stored energy equal to or greater than 19,307 J (14,240 ft-lb), or if the stored fluid MDP is greater than 690 kPa (100 psia), or if the fluid pressure is in excess of 103 kPa (15 psia) that will create a catastrophic hazard if the fluid is released.

The calculation of stored energy is performed assuming the fluid is a perfect gas that undergoes an adiabatic expansion. The calculation methodology and examples are discussed in Volume 2 of NASA-HDBK-5010. The requirement addressing risk of a catastrophic hazard if the fluid is released may be applicable if the fluid is a hazardous fluid per the definition in NASA-STD-5019A. The risk could be due to the fluid effects on humans in the environment, or some other consequence of the presence of the fluid in the environment, or effects on the pressurized fluid system due to loss of the fluid from the pressure vessel.

When NASA-STD-5019A was written, the version of ANSI/AIAA S-080 in effect was the 1998 version. Accordingly, the details in section 7.2.1 in NASA-STD-5019A are focused upon fracture control issues in the ANSI/AIAA S-080-1998 standard. A revision of the ANSI/AIAA

S-080 standard was being developed when NASA-STD-5019A was written. The requirements in section 7.2.1 in NASA-STD-5019A may also be applicable to subsequent versions of ANSI/AIAA S-080 by the following guidance in the section:

> "*Subsequent versions of ANSI/AIAA S-080 with modifications that implement the technical content as mandated in this section may be used with the approval of the RFCB."*

Revision A of ANSI/AIAA S-080 was approved on 3/20/2018.

NOTE: Per the guidance copied above, to use the ANSI/AIAA S-080A-2018 standard for fracture control of pressure vessels per requirements in NASA-STD-5019A, approval is needed from the RFCB. Then, section 7.2.1 requirements in NASA-STD-5019A will also modify the content of ANSI/AIAA S-080A-2018.

If later versions of ANSI/AIAA S-080 are developed that are approved for use by the RFCB, section 7.2.1 requirements in NASA-STD-5019A will also modify the content of the later version of ANSI/AIAA S-080. In that situation, the discussions in section 7.2.1 in this Handbook would provide guidance for applying section 7.2.1 requirements in NASA-STD-5019A to the later version of ANSI/AIAA S-080. In that situation, the guidance discussions in section 7.2.1 in this Handbook may need some modifications, which if approved by the RFCB, would apply to the later version of ANSI/AIAA S-080.

For convenience, these two ANSI/AIAA standards will be referred to in the remainder of this section 7.2.1 more concisely as the S-080-1998 and the S-080A-2018 standards. The S-080A-2018 standard was developed in parallel with a companion standard, ANSI/AIAA S-081B-2018 for COPVs that was approved on the same date. It will be referred to as S-081B-2018. Section 7.2.2 in this Handbook discusses S-081B-2018 and ANSI/AIAA S-081-2000 in this Handbook.

These new 2018 standards are greatly changed from previous versions. The Foreword in each document outlines some of the revisions. One change in both S-080A-2018 and S-081B-2018 is they only use the term "damage tolerance" instead of "safe-life." The discussions in section 7.2.1 of this Handbook will also use the term "damage tolerance" life.

Section 7.2.1 in this Handbook will discuss application of the section 7.2.1 requirement items in NASA-STD-5019A to both S-080-1998 and S-080A-2018. The beginning of each discussion will address S-080-1998, and in some cases, also address S-080A-2018. The usual style will address S-080-1998 first, and S-080A-2018 in separate paragraphs.

Both S-080A-2018 and S-081B-2018 use the same organization and section numbers, and much of the content is common to both standards. A summary listing the sections and fracture control aspects in these 2018 versions is provided below. Although there are differences in the two standards, the summary below is applicable to both, except section titles change as S-080A-2018 is for Metallic Pressure Vessels, Pressurized Structures, and Pressure Components. S-081B-2018 is for COPVs.

These standards have sections on:

- Responsibilities of the owner, the procuring authority, and the manufacturer. There is also a section on tailoring the requirements in the standard.
- Expanded list of applicable documents, vocabulary, and definitions.
- Technical content in the following sections:
  - Section 5: general design aspects, including system analysis, performance requirements, and materials,
  - Section 6: verification; high-level requirements for stability and fracture control,
  - Section 7: analysis - addresses material properties and analysis models used to assess performance, including strength, loads, stability, volume, physical envelope, mass, environments, and fracture control–damage tolerance,
  - Sections 8 and 9: aspects of manufacturing, quality assurance, and documentation,
  - Section 10: verifications by test, including damage tolerance and qualifications, and
  - Sections 11 and 12: operations, maintenance, and documentation retention.

The following list of sections in S-080A-2018 were found to be most pertinent to the fracture control requirements in section 7.2.1 of NASA-STD-5019A:

- Section 4.1, Acronyms and Abbreviated Terms: the terms relating to material fracture and crack growth,
- Section 4.2, Terms and Definitions: the fracture control definitions, including damage tolerance life, service, life, stress-corrosion cracking, and sustained load crack growth,
- Section 5.1.2 defines service category,
- Section 5.1.6 defines service life,
- Section 5.2.1, Table 1, section 5.2.2, and section 5.2.3 specify structural design factors,
- Section 5.2.13 and 5.2.13.1 define damage tolerance life design aspects,
- Section 6.2.1 specifies criteria for damage tolerance analysis using LEFM vs. testing,
- Section 7.1 defines structural and fracture control material properties,
- Section 7.3 specifies analysis models,
- Section 7.5.1 specifies damage tolerance life analysis,
- Section 10.1 specifies damage tolerance life test is to use coupon specimen per section 10.1.1 or pressurized hardware specimen (i.e., pressure vessels) per section 10.1.2 (in S-081B-2018, section 10.1.2 is for COPVs),
- Section 10.4.2 specifies nondestructive testing, and section 10.4.6 describes proof testing, and
- Sections 11.5 through 11.7 address inspection, maintenance, material review board, and repair.

Documentation is in the following:

- Section 9.5 describes the inspection and test plan; section 9.7 is quality documentation,
- Section 11.9 is operations documentation, including verification test and analysis results, and
- Section 12 includes a document list and specifies retention for the life of the hardware.

NASA-STD-5019A, Item 7.2.1.a

Item 7.2.1.a applies to both S-080-1998 and S-080A-2018. It ensures section 4.1 [FCR 1] requirements for a Fracture Control Plan in NASA-STD-5019A are imposed on damage tolerance assessments of flight hardware. Section 4.1 requirements are discussed in section 4.1 in this Handbook. Details for each flight hardware item are expected to be provided in the Fracture Control Documentation and Verification as detailed in section 9 in NASA-STD-5019A.

NASA-STD-5019A, Item 7.2.1.b

Item 7.2.1.b requires replacement of three technical terms found in S-080-1998 and S-080A-2018 so that fracture control requirement terminology agrees with NASA-STD-5019A.

NASA-STD-5019A, Item 7.2.1.b(1)

Item 7.2.1.b(1) replaces the fluid pressure quantity "maximum expected operating pressure" i.e., "MEOP," with the term "maximum design pressure," i.e., "MDP," with a definition given in section 3.1 of NASA-STD-5019A, which is also copied below:

> "Maximum Design Pressure: The highest possible operating pressure considering maximum temperature, maximum relief pressure, maximum regulator pressure, and, where applicable, transient pressure excursions. MDP for human-rated hardware is a two-failure tolerant pressure, i.e., it will accommodate any combination of two credible failures that will affect pressure. Some programs have defined MDP as a two-fault tolerant pressure."

The definition of MDP results in a larger pressure than the MEOP which does not address the two-failure-tolerant pressure condition.

NASA-STD-5019A, Item 7.2.1.b(2)

Item 7.2.1.b(2) replaces the word "nominal" with the word "average" in three S-080-1998 sections 4.2.6, 4.2.7, and 4.3.3.

The term "nominal" is not a statistically defined quantity. It is a categorical quantity "in name only" used for identification. These changes are needed so that damage tolerance assessments of pressure vessels built per S-080-1998 will satisfy the requirements in NASA-STD-5019A, item

7.3.2.e, that specifies: "Use critical stress intensity factor and cyclic threshold stress intensity range (ΔK_{th}) values that are less than or equal to the average values."

S-080A-2018 defines damage tolerance assessment material data using the word "nominal" in section 7.1 2) in two places, in section 7.4.12 in one place, and in 7.5.1 in two places. Item 7.2.1.b(2) requires replacing all these occurrences of the word "nominal" with the word "average."

Note: Item 7.2.1.e(5) also modified the wording in S-080-1998 sections 4.2.7 and 4.3.3, and items 7.2.1.e(6), e(6)A, and e(6)B further modified S-080-1998, section 4.2.7. The application of these items to S-080A-2018 is also described in discussion for each item in this Handbook.

NASA-STD-5019A, Item 7.2.1.b(3)

Item 7.2.1.b(3) addresses the definition of service life in S-080-1998, section 3, which did not conform to the definition in NASA-STD-5019A. Accordingly, item 7.2.1.b(3) modifies all occurrences of the term "service life" to have the meaning defined in section 3.2 in NASA-STD-5019A.

S-080A-2018 defines service life in section 4.2, Terms and Definitions. The S-080A-2018 definition of service life is close but not equivalent to the definition in NASA-STD-5019A. Accordingly, item 7.2.1.b(3) modifies all occurrences of the term "service life" to have the meaning defined in section 3.2 in NASA-STD-5019A.

NASA-STD-5019A, Item 7.2.1.c

Item 7.2.1.c addresses unique content in S-080-1998 and specifies the requirements to be applied for fracture control assessment are those in "section 5.1, Approach A, Path 2, as detailed in section 5.1.2 of S-080-1998.

S-080A-2018 requirements have undergone major changes relative to the S-080-1998 version. The item 7.2.1.c purpose is applied for S-080A-2018 to specify the appropriate category in section 5.1.2, Service Category. The appropriate service category is category 1, because section 5.2.13 specifies hardware in that category has to satisfy damage tolerance life requirements.

NASA-STD-5019A, Item 7.2.1.d

Item 7.2.1.d imposes five modifications to the S-080-1998, section 4.2.7 damage tolerance assessment analysis and test requirements so they will satisfy requirements in NASA-STD-5019A.

These five modifications also apply to damage tolerance analysis and test requirements for pressure vessels built to S-080A-2018 as described below.

NASA-STD-5019A, Item 7.2.1.d(1)

Item 7.2.1.d(1) modifies the S-080-1998 section 4.2.7, Safe-Life Requirements analyses and tests to represent the worst-case flaw location, shape, aspect ratio,[11] and orientation.

S-080-1998, section 4.2.7, states undetected flaws are assumed to be in critical locations and the most unfavorable orientation with respect to the stress and material properties. It also states the size of the flaws is based on either NDE or the acceptance proof testing and specifies an (a/2c) range of 0.1 to 0.5. These requirements satisfy item 7.2.1.d(1) for analysis. If damage tolerance testing is used, there is no requirement in S-080-1998 for it to represent the worst-case flaw location, shape, aspect ratio, and orientation. Item 7.2.1.d(1) imposes these requirements on damage tolerance test assessments.

S-080A-2018 defines required damage tolerance assessments in three locations. Section 5.2.13.1, Damage Tolerance Life Design, has an overall "design" approach that defines the general aspects applied to assessments whether performed by analysis or test. Section 7.5.1 details damage tolerance life analysis approach and requirements. Section 10.1 specifies damage tolerance life tests using either coupon specimen in section 10.1.1 or pressurized hardware (i.e., pressure vessels) in section 10.1.2.

S-080A-2018, section 5.2.13.1, imposes detailed requirements for damage tolerance life design analysis and test assessments that address the following: NDE based initial flaw size, worst case locations and orientation, aspect ratios of 0.1 to 0.5 and within that range, and beyond that range if the potential worst case is shown to be a broader range, including both elliptical embedded and semi-elliptical surface flaws, and documentation of rationale for worst-case location whether the method is by analysis or test. This section adequately addresses item 7.2.1.d(1) requirements.

It is noted a sentence in S-080A-2018, section 5.2.13.1, prohibits use of proof test logic for flaw screening. Section 8.1.3 in NASA-STD-5019A permits proof testing for flaw screening if documented in the FCP and approved by the RFCB. If proof test logic is, the FCP would need to state it is tailoring S-080A-2018 to implement the proof testing. Tailoring of S-080A-2018 is permitted per section 2, Tailoring.

NASA-STD-5019A, Item 7.2.1d(2)

Item 7.2.1.d(2) requires the S-080-1998, section 4.2.7 damage tolerance assessment analysis and test process for selecting the worst-case flaw location, shape, aspect ratio, and orientation to be based on vessel stress/strain response, material strength, crack growth properties, and be

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[11] Care needs to be taken in the use of aspect ratios. Different references and applications define aspect ratios differently. The characteristic dimensions of the crack, a and c vary with crack geometry (surface, corner, through, etc.) and they may be defined differently across references, and so is the case of the crack aspect ratios. In some references, the characteristic dimensions are compared one to one (a/c), but in some references they are defined as a/2c. When cross-referencing aspect ratios, it is important for the analyst to verify that the definition of aspect ratios for their application is consistent.

documented in the analysis report. Relevant additional guidance can be found in section 7.3.2a in this Handbook.

S-080-1998, section 4.2.7, does not address the detail process used to determine the damage tolerance requirements. Item 7.2.1.d(2) imposes requirements that the process for selecting the worst-case location, shape, aspect ratio, and orientation should be based on the vessel stress/strain response and material strength and crack growth properties and be documented in the analysis report.

S-080A-2018, section 5.2.13.1, as described above under item 7.2.1.d(1), imposes detailed requirements for damage tolerance life design analysis and test assessments that satisfy the item 7.2.1.d(2) requirement for the process and also requires the rationale for the determination of the worst-case location(s) to be documented. S-080A-2018, section 5.2.13.1, satisfies the item 7.2.1.d(2) requirements.

NASA-STD-5019A, Item 7.2.1.d(3)

Item 7.2.1.d(3) requires the S-080-1998, section 4.2.7 damage tolerance assessment to determine the worst-case flaw location, shape, aspect ratio, and orientation is to address all regions of the pressure vessel, including the boss and any internal and external attachments.

S-080-1998, section 4.2.7, has general requirements that do not address the item 7.2.1.d(3) requirements. Item 7.2.1.d(3) imposes the requirement to include the boss and any internal and external attachments in the assessment.

S-080A-2018, section 5.2.13.1, imposes a requirement that may include item 7.2.1.d(3) with the wording stating: "The worst-case location assessment shall include all regions of the pressurized hardware." Regardless, since item 7.2.1.d(3) is imposed on S-080A-2018, the boss and any internal and external attachments should be included in the worst-case damage tolerance assessment.

NASA-STD-5019A, Item 7.2.1.d(4)

Item 7.2.1.d(4) requires the S-080-1998, section 4.2.7 damage tolerance assessment analysis and test loading spectra to include all loadings experienced during the service life, including those specified in section 7.3.1 in NASA-STD-5019A, as described below, unless the RFCB approves the exclusion of specific loadings as insignificant. Section 4.2.7 does not specify the loadings to be assessed, but section 4.2.1 does specify "anticipated load-pressure-temperature history and associated environments throughout the service life shall be determined in accordance with specified mission requirements" which is followed by a list that describes aspects of the included loadings that "shall be used to define the design load/environment spectra that shall be used for both design analysis and testing."

Loadings specified in section 7.3.1 in NASA-STD-5019A are all anticipated significant loadings, both cyclic and sustained, throughout its service life such as loads due to accelerations, pressures, temperature, environmental conditions, including preloads and residual stress. Other loadings that are included if applicable are weld joint stress risers such as peaking and mismatch, and effects of and barriers, if leak detection is part of the strategy, when pressure is assumed to decrease due to leakage from a crack. If a propellant management device can impart loads on the pressure shell, these loads should be included. Also, if the pressure vessel is exposed to mission environments, including but not limited to, credible impacts from crew activities or vehicle loss of external surface mass, micro-meteoroid and orbital debris (MMOD), extravehicular activity (EVA) inadvertent contacts, or EVA tool impacts, the pressure vessel should also be assessed for those loadings.

There is relevant guidance in NASA-STD-5019A, section 7.3.1, that states:

> *"Include the worst-case allowed or weld joint peaking and mismatch effects for damage tolerance assessments by analysis or test. The assessment analysis or test is to capture the effect of peaking and mismatch on stress gradients affecting crack growth and fracture. Standard tensile strength tests of ductile materials are not adequate to assess these conditions."*

Guidance in NASA-STD-5019A after item 7.2.1.d(4) states:

> "*For example, with approval of the RFCB, service life loadings that affect the safe-life of a particular region of the vessel by less than 5 percent may be excluded from the safe-life assessment of these regions."*

If this guidance approach is used for either S-080-1998 or S-080A-2018 damage tolerance assessments, it should be documented in the FCP and receive RFCB approval.

Note the above cited guidance "5 percent" method is different from usual NASGRO® crack growth analyses that apply a cyclic threshold stress intensity range (ΔK_{th}) that eliminates stress intensity ranges less than the ΔK_{th} value. The ΔK_{th} value has to satisfy item e(5) criteria (i.e., it should be less than or equal to the average of test data).

S-080A-2018, sections 5.1.5, 5.1.6, 5.2.12, and 5.2.13.1, specify loadings that should be evaluated in the damage tolerance life assessment. Note that S-080A-2018, sections 5.1.6 and 5.2.13.1, impose a minimum of 13 full cycles to "MEOP" (which is modified by item c(1) to be MDP). Item 7.2.1d(4) requires the assessment analysis and test loading spectra to include all loadings experienced during the service life, including those specified in section 7.3.1 in NASA-STD-5019A, which are described above, unless the RFCB approves the exclusion of specific loadings as insignificant. The AIAA-S-080A-2018 minimum of thirteen (13) full-service cycles should be followed.

NASA-STD-5019A, Item 7.2.1.d(5)

Item 7.2.1.d(5) specifies the damage tolerance assessments (which include items 7.2.1.d(1) through 7.2.1.d(4)) are to show that all safe-life (i.e., damage tolerance) requirements are met for the entire mission service life. The definition of "Service Life" is in section 3.2, Definitions, in NASA-STD-5019A, which is imposed on S-080-1998 and S-080A-2018 by item b(3).

S-080-1998, section 4.2.7, Safe-Life Requirements, states: "For those pressurized hardware items which are readily accessible for periodic inspection and repair, the safe-life shall be at least four (4) times the interval between scheduled inspection and/or refurbishment." This does not agree with the item 7.2.1.d(5) requirement that uses the definition of "service life" in NASA-STD-5019A, which is imposed on S-080-1998 by item 7.2.1.b(3). Item 7.2.1.d(5) modifies section 4.2.7 to state: "The assessments are to show all safe-life requirements are met for the entire mission service life."

The guidance following item 7.2.1.d(5) discusses possible "depot" intervals where a depot may include inspection and repair opportunities to demonstrate sufficient damage tolerance to reach the next "depot" evaluation. The guidance notes this would have to be proposed as an alternative approach by meeting requirements in section 10 in NASA-STD-5019A to describe proposed "depot" intervals in the FCP, and it would need approval per section 10 in NASA-STD-5019A.

S-080A-2018, section 5.2.13.1, specifies: "The region(s) of the pressurized hardware to which damage tolerance life is applied shall be designed such that it possesses a minimum damage tolerance life of four (4) times the service life without sustained load crack growth, detrimental deformation, leakage, or rupture," which only partially satisfies the item 7.2.1d(5) requirement. The wording "The region(s) of the pressurized hardware to which damage tolerance life is applied" is defined in S-080A but is intended to allow multiple damage tolerance analyses or tests to address a single tank. In some cases, a single worst-case analysis or test cannot address the entire tank acreage. Instead, S-080A allows for multiple NDE inspection methods, thicknesses, and material properties to be used to address damage tolerance life. This approach is consistent with NASA-STD-5019A. The item 7.2.1d(5) statement imposes a clear requirement on S-080A-2018 damage tolerance life assessments that supersedes the S-080A-2018, section 5.2.13.1 statement.

The topic of missions with "depot" intervals is not discussed in S080A-2018. If the "depot" mission service life were proposed as an alternative approach per section 10 in NASA-STD-5019A, the approach would also need to tailor the S-080A-2018 service lifetime used for fracture control assessments. Tailoring of S-80A-2018 is permitted per section 2, Tailoring.

NASA-STD-5019A, Item 7.2.1.e

Item 7.2.1.e specifies six additional requirements that assessments have to satisfy to demonstrate NASA-STD-5019A damage tolerance requirements are satisfied for a pressure vessel following the requirements of S-080-1998, section 4.2.7. These six items are in addition to the requirements imposed by items 7.2.1.d(1), d(2), d(3), d(4), and d(5).

These six items also have to be satisfied by assessments demonstrating damage tolerance requirements are satisfied for a pressure vessel following the requirements of the S-080A-2018 standard.

NASA-STD-5019A, Item 7.2.1.e(1)

Item 7.2.1.e(1) specifies before an S-080-1998 assessment is begun, pre-approval from the RFCB has to be obtained for all crack growth computer analysis programs other than NASGRO®.

S-080A-2018, section 7.5.1, on Damage Tolerance Life Analysis states: "The analysis may be performed using a crack growth software package." Assessments of pressure vessels built to S-080A-2018 will need to utilize the NASGRO® program or obtain pre-approval from the RFCB if other crack growth computer analysis programs are to be used.

NASA-STD-5019A, Item 7.2.1.e(2)

Item 7.2.1.e(2) requires a determination whether damage tolerance analysis assessments can or cannot simulate crack growth in the pressure vessel. If analyses based on LEFM are invalidated by plasticity or other effects, the damage tolerance assessment has to be performed by test.

S-080-1998, section 4.2.7, states: "Safe-life testing in lieu of safe-life analysis is an acceptable alternative to demonstrate safe-life, provided that ... a crack growth test program is implemented on pre-flawed specimens representative of the structure design." The issue of validity of a damage tolerance assessment by analysis is not addressed. Item 7.2.1.e(2) imposes the requirement to determine if assessments using S-080-1998 can be performed by analysis or have to be performed by test.

Applicability of LEFM has to be considered, for example, where plasticity is large, or if material grain size is large relative to the crack or crack-tip ligament, LEFM predictions of material response are not valid. A different issue that would still be challenging could be if material fracture and/or crack growth properties vary greatly from one region to another so that material data samples are not representative of a location that contains the worst-case crack.

S-080A-2018, section 6.2.1, addresses the purpose of the item 7.2.1.e.(2) requirements. It requires the damage tolerance life to be verified either by analysis or test, and "the damage tolerance life requirement may be verified by analysis only if both of the following conditions are met:

1. The pressurized hardware (i.e., the pressure vessel) is shown to be elastically responding and characterized by LEFM.

2. The fracture properties of the pressurized hardware (i.e., the pressure vessel) are determined in accordance with section 7.1."

The term "elastically responding" relates to whether the metallic shell experiences plastic deformation due to loadings during the vessel lifetime that exceed the local yield strength. Situations that do not satisfy the requirements in S-080A-2018, section 6.2.1, for assessment by analysis should be assessed by testing per the requirements in S-080A-2018, sections 10.1 and 10.1.2 or 10.2.2.

NASA-STD-5019A, Item 7.2.1.e(3)

Item 7.2.1.e(3) is a specific requirement imposed on use of the NASGRO® program due to particular aspects of that program. It states if NASGRO® is used, either set Bk to zero, or set Bk such that the stress intensity factor for the part thickness is less than or equal to the critical stress intensity value for the metal thickness with approval of the delegated Technical Authority or the RFCB. The reason for this requirement is that Bk is a fitting parameter to a data set that may not conservatively represent the variation of fracture toughness of the pressure vessel material with thickness.

This requirement is not addressed in either S-080-1998 nor S-080A-2018, which are general standards that do not specify the analysis program to be used. The item 7.2.1.e(3) requirement is imposed on both S-080-1998 and S-080A-2018. Note that item 7.2.1.e(1) would also be applicable if the assessment did not use the NASGRO® program.

NASA-STD-5019A, Item 7.2.1.e(4)

Item 7.2.1.e(4) is a broader statement of the requirement to demonstrate a safety factor of 4 on the damage tolerance life without failure (hazardous leak or fracture instability) by analyses that assess all applicable effects causing crack growth as a result of cyclic loadings. The factor of 4 applies in general, including items 7.2.1.e(4)A, e(4)B, and e(4)Bi but not 7.2.1.e(4)Bii which has unique requirements. Portions of this requirement are already imposed by item 7.2.1.d(5) as discussed in this Handbook for both S-080-1998 and S-080A-2018. Note also that item 7.2.1.d(2)D specifies assessments are to include all loadings experienced during the service life, including those specified in NASA-STD-5019A, section 7.3.1, which includes both cyclic and sustained loadings. This requirement implies that non-catastrophic leakage is allowed within 4 lifetimes; i.e., an NDE procedure may be applied that guarantees absence of rupture but not fully the absence of non-catastrophic leakage.

Items 7.2.1.e(4)A, e(4)B, e(4)Bi, and e(4)Bii impose unique requirements on damage tolerance assessments that are in addition to those in items 7.2.1.d(1) through d(5). Their purpose is to ensure damage tolerant parts are likely to survive the required number of service lifetimes without failure due to a hazardous leak or a fracture instability for the special situations described in these requirements. The service life spectrums, and critical stress intensity or residual strength referenced in these 7.2.1.e(4) items are the values resulting from the worst damage tolerance situation resulting from items 7.2.1.d(1) through d(5).

Neither S-080-1998 or S-080A-2018 address the requirements in items 7.2.1.e(4)A, e(4)Bi, and e(4)Bii. These requirements should be applied to analysis assessments of pressure vessels built to either S-080-1998 or S-080A-2018. Spectra needs to account for proof tests spaced periodically through life. These are meant to result in analysis that contain load blocks of proof and mission cycles. This will prevent the stacking of highest load cycles at the beginning or the end of the spectrum.

Also, note that either of the EAC or SLC requirements imposed in item 7.2.1.e(6) may be the controlling (i.e., smallest) material damage tolerance quantity that should not be exceeded by the applied cyclic and sustained loadings to avoid failures when performing the damage tolerance assessments imposed by items 7.2.1.e(4), e(4)A, e(4)B, e(4)Bi, and e(4)Bii. This possibility is flagged by the guidance in NASA-STD-5019A that follows item 7.2.1.e(6) but is placed more prominently here as it is applicable to all analysis assessments.

The following guidance refers readers to requirements in item 7.2.1.e(6):

> *Assessments of metallic alloys that are susceptible to crack growth related to SLC or EAC during the service life are addressed in item (6) below.*

NASA-STD-5019A, Item 7.2.1.e(4)A

Item 7.2.1.e(4)A specifies an approach to ensure the damage tolerant life assessment result will be conservative when loading sequences are unknown. If the sequence of high/low loads is a well-defined sequence for the lifetime of the part, the last cycle of the loading spectrum may be used to assess crack stability. Relevant additional guidance can be found in item 7.3.2c in this Handbook. If the loading spectrum sequence of high/low loads is variable or unknown, this section requires use of the loading spectrum limit load to assess fracture. The crack size used is the final size after four lifetimes of crack growth. A conservative approach is to always use the limit load to assess fracture of the final crack size. The fracture strength may be computed using the critical stress intensity factor when LEFM is applicable. If LEFM is not applicable, item 7.2.1.e(2) requires the residual strength to be determined from tests, which would be using cracked specimen that simulate the final crack size fracture condition.

NASA-STD-5019A, Item 7.2.1.e(4)B

Typically, a single event for fracture control on a pressure vessel is not valid for fracture control analysis. There are always acceptance proof test, acceptance leak test, and subsequent system level pressure tests. There also may be dynamic and external loads. All loading should be considered in the analysis.

This section pertains specifically a single-event scenario in item 7.2.1.e(4)B of NASA-STD-5019A.

Item 7.2.1.e(4)B addresses conditions where the service lifetime is a single event, or the fatigue crack growth is small relative to the critical crack size for fracture. This is a relative statement. Since no bounds specify when item 7.2.1.e(4)B does or does not apply, item 7.2.1.e(4)B situations should be evaluated when performing fracture control assessments, especially those with small increases of the initial crack size at the end of four lifetimes.

The item 7.2.1.e(4)B requirement establishes that either item 7.2.1.e(4)Bi or 7.2.1.e(4)Bii is satisfied. When LEFM is applicable, the test data can be standard fracture toughness test data. If LEFM is not applicable, item 7.2.1.e(2) requires tests to determine residual strength. Also, per the requirements in items 7.2.1.d(1) through 7.2.1.d(5) as discussed in this Handbook, if the fracture properties vary in different regions of the vessel, fracture toughness data will be needed for each characteristic region.

NASA-STD-5019A, Item 7.2.1.e(4)Bi

Item 7.2.1.e(4)Bi requires the fracture assessment to show fracture does not occur for the following condition. The fracture assessment should compute the final crack size for an initial crack size increased by 4 lifetimes of crack growth. As noted in item 7.2.1.e(4)A, if the loading spectrum sequence of high/low loads is variable or unknown, a conservative approach should be used by applying the limit loading experienced during the lifetime to the final crack size to predict critical stress intensity or residual strength after 4 lifetimes. This fracture condition is referred to as the item 7.2.1.e(4)Bi critical fracture value. The item 7.2.1.e(4)Bi requirement is to show the 7.2.1.e(4)Bi critical fracture value is less than or equal to the <u>lower bound</u> critical stress intensity factor or residual strength of fracture data described in item 7.2.1.e(4). Notice that item 7.2.1.e(4)Bi is comparing to a <u>lower bound</u> critical stress intensity factor or residual strength, which is <u>less</u> than the criteria imposed in item 7.2.1.e(5).

<u>NOTE on lower bounds</u>: A lower bound value should be based upon a sufficient number of specimen tests to sample the amount of scatter in the fracture property. Comparison of the lower bound to all test data should show that scatter of the fracture data does not, and likely will not, result in a smaller critical fracture value. For a normal statistical distribution, the "Empirical Rule" states 95% of the data will fall within two standard deviations, and 99.7% of the data will fall within three standard deviations. A value defined by the mean less two standard deviations will be close to a lower bound, while a value determined by the mean less three standard deviations will ensure a lower bound is obtained, provided there is enough data for this statistics rule to be meaningful. Statistical analysis of test data as it is accumulated for additional samples may assist in identifying if a lower bound value has been obtained.

NASA-STD-5019A, Item 7.2.1.e(4)Bii

Item 7.2.1e(4)Bii requires the fracture assessment to show that fracture does not occur for the following conditions. The initial crack size is increased by only 1 lifetime of crack growth to the predicted final crack size. (Note: The 1 lifetime is a unique requirement that is only applicable for this item 7.2.1.e(4)Bii assessment, which applies the 1.4 multiplier described later as compensation.) Per item 7.2.1.e(4)A, if the loading spectrum sequence of high/low loads is variable or unknown, a conservative approach should be used by applying the limit loading experienced during the lifetime to the final crack size to predict critical stress intensity or residual strength after 1 lifetime. This value is multiplied by a factor of 1.4 to compute the item e(4)Bii value of critical stress intensity factor or residual strength. This 7.2.1.e(4)Bii value should satisfy item 7.2.1.e(5), meaning it should be less than or equal to the average value of the material critical stress intensity factor or residual strength, resulting in a margin greater than zero. The margin calculation is described in more detail in item 7.5.1d in this Handbook.

NASA-STD-5019A, Item 7.2.1.e(5)

Item 7.2.1.e(5) imposes the requirement in section 7.3.2.e in NASA-STD-5019A on S-080-1998, section 4.2.7 analysis assessments to use damage tolerance critical stress intensity factor and cyclic threshold (ΔK_{th}) that are "less than or equal to the average values."

Item 7.2.1.b(2) already replaced the word "nominal" with "average" in S-080-1998 sections 4.2.6, 4.2.7, and 4.3.3. A note was placed in item 7.2.1b(2) pointing to additional modifications of other terms as specified in items 7.2.1.e(5), e(6), e(6)A, and e(6)B.

Item 7.2.1.e(5) further modifies S-080-1998, sections 4.2.7 and 4.3.3, to impose criteria that both critical stress intensity factor (or residual strength if that is the pertinent fracture quantity) and cyclic threshold stress intensity range (ΔK_{th}) material values are to be "less than or equal to the average values."

Observe that items 7.2.1.e(4)Bi, e(6), e(6)A, and e(6)B are not affected, as they are unique in that they impose lower bound criteria to avoid the failure conditions addressed in those items. Also, item 7.2.1.e(4)Bi has a "NOTE on lower bounds" that discusses the number of tests and relevant statistics when determining lower bound values.

Item 7.2.1.e(5) also modifies S-080A-2018 material critical stress intensity factor data and cyclic threshold stress intensity range (ΔK_{th}) data that are used for assessments. Item 7.2.1.e(5) changes these material values to be less than or equal to average values of the data. The affected sections in S-080A-2018 are:

- Section 7.1 2) lists the following terms: "plane strain fracture toughness, K_{IC}," "surface-crack fracture toughness, K_{IE}," and "fatigue crack growth rates, da/dN, dc/dN." (Note the "fatigue crack growth rates, da/dN, dc/dN" will either include cyclic threshold stress intensity range, $\Delta K_{th,}$ in representative equation form or as data points in the crack growth rate data, and item 7.2.1.e(5) modifies these values to be "less than or equal to average values of the data.")
- Section 7.5.1 refers to the following: "fracture toughness," "fatigue crack growth rate data," da/dN, "surface or embedded crack fracture toughness," and "crack extension resistance," K_R, which again are modified by item 7.2.1.e(5) to be "less than or equal to the average values."

These modifications are shown below in the format used in sections of S-080A-2018 that implements the combined requirements of items 7.2.1.b(2), e(5), e(6), e(6)A, and e(6)B.

NASA-STD-5019A, Items 7.2.1.e(6), e(6)A, and e(6)B

The following acronyms and definitions in NASA-STD-5019A and this Handbook are needed to understand the requirements imposed in items 7.2.1.e(6), e(6)A, and e(6)B.

Section 3.1, Acronyms, Abbreviations, and Symbols: EAC, K_{EAC}, K_{IEAC}, K_{ISCC}, SLC and K_{SLC}.
Section 3.2, Definitions: EAC, K_{EAC}, K_{ISCC}, K_{IEAC}, and SLC.

The reader is referred to section 3.2 definitions and the footnotes for EAC and SLC. Citations of the two references in the EAC and SLC definitions are given in Appendix B.4 in NASA-STD-5019A and are recommended for background study of EAC and SLC.

NOTE on EAC and SLC testing: Specialized testing is needed to determine the material data to satisfy the EAC and SLC requirements in items 7.2.1.e(6), e(6)A, and e(6)B if no data exist. Testing of specimen representative of the material, environment (including exposures to all fluids), and maximum applied stress intensity factor is needed. EAC testing is specified in ASTM E1681. For SLC, as noted in the definition of SLC in NASA-STD-5019A, "A threshold stress intensity factor can be obtained by procedures such as those in ASTM E1681 for the case of an inert or vacuum environment."

Items 7.2.1.e(6) and e(6)A impose requirements on metallic alloys susceptible to EAC or SLC or both, that require assessments to use a lower bound value of stress intensity factor threshold of EAC and SLC if the material exhibits these behaviors in the application conditions. Item 7.2.1.e(6)B requires assessments to show the applied stress intensity factors for the largest service loading is smaller than the lower bound stress intensity factor thresholds of EAC and SLC behavior at the end of 4 lifetimes. Item 7.2.1.e(4)Bi has a "NOTE on lower bounds" that discusses the number of tests and relevant statistics when determining lower bound values.

S-080-1998, section 4.2.7, discusses "Stress-Corrosion Cracking" as defined in the Vocabulary in that standard and is referenced in section 4.2.7 as K_{ISCC}. S-080-1998 requires the maximum applied stress intensity factor, including tensile residual stresses, to be less than K_{ISCC} in the appropriate environment. Section 3.2, Definitions, in NASA-STD-5019A lists K_{ISCC} and states K_{EAC} is often denoted as K_{ISCC} in the literature. The S-080-1998 requirement to be less than K_{ISCC} (i.e., K_{EAC}) is changed by the requirements in items 7.2.1.e(6), e(6)A, and e(6)B to not exceed the lower bound value of K_{EAC} (or K_{IEAC}, as appropriate for the pressure vessel thickness). Searches of S-080-1998 did not find any requirements addressing SLC. In summary, the requirements in items 7.2.1.e(6), e(6)A, and e(6)B for EAC and SLC are not satisfied for pressure vessels built to S-080-1998 requirements. To satisfy these items, damage tolerance assessments of pressure vessels built to S-080-1998 has to demonstrate the applied stress intensity factor for the largest service load plus residual stresses at the end of 4 lifetimes are smaller than the lower bound stress intensity factor thresholds for K_{EAC} and K_{SLC}.

S-080A-2018, section 4.2, Terms and Definitions, defines sustained load crack growth as "growth of a pre-existing crack in susceptible metallic alloys under sustained stress, without assistance from an external environment." Section 4.2 also defines stress-corrosion cracking as "a mechanical-environmental induced failure process in which sustained tensile stress and chemical attack combine to initiate and propagate a crack or a crack-like flaw. These definitions are the same as SLC and EAC in NASA-STD-5019A.

Regarding SLC requirements, section 5.2.13.1, Damage Tolerance Life Design, states: "The region(s) of the pressurized hardware (i.e., pressure vessel) to which damage tolerance life is applied shall be designed such that it possesses a minimum damage tolerance life of four (4) times the service life without sustained load crack growth . . .." Section 10.1.1, Damage Tolerance Life Test—Coupon Specimens, requires examination of the fracture surfaces produced during the testing "to identify if sustained load crack growth occurred during testing" and requires the testing to confirm no sustained load crack growth occurred during the test. There is also a note stating: "For some materials, it is difficult to differentiate between stable crack extension and sustained load crack growth" which casts doubt as to the reliability of relying on examination of the fracture surface. The same statements appear in section 10.1.2, Damage Tolerance Life Test—Pressurized Hardware specimens.

Regarding EAC requirements, the term appears in section 7.1, Metallic Material Properties, in item 2 as a material property that is required to be "either A-basis or nominal values" which does not satisfy requirements in items 7.2.1.e(6), e(6)A, and e(6)B to be a lower bound value. Section 7.5.1, Damage Tolerance Life Analysis, requires: "At all times in the service life, the applied stress intensity factor shall be less than the surface or embedded crack fracture toughness . . . and K_{IEAC} for the applicable environment (such as hydrogen embrittlement)." This imposes an EAC requirement, but it does not satisfy items 7.2.1.e(6), e(6)A, and e(6)B because the value is not specified to be a lower bound, and the term "service life" should be "damage tolerance life," which is specified to be 4 times the service life in section 5.2.13.1. Also, section 10.1, Damage Tolerance Life Test, states: "The effects of service environment (e.g., temperature, humidity, fluids) shall be accounted for either by representative testing or by analytical rationale." The wording "or by analytical rationale" does not satisfy item 7.2.1.e(6) that requires lower bound values of EAC and SLC which are obtained by tests.

In summary, the S080A-2018 requirements to prevent failures due to SLC and EAC are not in agreement with the requirements in items 7.2.1.e(6), e(6)A, and e(6)B.

A question may arise as whether S080A-2018 be modified so that it satisfies the requirements. To assist users of S-080A-2018 in understanding the issues, versions of these three sections are provided with changes underlined that would satisfy items 7.2.1.e(6), e(6)A, and e(6)B requirements in NASA-STD-5019A.

A tailored version of the S-080A-2018, section 7.1 2) bullet list and following paragraphs is provided below. Also note in the literature K_{EAC} is often denoted as K_{ISCC}, the stress intensity factor threshold for plane strain stress corrosion cracking per sections 3.1 and 3.2 in NASA-STD-5019A. For this reason, and to be consistent with S-080A-2018, section 8.2, Corrosion Control and Fluid Compatibility, that prohibits operational, test, and manufacturing fluids from coming into contact with the pressurized hardware that cause corrosion, stress corrosion cracking, change to mechanical or fracture properties, or other deleterious effects that would reduce performance," the reference in section 7.1 2) to "corrosion fatigue growth rates" is deleted.

Changes are shown that satisfy the following damage tolerance requirements:

- K_{IC}, K_{IE}, and ΔK_{th} data requirements are per item 7.2.1.e(5),
- Fatigue crack growth rates, da/dN, dc/dN, are per NASA-STD-5019A section 7.3.2.d, and
- K_{EAC} and K_{SLC} are per items 7.2.1.e(6), e(6)A, and e(6)B. (If these changes are implemented in S-080A-2018, the definition of K_{SLC} would also be needed.)

The tailored version of S-080A-2018, section 7.1 2) (changes are underlined), follows:

7.1 2) Material property values based on standards such as those developed by ASTM may be used for the following:

Use values that are less than or equal to the average values to determine:

- Plane strain fracture toughness, K_{IC}, surface-crack fracture toughness, K_{IE}, and cyclic threshold stress intensity range (ΔK_{th}).

Use values that are greater than or equal to the average values to determine:

- Fatigue crack growth rates, da/dN, dc/dN

Use lower bound values for assessments of the following:

- Stress intensity factor thresholds for plane strain environmentally assisted cracking, K_{EAC} or K_{IEAC} as appropriate, and sustained load crack growth, K_{SLC}.

Use A-basis or nominal values that are lower bound values for assessments of the following:

- Fatigue, stress, and strain with respect to number of cycles, S-N, or ε-N data.

. . . Sufficient data shall be obtained either from conducting tests or other available sources so that values as specified above can be established.

S-080A-2018, section 7.5.1, Damage Tolerance Life Analysis, third and fourth paragraphs are copied below with changed wording underlined. Note the 4th paragraph reference to "service life" is also changed to "damage tolerance life" since that is defined in S-080A-2018, section 5.2.13.1, as 4 times the service life; this change is needed so that it satisfies the 4 lifetimes requirement.

Tailored versions of 3rd and 4th paragraphs of S-080A-2018, section 7.5.1 (changes are underlined), follow:

The analysis shall use values that are less than or equal to the average values of the following fracture properties (residual strength, fracture toughness, stable crack extension resistance, cyclic threshold stress intensity range (ΔK_{th}), and lower bound values for analysis assessments using the following fracture properties (K_{EAC}), and sustained load crack growth, K_{SLC}), and values that are greater than or equal to the average values of the crack growth rates for fatigue: da/dN and dc/dN, associated with each alloy, heat-treat condition, thickness, and product form in the applicable thermal and chemical environments. If fracture toughness properties are not known for the materials used in the pressurized hardware, then those properties are determined from a characterization test program, as specified in Section 7.1.

At all times in the damage tolerance life, the applied stress intensity factor shall be less than the surface or embedded crack fracture toughness (see ASTM E2899) and less than the lower bound value of K_{IEAC} for the applicable environment (such as hydrogen embrittlement) and the stress intensity factor for sustained load crack growth, K_{SLC}.

The tailored version of S-080A-2018, section 10.1 (changes are underlined), follow:

> "The effects of service environment (e.g., temperature, humidity, fluids) and sustained loading on damage tolerance material properties K_{EAC} and K_{SLC} shall be determined by test data as specified in section 7.1 2)."

NASA-STD-5019A, Item 7.2.1f

Item 7.2.1.f of NASA-STD-5019A addresses proof testing. It requires the test duration to be minimized and also to verify the pressure is stable, because unexpected changing pressure could indicate a failure in progress.

S-080-1998, section 5.1.1.4, has a requirement "the proof pressure level shall be maintained for five (5) minutes minimum." To also comply with the item 7.2.1.f requirement, test measurements to ensure the vessel does not leak or lose pressure should be completed during the five minutes when pressure is maintained.

S-080A-2018, section 10.4.6, Proof Test requirements states: "The duration of the proof test hold shall be sufficient to verify pressure stability." The pressure test will also need to minimize the duration of the test.

NASA-STD-5019A, Item7.2.1.g

Item 7.2.1.g of NASA-STD-5019A imposes requirements on assessments of pressure vessels built to S-080-1998 if the section 4.2.7 option to use testing to satisfy damage tolerance requirements is planned.

Item 7.2.1.g also imposes requirements on assessments of pressure vessels built to S-080A-2018 if the assessment is to be performed by tests.

NASA-STD-5019A, Items 7.2.1.g(1), g(1)A, g(1)B

Items 7.2.1.g(1), g(1)A, and g(1)B of NASA-STD-5019A apply to pressure vessels built to either S-080-1998 or S-080A-2018. These items require the testing approach and rationale to be documented in the FCP and receive RFCB approval before implementation.

The testing approach should describe the proposed testing in sufficient detail to demonstrate it addresses all the aspects discussed in item 7.2.1.g(2). Planned test details should be provided such as whether test specimen will replicate some or all of the pressure vessel conditions, including material characteristics, loading and stress states, loading spectrum, initial crack configurations, and effects of environments.

Include a description of the information to be obtained from the tests and how it will be used to demonstrate requirements have been satisfied by the testing. This provides an opportunity for the RFCB to comment on their evaluation as to whether the testing plans address the requirements in NASA-STD-5019A.

NASA-STD-5019A, Item 7.2.1.g(2)

Item 7.2.1.g(2) of NASA-STD-5019A states the testing is to demonstrate the hardware meets the damage tolerance lifetime and failure condition requirements in S-080-1998 "as modified in the NASA Technical Standard" for initial flaws in the worst location, aspect ratio, and orientation in conditions that represent the service environments. The testing should address all the aspects imposed in section 7.2.1 in NASA-STD-5019A which affect testing and application of the data to pressure vessels, including items 7.2.1.d(1) through d(5). Discuss how the testing will conservatively bound the situations addressed by analysis in items 7.2.1.e(4), e(4)A, e(4)Bi, and e(4)Bii. Discuss how the risk of failure due to EAC or SLC will be addressed by existing data if it is available, or by tests to determine the lower bound values of thresholds for K_{EAC} and K_{SLC} as discussed in items 7.2.1.e(6), e(6)A, and e(6)B in this Handbook. These aspects are supplemented by the testing requirements in section 7.3.3 in NASA-STD-5019A, such as items 7.2.1.c, d, e, and f. The guidance at the end of section 7.3.3 is also helpful.

The above discussion is also applicable if the pressure vessel is built per S-080A-2018, because the discussion is describing the requirements imposed by items 7.2.1.g and g(2) in NASA-STD-5019A, not aspects of S-080-1998.

NASA-STD-5019A, Item 7.2.1.g(3)

Item 7.2.1.g(3) of NASA-STD-5019A specifies the testing activities are to be described in reports showing the objectives have been achieved. The testing and results are to be documented in accordance with section 9.1 and cited in the FCSR per requirements in NASA-STD-5019A.

NASA-STD-5019A, Item 7.2.1.h

Item 7.2.1.h of NASA-STD-5019A states section 5.1.2.6, Special Provision, in S-080-1998 is not allowed. Guidance in this section states: "Pressure vessels as defined by NASA are always fracture critical," clarifying the "Special Provision" is not an acceptable procedure.

There is nothing comparable to the S-080-1998 "Special Provision" content in S-080A-2018, so item 7.2.1.h does not apply to it.

NASA-STD-5019A, Item 7.2.1.i

Item 7.2.1.i addresses vessels with crack-like flaws "induced during the manufacturing process" and states they "are not accepted as flight hardware unless a process for remediation repair has been established and the delegated Technical Authority approves the part and process." The delegated Technical Authority is described in section 1.3 in NASA-STD-5019A.

S-080-1998, section 4.7.4, specifies repair and refurbishment requirements "when inspections reveal structural damage or defects exceeding the permissible levels. It requires the damaged hardware to be repaired, refurbished, or replaced, as appropriate. Also, it requires all repaired or refurbished hardware to be re-certified by the applicable acceptance test procedure for new hardware to verify the part for use and its structural integrity. Additionally, item 7.2.1.i requires the process to have been established, and both the process and the refurbished part are to be approved by the delegated Technical Authority described in section 1.3 in NASA-STD-5019A.

S-080A-2018 has sections that address most of item 7.2.1.i requirements. S-080A-2018, section 11.7, Repair and Refurbishment, states: "If repair or refurbishment is allowed by the procuring authority, any repaired or refurbished". . . hardware shall be re-certified after each repair or refurbishment to verify its structural integrity and suitability for service." A repair protocol is listed in section 11.7 which is subject to evaluation by a material review board as defined in section 11.6. An additional aspect imposed by item 7.2.1.i on hardware built using S-080A-2018 is the delegated Technical Authority, as identified in NASA-STD-5019A, would need to approve repair or refurbishment of the flight hardware.

Additionally, guidance in NASA-STD-5019A after item 7.2.1.i that is applicable to both standards states:

> *Refer to section 8.1.5 of this NASA Technical Standard for further requirements and guidance. This pertains to the repair of small manufacturing or cosmetic defects in the composite. There are no acceptable established processes for repairing impact damage to the composite overwrap. Accidental impacts that do not leave obvious visible damage indications are to be logged, the impact site assessed by qualified inspectors, and the hardware approved for use by the delegated Technical Authority.*

Section 8.1.5 in NASA-STD-5019A requires assessment actions if a detected flaw is proposed to be used for flight without being repaired or replaced.

NASA-STD-5019A, Items 7.2.1.j, j(1), j(2)

Item 7.2.1.j has two parts that apply to S-080-1998. Item 7.2.1.j(1) supplements the quality assurance requirements in S-080-1998, section 4.6 (and its subsections), with requirements in section 8 in NASA-STD-5019A. Item 7.2.1.j(2) states if there is a conflict for quality assurance between NASA-STD-5019A and the S-080-1998 requirements, requirements in the NASA-STD-5019A take precedence.

Items 7.2.1.j(1) and j(2) also apply to and take precedence over quality assurance sections in S-080A-2018 that are specified in a distributed documentation structure. Quality assurance is treated at a high level in section 9 (and its subsections), which point to related technical and detailed topics in sections under other headings, which may or may not go into technical details. For example, the inspection and test plan (ITP) has high-level requirements in section 9.5, the NDT sensitivity for damage tolerance life is specified in section 5.2.13.1, and points to section 10.4.2 for NDE technique, which only has high-level statements. In a flight hardware assessment, additional details would be required on the sensitivity of the NDE technique and the basis establishing that sensitivity.

NASA-STD-5019A, Items 7.2.1.k, k(1), k(2), k(3)

Item 7.2.1.k of NASA-STD-5019A tailors S-080-1998 requirements for fracture critical part documentation and reporting with requirement items 7.2.1.k(1), k(2), and k(3).

Item 7.2.1.k(1) supplements the S-080-1998 requirements for fracture critical part documentation and reporting with requirements in section 9 and its subsections of NASA-STD-5019A.

Item 7.2.1.k(2) states if there is a conflict, S-080-1998 requirements for documentation and reporting are superseded by NASA-STD-5019A requirements in section 9 and its subsections.

Item 7.2.1.k(3) identifies documents described in S-080-1998 to be included as part of the FCSR, namely the section 4.2.5 stress report and the section 4.2.7 damage tolerance analysis report. Also, guidance after section 7.2.1.k in NASA-STD-5019A states:

> *Note that S-080-1998 also addresses other hardware types, but only the metallic pressure vessel requirements as tailored in this section are applicable for this NASA Technical Standard.*

S-080A-2018 content and organization is changed dramatically from S-080-1998.

Items 7.2.1.k(1) and k(2) impose NASA-STD-5019A requirements in section 9 (and its subsections) as both supplementary and superseding requirements on S-080A-2018 sections that document fracture critical part tests, assessments, and reporting. S-080A-2018 has a distributed documentation structure. Examples are the following:

- Section 9.5 describes the ITP, which is the master plan for all manufacturing quality control,
- Section 9.6 describes the Inspector (Composite Overwrap) Qualification, which specifies a qualified inspector's skill requirements,
- Section 9.7 describes qualification reporting documenting verification of compliance with all design requirements by analysis and test,
- Section 10.3 describes the Damage Control Plan that is to mitigate credible sources of mechanical and other forms of damage to the COPV during manufacturing and throughout the service life as verified by test,
- Section 11.9 describes operations documentation consisting of all inspection records, verification test and analysis results, transportation and handling records, vehicle integration processing data, and test and operation data, and
- Section 12 lists documents.

Item 7.2.1.k(3) specifies fracture control documents to be included in the FCSR as the S-080-1998 stress analysis report and the damage tolerant analysis report. Equivalent information documents produced as required in S-080A-2018 are needed in the FCSR. The documents may include any of the many analyses, damage tolerance, and qualification reports listed in S-080A-2018, sections 7, 9, 10, 11, and 12. The RFCB may be consulted to confirm which documents are to be provided in the FCSR.

7.2.2 Fracture Critical COPVs and Composite Overwrapped Pressurized Fluid Containers (NASA-STD-5019A, Section 7.2.2)

NASA-STD-5019A:

7.2.2 Fracture Critical COPVs and Composite Overwrapped Pressurized Fluid Containers

This category pertains to composite overwrapped pressure vessels and pressurized fluid containers that are designed to meet ANSI/AIAA S-081-2000, Space Systems - Composite Overwrapped Pressure Vessels (COPVs). Composite overwrapped pressurized fluid containers are pressurized parts with a composite structure fully or partially encapsulating a metallic liner and that do not meet the definition of a pressure vessel. Fracture critical COPVs and composite overwrapped pressurized fluid containers meeting other codes/standards are addressed in section 7.2.3 in this NASA Technical Standard.

For fracture critical COPVs and all other fracture critical composite overwrapped pressurized fluid containers with a metallic liner, show compliance with ANSI/AIAA S-081-2000, with modifications as specified below in items a through m, to satisfy requirement [FCR 11] section 7.2.b in this NASA Technical Standard.

Subsequent versions of ANSI/AIAA S-081 with modifications that implement the technical content as mandated in this section may be used with the approval of the RFCB.

a. The ANSI/AIAA S-081-2000 requirements are followed for the assessment and qualification of all the composite overwrapped vessels and composite overwrapped pressurized fluid containers with metallic liners addressed by this section, regardless of the vessel fluid pressure, energy, or hazardous nature, with the modifications specified in this section in this NASA Technical Standard.

b. The damage tolerance assessment approach is described in the FCP in accordance with section 4.1 [FCR 1] in this NASA Technical Standard.

c. All occurrences of the following terms in ANSI/AIAA S-081-2000 are replaced with the terms having meanings as specified below:

(1) All occurrences of "maximum expected operating pressure" and "MEOP" are substituted with “maximum design pressure” and "MDP" as defined in this NASA Technical Standard in section 3.2.

(2) The word "nominal" is replaced with the word "average" in all ANSI/AIAA S-081-2000 sections.

(3) All occurrences of the term "service life" are to have the meaning defined in this NASA Technical Standard in section 3.2 for "service life."

d. ANSI/AIAA S-081-2000 section 4.2 requirements are met with the following modifications:

(1) In ANSI/AIAA S-081-2000 section 4.2, the damage tolerance, i.e., safe-life, approach (b) is the only acceptable approach.

(2) The ANSI/AIAA S-081-2000 section 4.2.7 safe-life requirements are met with the following modifications:

A. The safe-life assessment analysis and test assessments are to encompass and represent the worst-case flaw location, shape, aspect ratio, and orientation.

B. The process for selecting the worst-case location, shape, aspect ratio, and orientation is based on liner stress/strain response and material strength and crack growth properties and documented in the analysis report.

C. The assessment determining the worst-case location, shape, aspect ratio, and orientation includes all regions of the liner and boss, including the shear region of the boss and any internal and external attachments.

D. The safe-life assessment analysis and test loading spectra are to include all loadings experienced during the service life, including those specified in this NASA Technical Standard in section 7.3.1, unless the RFCB approves the exclusion of specific loadings as insignificant for a component assessment.

For example, with approval of the RFCB, service life loadings that affect the safe-life of a particular region of the liner, boss, or shear region of the boss by less than 5 percent may be excluded from the safe-life assessment of these regions.

E. The assessments are to show all safe-life requirements are met for the entire mission service life.

The mission service life includes all of the hardware activities included in the hardware mission as defined in NPR 7120.5, for the duration of the service life as defined in section 3.2 in this NASA Technical Standard. If the mission service life includes periodic "depot" intervals (opportunity for inspection) with fully qualified screening inspections that ensure acceptable hardware has sufficient life, including the service life factor, to reach the next "depot" evaluation, this "depot" interval-based service-life approach may be proposed as an alternative approach by meeting the requirements in section 10 in this NASA Technical Standard.

(3) Autofrettage is included in the service life unless liner NDE is performed after autofrettage.

(4) The assessment of crack growth related to the autofrettage cycle is determined by test in accordance with ANSI/AIAA S-081-2000 section 5.2.1, unless prior approval is provided by the RFCB for an analytical approach.

e. When performing analysis to show safe life for linearly responding portions of the metal liner in accordance with ANSI/AIAA S-081-2000 section 4.2.7, apply the following modifications:

(1) Obtain pre-approval from the RFCB for all crack growth computer analysis programs other than NASGRO®.

(2) If the analysis ability to simulate crack growth is invalidated by plasticity or other effects, the assessment is performed by test.

(3) If NASGRO® is used, either set B_k to zero, or set B_k such that the stress intensity factor for the part thickness is less than or equal to the critical stress intensity value with approval of the Technical Authority or the RFCB.

(4) The analysis shows that the parts survive 4 service lives without failure by assessments that address all applicable effects causing crack growth as a result of cyclic loading, using the following criteria:

Assessments of metallic alloys that are susceptible to crack growth related to SLC or EAC during the service life are addressed in item 6 below.

A. If the loading sequence of high/low loads is unknown, then damage tolerance analysis is to show that the stress intensity factor at limit load is less than the critical stress intensity factor or that the part applied load does not exceed the residual strength at the end of 4 lifetimes.

B. If the service lifetime is a single event or the amount of fatigue crack growth is small relative to the critical crack size for unstable crack growth, the analysis is to show reserve capability against fracture by meeting either of the following:

i. A lower bound critical stress intensity factor or residual strength at the end of 4 lifetimes.

ii. A factor of 1.4 on critical stress intensity factor or residual strength after 1 lifetime.

(5) Use critical stress intensity factor and cyclic threshold stress intensity range (ΔK_{th}) values that are less than or equal to the average values.

(6) For metallic alloys susceptible to EAC or SLC or both, satisfy all of the following:

A. Use the lower bound value of stress intensity factor threshold for assessment of EAC (K_{EAC} or K_{IEAC} as appropriate), and SLC if the material exhibits these behaviors in the application conditions.

B. Show that the applied stress intensity factor related to the largest service load is smaller than the lower bound stress intensity factor thresholds determined in item A above at the end of 4 lifetimes.

f. When performing proof testing in accordance with ANSI/AIAA S-081-2000 section 5.1.2, the duration of the proof test loading is minimized while also meeting the requirement to verify the pressure stability.

g. When performing assessment to show safe-life by test for non-linear response of the metal liner in accordance with ANSI/AIAA S-081-2000 section 5.2.1, apply the following items:

(1) The testing approach and rationale are subject to both of the following:

A. Provided to the RFCB for approval before implementation.
B. Documented in the FCP.

(2) The testing is to show that the hardware meets the damage tolerance lifetime and failure condition requirements in ANSI/AIAA S-081-2000 as modified in this NASA Technical Standard for initial flaws in the worst location and orientation in conditions that account for the service environments.

(3) Testing reports showing that the testing objectives have been achieved and are documented in accordance with section 9.1 of this NASA Technical Standard and cited in the FCSR.

h. ANSI/AIAA S-081-2000 section 4.2.10 damage control requirements are to include the section 4.2.10.2.1 protective cover approach with the following additional requirements:

(1) The covers are required regardless of the COPV burst factor, wall thickness, hazardous or nonhazardous nature of the fluid, or energy content.

(2) If the vessel is exposed to risk of damage during any parts of the service life where the initially applied covers are not present, additional damage controls are selected from the options in ANSI/AIAA S-081-2000 section 4.2.10.

The additional damage controls referenced in item h.2 above may be needed if protective covers are removed before launch and the vessel has risk of damage during the remainder of its service life or if there are different risks to the vessel during its service life because of environments or service loadings that also need to be addressed by damage controls. All options, separately or in combination, may be used, including specialized covers for flight conditions.

i. Apply the following items if the composite overwrap is constrained by external structure or if it is part of a load path supporting the COPV for service life loads other than pressure loads:

(1) Perform an assessment validated by testing that shows the overwrap with the external structure loads meets all strength, fatigue, and life requirements in ANSI/AIAA S-081-2000.

(2) The assessment is to include effects of damage conditions that are not screened by the protections imposed in accordance with ANSI/AIAA S-081-2000 section 4.2.10 with the modifications in this section of this NASA Technical Standard.

j. Vessels with crack-like flaws in the metal liner that are induced during the manufacturing process are not accepted as flight hardware unless a process for remediation repair has been established and the Technical Authority approves the part and process.

Refer to section 8.1.5 in this NASA Technical Standard for further requirements and guidance.

k. Damage in other regions of the vessel may be repaired with an established, proven process if approved by the Technical Authority.

Refer to section 8.1.5 of this NASA Technical Standard for further requirements and guidance. This pertains to the repair of small manufacturing or cosmetic defects in the composite. There are no acceptable established processes for repairing impact damage to the composite overwrap. Accidental impacts that do not leave obvious visible damage indications are to be logged, the impact site assessed by qualified inspectors, and the hardware approved for use by the Technical Authority.

l. The ANSI/AIAA S-081-2000 requirements for quality assurance in section 4.5 in that document are supplemented and superseded by requirements in section 8 (and its subsections) in this NASA Technical Standard.

m. The ANSI/AIAA S-081-2000 requirements for fracture critical part documentation and reporting are subject to the following:

(1) Requirements in section 9 (and its subsections) of this NASA Technical Standard.

(2) If there is a conflict with ANSI/AIAA S-081-2000, the requirements are superseded by requirements in section 9 (and its subsections) of this NASA Technical Standard.

(3) The ANSI/AIAA S-081-2000 section 4.2.7 safe-life and analysis reports and the 4.2.10 Mechanical Damage Control Plan (MDCP) are provided as part of the FCSR documentation.

The entity responsible for delivery of the MDCP (NASA, prime contractor, or other subcontractors) determines who develops the MDCP, which is subject to RFCB approval.

Section 7.2.2 in this Handbook describes application of the requirements in section 7.2.2 in NASA-STD-5019A upon fracture critical COPVs and all other composite overwrapped pressurized fluid containers with a metallic liner that are designed and built to the ANSI/AIAA S-081-2000 standard. For additional guidance on the applicability of LEFM for COPV liners, see Volume 2, 7.2.2.1 of NASA-HDBK-5010 A.

When NASA-STD-5019A was written, the version of ANSI/AIAA S-081 in use for NASA COPVs was the 2000 version. Accordingly, the details in section 7.2.2 in NASA-STD-5019A are focused upon fracture control issues in ANSI/AIAA S-081-2000. A revision of the ANSI/AIAA S-081 standard was being developed when NASA-STD-5019A was written. The requirements in section 7.2.2 in NASA-STD-5019A may also be applicable to subsequent versions of ANSI/AIAA S-080 by the following guidance in the section:

> "*Subsequent versions of ANSI/AIAA S-081 with modifications that implement the technical content as mandated in this section may be used with the approval of the RFCB.*"

ANSI/AIAA S-081 was revised to ANSI/AIAA S-081B-2018 approved 3/20/2018.

NOTE: Per the guidance copied above, to use the ANSI/AIAA S-081B-2018 standard for fracture control of COPVs per requirements in NASA-STD-5019A, approval is needed from the RFCB. Then the section 7.2.2 requirements in NASA-STD-5019A will also modify the content of ANSI/AIAA S-081B-2018.

If later versions of ANSI/AIAA S-081 are developed that are approved for use by the RFCB, the section 7.2.2 requirements in NASA-STD-5019A will also modify the content of the later version of ANSI/AIAA S-081. In that situation, the discussions in section 7.2.2 in this Handbook would provide guidance for applying the section 7.2.2 requirements in NASA-STD-5019A to the later version of ANSI/AIAA S-081. In that situation, the guidance discussions in section 7.2.2 in this Handbook may need some modifications, which if approved by the RFCB, would apply to the later version of ANSI/AIAA S-081.

For convenience, these two ANSI/AIAA standards will be referred to in the remainder of this section 7.2.2 more concisely as the S-081-2000 and the S-081B-2018 standards. The S-081B-2018 standard was developed in parallel with a companion standard, ANSI/AIAA S-080A-2018 for metallic pressure vessels, pressurized structures, and pressure components, that was approved on the same date. It will be referred to as S-080A-2018. Section 7.2.1 in this Handbook discusses S-080A-2018 and ANSI/AIAA S-080-1998 in this Handbook.

These new 2018 standards are greatly changed from previous versions. The Foreword in each document outlines some of the revisions. One change in both S-081B-2018 and S-080A-2018 is they only use the term "damage tolerance" instead of "safe-life." The discussions in section 7.2.2 of this Handbook will also use the term "damage tolerance" life.

Section 7.2.2 in this Handbook will discuss application of the section 7.2.2 requirement items in NASA-STD-5019A to both S-081-2000 and S081B-2018. The beginning of each discussion will address S-081-2000, and in some cases, also address S-081B-2018. The usual style will discuss S-081-2000 first, and S081B-2018 in separate paragraphs.

Both S-081B-2018 and S-080A-2018 use the same organization and section numbers, and much of the content is common to both standards. A summary listing the sections and fracture control aspects in these 2018 versions is provided in section 7.2.1 in this Handbook. Although there are differences in the two standards, most all of the summary is applicable to both of them and will not be repeated in this section.

NASA-STD-5019A, Item 7.2.2.a

Section 7.2.2.a applies to both S-081-2000 and S081B-2018. Section 7.2.2.a defines the scope of section 7.2.2 in NASA-STD-5019A. Section 7.2.2 goes beyond the scope of S-081-2000, which is limited to COPVs that satisfy the definition of a pressure vessel. The scope of section 7.2.2 includes all other composite overwrapped pressurized fluid containers with a metallic liner regardless of the vessel fluid pressure, energy, or hazardous nature of the fluid. The scope of section 7.2.2 was expanded because all composite overwrapped vessels with metal liners share similar structural characteristics, namely a pressurized fluid container with a composite overwrap and a metallic liner. They also present risks in the event of a failure related to damage tolerance that can be addressed using the same fracture control requirements and methodology.

S-081-2000, section 1.2, Application, states the standard is applicable to metal-lined COPVs used for spaceflight, and that requirements in S-080-1998 are used for the metallic liner. It also states the term COPV in that standard is used to mean a metal-lined COPV. It has a comment on non-metal liners. The comment does not mean COPVs with non-metal liners can be assessed by section 7.2.2 in NASA-STD-5019A. COPVs with non-metal liners are addressed in item 7.2.3c in NASA-STD-5019A.

S-081B-2018, section 1.2, Applicability, states the standard is applicable only to COPVs containing a metallic liner and constructed with a carbon fiber/polymer matrix overwrap. It also states COPVs that include a fiberglass overwrap layer that serves only to protect the vessel from impact damage are permitted. These restrictions are applicable for assessments of COPVs built to S-081B-2018 that follow the requirements in section 7.2.2 in NASA-STD-5019A, as discussed in section 7.2.2 in this Handbook.

NASA-STD-5019A, Item 7.2.2.b

Section 7.2.2.b applies to both S-081-2000 and S081B-2018. It ensures section 4.1 [FCR 1] requirements for a Fracture Control Plan in NASA-STD-5019A are imposed on damage tolerance assessments of flight hardware. Section 4.1 requirements are discussed in section 4.1 in this Handbook. Details for each flight hardware item are expected to be provided in the Fracture Control Documentation and Verification as detailed in section 9 in NASA-STD-5019A.

NASA-STD-5019A, Item 7.2.2.c

Section 7.2.2.c requires replacement of three technical terms found in S-081-2000 and S-081B-2018 so that fracture control requirement terminology agrees with NASA-STD-5019A.

NASA-STD-5019A, Item 7.2.2.c(1)

Item 7.2.2.c(1) replaces the fluid pressure quantity "maximum expected operating pressure," i.e., "MEOP," with the term "maximum design pressure," i.e., "MDP" with a definition given in section 3.1 of NASA-STD-5019A, which is also copied below:

> "Maximum Design Pressure: The highest possible operating pressure considering maximum temperature, maximum relief pressure, maximum regulator pressure, and where applicable, transient pressure excursions. MDP for human-rated hardware is a two-failure tolerant pressure, i.e., it will accommodate any combination of two credible failures that will affect pressure. Some programs have defined MDP as a two-fault tolerant pressure."

The definition of MDP results in a larger pressure than with the MEOP which does not address the two-failure tolerant pressure condition.

NASA-STD-5019A, Item 7.2.2.c(2)

Item 7.2.2.c(2) replaces the word "nominal" with the word "average" in two S-081-2000 sections: 3, Vocabulary, in the definition of residual strength, and 4.2.6.

In addition, as noted in section 7.2.2.a, S-081-2000, section 1.2, Application, states: S-080-1998 is used for the metallic liner. S-080-1998 should also be tailored to replace the word "nominal" with the word "average" in three S-080-1998 sections: 4.2.6, 4.2.7, and 4.3.3 as also described in item 7.2.1.b(2) in this Handbook.

The term "nominal" is not a statistically defined quantity. It is a categorical quantity "in name only" used for identification. These changes are needed so that damage tolerance assessments of

COPVs built per these standards will satisfy the requirements in NASA-STD-5019A, item 7.3.2.e, that specifies: "Use critical stress intensity factor and cyclic threshold stress intensity range (ΔK_{th}) values that are less than or equal to the average values."

S-081B-2018 defines damage tolerance assessment material data using the term "nominal" in section "7.1 2)" in two places—in section 7.4.12 in one place, and in 7.5.1 in two places. Item 7.2.2.c(2) requires replacing all these occurrences of the word "nominal" with the word "average."

Note: Item 7.2.2.e(5) also modified the wording in S-080-1998, sections 4.2.7 and 4.3.3; and items 7.2.2.e(6), e(6)A, and e(6)B further modified S-080-1998, section 4.2.7. The application of these items to S-080A-2018 is also described in discussion for each item in this Handbook.

NASA-STD-5019A, Item 7.2.2.c(3)

Item 7.2.2.c(3) addresses the definition of service life in S-081-2000, section 3, which did not conform to the definition in NASA-STD-5019A. Accordingly, item 7.2.2.c(3) modifies all occurrences of the term “service life” to have the meaning defined in section 3.2 in NASA-STD-5019A.

S-081B-2018 defines service life in section 4.2, Terms and Definitions. The S-081B-2018 definition of service life is close, but not equivalent to the definition in NASA-STD-5019A. Accordingly, item 7.2.2.b(3) modifies all occurrences of the term "service life" to have the meaning defined in section 3.2 in NASA-STD-5019A.

NASA-STD-5019A, Item 7.2.2.d

Item 7.2.2.d imposes four modifications to the S-081-2000 damage tolerance assessment analysis and test requirements so they will satisfy requirements in NASA-STD-5019A.

Item 7.2.2.d modifications are also evaluated for applicability to the S-081B-2018 standard.

NASA-STD-5019A, Item 7.2.2.d(1)

Item 7.2.2.d(1) specifies in S-081-2000, section 4.2, that item 7.2.2.b, the damage tolerance, i.e., safe-life, approach, is the only acceptable approach.

S-081B-2018 requirements have undergone major changes relative to the S-081-2000 version. The item 7.2.2.d(1) comparable section in S-081B-2018 is section 5.1.2, Service Category. The requirements imposed by item 7.2.2.d(1) may be applied to S-081B-2018, section 5.1.2, to specify the appropriate service category, which is category 1, because section 5.2.13 specifies a COPV in that category has to satisfy damage tolerance life requirements.

S-081B-2018, section 5.2.13, category 1 also imposes Leak-Before-Burst (LBB) upon COPVs except for the boss. Section 5.2.13 also states: “The shear region of the boss is exempt from fracture control and defines the shear region of the boss as that portion of the liner at the edge of the composite where a high shear stress results from the internal pressure." The shear region of the boss is specifically included in fracture control by item 7.2.2.d(2)C, and is discussed in item 7.2.2.d(2)C.

NASA-STD-5019A does not impose a requirement to satisfy LBB in section 7.2.2. Accordingly, that requirement in S-081B-2018, section 5.2.13, may not be imposed on COPVs specified to satisfy NASA-STD-5019A. To formally avoid imposing the LBB requirement, the section 5.2.13 requirements could be modified per the Tailoring process described in S-081B-2018 in section 2.

NASA-STD-5019A, Item 7.2.2.d(2)

Item 7.2.2.d(2) imposes five additional modification items to S-081-2000 section 4.2.7 to bring fracture control requirements in that standard into agreement with the requirements in NASA-STD-5019A. Each additional modification item also includes a paragraph addressing relevant S-080A-2018 requirements.

NASA-STD-5019A, Item 7.2.2.d(2)A

Item 7.2.2.d(2)A of NASA-STD-5019A requires S-081-2000, section 4.2.7 damage tolerance analysis and test assessments to represent the worst-case flaw location, shape, aspect ratio, and orientation.

S-081-2000, section 4.2.7, states damage tolerance analysis requirements apply only to elastically responding metallic liners, integral bosses, and elastically responding regions of a generally plastic responding liner, and that requirements imposed are those in S-080-1998 section 4.2.7. The analysis requirements in S-080-1998, section 4.2.7, are discussed in this Handbook in item 7.2.1.d(1) and will not be repeated here. In summary, S-080-1998 requirements satisfy item d(2)A analysis requirements.

S-081-2000, section 4.2.7, specifies for plastically responding regions of metallic liners, testing is the only acceptable method, and points to section 5.1. There are no damage tolerance tests specified in section 5.1. It is presumed there is an error in this standard, and the testing reference should be to section 5.2.1, Safe-Life Demonstration. There are two options detailed in S-081-2000: section 5.2.1.1 describes testing using uniaxial coupons, and section 5.2.1.2 describes testing using COPVs.

S-081-2000, section 5.2.1.1, requires coupons that "duplicate the materials . . . , processes, and thickness of the liner" with surface cracks that "shall not be smaller in size than the flaw sizes established by the appropriate acceptance NDI methods" and "the flaw shape parameter, a/2c shall range from 0.1 to 0.5." These requirements do not include representation of the worst-case flaw location, shape, aspect ratio, and orientation. Item 7.2.2.d(2)A imposes these requirements on S-081-2000 damage tolerance test assessments. The application of item 7.2.2.d(2)A requirements for testing are included in item 7.2.2.d(4) discussions in this Handbook.

S-081B-2018 defines required damage tolerance assessments in three locations. Section 5.2.13.1, Damage Tolerance Life Design, has an overall "design" approach that defines the general aspects applied to assessments whether performed by analysis or test. Section 7.5.1 details damage tolerance life analysis approach and requirements. Section 10.1 specifies damage tolerance life tests using either coupon specimen in section 10.1.1 or using COPV specimen in section 10.1.2.

S-081B-2018, section 5.2.13.1, imposes detailed requirements for damage tolerance life design analysis and test assessments that address the following: NDE-based initial flaw size, worst-case locations and orientation, aspect ratios of 0.1 to 0.5 and within that range, and beyond that range if the potential worst case is shown to be a broader range, including both elliptical embedded and semi-elliptical surface flaws, and documentation of rationale for worst-case location whether the method is by analysis or test. This adequately addresses item 7.2.2.d(2)A requirements.

It is noted a sentence in S-081B-2018, section 5.2.13.1, prohibits use of proof test logic for flaw screening. Section 8.1.3 in NASA-STD-5019A permits proof testing for flaw screening if it is documented in the FCP and approved by the RFCB. If proof test logic is, the FCP would need to state it is tailoring S-081B-2018 to implement the proof testing. Tailoring of S-081B-2018 is permitted per section 2, Tailoring.

NASA-STD-5019A, Item 7.2.2.d(2)B

Item 7.2.2.d(2)B requires S-081-2000, section 4.2.7 damage tolerance analysis and test assessment process for selecting worst-case flaw location, shape, aspect ratio, and orientation to be based on vessel stress/strain response, material strength, and crack growth properties and be documented in the analysis report.

S-081-2000, section 4.2.7, states damage tolerance analysis requirements apply only to elastically responding metallic liners, integral bosses, and elastically responding regions of a generally plastic responding liner, and requirements imposed are those in S-080-1998, section 4.2.7.

S-080-1998, section 4.2.7, does not address the detail process used to determine the damage tolerance requirements. Item 7.2.2.d(2)B imposes requirements on elastically responding regions of the liner and boss that the analysis process for selecting the worst-case location, shape, aspect ratio, and orientation should be based on liner stress/strain response and material strength and crack growth properties and be documented in the analysis report.

S-081-2000, section 4.2.7, specifies for plastically responding regions of metallic liners, testing is the only acceptable method, and as noted in item 7.2.2.d(2)A, the applicable section is 5.2.1.1 for testing using uniaxial coupons, and section 5.2.1.2 for testing using COPVs. These sections do not impose the requirements in item 7.2.2.d(2)B. Item 7.2.2.d(2)B imposes requirements that the process for selecting the worst-case location, shape, aspect ratio, and orientation has to be based on liner stress/strain response and material strength and crack growth properties and be documented in the analysis report. The application of item 7.2.2.d(2)B requirements for testing are included in item 7.2.2.d(4) discussions in this Handbook.

S-081B-2018, section 5.2.13.1 as described above under item 7.2.2.d(2)A, imposes detailed requirements for damage tolerance life design analysis and test assessments that satisfy the item d(2)B requirement for the process and also requires the rationale for the determination of the worst-case location(s) to be documented. S-081B-2018, section 5.2.13.1, satisfies the item 7.2.2.d(2)B requirements.

NASA-STD-5019A, Item 7.2.2.d(2)C

Item 7.2.2.d(2)C of NASA-STD-5019A requires the S-081-2000, section 4.2.7 damage tolerance assessment to determine the worst-case flaw location, shape, aspect ratio, and orientation is to address all regions of the liner and boss, including the shear region of the boss and any internal and external attachments. Assessment of dominate shear stress regions is discussed below in item 7.2.2.d(2)C.

S-081-2000, section 4.2.7, states damage tolerance analysis requirements apply only to elastically responding metallic liners, integral bosses, and elastically responding regions of a generally plastic responding liner, and requirements imposed are those in S-080-1998, section 4.2.7. S-080-1998, section 4.2.7, has general requirements that do not address item 7.2.2.d(2)C requirements. Item 7.2.2.d(2)C imposes the requirement to include all elastic responding regions of the liner and boss, including the shear region of the boss and any internal and external attachments in the assessment.

S-081-2000, section 4.2.7, specifies for plastically responding regions of metallic liners, testing is the only acceptable method; and as noted in item 7.2.2.d(2)A, the applicable S-081-2000 section is 5.2.1.1 for testing using uniaxial coupons and section 5.2.1.2 for testing using COPVs. These sections do not impose the requirements that are in item 7.2.2.d(2)C, which requires the testing assessment to address all regions of the liner and boss, including the shear region of the boss, and any internal and external attachments in the assessment. These requirements should be included in testing assessments.

S-081B-2018, section 5.2.13.1, imposes a requirement that may include those in item 7.2.2.d(2)C with wording stating: "The worst-case location assessment shall include all regions of the liner (including the boss)." Regardless, since item 7.2.2.d(2)C of NASA-STD-5019A is imposed on S-081B-2018, all regions of the liner and boss, including the shear region of the boss, and any internal and external attachments should also be included in the worst-case damage tolerance assessments.

The item 7.2.2.d(2)C requirement the assessment includes all regions of the liner and boss, including the shear region of the boss, overrides the statement in section 5.2.13 that states: "The shear region of the boss is exempt from Fracture Control." An assessment that is including item 7.2.2.d(2)C requirements may need to state it is tailoring S-081B-2018, section

5.2.13.1, to fulfill the requirements in NASA-STD-5019A. The application of item 7.2.2.d(2)C requirements for testing assessments are included in item 7.2.2.d(4) discussions in this Handbook.

The shear region of the boss pertains only to a cylindrical shear plane that occurs at the junction of the outer mold line of the boss and the edge of the composite at the boss (at the composite boss turn-around). Local regions of bending that occur in the liner near the boss are not a part of the shear region of the boss. Assessment of the shear region is not addressed with typical fracture testing nor in the NASGRO® crack growth program. One suggestion is to perform tests of specimen representative of the most highly stressed shear dominated geometry region with worst-case crack stress intensity factors for mode II and/or mode III fracture, depending on the conditions that describe the local shear stress region that also meets the requirements in items 7.2.2.d(2)A and d(2)B of NASA-STD-5019A applied to the dominant shear stress region. Another suggestion is to minimize fracture risk in the shear stress dominated region by improved and/or redundant NDE to more reliably screen for detectable defects. Nearby areas experiencing dominant tension or bending stresses should be assessed for damage tolerance using the usual NDE and damage tolerance analysis or testing assessment methods. Whatever assessment approach is proposed for this situation, it may need approval by the RFCB.

NASA-STD-5019A, Item 7.2.2.d(2)D

Item 7.2.2.d(2)D of NASA-STD-5019A requires the S-081-2000, section 4.2.7 damage tolerance assessment analysis and test loading spectra to include all loadings experienced during the service life, including those specified in section 7.3.1 in NASA-STD-5019A, as described below, unless the RFCB approves the exclusion of specific loadings as insignificant. Section 4.2.7 does not specify the loadings to be assessed, but section 4.2.1 does specify "anticipated load-pressure-temperature history and associated environments throughout the service life shall be used to define the design load/environment spectra that shall be used for both design analysis and testing."

Loadings specified in section 7.3.1 in NASA-STD-5019A are all anticipated significant loadings, both cyclic and sustained, throughout its service life such as loads due to accelerations, pressures, temperature, environmental conditions, including preloads and residual stress. Other loadings that are included if applicable are weld joint stress risers such as peaking and mismatch, and effects of coatings and barriers, if leak detection is part of the strategy, when pressure is assumed to decrease due to leakage from a crack. Also, if the COPV is exposed to mission environments, including but not limited to, credible impacts from crew activities or vehicle loss of external surface mass, MMOD, EVA inadvertent contacts, or EVA tool impacts, the COPV should also be assessed for those loadings. The application of item 7.2.2.d(2)D requirements for testing are included in item 7.2.2.d(4) discussions in this Handbook.

There is relevant guidance in NASA-STD-5019A, section 7.3.1, that states:

> *"Include the worst-case allowed or weld joint peaking and mismatch effects for damage tolerance assessments by analysis or test. The assessment analysis or test is to capture*

> *the effect of peaking and mismatch on stress gradients affecting crack growth and fracture. Standard tensile strength tests of ductile materials are not adequate to assess these conditions."*

Guidance in NASA-STD-5019A after section 7.2.2.d(2)D states:

> "*For example, with approval of the RFCB, service life loadings that affect the safe-life of a particular region of the vessel by less than 5 percent may be excluded from the safe-life assessment of these regions."*

If this guidance approach is used for either S-081-2000 or S-080A-2018 damage tolerance assessments, it should be documented in the FCP and receive RFCB approval.

Note the above cited guidance "5 percent" method is different from usual NASGRO® crack growth analyses that apply a cyclic threshold stress intensity range (ΔK_{th}), that eliminates stress intensity ranges less than the ΔK_{th} value. The ΔK_{th} value should satisfy item 7.2.2.e(5) criteria, i.e., it has to be less than or equal to the average of test data.

S-081B-2018, sections 5.1.5, 5.1.6, 5.2.12, and 5.2.13.1, specify loadings that should be evaluated in the damage tolerance life assessment. Note that S-081B-2018, sections 5.1.6 and 5.2.13.1, impose a minimum of 13 full cycles to "MEOP" (which is modified by item 7.2.2.c(1) to be MDP). Item 7.2.2.d(2)D of NASA-STD-5019A requires the assessment analysis and test loading spectra to include all loadings experienced during the service life, including those specified in section 7.3.1 in NASA-STD-5019A, which are described above, unless the RFCB approves the exclusion of specific loadings as insignificant. The application of item 7.2.2.d(2)D requirements for testing are included in item 7.2.2.d(4) discussions in this Handbook.

NASA-STD-5019A, Item 7.2.2.d(2)E

Item 7.2.2.d(2)E of NASA-STD-5019A specifies the damage tolerance assessments (i.e., items 7.2.2.d(2)A through d(2)D, which all modify the S-081-2000 analysis and test requirement) are to show that all safe-life (i.e., damage tolerance life) requirements are met for the entire mission service life. The definition of "service life" in section 3.2, Definitions, in NASA-STD-5019A is imposed on S-081-2000 (and thereby on S-081B-2018) by item 7.2.2.c(3). The application of item 7.2.2.d(2)E requirements for testing are included in item 7.2.2.d(4) discussions in this Handbook.

S-081-2000, section 4.2.7, refers analysis of elastically responding metallic liners to S-080-1998, which is modified as discussed in item 7.2.1.d(5) and will not be repeated here. The S-081-2000, section 4.2.7 statement: "For those COPVs, which are readily accessible for periodic inspection and repair, the safe-life shall be at least four (4) times the interval between scheduled inspection and/or refurbishment" is modified by item 7.2.2.d(2)E to state: "The assessments are to show all safe-life requirements are met for the entire mission service life."

The guidance following item 7.2.2.d(2)E discusses possible "depot" intervals where a depot may include inspection and repair opportunities to demonstrate sufficient damage tolerance to reach the next "depot" evaluation. The guidance notes this would have to be proposed as an alternative approach by meeting requirements in section 10 in NASA-STD-5019A to describe proposed "depot" intervals in the FCP, and it would need approval per section 10 in NASA-STD-5019A.

S-081B-2018, section 5.2.13.1, specifies: "The region(s) of the COPV to which damage tolerance life is applied shall be designed such that it possesses a minimum damage tolerance life of four (4) times the service life without sustained load crack growth, detrimental deformation, leakage, or rupture," which only partially satisfies the item 7.2.2.d(2)E requirement. The wording "The region(s) of the pressurized hardware to which damage tolerance life is applied" is not clear and may be in violation of requirements in NASA-STD-5019A. The item 7.2.2.d(5) statement imposes a clear requirement on S-081B-2018 damage tolerance life assessments that includes all the COPV liner and supersedes the S-081B-2018, section 5.2.13.1 statement. Assessments that address areas of the COPV that are not included in the S-081B-2018 approach may need to state they are following the requirements in NASA-STD-5019A. The application of item 7.2.2.d(2)E requirements for testing assessments are included in item 7.2.2.d(4) discussions in this Handbook.

The topic of missions with "depot" intervals is not discussed in S081B-2018. If the "depot" mission service life were proposed as an alternative approach per section 10 in NASA-STD-5019A, the approach may need to tailor the S-080A-2018 service lifetime used for fracture control assessments. Tailoring of S-81B-2018 is permitted per section 2, Tailoring.

NASA-STD-5019A, Item 7.2.2.d(3)

Item 7.2.2.d(3) of NASA-STD-5019A states: "Autofrettage is included in the service life unless liner NDE is performed after autofrettage." S-081-2000 addresses autofrettage in section 5.2.1.1, Safe-Life Demonstration Testing Using Coupons. In this section, the testing spectrum is required to include all liner strains in sequence after the NDE inspection, including autofrettage if it occurs after the NDE inspection, which is in agreement with the item 7.2.2.d(3) requirement. The application of item 7.2.2.d(3) requirements for testing are included in item 7.2.2.d(4) discussions in this Handbook.

Note: If liner NDE is performed before autofrettage, a question arises: How are the autofrettage loading effects on manufacturing cracks to be assessed when it is included in the service life? It is a complex situation since the autofrettage exceeds the yield stress and that may violate the LEFM assumptions made by analytical predictions of crack growth. This situation is addressed by the item 7.2.2.d(4) requirement to perform the assessment of autofrettage by test.

S-081B-2018, section 4.2, Terms and Definitions under Service life, states; "The service life includes all manufacturing (including autofrettage, if one is performed) . . ." and includes NOTE 1 stating: "For damage tolerance assessment, the portion of the service life prior to screening (NDT) for pre-existing flaws may be excluded." Similarly, section 5.2.13.1, Damage Tolerance Life Design, states: "NOTE Autofrettage, if one is performed, is included in the service life for damage tolerance assessment, provided the autofrettage cycle occurs after NDT." S-081B-2018 is in agreement with item 7.2.2.d(3). The item 7.2.2.d(3) requirements for testing are included in item 7.2.2.d(4) discussions in this Handbook.

NASA-STD-5019A, Item 7.2.2.d(4)

Item 7.2.2.d(4) of NASA-STD-5019A specifies assessment of crack growth due to an autofrettage cycle is determined by test per S-081-2000, section 5.2.1, unless prior approval is provided by the RFCB for an analytical approach.

S-081-2000, Section 5.2.1, includes two sub-paragraph options. Section 5.2.1.1, Safe-Life Demonstration Testing Using Coupons, specifies testing using a surface crack with uniaxial coupons which meet validity requirements for a recognized standard and represent the materials, processes, and thickness of the liner. Section 5.2.1.2, Safe-Life Demonstration Using COPVs, states requirements for the test COPV to be representative of the flight COPV (liner materials and processing, liner thickness, COPV configuration and reinforcing composite stiffness), and requires surface cracks to be put in the liner "at pre-determined locations" and the COPV is to be pressurized according to the same spectrum and procedure in section 5.2.1.1. Both S-081-2000, section 5.2.1 options satisfy the item 7.2.2.d(4) requirement for the assessment to be performed by test as the usual procedure.

As noted in items 7.2.2.d(2)A and d(2)B discussions, the S-081-2000, section 5.2.1 test options do not satisfy items that are discussed in this Handbook, including item 7.2.2.d(2)A, which requires the flaw testing to be representation of the worst-case flaw location, shape, aspect ratio, and orientation, nor item 7.2.2.d(2)B, which imposes requirements the process for selecting the worst-case location, shape, aspect ratio, and orientation, should be based on liner stress/strain response and material strength and crack growth properties, and be documented in the analysis report. Also, testing has to address requirements imposed in item 7.2.2.d(2)C to include all regions of the liner and boss, including the shear region of the boss and any internal and external attachments in the assessment should also be addressed in the assessment testing. And, as required by item 7.2.2.d(2)D, test loading spectra has to include all loadings experienced during the service life, including those specified in section 7.3.1 in NASA-STD-5019A. And, per item 7.2.2.d(3), autofrettage should be included in the service life simulation testing.

With these above cited modifications, the S-081-2000, section 5.2.1 test options could satisfy items 7.2.2.d(2)A through d(2)E, d(3),and d(4) requirements and demonstrate that safe-life (i.e., damage tolerance life) requirements in NASA-STD-5019A are met for the entire mission service life.

Note: For an elastically responding liner, if autofrettage is performed before liner NDE, it raises a question as to the reliability of NDE to detect cracks, because cracks due to manufacturing processes may be affected by the autofrettage in complex manners. The autofrettage loading phase may cause additional crack growth and opening of the crack, while the autofrettage unloading phase may cause closure of the crack which may reduce the ability of NDE to detect cracks. Testing of the NDE capability is advised along with the determination of effects of autofrettage on crack growth that is required by item 7.2.2.d(4). Tight cracks could occur in plastically responding liners at any time in the spectrum and the capability of the NDE should be considered throughout the lifetime.

No test procedure was found in searches of S-081B-2018 for "autofrettage" in an attempt to determine how that standard assesses the amount of crack growth related to an autofrettage cycle for an elastically responding COPV. Test methods described in the standard using COPVs or coupons could be used to quantify the crack growth associated with autofrettage, or analysis could be used to quantify crack growth for an elastically responding liner. Section 7.5.1 allows a separate analysis using Elastic Plastic Fracture Mechanics with supporting data and describes the analysis in an example. Details in that section's fourth paragraph are non-conservative, namely the statement: "for analysis of the autofrettage cycle. . . the analysis factor of four may be waived provided conservative crack growth properties and methodology are used in the determination of crack growth for autofrettage." The factor of four is a requirement in NASA-STD-5019A and cannot be "waived." The section also states: "The data used for the [elastic-plastic fracture mechanics] EPFM analysis shall conservatively represent the material alloy, condition, thickness, and autofrettage cycle as validated through testing." This statement is not enough to satisfy the item 7.2.2.d(4) requirement to actually test to determine the amount of crack growth in an autofrettage loading.

In summary, S-081B-2018 does not have a requirement to conduct a test that quantifies the amount of crack growth for autofrettage as is required in item 7.2.2.d(4). S-081B-2018 does not satisfy the item 7.2.2.d(4) requirement. An assessment of a COPV liner would need to perform testing as specified in S-081-2000 as described above and in items 7.2.2.d(2)A through d(2)E, d(3), and d(4) to satisfy the requirements in NASA-STD-5019A. If the S-081B-2018 analytical procedure were to be used, prior approval would be needed from the RFCB for the analytical procedure, and it would need to include the factor of four on crack growth predicted for autofrettage.

NASA-STD-5019A, Item 7.2.2.e

Item 7.2.2.e of NASA-STD-5019A applies six modifications to S-081-2000, section 4.2.7 requirements if assessment of a COPV built to that standard uses analysis to demonstrate damage tolerance requirements are satisfied.

The six-item 7.2.2.e modifications are also discussed if the pressure vessel is built to the S-081B-2018 standard.

NASA-STD-5019A, Item 7.2.2.e(1)

Item 7.2.2.e(1) of NASA-STD-5019A specifies before an S-081-2000 assessment is begun, pre-approval from the RFCB has to be obtained for all crack growth computer analysis programs other than NASGRO®.

S-081B-2018, section 7.5.1 on Damage Tolerance Life Analysis, states: "The analysis may be performed using a crack growth software package." Assessments of pressure vessels built to S-081B-2018 will need to utilize the NASGRO® program or obtain pre-approval from the RFCB if other crack growth computer analysis programs are to be used.

NASA-STD-5019A, Item 7.2.2.e(2)

Item 7.2.2.e(2) of NASA-STD-5019A requires a determination whether damage tolerance analysis assessments can or cannot simulate crack growth in the COPV liner. If analyses based on LEFM are invalidated by plasticity or other effects, the damage tolerance assessment has to be performed by test.

S-081-2000, section 4.2.7, Safe-Life Requirements, states: "for plastically responding regions of metallic liners, testing is the only acceptable method to demonstrate safe-life" and "the test requirements of section 5.1 shall apply." The section reference appears to be in error and should be 5.2.1. with options 5.2.1.1, Safe-Life Demonstration Testing Using Coupons, and 5.2.1.2, Safe-Live Demonstration Using COPVs. Item 7.2.2.d(4) has discussion on testing assessments, which are required by item 7.2.2.e(2) when analyses based on LEFM are invalidated by plasticity or other effects.

Examples where analyses based on LEFM may not simulate crack growth include when crack tip plasticity results in loss of constraint of the crack tip ligament. This could occur due to the magnitude of applied loadings and/or approach of the crack tip to a boundary such as the back face of a surface crack. Another example when LEFM assumptions are not valid could be if the material grain size is large relative to the crack or crack-tip ligament, such that discrete grain sizes and stresses dominate the conditions at the crack tip. In this situation, LEFM predictions that are presumed to have a continuum material response are not relevant. Another example could occur if material fracture and/or crack growth properties vary greatly from one local crack tip region to another, so that material models are not representative of crack locations that contain the worst-case crack.

S-081B-2018, section 6.2.1, addresses the purpose of item 7.2.2.e(2) requirements. It requires the damage tolerance life to be verified either by analysis or test, and "the damage tolerance life requirement may be verified by analysis only if both of the following conditions are met:

1. The liner (or region of the liner) is shown to be elastically responding and characterized by linear elastic fracture mechanics (LEFM).

2. The fracture properties of the pressurized hardware are determined in accordance with Section 7.1."

The term "elastically responding" relates to whether the metallic liner or regions of the liner experience plastic deformation after autofrettage during the vessel lifetime that exceed the local yield strength. Situations that do not satisfy the requirements in S-081B-2018, section 6.2.1, for assessment by analysis should be assessed by testing per the requirements in S-081B-2018, sections 10.1, 10.1.1, or 10.1.2, provided the S-081B-2018 sections are relevant. For example, as discussed in item 7.2.2.d(4), S-081B-2018 does not have a test approach for assessment of crack growth due to autofrettage.

NASA-STD-5019A, Item 7.2.2.e(3)

Item 7.2.2.e(3) of NASA-STD-5019A is a specific requirement imposed on use of the NASGRO® program due to particular aspects of that program. It states if NASGRO® is used, either set Bk to zero, or set Bk such that the stress intensity factor for the part thickness is less than or equal to the critical stress intensity value with approval of the delegated Technical Authority or the RFCB. The reason for this situation and the requirement is that Bk is a fitting parameter to a data set that may not conservatively represent the variation of fracture toughness of the pressure vessel material with thickness.

This requirement is not addressed in either S-081-2000 nor S-081B-2018, which are general standards that do not specify the analysis program to be used. The item 7.2.2.e(3) requirement is imposed on both S-081-2000 and S-081B-2018. Note that section 7.2.2.e(1) would also be applicable if the assessment did not use the NASGRO® program.

NASA-STD-5019A, Item 7.2.2.e(4)

Item 7.2.2.e(4) of NASA-STD-5019A is a broader statement of the requirement to demonstrate a safety factor of 4 on the damage tolerance life without failure (hazardous leak or fracture instability) by analyses that assess all applicable effects causing crack growth as a result of cyclic loadings. This applies in general and also to items 7.2.2.e(4)A, e(4)B, e(4)Bi but not e(4)Bii which has unique requirements. Portions of this requirement are already imposed by item 7.2.2.d(2)E as discussed in this Handbook for both S-081-2000 and S-081B-2018. Note also that item 7.2.2.d(2)D specifies assessments are to include all loadings experienced during the service life, including those specified in NASA-STD-5019A, section 7.3.1, which includes both cyclic and sustained loadings.

Items 7.2.2.e(4)A, e(4)B, e(4)Bi, and e(4)Bii of NASA-STD-5019A impose unique requirements on damage tolerance assessments that are in addition to those in items 7.2.2.d(2)A through d(2)E. Their purpose is to ensure damage tolerant parts are likely to survive the required number of service lifetimes without failure due to a hazardous leak or a fracture instability for the special situations described in these requirements. The service life spectrums and the critical stress intensity or residual strengths referenced in these items are the critical ones resulting from damage tolerance assessments that satisfy the requirements specified in items 7.2.2.d(2), d(2)A through d(2)E, d(3), and d(4).

Neither S-081-2000 or S-081B-2018 address the requirements in items 7.2.2.e(4)A, e(4)Bi, and e(4)Bii. These requirements should be applied to analysis assessments of COPVs built to either S-081-2000 or S-081B-2018.

Also, note that either of the EAC or SLC requirements imposed in item 7.2.2.e(6) may be the controlling (i.e., smallest) material damage tolerance quantity that should not be exceeded by the applied cyclic and sustained loadings to avoid failures when performing the damage tolerance assessments imposed by items 7.2.2.e(4), e(4)A, e(4)B, e(4)Bi, and e(4)Bii. This possibility is flagged by the guidance in NASA-STD-5019A that follows item 7.2.2.e(4). The guidance is applicable to all analysis assessments.

The following guidance refers readers to requirements in item 7.2.2.e(6):

> *"Assessments of metallic alloys that are susceptible to crack growth related to SLC or EAC during the service life are addressed in item (6) below."*

NASA-STD-5019A, Item 7.2.2.e(4)A

Item 7.2.2.e(4)A of NASA-STD-5019A specifies an approach to ensure the damage tolerant life assessment result will be conservative when loading sequences are unknown. If the sequence of high/low loads is a well-defined sequence for the lifetime of the part, the last cycle of the loading spectrum may be used to assess fracture. If the loading spectrum sequence of high/low loads is variable or unknown, this section requires use of the loading spectrum limit load to assess fracture. The crack size used is the final size after four lifetimes of crack growth. A conservative approach is to always use the limit load to assess fracture of the final crack size. The fracture strength may be computed using the critical stress intensity factor when LEFM is applicable. If LEFM is not applicable, item 7.2.2.e(2) requires the residual strength to be determined from tests, which would be using cracked specimen that simulate the final crack size fracture condition.

NASA-STD-5019A, Item 7.2.2.e(4)B

Item 7.2.2.e(4)B of NASA-STD-5019A addresses conditions where the service lifetime is a single event or the fatigue crack growth is small relative to the critical crack size for fracture. This is a relative statement. Since no bounds specify when item 7.2.2.e(4)B does or does not apply, item 7.2.2.e(4)B situations should be evaluated when performing fracture control assessments, especially those with small increases of the initial crack size at the end of four lifetimes.

The item 7.2.2.e(4)B requirement is to establish that either item 7.2.2.e(4)Bi or e(4)Bii is satisfied. When LEFM is applicable, the test data can be standard fracture toughness test data. If LEFM is not applicable, item 7.2.2.e(2) requires tests to determine residual strength. Also, per the requirements in items 7.2.2.d(2)A through d(2)E as discussed in this Handbook, if the fracture properties vary in different regions of the liner, fracture toughness data will be needed for each characteristic region.

NASA-STD-5019A, Item 7.2.2.e(4)Bi

Item 7.2.2.e(4)Bi of NASA-STD-5019A requires the fracture assessment to show fracture does not occur for the following condition. The fracture assessment should compute the final crack size for an initial crack size increased by 4 lifetimes of crack growth. As noted in item 7.2.2.e(4)A, if the loading spectrum sequence of high/low loads is variable or unknown, a conservative approach should be used by applying the limit loading experienced during the lifetime to the final crack size to predict critical stress intensity or residual strength after 4 lifetimes. This fracture condition is referred to as the item 7.2.2.e(4)Bi critical fracture value. The item 7.2.2.e(4)Bi requirement is to show the e(4)Bi critical fracture value is less than or equal to the lower bound critical stress intensity factor or residual strength of fracture data described in item 7.2.2.e(4)B. Notice that item 7.2.2.e(4)Bi is comparing to a lower bound critical stress intensity factor or residual strength, which is less than the criteria imposed in item 7.2.2.e(5).

NOTE on lower bounds: A lower bound value should be based upon a sufficient number of specimen tests to sample the amount of scatter in the fracture property. Comparison of the lower bound to all test data should show that scatter of the fracture data does not, and likely will not, result in a smaller critical fracture value. For a normal statistical distribution, the "Empirical Rule" states 95% of the data will fall within two standard deviations, and 99.7% of the data will fall within three standard deviations. A value defined by the mean less two standard deviations will be close to a lower bound, while a value determined by the mean less three standard deviations will ensure a lower bound is obtained—provided there are enough data for this statistics rule to be meaningful. Statistical analysis of test data as it is accumulated for additional samples may assist in identifying if a lower bound value has been obtained.

NASA-STD-5019A, Item 7.2.2.e(4)Bii

Item 7.2.2.e(4)Bii of NASA-STD-5019A requires the fracture assessment to show that fracture does not occur for the following conditions. The initial crack size is increased by 1 lifetime of crack growth to the predicted final crack size. (Note: One (1) lifetime is a unique requirement that is only applicable for this item 7.2.2.e(4)Bii assessment conditions.) Per item 7.2.2.e(4)A, if the loading spectrum sequence of high/low loads is variable or unknown, a conservative approach should be used by applying the limit loading experienced during the lifetime to the final crack size to predict critical stress intensity or residual strength after 1 lifetime. This value is multiplied by a factor of 1.4 to compute the item 7.2.2.e(4)Bii value of critical stress intensity factor or residual strength. This e(4)Bii value should satisfy item 7.2.2.e(5), meaning it should be less than or equal to the average value of the material critical stress intensity factor or residual strength.

NASA-STD-5019A, Item 7.2.2.e(5)

Item 7.2.2.e(5) of NASA-STD-5019A imposes the requirement in item 7.3.2.e on S-081-2000 to use damage tolerance critical stress intensity factor and cyclic threshold (ΔK_{th}) that are "less than or equal to the average values."

Item 7.2.2.c(2) of NASA-STD-5019A already replaced the word "nominal" with "average" in both S-081-2000, sections 3 and 4.2.6, and in referenced S080-1998, sections 4.2.6, 4.2.7, and 4.3.3. A note was placed in item 7.2.2.c(2) pointing to additional modifications of other terms as specified in items e(5), e(6), e(6)A, and e(6)B.

Item 7.2.2.e(5) further modifies S-081-2000 sections that reference critical stress intensity factor, residual strength, or cyclic threshold stress intensity range (ΔK_{th}). No references to these were found, because S-081-2000 refers to S-080-1998 for liner analyses that use these data. Accordingly, item 7.2.2.e(5) further modifies S-080-1998, sections 4.2.7 and 4.3.3, to impose criteria that both critical stress intensity factor (or residual strength if that is the pertinent fracture quantity) and cyclic threshold stress intensity range (ΔK_{th}) material values are to be less than or equal to the average values. This is also discussed in section 7.2.1.e(5) in this Handbook.

Observe that items 7.2.2.e(4)Bi, e(6) , e(6)A, and e(6)B are not affected, as they are unique in that they impose lower bound criteria to avoid the failure conditions addressed in those items. Also, item 7.2.2.e(4)Bi has a "NOTE on lower bounds" that discusses the number of tests and relevant statistics when determining lower bound values.

Item 7.2.2.e(5) also modifies S-081B-2018 material critical stress intensity factor data, and cyclic threshold stress intensity range (ΔK_{th}) data that are used for assessments. Item 7.2.2.e(5) changes these material data to be less than or equal to average values of the data. The affected sections in S-081B-2018 are:

- Section "7.1 2)" which uses the following terms: "plane strain fracture toughness," K_{IC}, "surface-crack fracture toughness," K_{IE}, and "fatigue crack growth rates da/dN, dc/dN."

  (Note the "fatigue crack growth rates, da/dN, dc/dN" will either include cyclic threshold stress intensity range, $\Delta K_{th,}$ in representative equation form or as data points in the crack growth rate data, and item 7.2.2.e(5) modifies these values to be "less than or equal to average values of the data.")

- Section 7.5.1 refers to" fracture toughness," "fatigue crack growth rate data," da/dN, "surface or embedded crack fracture toughness," and "crack extension resistance," K_R, which again are modified by item 7.2.2.e(5) to be "less than or equal to the average values."

These modifications are shown below in proposed modified sections of S-081B-2018 that implement the requirements imposed by items 7.2.2.e(5), e(6), e(6)A, and e(6)B.

NASA-STD-5019A, Items 7.2.2.e(6), e(6)A, e(6)B

The following acronyms and definitions in NASA-STD-5019A are relevant to the requirements imposed in items 7.2.2.e(6), e(6)A, and e(6)B: Section 3.1, Acronyms, Abbreviations, and Symbols: EAC, K_{EAC}, K_{IEAC} K_{ISCC}, SLC and K_{SLC}; and section 3.2, Definitions: EAC, $K_{EAC,}$ K_{ISCC}, K_{IEAC}, and SLC.

The reader is referred to section 3.2, Definitions, and the footnotes for EAC and SLC. Citations of the two references in the EAC and SLC definitions are given in Appendix B.4 in NASA-STD-5019A and are recommended for background study of EAC and SLC.

NOTE on EAC and SLC testing: Specialized testing is needed to determine the material data to satisfy the EAC and SLC requirements in items 7.2.2.e(6), e(6)A, and e(6)B if no data exist. Testing of specimen representative of the material, environment (including exposures to all fluids), and maximum applied stress intensity factor is needed. EAC testing is specified in ASTM E1681. For SLC, as noted in the definition of SLC in NASA-STD-5019A, "A threshold stress intensity factor can be obtained by procedures such as those in ASTM E1681 for the case of an inert or vacuum environment."

Items 7.2.2.e(6) and e(6)A of NASA-STD-5019A impose requirements on metallic alloys susceptible to EAC or SLC or both, that require assessments to use a lower bound value of stress intensity factor threshold of EAC and SLC if the material exhibits these behaviors in the application conditions. Item 7.2.2.e(6)B of NASA-STD-5019A requires assessments to show the applied stress intensity factors for the largest service loading is smaller than the lower bound stress intensity factor thresholds of EAC and SLC behavior at the end of 4 lifetimes. Item 7.2.2.e(4)Bi has a "NOTE on lower bounds" that discusses the number of tests and relevant statistics when determining lower bound values.

S-081-2000, section 3, Vocabulary, describes stress-corrosion cracking as a mechanical-environmental-induced failure process in that sustained tensile stress and chemical attack combine to initiate and propagate a crack in a metal part. S-081-2000, section 5.2.1.3: "Sustained Load Crack Growth Demonstration of Safe-Life" describes liner material coupon testing if data do not exist. The testing is "for all fluids that are introduced into the COPV under pressure." The coupon is required not to show evidence of sustained load crack growth on post-test examination of the crack surfaces after a minimum of 1000 hours of exposure at the fluid pressure strain. This phenomenon is called "EAC" in NASA-STD-5019A. The S-081-2000 requirements address items 7.2.2.e(6), e(6)A, and e(6)B requirements for EAC provided 4 lifetimes is less than 1000 hours, AND the lower bound data for K_{EAC} are not exceeded. If 4 lifetimes are greater than 1000 hours, the S-081-2000 testing is not adequate. Searches of S-081-2000 did not find any requirements for assessments for SLC. Damage tolerance assessments for COPVs built per S-081-2000 should satisfy items 7.2.2.e(6), e(6)A, and e(6)B requirements by citing test data representative of the metal liner material and stresses, for all fluid exposures and SLC conditions, that demonstrate the items 7.2.2.e(6), e(6)A, and e(6)B EAC and SLC requirements are satisfied.

S-081-2000, section 4.2.7, Safe-Life Requirements, states: "For elastically responding metallic liners and integral bosses, and for elastically responding regions of a generally plastic responding liner, the safe-life requirements of ANSI/AIAA S-080, Section 4.2.7 shall apply." Discussion of requirements per items 7.2.2.e(6), e(6)A, and e(6)B for S-080-1998 is in section 7.2.1, items 7.2.2.e(6), e(6)A, and e(6)B and will not be repeated in this section.

S-081B-2018, section 4.2, Terms and Definitions, defines sustained load crack growth as "growth of a pre-existing crack in susceptible metallic alloys under sustained stress, without assistance from an external environment." Section 4.2 also defines stress-corrosion cracking as "a mechanical-environmental-induced failure process in which sustained tensile stress and chemical attack combine to initiate and propagate a crack or a crack-like flaw." These definitions are the same as SLC and EAC in NASA-STD-5019A.

Regarding SLC requirements, section 5.2.13.1, Damage Tolerance Life Design, states: "The region(s) of the COPV to which damage tolerance life is applied shall be designed such that it possesses a minimum damage tolerance life of four (4) times the service life without sustained load crack growth . . .." Section 10.1.1, Damage Tolerance Life Test—Coupon Specimens, requires examination of the fracture surfaces produced during the testing "to identify if sustained load crack growth occurred during testing" and requires the testing to confirm no sustained load crack growth occurred during the test. There is also a note stating: "For some materials, it is difficult to differentiate between stable crack extension and sustained load crack growth" which casts doubt as to the reliability of relying on examination of the fracture surface. The same statements appear in section 10.1.2, Damage Tolerance Life Test—COPV specimens.

Regarding EAC requirements, the term appears in section 7.1, Metallic Material Properties, in item 2) as a material property that is required to be "either A-basis or nominal values" which does not satisfy requirements in items 7.2.2.e(6), e(6)A, and e(6)B to be a lower bound value. Section 7.5.1, Damage Tolerance Life Analysis, requires: "At all times in the service life, the applied stress intensity factor shall be less than the surface or embedded crack fracture toughness . . . and K_{IEAC} for the applicable environment (such as hydrogen embrittlement)." This imposes an EAC requirement, but it does not satisfy items 7.2.2.e(6), e(6)A, and e(6)B because the value is not specified to be lower bound, and the term "service life" should be "damage tolerance life," which is specified to be 4 times the service life in section 5.2.13.1. Also, section 10.1, Damage Tolerance Life Test, states: "The effects of service environment (e.g., temperature, humidity, fluids) shall be accounted for either by representative testing or by analytical rationale." The wording "or by analytical rationale" does not satisfy item 7.2.2.e(6) that requires lower bound values of EAC and SLC that are obtained by tests.

In summary, the S081B-2018 requirements to prevent failures due to SLC and EAC are not in agreement with the requirements in items 7.2.2.e(6), e(6)A, and e(6)B.

A question may arise as to how S081B-2018 could be modified so that it satisfies the requirements in NASA-STD-5019A. The sections of S081B-2018 that are cited above are similar to the sections of S-080A-2018 that are discussed in items 7.2.1.e(6), e(6)A, and e(6)B in this Handbook. That discussion also includes proposed revisions of S-080A-2018 sections to bring them into compliance with requirements in NASA-STD-5019A. The proposed revisions also help clarify the issues. The proposed revisions of S-080A-2018 could also be applied to guide revisions of S081B-2018.

NASA-STD-5019A, Item 7.2.2.f

Item 7.2.2.f of NASA-STD-5019A addresses proof testing. It requires the test duration to be minimized and also to verify the pressure is stable, because unexpected changing pressure could indicate a failure in progress.

S-081-2000, section 5.1.2, has a requirement: ". . . the duration of the proof test shall be sufficient to verify pressure stability." To also comply with the item 7.2.2.f requirement to minimize the duration of the proof test, test measurements to ensure the vessel does not leak or lose pressure should be completed rapidly during the time when pressure is maintained.

S-081B-2018, section 10.4.6, Proof Test, requirement states: ". . . the duration of the proof test hold shall be sufficient to verify pressure stability." The pressure test will also need to minimize the duration of the test.

NASA-STD-5019A, Item 7.2.2.g

Item 7.2.2.g of NASA-STD-5019A imposes requirements on assessments of COPVs built to S-081-2000 when the section 5.2.1 option to show damage tolerance life of the non-linear response of the metal liner is to be performed by test.

Item 7.2.2.g imposes the same requirements on COPVs built to S-081B-2018.

NASA-STD-5019A, Items 7.2.2.g(1), g(1)A, g(1)B

Items 7.2.2.g(1), g(1)A, and g(1)B of NASA-STD-5019A apply to COPVs built to either S-081-2000 or S-081B-2018. These items require the testing approach and rationale to be documented in the FCP and receive RFCB approval before implementation.

The testing approach should describe the proposed testing in sufficient detail to demonstrate it addresses all the aspects discussed in item 7.2.2.g(2). Planned test details should be provided such as whether test specimen will replicate some or all of the COPVs conditions, including material characteristics, loading and stress states, loading spectrum, initial crack configurations, and effects of environments.

Include a description of the information to be obtained from the tests and how it will be used to demonstrate requirements have been satisfied by the testing. This provides an opportunity for the RFCB to comment on their evaluation as to whether the plans will address NASA-STD-5019A requirements.

NASA-STD-5019A, Item 7.2.2.g(2)

Item 7.2.2.g(2) of NASA-STD-5019A states the testing is to demonstrate the hardware meets the damage tolerance lifetime and failure condition requirements in S-081-2000 "as modified in the NASA Technical Standard" for initial flaws in the worst location, aspect ratio, and orientation in conditions that represent the service environments. The testing should address all aspects imposed in section 7.2.2 in NASA-STD-5019A which affect testing and application of the data to COPVs, including items 7.2.2.d(2)A through d(2)E, d(3), and d(4). Discuss how the testing will conservatively bound the situations addressed by analysis in items 7.2.2.e(4), e(4)A, e(4)Bi, and e(4)Bii. Discuss how the risk of failure due to EAC or SLC will be addressed by existing data if available or by tests to determine the lower bound values of thresholds for K_{EAC} and K_{SLC} as discussed in items 7.2.2.e(6), e(6)A, and e(6)B in this Handbook. These aspects are supplemented by the testing requirements in section 7.3.3 in NASA-STD-5019A, such as items 7.2.2.c, d, e, and f. The guidance at the end of section 7.3.3 is also helpful.

The above discussion is also applicable if the COPV is built per S-080A-2018, because the discussion is describing the requirements imposed by items 7.2.2.g and g(2) in NASA-STD-5019A, not aspects of S-081-2000.

NASA-STD-5019A, Item 7.2.2.g(3)

Item 7.2.2.g(3) of NASA-STD-5019A specifies the testing activities are to be described in reports showing the objectives have been achieved and are documented in accordance with section 9.1 and cited in the FCSR per requirements in NASA-STD-5019A as discussed in this Handbook.

NASA-STD-5019A, Items 7.2.2.h, h(1), h(2)

Items 7.2.2.h, h(1), and h(2) of NASA-STD-5019A impose requirements for use of protective covers to mitigate risks of impact damage to the COPV.

Items 7.2.2.h and h(1) in NASA-STD-5019A impose protective covers for COPVs. These items nullify the S-081-2000, section 4.2.10 statements that damage controls are not required for COPVs with burst strength and thickness criteria stated in section 4.2.10. They also nullify the exemptions in section 4.2.10.2 based on COPV stored energy and the hazardous or nonhazardous nature of the COPV fluid.

The protective covers are required in section 4.2.10.2.1 specifications to completely protect the COPV under the worst credible threats defined per section 4.2.10.1, Damage Control Plan. This Plan is required to delineate all potentially damaging events and document the conditions (source and magnitude of threat and state of pressurization of the COPV). Section 4.2.10.2.1 also requires the effectiveness of the protector covers to be demonstrated by tests. The covers are specified to allow transmission of less than 6.8 J (5 ft-lbf) energy or reduce the transmitted energy to less than one half of the energy that has been demonstrated to be an acceptable level by damage tolerance or residual strength testing of pressurized specimen.

Item 7.2.2.h(2) requires additional damage controls if the COPV service life has occurrences where the initially required covers are not present but the COPV is exposed to risk of damage during any remaining parts of the service life. The additional damage controls are to be selected from the options in section 4.2.10 listed below. Each option has additional requirements stated in the identified section:

- Section 4.2.10.2.1 – protective covers (these could be different from the initial covers according to the specific damage threats identified in the Damage Control Plan for the phase in the service life when these covers would be used).
- Section 4.2.10.2.2 – indicators, which may be used when protective covers are not used, or they may be placed between the protective cover and the COPV. Their purpose is to give positive evidence of a mechanical damage event that is greater than or equal to the demonstrated damage tolerance or residual strength capability of the unprotected COPV. (If the indicator shows a damage event occurred, it will mean the COPV has been exposed to damage exceeding the damage tolerance or residual strength of the COPV.)
- Section 4.2.10.3 – mechanical damage tolerance demonstration the COPV has sufficient damage tolerance or residual strength to survive the worst-case events identified in the Damage Control Plan and the remaining damage tolerance service life loadings and environments without failure. There are two types of demonstration options: section 4.2.10.3.1 describes impact damage tolerance testing, and section 4.3.10.3.2 describes mechanical damage tolerance assessments.

The guidance following item 7.2.2.h provides additional explanation of the basis for the content of item 7.2.2.h(2):

> *The additional damage controls referenced in item h.2 above may be needed if protective covers are removed before launch and the vessel has risk of damage during the remainder of its service life or if there are different risks to the vessel during its service life because of environments or service loadings that also need to be addressed by damage controls. All options, separately or in combination, may be used, including specialized covers for flight conditions.*

S-081B-2018 automatically satisfies items 7.2.2.h and h(1) because it does not have conditions like those in S-081-2000 when protective covers are not required. In S-081B-2018, section 5.3, Damage Control Plan, describes the required development of a damage control plan (DCP) to identify and mitigate credible sources of mechanical and other forms of damage to the COPV during manufacturing and throughout the service life. The section states the DCP shall include the use of protective covers and may include additional protections such as damage indicators. The DCP is required to list mitigations to credible sources of damage to the COPV, and the mitigations are to be incorporated into work instructions and assembly procedures. The last sentence in this section states: "The DCP shall also specifically address any close proximity operations that could potentially damage the COPV after the close-out visual inspection has been performed." This statement raises the possibility of damage risks that are not addressed by the

DCP. Item 7.2.2.h(2) requires these situations to be identified and "additional damage controls" are to be imposed. Subsequent sections in S-081B-2018 appear to address these concerns. For example, section 5.1.15, Mechanical Damage Environment, requires the mechanical damage environment to be analyzed to determine credible sources of mechanical damage to the COPV throughout manufacturing and the service life. Section 7.4.14, Damage Control Plan Analysis, states the analysis shall show that the DCP will mitigate credible threats identified in the mechanical damage environment. In passing, it is noted the effectiveness of the damage controls are evaluated in the following S-081B-2018 sections: 10.3, Damage Control Test; 10.3.1, Worst-case threat damage tolerance life testing; 10.3.2, Visual mechanical damage threshold testing; and 10.3.4, Damage indicator testing." In summary, the requirements in S-081B-2018 address items 7.2.2.h, h(1), and h(2).

NASA-STD-5019A, Section 7.2.2.i, i(1), i(2)

Item 7.2.2.i of NASA-STD-5019A is applicable if the composite overwrap is constrained by external structure or if it is part of a load path supporting the COPV for loads other than pressure loads, such as launch or landing loads. Item 7.2.2.i requirements are not relevant if the cited situation does not exist. If the cited situation does exist, item 7.2.2.i requirements are imposed whether the applicable standard is S-081-2000 or S-081B-2018, as neither of these standards addresses all the item 7.2.2.i aspects.

Item 7.2.2.i(1) of NASA-STD-5019A requires structural analysis of the composite overwrap that assesses the potential for displacements or forces induced into the overwrap to cause damage of the overwrap. Item 7.2.2.i(1) also requires the structural assessment to be validated by testing. The testing is to demonstrate structural predictions of loadings and displacements affecting the composite overwrap are accurate or conservative. Item 7.2.2.i(1) requires the composite overwrap resulting conditions to meet all strength, fatigue, and life requirements in the applicable standard.

Item 7.2.2.i(2) of NASA-STD-5019A requires the assessment described in item 7.2.2.(1) to include effects of damage risks to which the composite overwrap is exposed that are not screened by protections imposed by other requirements. The other requirements are relevant ones in the applicable standard, and items h, h(1), and h(2) in NASA-STD-5019A as discussed in this Handbook.

NASA-STD-5019A, Item 7.2.2.j

Item 7.2.2.j of NASA-STD-5019A addresses vessels with crack-like flaws in the metal liner that are "induced during the manufacturing process" and states they "are not accepted as flight hardware unless a process for remediation repair has been established and the delegated Technical Authority approves the part and process." The delegated Technical Authority is described in section 1.3 in NASA-STD-5019A.

S-081-2000, section 4.6.4, specifies repair and refurbishment requirements "when inspections reveal structural damage or defects exceeding the permissible levels. It requires the damaged hardware to be repaired, refurbished, or replaced, as appropriate. Also, it requires all repaired or refurbished hardware to be re-certified by the applicable acceptance test procedure for new hardware to verify the part for use and its structural integrity. Additionally, item 7.2.2.j requires the process to have been established, and both the process and the refurbished part to be approved by the delegated Technical Authority described in section 1.3 in NASA-STD-5019A.

S-081B-2018 has sections that address item 7.2.2.j requirements. S-081B-2018, section 11.7, Repair and Refurbishment, states: "If repair or refurbishment is allowed by the procuring authority, then any repaired or refurbished COPV shall be re-certified after each repair or refurbishment to verify its structural integrity and suitability for service." It also states: "A repair protocol is developed which is to be approved in accordance with the applicable QA plan." Section 11.6 states: "A material review board (MRB) or other process shall be established to assess and disposition deviations, variances from standard procedures, and nonconformance condition." Section 11.6 also states: "The MRB shall be used to disposition identified issues and to authorize all corrective actions." In addition to the aspects cited above in S-081B-2018, item 7.2.2.j requires the delegated Technical Authority to approve both the part (i.e., the flight COPV) and the process used for repair.

Guidance in NASA-STD-5019A after item 7.2.2.j that is applicable to both standards states:

> *"Refer to section 8.1.5 in this NASA Technical Standard for further requirements and guidance."*

NASA-STD-5019A, Item 7.2.2.k

Item 7.2.2.k of NASA-STD-5019A addresses repair of COPVs that experience damage in regions that are not part of the metal liner. An example could be damage in the composite overwrap. Item 7.2.2.k states the COPV damage may be repaired provided an established process is available that has been approved by the delegated Technical Authority. Ideally, the process for likely types of damage would have been developed in advance, include quality assurance monitoring of the repair process, and have examples of repairs that were shown by tests to satisfy relevant performance requirements.

Item 7.2.2.j cited sections of S-081-2000 and S-081B-2018 are also applicable to item 7.2.2.k.

Guidance in NASA-STD-5019A after item 7.2.2.k that is applicable to both standards states:

> *"Refer to section 8.1.5 of this NASA Technical Standard for further requirements and guidance. This pertains to the repair of small manufacturing or cosmetic defects in the composite. There are no acceptable established processes for repairing impact damage to the composite overwrap. Accidental impacts that do not leave obvious visible damage indications are to be logged, the impact site assessed by qualified inspectors, and the hardware approved for use by the delegated Technical Authority."*

NASA-STD-5019A, Section 7.2.2.l

Section 7.2.2.l of NASA-STD-5019A imposes two aspects: (1) it supplements the quality assurance requirements in S-081-2000, section 4.5 (and its subsections) with the requirements in section 8 and its subsections in NASA-STD-5019A; and (2) this item states the requirements in NASA-STD-5019A take precedence if there is a conflict for quality assurance with the S-081-2000 requirements.

Section 7.2.2.l also applies to and takes precedence over quality assurance sections in S-081B-2018. Quality assurance in S-081B-2018 are specified in a distributed documentation structure. Quality assurance is treated at a high level in section 9 (and its subsections), which points to related technical and detailed topics in sections under other headings, which may or may not go into technical details. For example, the ITP has high-level requirements in section 9.5, the NDT sensitivity for damage tolerance life is specified in section 5.2.13.1, and points to section 10.4.2 for NDE technique, which only has high-level statements. In a flight hardware assessment, additional details would be required on the sensitivity of the NDE technique and the basis establishing that sensitivity.

NASA-STD-5019A, Items 7.2.2.m, m(1), m(2), and m(3)

Item 7.2.2.m of NASA-STD-5019A modifies S-080A-2000 requirements for fracture critical part documentation and reporting with requirement items 7.2.2.m(1), m(2), and m(3).

Item 7.2.2.m(1) of NASA-STD-5019A supplements the S-081-2000 requirements for fracture critical part documentation and reporting with the requirements in section 9 and its subsections of NASA-STD-5019A.

Item 7.2.2.m(2) of NASA-STD-5019A states if there is a conflict, the S-081-2000 requirements for documentation and reporting are superseded by NASA-STD-5019A requirements in section 9 and its subsections.

Item 7.2.2.m(3) of NASA-STD-5019A identifies documentation described in S-081-2000 that is to be included as part of the FCSR, namely the section 4.2.5 stress report, the section 4.2.7 damage tolerance analysis report, and the Mechanical Damage Control Plan (MDCP).

Guidance after section 7.2.2.m in NASA-STD-5019A states:

> *"The entity responsible for delivery of the MDCP (NASA, prime contractor, or other subcontractors) determines who develops the MDCP, which is subject to RFCB approval."*

S-081B-2018 content and organization have changed dramatically from S-081-2000. Items 7.2.2.m(1) and m(2) impose section 9 (and its subsections) as both supplementary and superseding requirements on the S-081B-2018 sections that document fracture critical part tests, assessments, and reporting. S-081B-2018 has a distributed documentation structure that includes the following:

- Section 9.5 describes the ITP, which is the master plan for all manufacturing quality control,
- Section 9.6 describes the inspector (composite overwrap) qualification, which specifies a qualified inspector's skill requirements,
- Section 9.7 describes qualification reporting documenting verification of compliance with all design requirements by analysis and test,
- Section 10.3 describes the Damage Control Plan that is to mitigate credible sources of mechanical and other forms of damage to the COPV during manufacturing and throughout the service life as verified by test,
- Section 11.9 describes operations documentation consisting of all inspection records, verification test and analysis results, transportation and handling records, vehicle integration processing data, and test and operation data, and
- Section 12 lists relevant documents.

Item 7.2.2.m(3) of NASA-STD-5019A specifies fracture control documents to be included in the FCSR as the S-081-2000 stress analysis report and damage tolerant analysis reports. Equivalent information documents produced as required in S-081B-2018 are needed in the FCSR. The documents may include any of the many analyses, damage tolerance, and qualification reports listed in S-081B-2018, sections 7, 9, 10, 11, and 12. The RFCB may be consulted to confirm which documents are to be provided in the FCSR.

7.2.3 Other Fracture Critical Pressure Vessels and Pressurized Fluid Containers (NASA-STD-5019A, Section 7.2.3)

NASA-STD-5019A:
7.2.3 Other Fracture Critical Pressure Vessels and Pressurized Fluid Containers

Satisfy the following for all other fracture critical pressure vessels and pressurized fluid containers that are not addressed in either section 7.2.1 or 7.2.2 in this NASA Technical Standard to satisfy requirement [FCR 11] 7.2.c in this NASA Technical Standard:

a. Document the proposed approach in the FCP in accordance with section 4.1 [FCR 1] in this NASA Technical Standard and include the following:

(1) A rationale for using a metallic pressure vessel, COPV, or composite overwrapped pressurized fluid container instead of one of the following:

A. An all-metal pressure vessel that meets the requirements of section 7.2.1 in this NASA Technical Standard, or

B. A COPV or composite overwrapped pressurized fluid container that meets the requirements of section 7.2.2 in this NASA Technical Standard.

(2) Describe the proposed approach that satisfies applicable requirements in items b, c, or d below in this section and the requirements in sections 8 and 9 in this NASA Technical Standard.

(3) Receive RFCB approval before implementing the proposed approach.

A rationale is required because detailed requirements for the approach have to be developed and documented in the FCP that satisfy the applicable requirements in b or c below and the guidance in this section, and the RFCB has to review and approval the proposed detailed approach. This presents a significant effort for the developer of the FCP and for the RFCB reviews.

b. The development approach is satisfied by comparison to requirements in sections 7.2.1 in this NASA Technical Standard for metallic pressure vessels or 7.2.2 in this NASA Technical Standard for COPVs and composite overwrapped pressurized fluid containers. The approach is to be equivalent to or an extension of all the requirements, including establishing that damage tolerance life is achieved without failure or leakage of the fluid, and provides equivalent risk mitigation of a catastrophic failure caused by flaws.

c. The proposed FCP approach for damage tolerance assessment of a fracture critical pressure vessel or pressurized fluid container that is all composite or has a non-metallic, i.e., an elastomeric, liner or other non-metallic components is to meet the general approach for fracture critical composite hardware in section 7.4 in this NASA Technical Standard and show that the damage tolerance required life is achieved without failure or leakage of the fluid.

d. The proposed FCP approach for damage tolerance assessment of a fracture critical all-metal pressurized fluid container is to meet the general approach for fracture critical metallic hardware in section 7.3 in this NASA Technical Standard and show that the damage tolerance life is achieved without failure or leakage of the fluid.

Note that if a fracture critical metallic "pressurized fluid container" is planned with attributes close to the definition of a pressure vessel, it may be advantageous to push it into the pressure vessel category to minimize later impacts as the project matures in case the initial design attributes increase.

There are currently no predefined approaches for pressure vessels or pressurized fluid containers that are qualified under a different code/standard than ANSI/AIAA S-080 or ANSI/AIAA S-081, such as the ASME Boiler and Pressure Vessel Code, section VIII, Divisions 1 or 2, or the United States Department of Transportation Code of Federal Regulations Title 49, Transportation. These codes/standards do not impose the structural integrity activities needed for damage tolerance that are specified in ANSI/AIAA S-080 and ANSI/AIAA S-081. As a result, the approaches used by these codes/standards to certify vessels do not facilitate meeting damage tolerance requirements as required in this NASA Technical Standard. Equivalence means that damage tolerance life analysis or test requirements in sections 7.2.1 *or 7.2.2 in the NASA Technical Standard are also applied in modified form for a vessel meeting section 7.2.3 in this NASA Technical Standard. Equivalence does not mean other types of assessment, such as fatigue calculations or cycle test, can be substituted for the damage tolerance methodology detailed in sections 7.2.1 and 7.2.2 in this NASA Technical Standard. Use of these codes/standards in combination with other activities may be proposed, however, as an alternative approach as described in [FCR 26] in section 10 in this NASA Technical Standard.*

In addition, other pressure vessels and pressurized fluid containers may be developed that are not addressed by existing codes or standards. Examples may include composite pressure vessels/containers without a metal liner or rubber-lined composite pressure vessels/containers.

For these other fracture critical vessels/containers, a unique approach is developed and proposed in the FCP that establishes equivalent methods of addressing material, structural, qualification, acceptance, and related aspects such as those in the ANSI/AIAA S-080 or ANSI/AIAA S-081 standards to support the damage tolerance assessment. Equivalence with the AIAA pressure vessel standards may include assessments and testing that include materials aspects, loadings, stress analysis, strength, environment effects, stiffness, thermal response, life, quality assurance, repairs, NDE requirements, acceptance processes including proof and leakage testing, damage tolerance control plans, and damage tolerance assessments by analysis and/or testing, and documentation. However, use of analytical techniques to establish damage tolerance is generally considered insufficiently developed for composite pressure vessels. For all-composite pressure vessels, the approaches described for fracture critical composite hardware in section 7.4 in the NASA Technical Standard should be incorporated, in addition to applicable equivalent requirements in ANSI/AIAA S-081.

For other types of vessels/containers, it should also be noted that, in addition to the section 9 documentation in this NASA Technical Standard showing the approach proposed in the FCP has been met, section 9.1.3.1 in this NASA Technical Standard requires providing supporting detailed technical information to the RFCB upon request, including drawings, material and processing data, detailed stress analysis, and damage tolerance analyses that are needed to support the damage tolerance assessment.

Early involvement with the RFCB is suggested for any vessels/containers to be assessed by this section.

Section 7.2.3 of NASA-STD-5019A applies to all other fracture critical pressure vessels and pressurized fluid containers that are not addressed in either section 7.2.1 or 7.2.2 in NASA-STD-5019A.

Notice section 7.2.2 includes fracture critical composite overwrapped pressurized fluid containers. These are pressurized parts with a composite structure fully or partially encapsulating a metallic liner, i.e., the same construction as the vessels addressed in ANSI/AIAA S-081. Note these vessels may not meet the definition of a pressure vessel yet are included in section 7.2.2 in

NASA-STD-5019A. They are included because they are structurally similar to the COPVs addressed in section 7.2.2, and that established approach is the best way to address this type of vessel for fracture control. The ANSI/AIAA S-081 standard does not prevent use of the standard for vessels that do not meet the NASA definition of a pressure vessel, which is copied below.

The definition of a pressure vessel in NASA-STD-5019A and in this Handbook is one that:

- Contains stored energy of 19,307 J (14,240 ft-lb) or greater based on adiabatic expansion of a perfect gas.
- Stores a gas that will experience an MDP greater than 690 kPa (100 psia).
- Contains a fluid (gas and/or liquid) in excess of 103 kPa (15 psia) that will create a hazard if released.

Pressurized hardware examples that may be candidates for this section 7.2.3 classification include:

a. Fracture critical metallic pressurized fluid containers, which do not have a high enough stored energy, pressure, or hazardous fluid to be classified as a pressure vessel but satisfy all other requirements for assessment as a fracture critical metallic pressure vessel per section 7.2.1.

b. Fracture critical metallic pressure vessels that have some aspect causing them not to be qualified under the applicable ANSI/AIAA requirement, which is S-080-1998 or the new version ANSI/AIAA S-080A-2018, depending on the program.

c. Fracture critical COPVs and composite overwrapped pressurized fluid containers that have some aspect causing them not to be qualified under the applicable ANSI/AIAA requirement, which is ANSI/AIAA S-081-2000 or the new version ANSI/AIAA S-081B-2018, depending on the program.

d. Other fracture critical pressurized fluid containers and pressure vessels with structures that are not compatible with either ANSI/AIAA S-080 nor ANSI/AIAA S-081.

Guidance in this section notes if a fracture critical metallic "pressurized fluid container" is planned with attributes close to the definition of a pressure vessel, it may be advantageous to push rated pressure higher into the pressure vessel category to minimize later impacts as the project matures in case the initial design attributes such as pressure or volume (i.e., energy) increase.

A fracture critical metallic pressurized fluid container example such as section 7.2.3.1 above in this Handbook could be assessed under items 7.2.3a and b in NASA-STD-5019A by satisfying all the section 7.2.1 requirements, although it does not satisfy the definition of a pressure vessel. If approved by the RFCB, this category may be treated as if it satisfied the criteria for assessment under section 7.2.1. This choice is the most straightforward way to demonstrate a fracture critical metallic pressurized fluid container satisfies fracture control requirements in NASA-STD-5019A.

The above examples 2 and 3 are cases where it may be simpler to meet the requirements in the applicable section 7.2.1 or 7.2.2 (according to hardware type) if the hardware design non-conforming aspect can be adapted to fit into one of these classifications. The approach would need to satisfy items 7.2.3.a and b requirements in NASA-STD-5019A.

The above example 4 in this Handbook is not close to the hardware addressed by either section 7.2.1 or 7.2.2 in NASA-STD-5019A. These would need to satisfy items 7.2.3.a, b, and c or d requirements.

NASA-STD-5019A, Item 7.2.3.a

This section requires documentation of the proposed approach in the Fracture Control Plan in accordance with section 4.1 [FCR 1] requirements in NASA-STD-5019A. The Fracture Control Plan is reviewed and approved by the RFCB.

NASA-STD-5019A, Item 7.2.3.a(1)

Item 7.2.3.a(1) of NASA-STD-5019A requires a rationale be provided for using a metallic pressure vessel, COPV, or composite overwrapped pressurized fluid container instead of one of the following:

a. An all-metal pressure vessel that meets the requirements of section 7.2.1 in NASA-STD-5019A, or

b. A COPV or composite overwrapped pressurized fluid container that meets the requirements of section 7.2.2 in NASA-STD-5019A.

Guidance is provided at the end of section 7.2.3.a that explains a rationale is required because detailed approaches have to be developed and documented in the FCP that satisfy requirements in the applicable items a, b, and either c or d, as described in this section in NASA-STD-5019A. The RFCB has to review and approve the proposed approach to proceed with the hardware development. These activities represent a significant effort for the hardware developer and the RFCB reviews as compared to following the prescribed approaches in sections 7.2.1 or 7.2.2 as appropriate for the hardware type in NASA-STD-5019A.

NASA-STD-5019A, Item 7.2.3.a(2)

Item 7.2.3.a(2) of NASA-STD-5019A requires description of the proposed approach that satisfies whichever of the items 7.2.3.b, and either c or d, are applicable to the hardware being addressed—each one is discussed later in this section. In addition, item 7.2.3.a(2) requires the proposed approach to also satisfy requirements in sections 8 and 9. This statement of the requirement to satisfy sections 8 and 9 is provided to help in understanding what should be provided. Sections 8 and 9 in NASA-STD-5019A impose requirements independently of the statement in section 7.2.3.a(2). These requirements are discussed briefly below under their headings:

Section 8 Requirements

Section 8, Flaw Screening, Traceability, and Material Selection, includes FCR 15 that requires all fracture critical parts to be screened for flaws with methods and techniques identified in the FCP. These topics are listed below under sections 8.1, 8.2, and 8.3. The reader is referred to these sections in this Handbook for details and discussion.

8.1 Flaw Screening

This section contains several sections with FCR requirements on the following topics: NDE for metallic parts, NDE for composite or bonded parts, screening of flaws by proof test or by process control, and assessment approaches for detected flaws.

8.2 Traceability for Fracture Control

In this section, FCR 21 imposes requirements on traceability for fracture critical parts and some NFC composite or bonded parts.

8.3 Material Selection and Usage for Fracture Critical Parts

In this section, FCR 22 places requirements on selection, processing, and use of materials for all fracture critical and NFC composite or bonded parts.

Section 9 Requirements

Section 9, Fracture Control Documentation and Verification, includes section 9.1, Fracture Control Documentation, and section 9.2, Verification. These section headings are listed below with a brief description. The reader is referred to these sections in this Handbook for details and discussion.

9.1 Fracture Control Documentation

Sections below this heading include section 9.1.1, Fracture Control Plan, which is noted to be part of the documentation. Section 9.1.2, Engineering Drawings, contains FCR 23 that requires fracture critical parts to be identified on engineering drawings with related fracture control information for traceability. Section 9.1.3 describes the FCSR in which FCR 24 requires a FCSR to be developed by the spaceflight hardware program or project with the content described in FCR 24. More details on the information to be in the FCSR are described in 9.1.3.1 guidance, and other documentation is described in 9.1.3.2.

9.2 Verification

In this section, FCR 25 requires verification of adherence of the flight hardware to the fracture control requirements in NASA-STD-5019A and specifies three aspects regarding content of the FCP and FCSR, the approval process, and a process for conflict resolution.

NASA-STD-5019A, Item 7.2.3.a(3)

Item 7.2.3.a(3) of NASA-STD-5019A states: "Receive RFCB approval before implementing the proposed approach." This requirement gives the RFCB an opportunity to review and comment on the planned approach before it begins. This requirement benefits both the hardware developer and the RFCB as significant issues may be identified early in the process to avoid them or minimize their impact.

NASA-STD-5019A, Item 7.2.3.b

Item 7.2.3.b of NASA-STD-5019A specifies the development approach for meeting this requirement, which is to be satisfied by comparison to requirements in either section 7.2.1 in NASA-STD-5019A for metallic pressure vessels or section 7.2.2 in NASA-STD-5019A for COPVs and composite overwrapped pressurized fluid containers. The approach is required to be equivalent to or an extension of all the requirements, including establishing that damage tolerance life is achieved without failure or leakage of the fluid, and provides equivalent risk mitigation of a catastrophic failure caused by flaws.

NASA-STD-5019A, Items 7.2.3.a, b, and either c or d Guidance

Guidance that appears later in section 7.2.3.a, b, c, or d in NASA-STD-5019A is copied below because it is especially relevant for hardware being developed under section 7.2.3.a, b, and either c or d.

> *There are currently no predefined approaches for pressure vessels or pressurized fluid containers that are qualified under a different code/standard than ANSI/AIAA S-080 or ANSI/AIAA S-081, such as the ASME Boiler and Pressure Vessel Code, Section VIII, Divisions 1 or 2, or the United States Department of Transportation Code of Federal Regulations Title 49, Transportation. These codes/standards do not impose the structural integrity activities needed for damage tolerance that are specified in ANSI/AIAA S-080 and ANSI/AIAA S-081. As a result, the approaches used by these codes/standards to certify vessels do not facilitate meeting damage tolerance requirements as required in this NASA Technical Standard. Equivalence means that damage tolerance life analysis or test requirements in sections 7.2.1 or 7.2.2 in the NASA Technical Standard are also applied in modified form for a vessel meeting section 7.2.3 in this NASA Technical Standard. Equivalence does not mean other types of assessment, such as fatigue calculations or cycle test, can be substituted for the damage tolerance methodology detailed in sections 7.2.1 and 7.2.2 in this NASA Technical Standard. Use of these codes/standards in combination with other activities may be proposed as an alternative approach as described in [FCR 26] in section 10 in this NASA Technical Standard.*
>
> *In addition, other pressure vessels and pressurized fluid containers may be developed that are not addressed by existing codes or standards. Examples may include composite*

pressure vessels/containers without a metal liner or rubber-lined composite pressure vessels/containers.

For these other fracture critical vessels/containers, a unique approach is developed and proposed in the FCP that establishes equivalent methods of addressing material, structural, qualification, acceptance, and related aspects such as those in the ANSI/AIAA S-080 or ANSI/AIAA S-081 standards to support the damage tolerance assessment. Equivalence with the AIAA pressure vessel standards may include assessments and testing that include materials aspects, loadings, stress analysis, strength, environment effects, stiffness, thermal response, life, quality assurance, repairs, NDE requirements, acceptance processes including proof and leakage testing, damage tolerance control plans, and damage tolerance assessments by analysis and/or testing, and documentation. Use of analytical techniques to establish damage tolerance is generally considered insufficiently developed for composite pressure vessels. For all-composite pressure vessels, the approaches described for fracture critical composite hardware in section 7.4 in the NASA Technical Standard should be incorporated, in addition to applicable equivalent requirements in ANSI/AIAA S-081.

For other types of vessels/containers, it should also be noted that, in addition to the section 9 documentation in this NASA Technical Standard showing the approach proposed in the FCP has been met, section 9.1.3.1 in this NASA Technical Standard requires providing supporting detailed technical information to the RFCB upon request, including drawings, material and processing data, detailed stress analysis, and damage tolerance analyses that are needed to support the damage tolerance assessment.

Early involvement with the RFCB is suggested for any vessels/containers to be assessed by this section.

NASA-STD-5019A, Item 7.2.3.c

This section specifies requirements for developing a proposed FCP approach for damage tolerance assessment of a fracture critical pressure vessel or pressurized fluid container that is all composite or has a non-metallic, i.e., an elastomeric, liner, or other non-metallic components. These vessel types are to meet the general approach for fracture critical composite hardware in section 7.4 in NASA-STD-5019A and discussed in this Handbook. The requirement imposed is to show that the damage tolerance required life is achieved without failure or leakage of the fluid.

NASA-STD-5019A, Item 7.2.3.d

Item 7.2.3.d specifies requirements for developing a proposed FCP approach for damage tolerance assessment of a fracture critical all-metal pressurized fluid container. These vessel types are to meet the general approach for fracture critical metallic hardware in section 7.3 in NASA-STD-5019A. The requirement imposed is to show that the damage tolerance life is achieved without failure or leakage of the fluid.

7.2.4 Fracture Critical Lines, Fittings, and Other Pressurized Components (NASA-STD-5019A, Section 7.2.4)

NASA-STD-5019A:
7.2.4 Fracture Critical Lines, Fittings, and Other Pressurized Components

For metallic fracture critical lines, fittings, and other pressurized components (hardware items that are part of a pressurized system, including valves, filters, regulators, heat pipes, and heat exchangers) that transfer hazardous fluids or when loss of pressurization results in a catastrophic hazard, to satisfy requirement [FCR 11] section 7.2.d in this NASA Technical Standard, meet either 7.2.4.a or 7.2.4.b (below).

a. Apply the following items (1) through (6) to parts where the only load of significance is related to pressure:

(1) The metallic material is not susceptible to crack extension related to EAC or SLC.

(2) Perform 100 percent inspection of all fusion joints in fracture critical pressure components using a qualified NDE method after proof test to inspect for the presence of unacceptable lack of penetration or other unacceptable conditions both on the surface and within the fusion joint.

(3) Reject any type of flaw indication in the final product that does not meet specification requirements.

NDE rejection indicates the need for formal review and part disposition.

(4) Proof test lines, fittings, joints, and other pressurized components or parts to a minimum of 1.5 times the MDP during individual acceptance or at the system level.

(5) An ECF less than 1.0 is not allowed without prior approval by the RFCB.

(6) Obtain RFCB approval that the part is manufactured using processes that have been established by reliability or by inspections of many similar parts to be extremely unlikely to produce parts with a flaw exceeding process specifications.

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

b. Satisfy section 7.3 in this NASA Technical Standard for parts that do not meet the criterion in 7.2.4.a.

Item 7.2.4.a is intended for hardware designed to carry primarily pressure loads. This hardware is designed with appropriate supports, brackets, or relief loops such that they are not subject to significant structural loads. Typically, these parts are produced under process control in large quantities, are identical parts, and are subjected to NDE and qualification testing to ensure the parts are reliable and present a low risk of containing detectable flaws that result in crack growth.

Pressurized components may have high pressures and energies, but this type of hardware is subject to high factors of safety imposed by other standards such as NASA-STD-5001. NASA-STD-5001 also requires implementation of AIAA S-080, which has a leak test requirement.

Section 7.2.4 of NASA-STD-5019A addresses metallic fracture critical lines, fittings, and other pressurized components (hardware items that are part of a pressurized system, including valves, filters, regulators, heat pipes, and heat exchangers) that transfer hazardous fluids. Loss of the fluid, or loss of pressurization, results in a catastrophic hazard.

There are two options: Item 7.2.4.a of NASA-STD-5019A specifies hardware aspects and imposed requirements that should be satisfied for hardware to be accepted in this classification. Option item 7.2.4.b does not presume the hardware satisfies the aspects described in option a. Hardware classified under item 7.2.4.b makes no presumptions about the hardware other than aspects required of all fracture critical hardware. Hardware classified under item 7.2.4.b has to satisfy the fracture control requirements specified in section 7.3, the general approach for fracture critical metallic parts assessment. Also, whether hardware is classified under either 7.2.4.a or 7.2.4.b, it is fracture critical hardware and should also satisfy requirements imposed in sections 8 and 9 in NASA-STD-5019A upon all fracture critical parts.

The guidance in this section has been rearranged to facilitate discussion of the guidance content.

NASA-STD-5019A, Item 7.2.4.a

Item 7.2.4.a of NASA-STD-5019A describes the expected stresses in the pressurized hardware. All loads the hardware experiences during its service lifetime including accelerations due to motions and all other applied loadings upon the hardware should be assessed for the stresses imparted into the pressurized hardware. Sufficient structural supports are required to be provided so that the following guidance is representative of the stresses in all of the pressurized hardware system components.

> *"Item 7.2.4.a is intended for hardware designed to carry primarily pressure loads. This hardware is designed with appropriate supports, brackets, or relief loops such that they are not subject to significant structural loads."*
>
> *"For loading (stresses) to be considered pressure dominant, all other loads (stresses) should be no greater than 20 percent of the pressure loads (stresses)."*

The following guidance describes aspects that should be descriptive of the hardware for it to be classified under section 7.2.4.a. The requirements in this section were written based on the following presumptions: (1) All the lines, fittings, and other pressurized components have proven capability to perform their intended purpose; (2) They are expected to have a very low probability of leakage or structural failure throughout the service lifetime due to defects of the hardware design, material, manufacturing, quality control, or inspection processes; and (3) The hardware is expected to be free from significant flaws and cracks. If these presumptions are not applicable for the hardware being considered for classification under section 7.2.4.a, the hardware should be classified under section 7.2.4.b.

> *"Typically, these parts are produced under process control in large quantities, are identical parts, and are subjected to NDE and qualification testing to ensure the parts are reliable and present a low risk of containing detectable flaws that result in crack growth."*

An example of hardware acceptable for Section 7.2.4.a of NASA-STD-5019A applications could be pipe that is produced in large quantities, with automated inspection of the pipe as it is being fabricated. Additional quality controls are in place such as extraction of pipe samples that are subjected to strength testing and inspections to confirm the capability of the pipe and the absence of significant defects that could grow during the pipe service lifetime. Other components may not be amenable to continuous fabrication and inspection and testing processes such as the above described pipe but are expected to be fabricated in quantity with equivalent highly controlled proven processes. Such processes include statistically based sampling of lots which are subjected to NDE inspections, strength testing, sectioning to check for internal defects, and material tests to confirm the product has the required strength and quality attributes.

This section relies on the above guidance being valid as it only requires inspection of the fusion joints. This presumes all the lines, fittings, and other pressurized components (hardware items that are part of a pressurized system, including valves, filters, regulators, heat pipes, and heat exchangers) do not contain flaws that could cause leaks or failures during the service lifetime of the hardware. If any hardware introduced into this pressure system is discovered not to satisfy these assumptions, that hardware has to be subjected to all the activities imposed on hardware per item 7.2.4.b requirements.

NASA-STD-5019A, Item 7.2.4.a(1)

Item 7.2.4.a(1) of NASA-STD-5019A requires the metallic material not to be susceptible to cracking due to EAC or SLC. These terms are defined in sections 3.1 and 3.2 in NASA-STD-5019A and this Handbook. This requirement means test data have to demonstrate the hardware material will not fail due to either of these modes of crack growth while exposed to the loading stresses and environments (including all fluids the hardware experiences) during the hardware service lifetime. Credible defects and acceptance criteria should be considered in the EAC and SLC assessment.

Brief summaries of EAC and SLC are provided below. Citations identifying the two references mentioned in the EAC and SLC descriptions are given in Appendix B.4 in NASA-STD-5019A. These papers are recommended examples of EAC and SLC occurrence and testing methods.

Environmentally Assisted Cracking (EAC): A cracking process in which the environment promotes crack growth or higher crack growth rates than would occur without the presence of the environment. See ASTM E1681. An example is available in published literature (Lewis and Kenny, 1976). EAC: environmentally assisted cracking, K_{EAC}: stress intensity threshold for EAC in a specific thickness, K_{IEAC}: stress intensity factor threshold for plane strain environmentally assisted cracking; K_{ISCC}: K_{EAC} is often denoted as K_{ISCC} in the literature.

Sustained Load Cracking (SLC): Growth of a pre-existing crack in susceptible metallic alloys under sustained stress without assistance from an external environment. A threshold stress intensity factor can be obtained by procedures such as those in ASTM E1681 for the case of an inert or vacuum environment. One publication determines the effects of hydrogen content and temperature on SLC in Ti-6Al-4V (Boyer and Spurr, 1978). SLC: sustained load cracking, K_{SLC}: stress intensity factor threshold for sustained load cracking.

NASA-STD-5019A, Item 7.2.4.a(2)

Item 7.2.4.a(2) of NASA-STD-5019A imposes inspection requirements after the proof test of the fusion joints. The joints do not have the same process-controlled assurance of reliability that the pressurized lines, fittings, and other pressurized components possess. The inspection is required to inspect 100 percent of each joint on the surface and within the joint. The inspection is to ensure there are no NDE detectable lack of penetration or other conditions that put the hardware at risk of premature crack growth, fracture, or other types of failure during the service lifetime of the hardware.

Proof test allows the opportunity for indications to open up and be detected by NDE that might otherwise have been too small to be detected prior to proof test.

NASA-STD-5019A, Item 7.2.4.a(3)

Item 7.2.4.a(3) of NASA-STD-5019A specifies the criteria that is imposed on inspections of the hardware per item 7.2.4.a(2). Item 7.2.4.a(3) is a general statement, so it imposes this criterion on the rest of the pressurized lines, fittings, and other components in the pressurized system if either the inspection specified in item 7.2.4.a(2) or the proof testing specified in item 7.2.4.a(4) exposes any type of flaw. The guidance in this item states NDE rejection also indicates the need for formal review and part disposition. Depending on the characteristics of the flaw and the type of NDE rejection, additional testing or NDE of the affected pressurized components may be required. The review also should evaluate the processes that produced the flaw to determine if modifications of those processes are indicated and if any other components or fusion joints could be affected.

NASA-STD-5019A, Item 7.2.4.a(4)

Item 7.2.4.a(4) of NASA-STD-5019A requires proof test of all the pressurized hardware to a minimum of 1.5 times the MDP. There is an option to perform the proof test of components individually during acceptance or when they are assembled into the pressurized system and proof tested at the system level. The advantage of performing individual proof tests of each component is it provides a certification screening of that component. If there is a failure caused by defects or inadequacy of that component during the proof test, it is limited to affecting that component. If testing is performed only at the system level, failure of one component may affect adjacent hardware. Also, there may be some difference in the pressure effects on an isolated component versus testing in the system configuration. The possible difference depends on the compliance of the end caps that seal the hardware when tested in isolation. The end caps may not have the same compliance as the connected system hardware. Also, to proof test the fusion joints, it is necessary to test the assembly of components that includes the fusion joints.

NASA-STD-5019A, Item 7.2.4.a(5)

Item 7.2.4.a(5) of NASA-STD-5019A states an Environmental Correction Factor less than 1.0 is not allowed unless it has been approved by the RFCB. Testing performed at an ECF less than 1.0 will not simulate the loads applied to the hardware when it is at full pressure, and this may not expose structural weaknesses in the hardware. Such weaknesses could occur due to inadequate structural strength, rigidity, or effects of flaws in the hardware. An assessment of the risks when the proof test is performed at a different temperature than the hardware experiences during its service lifetime should be compared with the benefit of screening for hardware flaws at the pressure corresponding to an ECF of 1.0.

NASA-STD-5019A, Item 7.2.4.a(6)

Item 7.2.4.a(6) of NASA-STD-5019A requires the RFCB to approve the pressurized components were manufactured using processes that have been established by reliability or by inspections of many similar parts to be extremely unlikely to produce parts with a flaw exceeding process specifications. This provides assurance the hardware is representative of the presumptions that justify use of section 7.2.4.a for pressurized fracture critical hardware. If the RFCB does not concur the hardware is appropriate for classification as section 7.2.4.a hardware, the hardware has to satisfy the requirements in section 7.2.4.b.

NASA-STD-5019A, Item 7.2.4.b

Item 7.2.4.b of NASA-STD-5019A requires pressurized components that do not satisfy the criteria to be classified as section 7.2.4.a parts to satisfy the fracture control requirements in section 7.3, General Approach for Fracture Critical Metallic Parts Assessment. Section 7.3 does not presume hardware has the attributes ascribed to the section 7.2.4.a components such as those specified in item 7.2.4.a(6).

The following guidance appears at the end of section 7.2.4 in NASA-STD-5019A. As described below, the guidance is not representative of the content in the current versions of the referenced documents and is not relevant:

> *"Pressurized components may have high pressures and energies, but this type of hardware is subject to high factors of safety imposed by other standards such as NASA-STD-5001. NASA- STD-5001 also requires implementation of AIAA S-080, which has a leak test requirement."*

The above guidance is compared to content in the referenced documents in the following discussion.

NASA-STD-5001B with Change 2, section 4.2.5.1a states:

"a. [FSR 42] Metallic pressure vessels and pressurized components shall be designed, qualified, and accepted per the requirements of ANSI/AIAA S-080, Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressurized Components."

Note that no factors of safety are imposed upon metallic pressure vessels and pressurized components in the current NASA-STD-5001 document. The cited guidance has no meaning.

ANSI/AIAA S-080A-2018 has the following content regarding leak test requirements:

"10.4.7 Leak Test
The pressurized hardware shall be leak tested at MEOP. The acceptable leak rate is identified in section 5.1.10."

"5.1.10 Acceptable Leak Rate
The pressure system shall be analyzed to determine the maximum acceptable leak rate."

Note there are no requirements in ANSI/AIAA S-080A-2018 specifying any criteria for determining the maximum acceptable leak rate, so the leak test "required" by ANSI/AIAA S-080A-2018 has unknown value.

It is also noted the ANSI/AIAA S-080A-2018 standard could be tailored. A program could tailor it and implement a meaningful maximum acceptable leak rate requirement.

7.2.5 Fracture Critical Habitable Modules and Volumes (NASA-STD-5019A, Section 7.2.5)

NASA-STD-5019A:

7.2.5 Fracture Critical Habitable Modules and Volumes

Satisfy the following for fracture critical habitable modules and volumes to meet requirement [FCR 11] section7.2.e in this NASA Technical Standard:

a. Establish that pressure shells are damage tolerant by satisfying sections 7.3 or 7.4 in this NASA Technical Standard for the appropriate material type.

b. Proof test pressure shells.

c. Perform post-proof test NDE of pressure shell welds.

d. Monitor and document operation to ensure that certification is not invalidated.

Proof tests are usually performed in the operational environment, or the test levels are adjusted via an ECF.

Proof test levels (factors) are defined either by structural requirements or those developed to provide flaw screening (section 8.1.3 [FCR 18] in this NASA Technical Standard). Section 8.2 in this NASA Technical Standard requires load history traceability for all fracture critical parts.

Flaw screening for the entire fracture critical structure is required in accordance with section 8 in this NASA Technical Standard. Pre-proof NDE is highly recommended to protect high-value structures and facilities.

A damage tolerance assessment considers the worst-case allowed weld joint peaking and mismatch effects (metallic structures) and residual stress effects (either by analysis or included as a part of material test data) for habitable structures and enclosures

Habitable modules are one of the more complex fracture critical structures in terms of both the hardware and requirements. In addition to the fracture control requirements imposed in this section and elsewhere for fracture critical hardware in NASA-STD-5019A, structural factors of safety requirements (FSR) are imposed to control unique failure modes of concern for this hardware. NASA-STD-5001B, section 4.2.5.2.1 on Habitable Modules, includes the following items:

a. [FSR 45] Habitable modules shall maintain dimensional stability required for functionality of structural and mechanical attachments, pressure connections, and openings for doors or hatches throughout their service life in the applicable environments.

b. [FSR 46] Habitable modules shall withstand applicable loads with the doors or hatches in the open and closed condition for the applicable ground and mission environments.

c. [FSR 47] The minimum design and test factors of safety for habitable modules, doors, and hatches shall be as specified in Table 5. [Table 5 in NASA-STD-5001B specifies both internal positive and negative pressure differential structural design factors.]

The above cited NASA-STD-5001B structural requirements are not fracture control requirements. Damage tolerance assessments may be needed that evaluate effects upon structural response to service loadings due to cracks in metallic hardware and damage mechanisms in composite or bonded hardware. Increasing damage in the hardware during the service lifetime may cause increased displacements or compliance under structural loadings that violate the cited structural requirements.

NASA-STD-5019A, Item 7.2.5.a

Item 7.2.5.a of NASA-STD-5019A requires the fracture control assessment to establish that pressure shells are damage tolerant by satisfying section 7.3 or 7.4 in NASA-STD-5019A for the appropriate material type. Sections 7.3 and 7.4 in this Handbook provide discussions of those requirements and their implementation. In addition, NASA-STD-5019A, section 8, imposes requirements for flaw screening, traceability of each fracture critical part, and the selection and usage of materials for fracture critical parts. Also, section 9 in NASA-STD-5019A imposes requirements for fracture control documentation and verification. These requirements are discussed in corresponding sections in this Handbook.

Guidance in section 7.2.5 in NASA-STD-5019A that clarifies assessments of welding geometric aspects and residual stresses is copied below.

> *A damage tolerance assessment considers the worst-case allowed weld joint peaking and mismatch effects (metallic structures) and residual stress effects (either by analysis or included as a part of material test data) for habitable structures and enclosures.*

With respect to weld joint peaking and mismatch effects on metallic structures, the guidance provided in NASA-STD-5019A, section 7.3.1, after item g is relevant and is copied below:

> *Include the worst-case allowed or weld joint peaking and mismatch effects for damage tolerance assessments by analysis or test. The assessment analysis or test is to capture the effect of peaking and mismatch on stress gradients affecting crack growth and fracture. Standard tensile strength tests of ductile materials are not adequate to assess these conditions.*

NASA-STD-5019A, Item 7.2.5.b

Item 7.2.5.b of NASA-STD-5019A requires a proof test be performed on the pressurized shells. Relevant guidance in this section is copied below.

> *Proof tests are usually performed in the operational environment, or the test levels are adjusted via an ECF.*
>
> *Proof test levels (factors) are defined either by structural requirements or those developed to provide flaw screening (section 8.1.3 [FCR 18] in the NASA Technical Standard). Section 8.2 in the NASA Technical Standard requires load history traceability for all fracture critical parts.*
>
> *Flaw screening for the entire fracture critical structure is required in accordance with section 8 in this NASA Technical Standard. Pre-proof NDE is highly recommended to protect high-value structures and facilities.*

The proof test may be utilized to screen for flaws as discussed in section 8.1.3 in this Handbook. It also may be imposed as a structural strength qualification requirement by NASA-STD-5001B for metallic structures in section 4.2.1 and for composite/bonded structures in section 4.2.3. There are different requirements and proof test factors imposed by NASA-STD-5001B according to prototype and protoflight test approaches, the type of hardware, and the function of the hardware. The item 7.2.5.b proof test requirement in NASA-STD-5019A is imposed on fracture critical habitable modules and volumes regardless of the requirements imposed by NASA-STD-5001B. The NASA-STD-5001B requirements on the magnitude of the proof test factor may define the proof test factor imposed by item 7.2.5.b, unless the proof test is also being used to screen for flaws per section 8.1.3 in NASA-STD-5019A; in that case, the proof test factor is determined by section 8.1.3 for flaw screening. There may be other proof test requirements imposed by program-specific structural requirements on fracture critical habitable modules and volumes. In the event of conflicting requirements, it may be advisable to discuss the proof test factor with the RFCB and the delegated Technical Authority.

Also, it is advisable to utilize the proof test to validate structural and damage tolerance analysis models by instrumenting the hardware to record deformations and strains during the proof test.

NASA-STD-5019A, Item 7.2.5.c

Item 7.2.5.c requires post-proof test NDE of pressure shell welds. This requirement is also imposed by section 8.1.1 NDE for Metallic Parts in NASA-STD-5019A as discussed in this Handbook. If defects are detected, they have to be assessed as prescribed in section 8.1.5 as discussed in this Handbook. This item does not discuss joints in composite or bonded hardware. Section 8.1.2 in NASA-STD-5019A imposes the following requirement:

> "For hardware that is proof tested as part of acceptance, perform pre-proof and postproof test NDE at critical joints, discontinuities, and other critical locations identified in the FCP for all hardware, i.e., critical hardware locations not screened for specific flaws with the proof test."

The module may also be monitored for leaks during the proof test. These may not be detectible if the module pressure shell has coatings that inhibit leakage of fluids. This aspect is addressed by the item 7.3.1.f requirement in NASA-STD-5019A that states:

> "Include the influence of all coatings and barriers on pressure-loaded parts for any scenarios where pressure is assumed to decrease because of leakage from a crack."

NASA-STD-5019A, Item 7.2.5.d

Item 7.2.5.d of NASA-STD-5019A requires monitoring and documenting the habitable modules and volumes operations to ensure that the hardware certification is not invalidated. The aspects of particular concern are the pressures the hardware experiences, the number of pressure cycles, and all other significant loadings the hardware experiences during its damage tolerance service life. An alert system should be in place to flag forthcoming planned operations that could exceed those in the damage tolerance service life for which the hardware has been assessed and certified.

7.2.6 Fracture Critical Pressurized Structures (NASA-STD-5019A, Section 7.2.6)

NASA-STD-5019A:
7.2.6 Fracture Critical Pressurized Structures

This section is intended for pressurized structures such as launch vehicle main propellant tanks that carry internal pressure and vehicle structural loads.

Satisfy the following for fracture critical pressurized structures to meet requirement [FCR 11] section 7.2.f in this NASA Technical Standard:

a. Proof test all flight articles.

b. For metallic pressurized structures, establish damage tolerance by satisfying section 7.3 in this NASA Technical Standard.

c. For metallic pressurized structures, perform post-proof test NDE in accordance with section 8.1.1 in this NASA Technical Standard, in addition to other necessary flaw screening required in section 8 in this NASA Technical Standard, in the following manner:

Standard NDE is acceptable.

(1) Welded regions where proof testing adequately screens for flaws are subject to the following:

  A. Perform post-proof NDE (surface and volumetric) of all welded regions for the first flight article (as a minimum).

  B. Also perform post-proof NDE of all affected weld regions (including those that are adequately screened for flaws by proof test) subjected to significant process, material, or vendor changes for the first flight article incorporating the significant changes.

(2) For welded regions where proof testing does not adequately screen for flaws, perform post-proof NDE (surface and volumetric) of all welded regions for all flight articles.

(3) All weld intersections, weld repair regions, and weld transition regions, including friction plug pull weld regions, are to receive post-proof NDE (surface and volumetric) for all flight articles.

d. For composite or bonded pressurized structures, provide the damage tolerance approach and rationale to the RFCB for approval before implementation.

For composite or bonded pressurized structures, the requirements in section 7.4 in this NASA Technical Standard are a good starting point as a fracture control approach but will need enhancement to provide adequate protection against catastrophic hazard.

e. For composite or bonded pressurized structures, perform post-proof NDE as described in section 8.1.2 in this NASA Technical Standard.

Proof tests are usually performed in the operational environment, or the test levels are adjusted via an ECF.

Proof test levels (factors) are defined either by structural requirements or by those developed to provide flaw screening (section 8.1.3 [FCR 18] in this NASA Technical Standard). Section 8.2 in this NASA Technical Standard requires load history traceability for all fracture critical parts. The use of pressurized structures should be monitored with documentation of the operational history to ensure that certification is not invalidated.

The proof test factor for these structures is a minimum of 1.05 in accordance with NASA-STD-5001. This may result in a high stress during proof and possible growth of large flaws in the structure during the proof test. In accordance with the guidance in section 8.1.3 in this NASA Technical Standard, the flaw size used in the life assessment of these structures in regions where the proof test is used for flaw screening needs to adequately account for possible flaw growth during the proof test (typically established by laboratory damage tolerance tests).

Although it may be difficult to obtain adequate flaw screening for all welded regions via a proof pressure test because of external vehicle loads, the proof test is designed to provide as much flaw screening for welds as is practical.

Flaw screening for the entire fracture critical structure is required in accordance with section 8 in this NASA Technical Standard. Pre-proof NDE is highly recommended to protect high-value structures and facilities.

Damage tolerant assessment considers the worst-case allowed weld joint peaking and mismatch effects (metallic structures) and residual stress effects (either by analysis or included as a part of material test data) for pressurized structures.

As stated in the requirements guidance, this classification is intended for pressurized structures such as launch vehicle main propellant tanks that carry internal pressure and vehicle structural loads.

NASA-STD-5019A, Item 7.2.6.a

All pressurized flight structures are required to be acceptance proof tested as a part of the demonstration that the hardware is suitable for flight. For pressurized structures, this generally includes both pressure and externally applied loads to envelope flight stresses. Test fixtures and support structures should be designed to allow application of all relevant loads. Proof test factors are determined by the governing structural criteria requirements or by the factor derived to provide flaw screening if flaw screening by proof test is pursued. For example, the minimum proof test factor from NASA-STD-5001 is 1.05 and should include an environment correction factor if the test is not conducted in the operational environment. Application of a proof test factor to achieve flaw screening for welded regions is highly desirable and provides demonstrable assurance against failure due to fracture during the service life.

NASA-STD-5019A, Item 7.2.6.b

Metallic pressurized structures are required to have damage tolerance assessed by the approach required in section 7.3 of NASA-STD-5019A. This approach includes development of a load spectrum and assessment by analysis, test, or both. As for other parts, damage tolerance assessment provides an understanding of defect sensitivity for the pressurized structure. Several locations may need to be assessed such as the pressure shell walls, welded regions, and attachment locations. The damage tolerance assessment should provide a determination of the predicted life for an assumed flaw consistent with the flaw screening method implemented. The predicted life is required to be at least 4 times the service lifetime.

NASA-STD-5019A, Item 7.2.6.c

Section 7.2.6.c of NASA-STD-5019A specifically addresses how NDE is required to be performed for welded regions after the proof test of the hardware. Although specific details are not provided in section 7.2.6 for NDE requirements in every region throughout the pressurized structure, flaw screening (typically NDE) is required for the entire fracture critical pressurized structure per section 8 of NASA-STD-5019A. Many regions may be screened by NDE prior to proof testing and often prior to assembly of each subassembly (e.g., base metal plates typically get NDE prior to acceptance of the plates from the vendor). NDE prior to the proof test for many regions, if not all regions, of the pressurized structure is recommended as a risk mitigation activity for the proof test facility. The fundamental need is that all portions of the pressurized structure receive flaw screening at a level consistent to screen the flaw size evaluated by damage tolerance assessment.

Welds are specifically addressed due to the tendency of the weld process to form cracks and because cracks may grow during the proof test or become more easily detectable after proof test. Residual stresses in the welds can act to conceal flaws that are more detectable after a proof test has been performed.

The following subsections address flaw screening in the welds for proof test and NDE.

NASA-STD-5019A, Item 7.2.6.c(1)

Proof testing that adequately screens for flaws is such that any flaw which survives the proof test will also survive the required 4X service lifetimes. When possible, demonstration by analysis may be developed and provided to the RFCB for approval. Due to the possibility for potential ductile tearing or significant crack tip plasticity during the proof test, flaw screening capability is often demonstrated via a simulated service laboratory coupon or wide panel fracture test. The simulated service test typically involves loading a fracture specimen in the laboratory to the point of imminent failure, then applying the service spectrum 4X times to demonstrate damage tolerance capability for a flaw that 'barely' survives the proof test without failure.

Items 7.2.6.c(1)A and B of this section require that post-proof NDE be performed (surface and volumetric) for all welded regions of the first flight article and to all affected weld regions subject to any process, material, or vendor changes. This is required irrespective of whether or not the weld region has adequate proof test flaw screening. Historically, pressurized structures have had several articles with full NDE of all welded regions. This is usually performed to provide a database of how well the weld process is performing and to have a baseline of acceptable weld NDE for use in comparison to NDE indications that may exist in subsequent flight articles. An NDE weld database also provides for a better understanding of any potential weld process changes as subsequent flight articles are manufactured.

NASA-STD-5019A, Item 7.2.6.c(2)

Even with the most rigorous approach to pursuing flaw screening via proof test for the welded regions of a pressurized structure, there will likely be some weld regions where flaw screening is not achievable with the proof test. One difficulty with achieving proof test logic may include encompassing vehicle flight loads other than pressure (axial, shear, bending, and torsional loading in the vehicle due to thrust and flight dynamics).

For scenarios where proof testing does not provide adequate flaw screening in the welds, those welded regions are required to receive surface and volumetric post-proof NDE for all flight pressurized structure articles.

NASA-STD-5019A, Item 7.2.6.c(3)

There are typically several welded regions in a pressurized structure where assessment of flaw screening via proof test, either by analysis or laboratory test, is not practical due to the complexity of the weld region or difficulty in determining the critical flaw location within a region. Weld regions such as intersections, repairs, transitions (e.g., start-stop regions), and friction plug pull regions represent the most common examples. These weld regions are required to receive surface and volumetric post-proof NDE for all flight articles.

NASA-STD-5019A, Item 7.2.6.d

Section 7.2.6.d of NASA-STD-5019A recognizes that there are no established standard methods that have been in consistent use for classifying and assessing fracture critical composite or bonded pressurized structures. The concepts throughout section 7.4 of NASA-STD-5019 provide a fundamental basis for establishing damage tolerance of a fracture critical composite or bonded pressurized structure. There may be other failure modes such as leakage of a hazardous fluid after an impact or due to manufacturing flaws that should be addressed in addition to the residual strength and life requirements in section 7.4 of NASA-STD-5019.

The approach for damage tolerance assessment should be provided to the RFCB early enough during hardware development to allow iterative discussions and subsequent implementation without negatively affecting project schedules and budgets.

NASA-STD-5019A, Item 7.2.6.e

Flaw screening for fracture critical composite or bonded pressurized structures require post-proof NDE as described in section 8.1.2 of NASA-STD-5019. All hardware regions require post-proof NDE except for NFC low-released mass or contained parts, which do not require any NDE. Composite or bonded hardware that is proof tested should receive pre-proof and post-proof NDE as identified in section 8.1.2.c of NASA-STD-5019, as copied below:

> “For hardware that is proof tested as part of acceptance, perform pre-proof and post-proof test NDE at critical joints, discontinuities, and other critical locations identified in the FCP for all hardware, i.e., critical hardware locations not screened for specific flaws with the proof test.”

Although proof testing as a flaw screening approach is not prohibited for fracture critical composite or bonded pressurized structure, the areas likely to have acceptable flaw screening via proof test are the acreage regions away from critical joints, discontinuities, ply drops, or sectional changes.

Note that all composite hardware is required to receive proof testing per NASA-STD-5001 unless an alternative approach is approved per the process defined in NASA-STD-5001.

7.2.7 Fracture Critical Rotating Hardware (NASA-STD-5019A, Section 7.2.7)

NASA-STD-5019A
7.2.7 Fracture Critical Rotating Hardware

Satisfy the following for fracture critical rotating hardware, including rotating hardware that does not satisfy the conditions in NFC rotating hardware section 6.1.3 in this NASA Technical Standard, to meet requirement [FCR 11] in section 7.2.g in this NASA Technical Standard:

a. The rotating hardware is to satisfy the appropriate section 7.3 or section 7.4 in this Standard for the material type.

b. The rotating hardware is proofed by a spin test to a minimum rotational energy factor of 1.05, i.e., rotational test speed = $\sqrt{1.05\ \omega^2}$, and one of the following performed:

(1) Perform NDE in accordance with section 8.1 in this NASA Technical Standard before and after the spin proof test.

(2) Establish that the spin proof test adequately screens for flaws (section 8.1 in this NASA Technical Standard) and that this approach for flaw screening is approved by the RFCB.

Proof tests are usually performed in the operational environment, or the test levels are adjusted via an ECF.

In section 7.2.7 of NASA-STD-5019A, there are two top-level items and additional detailed requirements describing ways rotating hardware may be shown to satisfy requirements for classification as acceptable fracture critical rotating hardware.

NASA-STD-5019A, Item 7.2.7.a

Item 7.2.7.a in NASA-STD-5019A imposes the appropriate general approach for fracture critical hardware assessments according to the material type. Refer to section 7.3 or 7.4 in this Handbook for discussions on satisfying the appropriate material type requirements. Satisfying this requirement provides assurance the rotating hardware will have adequate damage tolerance strength for the hardware lifetime for the applied loadings.

This requirement does not specifically address the non-rotating structures that are supporting the rotating hardware. The non-rotating supporting structures should also satisfy fracture control requirements as the rotating hardware would have a failure mode due to inadequate supporting structure if not included.

All anticipated significant loadings have to be assessed in structures subject to fracture control assessments as required in section 7.3.1 in NASA-STD-5019A. There is a possible loading that is unique to rotating hardware that should be included in the assessment loads if it is a credible loading event. Rotating hardware may experience a sudden stop that could potentially cause very large impulsive loads on the structures. The sudden stop loading is described in section 6.1.3.c(3) in this Handbook. Additionally, item 6.1.3.c(3), including items A and B under that item in this Handbook, describe approaches that could be utilized to make the sudden stop scenario a non-credible event.

NASA-STD-5019A, Item 7.2.7.b

Item 7.2.7.b in NASA-STD-5019A requires the hardware to be subjected to a spin proof test at an elevated rotational speed and specifies a factor of 1.05 is to be applied. The requirement is stated as "minimum rotational energy factor of 1.05." The rotational kinetic energy is $0.5*\mathbf{I}\boldsymbol{\omega}^2$ where $\mathbf{I}$ is the rotor mass moment of rotational inertia at rotational speed $\boldsymbol{\omega}$**.** Since $\boldsymbol{\omega}$ is squared for computing the rotational kinetic energy, to get the factor is applied to this term directly and sits under the square root. Stating it simply, the minimum proof test speed has to be equal to the maximum rotational speed multiplied by the square root of 1.05. This spin test loading will provide a small margin to assure the rotor strength exceeds the design in the as-built condition.

In addition to the spin proof test, the structure is to be assessed by the requirements in either item 7.2.7.b(1) or 7.2.7.b(2) in NASA-STD-5019A. These additional requirements are different ways of assuring the rotating structure fracture control lifetime satisfies the applicable fracture control requirements in either section 7.3 or 7.4 in NASA-STD-5019A, according to the type of hardware material.

NASA-STD-5019A, Item 7.2.7.b(1)

Item 7.2.7.b(1) in NASA-STD-5019A requires NDE to be performed on the rotor before and after the spin proof test in accordance with the requirements in section 8.1 in NASA-STD-5019A. Refer to section 8.1 in this Handbook for details on satisfying requirements for flaw screening. The purpose of this requirement is to ensure the NDE capability to detect flaws is sufficient for screening so that flaws will not grow to critical size and cause structural failure during the hardware lifetime, including the required service life factor.

NASA-STD-5019A, Item 7.2.7.b(2)

Section 7.2.7.b(2) in NASA-STD-5019A requires the spin proof test to adequately screen for flaws of a size that could grow to critical size and cause structural failure during the hardware lifetime, including the required service life factor. This section also requires the flaw screening approach to be approved by the RFCB.

In addition, section 8.1.3 in NASA-STD-5019A has the following requirement:

> "[FCR 18] If proof testing is used as the flaw screening technique for fracture critical parts, the approach shall be documented in the FCP with rationale establishing that it is an applicable approach that has been approved by the RFCB."

> *"[Rationale: Proof test may be used for flaw screening. However, few parts, materials, and applications lend themselves to a simple proof test strategy. Environmental effects, temperature, test fixture, inertial loads, and other complexities require careful consideration before accepting proof as the sole method for flaw screening. If proof test is used for flaw screening, an understanding of the planned approach and anticipated effectiveness needs to be approved by the RFCB and documented in the FCP.]"*

Refer to section 8.1.3 in this Handbook for further discussion on the use of proof testing as a flaw screening technique.

Additionally, guidance at the end of section 7.2.7 in NASA-STD-5019A advises that proof tests such as the ones required for fracture critical rotating hardware by a spin test are usually performed in the operational environment. In the event that test is not feasible, the proof test loading can be conducted at other test conditions provided the loading is adjusted by an ECF factor to accomplish the required goal of the testing. In this situation, the approach and justification for the ECF factor have to have RFCB approval.

7.2.8 Fracture Critical Fasteners (NASA-STD-5019A, Section 7.2.8)

NASA-STD-5019 A
7.2.8 Fracture Critical Fasteners

Satisfy the following for fracture critical fasteners to meet requirement [FCR 11] section 7.2.h in this NASA Technical Standard:

a. Design, fabricate, purchase, and implement fracture critical fasteners with all of the following attributes.

(1) Fasteners are fabricated from a metal with high resistance to stress corrosion cracking, as defined in MSFC-STD-3029.

(2) Fasteners are fabricated, procured, and inspected in accordance with NASA-STD-6008, and an equivalent military standard, NAS, proprietary, or commercial aerospace specification approved by the RFCB.

(3) The fastened joint complies with NASA-STD-5020 without joint separation in the nominal configuration.

(4) Fasteners have rolled threads and are assessed to demonstrate they meet the fatigue requirements in NASA-STD-5001.

(5) Fasteners manufactured from titanium alloys require additional coordination with the RFCB for approval.

Titanium alloys, such as Ti-6Al-4V (including annealed and STA conditions), cp-Ti, and other titanium alloys, have potential generic EAC or SLC failure modes that are to be addressed in the assessment with test data from flawed fasteners in the applicable service life environments.

(6) The fasteners are not made from a low fracture toughness alloy, as defined in section 3.2 in this NASA Technical Standard.

(7) Fasteners are not reworked or custom made unless the application is approved by the RFCB.

b. Include preload and its effect on flaws and cyclic stresses in the damage tolerance assessment.

c. Inspect all fracture critical fasteners by the eddy current NDE technique or use proof testing to screen for flaws.

> d. Assume a flaw in the most critical location of a size consistent with NDE sensitivity or proof-test level in the damage tolerance analysis.
>
> *General NDE flaw sizes are given in NASA-STD-5009, Nondestructive Evaluation Requirements for Fracture Critical Metallic Components; but for specific guidelines on eddy current methodology, PRC-6509, Process Specification for Eddy Current Inspection, can be used as a reference.*
>
> e. Proof-load test inserts used in conjunction with fracture critical fasteners to a minimum factor of 1.2 after installation.
>
> *This would include, for example, inserts bonded or potted into composite and sandwich structures, as well as inserts installed into metallic structures. Note that composite structures require additional considerations, as given in section 7.4 in this NASA Technical Standard.*
>
> f. Store and control fracture critical fasteners after inspection or testing to keep them isolated from other fasteners.

Designers and analysts are encouraged to design fastener applications for classification as NFC low-released mass, contained, low-risk or fail-safe. Potential catastrophe due to a single fastener failure should also be avoided. Fasteners that do not comply with the various NFC criteria detailed in NASA-STD-5019A, section 6.1.1, should be classified fracture critical.

Fracture critical fasteners have to satisfy the requirements of NASA-STD-5019A, section 7.2.h, to meet [FCR 11], which requires compliance with the details of section 7.2.8. This includes the design, manufacture, procurement, and use of fracture critical fasteners following various NASA standards, namely:

a. Using materials not sensitive to stress corrosion cracking (see MSFC-STD-3029, Guidelines for the Selection of Metallic Materials for Stress Corrosion Cracking Resistance in Sodium Chloride Environments).

b. Using fasteners fabricated, procured, and inspected according to a military, NAS, or equivalent approved commercial aerospace specification to satisfy NASA-STD-8739.14, NASA Fastener Procurement, Receiving Inspection, and Storage Practices for NASA Mission Hardware.

c. Designing fastened joints with positive separation margins per NASA-STD-5020, Requirements for Threaded Fastening Systems in Spaceflight Hardware, sections 4.3 and 6.5.

d. Employing fasteners with rolled threads which meet fatigue requirements of NASA-STD-5001.

e. Avoiding use of low fracture toughness materials as defined by NASA-STD-5019A, section 3.2.

f. Not be reworked or custom made without prior RFCB approval.

Fracture critical fasteners should be of the highest aerospace quality manufactured from alloys such as A286 steel, 300-series CRES, Inconel® 718, MP35N alloy, or similarly fracture tough and environmentally compatible material. Procurement specifications are presented in section 6.1.1.4 above.

Fracture critical fasteners in tension and/or bending have to be assessed for damage tolerance. Preload and its effect on flaws and cyclic stresses should be considered in the damage tolerant assessment through all phases of the mission (i.e., fracture spectra). The methodology provided in NASA-STD-5020 should be used in calculating the preload in a fracture fastener (i.e., see section 6.1). Further, one should consider whether it will be acceptable to remain conservative for the analysis and assume that all external alternating “live” load is experienced by the fastener versus shared with the joint; see section 6.2.1.2 and associated Appendices of NASA-STD-5020 for details.

All fracture critical fasteners have to be inspected by an acceptable NDE technique or proof tested to screen for flaws. Eddy current techniques are considered the standard approach for fasteners. Dye penetrant inspection is *not* recommended; the acid etch cleaning step cannot be used appropriately in the threaded region. Fasteners less than 5 mm (0.19 in) in diameter should be avoided, if possible, for fracture critical applications due to the difficulty in the NDE inspection of these small thread sizes and/or fillet head radii. Damage tolerant analysis should assume a flaw in the thread root and head transition of a size consistent with the NDE sensitivity (or proof test level) per NASA-STD-5009. As an example, the fastener integrity requirements outlined at NASA/GSFC per 541-PG-8072.1.2A, Goddard Space Flight Center (GSFC) Fastener Integrity Requirements, call for traceability, material test reports, tensile testing and 100% visual, dimensional, hardness, and NDE inspection. In lieu of hardness and NDE testing, the requirements do allow for 100% proof testing (per 541-WI-5330.1.16B, Proof Testing of Flight Hardware Fasteners) where the load applied establishes the largest flaw that may be present in the loaded portion of the fastener. Note that this testing is non-destructive when acceptable results are met. Unfortunately, in many cases it will not be possible to apply a sufficiently large proof load to detect the critical flaw size for crack growth analysis without causing general yielding of the fastener. For these cases, NDE is required.

If the crack growth analysis software NASGRO® is to be used for damage tolerance assessments, the following geometric crack cases should be considered for applicability with fracture critical fasteners (see section 2.2.1 of the NASGRO® User Manual for additional details):

TC07: Through crack (axial) in hollow cylinder.
TC08: Through crack (circumferential) in hollow cylinder.
SC07: Semi-elliptical surface crack (circumferential) in a solid cylinder.

SC08: Semi-elliptical surface crack (circumferential) in a threaded solid cylinder.
SC09: Constant-depth surface crack (circumferential) at thread root in cylinder.
SC10: Constant-depth surface crack (circumferential) in threaded pipe.
SC13: Semi-elliptical surface crack in bolt head fillet - shear bolt.
SC14: Semi-elliptical surface crack in bolt head fillet - tension bolt.

Including preload in fastener crack growth analysis using NASGRO® is implemented through a checkbox on the “Load Blocks” Tab below the Block Case Definition window. One should note that the mean value is added before the block is scaled by the given scale factors; ensure that all units are consistent before using (see section 2.2.5.1 of the NASGRO® User Manual for more information).

Fracture critical shear pins and fasteners used in applications designed primarily for shear loading (where bending stresses may be present) should also be assessed for damage tolerance and examined for crack-like flaws.

Pins, tangs, and/or lock wire used for assurance against fastener back-off, nuts, threaded inserts, and any similar fastener parts have to be of the highest aerospace quality when used in a fracture critical fastener application. These items are not classified as fracture critical and are exempt from fracture control, but it is required that this hardware be used with appropriate specifications and installation procedures.

Because of the unique materials, loading conditions, configurations, sizes, and/or stress distributions, a damage tolerant analysis of inserts is not feasible, nor is NDE possible. Inserts used in conjunction with fracture critical fasteners have to be proof-load tested to a minimum factor of 1.2x DLL after installation. This would include, for example, inserts bonded or potted into composite and sandwich honeycomb panel structures, as well as inserts installed into aluminum hardware.

Installation of fracture critical fasteners that rely on preload for structural performance, such as joint stability, control of fatigue stress range, etc., should employ appropriate proven methods to accurately apply required preloads; refer to NASA-STD-5020 for further guidance.

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

7.2.9 Fracture Critical Shatterable Components and Structures (NASA-STD-5019A, Section 7.2.9)

> **NASA-STD-5019 A**
> **7.2.9 Fracture Critical Shatterable Components and Structures**
>
> Satisfy the following for fracture critical shatterable components and structures to meet requirement [FCR 11] section 7.2.i in this NASA Technical Standard:

a. Follow the requirements contained in NASA-STD-5018 for fracture critical shatterable components in internal volumes.

b. Coordinate with the RFCB for fracture critical external shatterable components and structures.

Section 7.2.9 in NASA-STD-5019A describes the NASA fracture control requirements imposed upon fracture critical shatterable components and structures. To clarify which hardware is addressed by this section, the meaning of these terms has to be understood. The definitions are supplied in section 3.2, Definitions, in NASA-STD-5019A and in the same section in this Handbook and are discussed below.

In section 3.2, a component is defined as "a hardware unit considered a single entity for the purpose of fracture control" and also states "a component contains at least one part." Section 3.2 also states "part: hardware item considered a single entity for the purpose of fracture control." The term "structure"' is not defined in section 3.2; the context of use of this term in NASA-STD-5019A implies it is a part or a combination of parts that supports loads. In this Handbook section, the terms "component" and "structure" and "hardware" will be treated for fracture control as synonymous to the definition of "part," and it is presumed the part performs as a structure that supports loads during the service lifetime of the hardware.

The requirements in this section target "Fracture Critical Shatterable Components and Structures." Fracture critical parts are discussed in section 7 and 7.1 in this Handbook. As explained in section 7.1.a and b in this Handbook, fracture critical parts require mitigation activities to avoid catastrophic failure caused by a flaw. To evaluate the risk of failure due to a flaw, the part's sensitivity to flaws has to be known. Then, inspections may be used to exclude parts with critical size flaws. Also, knowledge of the part's sensitivity to loadings and damage sources that cause creation or growth of flaws is needed to assess the risk of a critical flaw developing during the part's service lifetime. Protection and redundant design strategies may help avoid risks of damage resulting in catastrophic failure due to a flaw during the part's service lifetime.

Shatterable materials are defined in section 3.2 in NASA-STD-5019A and in this Handbook as "any material that is prone to brittle failures during operation that could release many small pieces into the surrounding environment." The usual nature of shatterable materials is they may fail due to small cracks and crack-like defects. This may limit the practicality of the usual approach using NDE to screen the structure for critical size flaws. Flaw screening of fracture critical parts is a requirement per [FCR 15] in section 8 of NASA-STD-5019A, so it has to be performed. The particular type and implementation of the NDE should be selected to provide the maximum benefit for implementation of fracture control for the shatterable component or structure.

There are two unique aspects of shatterable components and structures that need to be considered and are also discussed in section 6.1.2 in this Handbook:

1. What is the consequence of the brittle failure of the component or structure, meaning a loss of structural capability, and

2. What is the consequence of the failure producing "many small pieces into the surrounding environment"?

Both aspects are addressed in this section that imposes two requirements, items 7.2.9.a and 7.2.9.b that are discussed below.

NASA-STD-5019A, Item 7.2.9.a

Item 7.2.9.a imposes the requirements in NASA-STD-5018, Strength Design and Verification Criteria for Glass, Ceramics, and Windows in Human Space Flight Applications Requirements for Threaded Fastening Systems in Spaceflight Hardware, for fracture critical shatterable components in internal spaces. One aspect this item addresses is the risk to humans if the component is in a habitable environment. Section 4.8.5, Containment, in NASA-STD-5018 states:

> "Materials that can shatter shall not be used in inhabited compartments unless positive protection is provided to prevent fragments greater than 50 μm (0.0020 in) maximum dimension from entering the cabin environment."

As discussed in section 6.1.2.1.a(2), if the shatterable component was being assessed as NFC per section 6.2.2 in NASA-STD-5019A, it would need to be in an enclosure providing containment, and the container would need to ensure fragments of the hardware exceeding 50 μm (0.0020 inches) in size could not escape from the containment. If the container had any openings, they would need screens that prevented escape of larger fragments.

Similarly, if the hardware being assessed per the requirements of this section 7.2.9 may be in a habitable volume during its service lifetime, the method of satisfying requirements in this section would also have to demonstrate the risk of release of fragments larger than 50 μm (0.0020 inches) was controlled.

In addition, if the shatterable component is not in a habitable environment but is in an enclosed volume or a location where debris fragments from a fracture of the component could affect the performance or function of other critical hardware, the consequences of that possibility would need to be assessed and included in the approach to mitigate the risks due to a fracture of the shatterable component or structure.

NASA-STD-5019A, Item 7.2.9.b

Item 7.2.9.b requires coordination with the RFCB which has to approve the approach and implementation of the methodology that is proposed to satisfy fracture control requirements as discussed in sections 7 and 7.1 in this Handbook for fracture critical external shatterable components and structures.

Item 7.9.2.b in NASA-STD-5019A does not prescribe an approach to satisfy fracture control requirements. The choices that could be used resulting in classification of the shatterable component in an NFC category are discussed in section 6.1.2 in this Handbook. Those approaches are presumably not applicable for situations with shatterable components being assessed per section 7.2.9.

There are no established approaches for fracture critical external shatterable components and structures that are imposed by this section. Each situation should be addressed with a suitable approach that is devised so it satisfies fracture control requirements and addresses all risks resulting from fracture of the external shatterable component. The effectiveness of a proposed approach to eliminating risks of a catastrophic fracture event should be established and the approach documented in the FCP that is presented to the RFCB for approval.

For example, suppose it was feasible to specify a design of the external shatterable component part(s) and related structures so as to be redundant, so that the hardware could perform all required functions without loss of capability if one or some probable number of the shatterable components experienced a fracture event. Suppose further it could be demonstrated that the risk of collateral damage from a fractured shatterable component was controlled, and that fracture of more than one or two of the shatterable components was remote due to implemented designs or fracture control activities such as a DTA, IDMP, and RTD as discussed in section 7.4. If the approach provided complete, comprehensive controls and activities and was demonstrated to satisfy all damage tolerance and structural requirements to prevent a catastrophic fracture event, it may be amenable to being classified under the requirements of section 7.2.9. Note also that such an approach would have to assess the effect of the external vehicle debris field criterion on the shatterable component(s) and the effect of a fracture of the shatterable external component(s) on the size and composition of the external vehicle debris field.

Refer to section 6.2.1(4) in NASA-STD-5019A for the requirements and guidance on the external vehicle debris field. There is also discussion in section 6.2.1 in this Handbook on the aspects of NFC low-released mass and the acceptable external debris field. The section 6.2.1(4) requirement and guidance are copied below:

> "6.2.1(4) External released mass or parts, including those that would be subjected to aerodynamic flow, may only be classified low-released mass when the program has established an acceptable debris field criterion and the parts fall within it."
>
> *"The program should provide the launch vehicle acceptable debris field criteria. The program or launch payload integrator has to address concerns of impact on adjacent payloads and other spacecraft."*

7.2.10 Fracture Critical Tools, Mechanisms, and Tethers (NASA-STD-5019A, Section 7.2.10)

NASA-STD-5019A:
7.2.10 Fracture Critical Tools, Mechanisms, and Tethers

The following are to be applied to fracture critical tools or mechanisms that are the only (no backup) means for performing a function where failure to perform the function would result in a catastrophic hazard or a tool or mechanism whose failure during use would, in itself, result in a catastrophic hazard. This classification includes safety-critical tethers.

Satisfy the following for fracture critical tools, mechanisms, and tethers to meet requirement [FCR 11] section 7.2.j in this NASA Technical Standard:

a. Perform NDE and damage tolerance assessment (as described in section 7.3 or section 7.4 in this NASA Technical Standard) for each fracture critical tool or mechanism to assure that flaws that could cause failure during use are not present.

b. Fracture critical springs require RFCB approval.

c. Qualification, design life verification, and acceptance testing are to comply with NASA-STD-5017, Design and Development Requirements for Mechanisms, for fracture critical mechanisms.

When NDE methods are not sufficient to screen for critical defects, rationale should be presented to the RFCB for approval that could include proof testing, statistical life testing, and other mechanical testing and analysis to provide further understanding of defect sensitivity in the part.

Springs should be designed to be fail-safe or redundant.

Tethers should be proof tested, inspected, and assessed for damage in accordance with applicable operational requirements.

Proof tests are usually performed in the operational environment, or the test levels are adjusted via an ECF. Other requirements such as NASA-STD-5001 provide proof test levels.

Section 7.2.10 in NASA-STD-5019A describes the NASA fracture control requirements imposed upon fracture critical tools, mechanisms, and tethers.

Tools are devices that are manually manipulated by a crew member to perform some activity with another object or perform a structural function. Mechanisms are defined in section 3.2 in NASA-STD-5019A as "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." Tethers provide a restraining action upon other parts.

The NFC category for tools, mechanisms, and tethers is discussed in section 6.1.5 in this Handbook. That section describes an approach for assessing hypothetical hardware that may be in several classifications during different phases of the part's lifetime, including this fracture critical classification during part of the lifetime. In section 7.2.10, it will be assumed the hardware is classified as fracture critical throughout its mission lifetime.

Guidance is provided in the beginning of this section in NASA-STD-5019A that clarifies this section is applicable to tools and mechanisms that are the only (i.e., have no backup) means for performing a function, where failure to perform the function would result in a catastrophic hazard. The guidance also notes this section applies to a tool, mechanism, and safety-critical tether whose failure during use would result in a catastrophic hazard. A safety-critical tether would be identified as part of the safety analysis process described in section 2.2.3 in NASA Procedural Requirements (NPR) 8705.2, Human-Rating Requirements for Space Systems, identified as Requirement 58378.

NASA-STD-5019A, Item 7.2.10.a

Item 7.2.10.a requires NDE and damage tolerance assessment to be performed on each tool or mechanism in accordance with NASA-STD-5019A NDE requirements in section 8 and the damage tolerance requirements in either section 7.3 for metallic or section 7.4 for composite or bonded hardware. The loadings experienced during the hardware lifetime for its certified usages will be needed, which should be established by testing or analyses.

Guidance in section 7.2.10 suggests if NDE methods cannot screen for the size of defects that are needed to establish the required damage tolerance life, this section suggests an alternative would be to develop a rationale and present it to the RFCB for approval for a different approach. Suggested approaches in the guidance include proof testing, statistical life testing, and other mechanical testing and analysis that provide understanding of the hardware defect sensitivity.

In addition, guidance in section 7.2.10 addresses assessment of tethers, and states:

> *Tethers should be proof tested, inspected, and assessed for damage in accordance with applicable operational requirements.*

And guidance regarding proof testing states:

> *Proof tests are usually performed in the operational environment, or the test levels are adjusted via an ECF. Other requirements such as NASA-STD-5001 provide proof test levels.*

NASA-STD-5019A, Item 7.2.10.b

Item 7.2.10.b in NASA-STD-5019A requires fracture critical springs to be approved by the RFCB. Guidance in this section states springs should be designed to be fail-safe or redundant.

Springs are discussed in NASA-STD-5017A in section 4.10, where the following guidance is provided:

> *Springs are a common mechanism component as well as a common source of problems. Spring redundancy can greatly improve mechanism reliability. There are two ways to achieve redundancy in a spring, as follows: (1) a second spring can be used, (2) use of a spring that retains functionality after one coil or element of the spring (e.g., a single conical spring in a stack) is fractured or otherwise compromised. Note that this last option generally requires use of a compression spring and that in the case of coil springs, the wire diameter and coil pitch have to be such that the two spring halves cannot thread into each other after a fracture.*
>
> *Determining that a spring failure is not credible requires demonstrating that adequate life and stress margins exist on the part. This can be accomplished with a combination of stress analysis, fatigue analysis, fracture control methods, and testing. Given the size of many springs used in mechanisms, fracture approaches are often not feasible and other steps have to be taken to demonstrate reliability.*
>
> *More information on spring use and design is available in Appendix A. [The reference is found to be item A.2.5 in the NASA-STD-5017A appendix. This item provides detailed discussions of spring issues, recommended designs, and factors of safety.]*

NASA-STD-5019A, Item 7.2.10.c

Item 7.2.10.c of NASA-STD-5019A requires qualification, design life verification, and acceptance testing of fracture critical mechanisms to comply with NASA-STD-5017. The latest version of the standard should be used. Review of the standard shows it has comprehensive coverage of the topic, with clearly defined requirements supplemented by detailed guidance and backup information in Appendix A.

An additional comment on "NFC Fail-Safe" classification after failure of a part of a mechanism in section 6.2.3.a, NFC Fail-Safe, permits a redundant structure to be classified as NFC Fail-Safe if:

> Documented assessment establishes that loss of any load path does not result in a catastrophic hazard and that risk of loss of the structural redundancy because of multi-site fatigue or damage of redundant load path structures from any source during the service life of the structure is not a credible concern.

The above cited classification requirements are not sufficient and do not apply for fracture critical mechanisms. A fracture critical mechanism may have a number of redundant load paths such that the loss of one load path does not lead to a local structural failure in the mechanism. The mechanism likely also has complex moving parts with interfaces that generate structural dynamic loads that affect structural integrity and the mechanism performance. This is discussed in NASA JSC Letter ES4-07-031 dated 6/19/2007 on Fracture Control of Mechanisms shown in Appendix A.

7.2.11 Fracture Critical Batteries (NASA-STD-5019A, Section 7.2.11)

NASA-STD-5019A:
7.2.11 Fracture Critical Batteries

Satisfy the following for fracture critical batteries to meet requirement [FCR 11] section 7.2.k in this NASA Technical Standard:

a. Comply with JSC 20793, Crewed Space Vehicle Battery Safety Requirements.

b. Comply with section 7.5.5 in this NASA Technical Standard for fracture critical batteries.

Section 7.2.11 in NASA-STD-5019A describes the NASA fracture control requirements imposed upon fracture critical batteries. NFC batteries are addressed in section 6.1.6 in this Handbook. Both types of batteries may be used in spaceflight systems and in accessories utilized by astronauts. They often contain toxic materials and may be subject to pressure and thermal cycling as they are charged and discharged. They may present a safety concern; in that case, controls are in place as discussed in section 6.1.6 and this section in this Handbook.

NASA-STD-5019A, Item 7.2.11.a

In item 7.1.11.a of NASA-STD-5019A, the fracture critical batteries have to comply with the requirements in NASA Johnson Space Flight Center JSC 20793, Crewed Space Vehicle Battery Safety Requirements. The current document is revision D dated March 2017. It has the following detailed descriptions of batteries for NASA missions.

JSC 20793, section 4.1.3, states:

> "Three levels of risk classifications have been defined for battery systems included in this specification. Threshold limits are defined based on contained energy and experience with specific manufacturing methods and cell formats. Safety of crew, vehicle, and mission may be a factor in selecting the appropriate classification. For systems which do not confirm with established limits, the next higher level of classification is recommended. Threshold limits are defined for each chemistry in section 6 of this document."

The three levels of risk classifications are Non-Critical, Critical, and Catastrophic as described below:

- Non-Critical – the lowest level of hazard control is reserved for low energy cells and battery designs for which standard emergency procedures are written and practiced. This classification level includes the following battery characteristics:
  - Low energy < 4 Wh per battery pack where each battery is thermally and electrically isolated (or < 60Wh for alkaline primary batteries) where Wh = Cell Capacity (Ah) × Cell Voltage (V), and
  - Rated with a toxicological level of 1 or 2, and
  - Contained within a not intentionally sealed compartment, and
  - Meet one of the following criteria for its chemistry:
- Alkaline Primary Batteries - Alkaline (non-rechargeable) cells in sizes D or smaller with a maximum of 12 V and/or 60 Wh and with cells either all in series or all in parallel and with no potential charging source and with the cells located in a vented compartment. Silver oxide cells are considered within this category.
- Lithium-ion Secondary Batteries – Commercial off-the-shelf (COTS) (rechargeable) lithium-ion button, cylindrical, or pouch batteries of up to 1000 mAh capacity. Battery is defined as one cell or a packaged or unpackaged assembly of two or more cells.
- Lithium Primary Batteries - COTS (non-rechargeable) lithium button cells (only Li-MnO2, Li-CFX and LiFeS2) of up to 1000 mAh capacity.
- Nickel Cadmium Batteries - Nickel-cadmium (rechargeable) batteries and cells of up to 1000 mAh capacity.
- Nickel-Metal Hydride Batteries - Nickel-metal hydride (rechargeable) silver ox batteries and cells of up to 1000 mAh capacity.
- Silver-Zinc Batteries - Silver-zinc (rechargeable) batteries and cells of up to 1000 mAh capacity.
- Zinc-Air Primary Batteries - Zinc-air (non-rechargeable) batteries and cells of up to 1000 mAh capacity.
- *Note: For primary cells, rated cell capacity is defined as the maximum stated capacity per cell product data sheet.*

- Critical – the intermediate level of risk classification requiring single-fault tolerance typical of commercial devices manufactured in high volumes for the global consumer. Batteries within this “Critical” classification shall be one of these chemistries and do not meet the “Non-Critical” classification:

  - Lithium Ion Secondary Batteries – COTS (rechargeable) lithium ion of less than 20 V and 60 Wh
  - Nickel Cadmium
  - Nickel Metal Hydride
  - Silver Zinc
  - Alkaline Primary
  - Lithium Primary
  - Zinc-Air

- Catastrophic – the highest level of risk classification requiring two-fault tolerance typical of custom, high-energy, or high-power designs.

The non-critical classification of fracture control is discussed further in section 5.1.1.1.g and provides a list of ways that classify batteries as non-fracture critical. Item 5.1.1.1.g(3) states:

> "Small batteries that fall under the noncritical category (see 4.1.3) are exempt from fracture control."

The process for classifying parts such as batteries in the non-critical category as exempt parts is described in section 5 in NASA-STD-5019A and sections 5 and 6.1.6 in this Handbook.

JSC 20793 imposes safety controls on these battery classifications. Key aspects of Engineering Evaluation, Qualification, and Acceptance Testing are discussed in section 4.2. Refer to JSC 20793 for details of the requirements and controls imposed on each battery classification.

NASA-STD-5019A, Item 7.2.11.b

Item 7.2.11.b of NASA-STD-5019A requires fracture critical batteries to comply with section 7.5.5, Fracture Critical Experiment Hazardous Fluid Containers, in NASA-STD-5019A.

The relevant guidance in the beginning of section 7.5.5 states it is limited to "payload and experiment applications at conditions defined in requirements below." A fracture critical battery is not likely to be an experiment, but it may be part of a payload or an experiment.

The requirements imposed in section 7.5.5 are listed below by their section letter and are discussed briefly with respect to fracture critical batteries. The guidance at the end of section 7.5.5 is copied at the end of discussion of section 7.2.11.b and should be followed when demonstrating the following requirements are satisfied:

7.5.5.a) The container is limited to an MDP of 152 kPa (22 psi, 1.5 atm) and a maximum volume of 0.05 m^3 (1.76 ft^3).

The battery design and certifications should be compatible with these requirements. If in doubt, testing could be used to determine the internal volume of the battery and whether it can withstand this amount of pressure.

7.5.5.b) An analysis is to show a positive margin against burst when a factor of 2.5 on MDP is used.

The battery compartment has to be a sealed container to withstand pressure without leaking. Analysis is required to demonstrate a positive margin against burst in the container structure at the specified pressure.

7.5.5.c) Perform proof test to 1.5 MDP.

The proof test must be performed and documentation certify that the required pressure was achieved.

7.5.5.d) Establish that no damage or detrimental deformation exists after the proof test.

This requires a dimensional inspection be performed before and after the proof test. A post-test NDE inspection is required by item "7.5.5.d" and also item "7.5.5.f," with documentation showing the requirement has been met.

7.5.5.e) Establish damage tolerance against rupture and leak by satisfying sections 8 and 9 in NASA-STD-5019A for all materials, section 7.3 in NASA-STD-5019A for metallic parts, section 7.4 in NASA-STD-5019A for composite or bonded parts, and by test or analysis as approved by the RFCB for other materials.

The requirement is to be satisfied according to the material composition of the battery pressure wall and structural supports and documented whether the requirement is met by analyses or testing and be approved by the RFCB.

7.5.5.f) In addition to section 8 requirements in NASA-STD-5019A, perform an NDE inspection of all fusion joints in the container after proof test to determine acceptable conditions both on the surface and within the fusion joint.

The required NDE inspection of the fusion joints, both their exterior surface and a volumetric inspection of the weld interior, has to be performed and documented.

7.5.5.g) Perform a leak test to 1.0 times the MDP.

The leak test has to be performed to the required pressure and documented.

In instances where NDE is not feasible, the manufacturer may employ a process-control program that assures the quality of the un-inspectable welds and obtain approval of the RFCB.

Proof tests are usually performed in the operational environment, or the test levels are adjusted via an ECF.

Inertial load effects (including attach points) may necessitate additional assessments beyond the items in this category.

The guidance about inertial load effects relates to the possibility the structure may experience peak stresses at or beyond the attachment points due to inertial accelerations. If inertial loads stress attachment structure weld joints that are not inspected per requirements in this section, they should also be inspected.

7.3 General Approach for Fracture Critical Metallic Parts Assessment (NASA-STD-5019A, Section 7.3)

NASA-STD-5019A:
7.3 General Approach for Fracture Critical Metallic Parts Assessment

[FCR 12] Each fracture critical metallic part that is not of a specific hardware type as described in section 7.2 in this NASA Technical Standard and is not approved by the RFCB as appropriate for an optional approach as described in section 7.5 in this NASA Technical Standard shall comply with one of the following item combinations: a and b; a and c; or a, b, and c:

a. Develop loading spectra by complying with section 7.3.1 in this NASA Technical Standard.

b. Perform assessment by analysis to comply with section 7.3.2 in this NASA Technical Standard.

c. Perform assessment by test to comply with section 7.3.3 in this NASA Technical Standard.

[Rationale: Fracture critical parts need activities performed to understand the sensitivity of the part if a flaw is present. These activities can range from a direct assessment of the part's capability with a flaw to acceptance tests that establish the part has sufficient capability to a combination of activities that provide sufficient information to mitigate the risk of failure related to undiscovered flaws.]

Use of an alternative approach requires unique rationale and approval by the RFCB as described in section 10 [FCR 26] in this NASA Technical Standard. The approaches in this requirement are the preferred approaches if followed completely.

Damage tolerant assessment used as the basis for acceptance of a fracture critical metallic part establishes all of the following:

- *The relevant critical failure mode for the part is identified.*
- *The appropriate load spectra are applied.*
- *The appropriate initial flaw size in a worst-case orientation based on the screening method implemented, in the worst location, is used.*
- *Conservative material data and analysis methods are used.*
- *One of the following (each of which is detailed in this section) is established:*

- *The part has a minimum service life factor of 4.*

- *The part is single loading event hardware and has a factor of 1.4 on critical stress intensity factor or residual strength.*

A damage tolerance assessment is performed to understand the sensitivity of a part to flaws. The requirement is necessary to mitigate risk of failure because of flaws that may still exist after implementation of flaw screening strategies. Fatigue-crack-growth empirical data have inherent scatter. When performing damage tolerance assessments, mean values are used, not a statistical lower bound. In addition, the prediction procedures have uncertainties related to the local stress levels, stress-intensity factor calculations, load spectra, and environmental effects. Errors in local stresses and stress-intensity factor calculations are grossly magnified when crack growth rates are evaluated while using the Paris growth law. Slight misjudgments of the spectrum can lead to large effects on crack growth. To account for all of these effects, a safety factor is applied on the predicted life. Thus, the life factor of 4 provides margin on uncertainties in analysis, prediction methodologies, and material property variations. The single load event factor of 1.4 on critical stress intensity factor, fracture toughness, or residual strength provides ultimate load capability with flaws that may go undetected and is representative of the requirements in NASA-STD-5001.

Generally, those parts identified as fracture critical have to be shown to be damage tolerant by analysis or test. In some cases, the part may be accepted for fracture control via a proof test of the flight article (see section 7.3.3). The damage tolerant demonstration is based on an initial flaw size that could be present in the part. This flaw size is traditionally established by NDE, process controls, or by proof testing. Analysis or test should consider all significant loadings, both cyclic and sustained, and in the appropriate environment that the part will experience during ground and flight phases. A load spectrum has to be developed as described in section 7.3.1.

7.3.1 Loading Spectra (NASA-STD-5019A, Section 7.3.1)

NASA-STD-5019A:
7.3.1 Loading Spectra

A loading spectrum is necessary for the damage tolerance life analysis or damage tolerance life test.

Develop loading spectra according to the following to satisfy requirement [FCR 12] section 7.3.a in this NASA Technical Standard:

a. Include all anticipated significant loadings, both cyclic and sustained, for each fracture critical part throughout its service life.

b. Include all load levels and the number of cycles or duration during the service life of the hardware, including proof test loads.

c. Include the effects of the appropriate environment for each fracture critical part throughout its service life.

d. Include the effects of preloads.

e. Include residual stresses and any weld joint discontinuities, such as peaking and mismatch, for cyclic and sustained loads during the service life of the hardware.

f. Include the influence of all coatings and barriers on pressure-loaded parts for any scenarios where pressure is assumed to decrease because of leakage from a crack.

g. Include the effects of impact loads and damage from mission environments, including but not limited to credible impacts from vehicle loss of external surface mass, MMOD, EVA inadvertent contacts, and EVA tool impacts during assessments of external structures and components.

Include the worst-case allowed or weld joint peaking and mismatch effects for damage tolerance assessments by analysis or test. The assessment analysis or test is to capture the effect of peaking and mismatch on stress gradients affecting crack growth and fracture. Standard tensile strength tests of ductile materials are not adequate to assess these conditions.

Proof load factors are listed in NASA-STD-5001 and may exist in program-specific requirements. Proof tests are usually performed in the operational environment, or the test levels are adjusted via an ECF.

A stress spectrum has to be developed for each fracture critical part when a damage tolerance assessment will be performed. The part's stress spectrum should include the stress level and the number of cycles or duration for each significant loading phase/event during the hardware's service life. Both cyclic and sustained stresses that the part will experience should be considered.

Typical loading phases or events and some examples of the types and sources of loads to be considered are listed in Table 7.3-1, Typical Hardware Phases and Potential Associated Loads and Stresses. Loads from the phases listed in this table should be considered, as applicable to a particular part. For example, a single mission payload would most likely have a single static strength test or a vibration test, a thermal vacuum test and a single launch load. On the other hand, a reusable launch vehicle may have been subjected to significant loads during proof testing, transportation (land, air, or sea), or ground-handling between flights in addition to those from multi-launches/ascents/descents and landings. All significant loadings and environments for all missions and events should be compiled into a service life for each fracture critical part. Effects of residual stresses and preloads have to be considered since they can affect the mean stress and thus the component service life. Welding joint discontinuities (e.g., inadequate joint penetration, overlap, etc.) and an autofrettage process of pressure vessels are examples of manufacturing steps leading to significant residual stresses that should be included in the load spectrum.

Table 7.3-1—Typical Hardware Phases and Potential Associated Loads and Stresses

PHASE/EVENT	**TYPE OF LOAD/STRESS**							
	Residual Stress	**Low Frequency**	**Random**	**Acoustic**	**Crew Induced**	**Thermal**	**Pressure**	**Shock**
Manufacturing	X							
Assembly/Preload	X							
Ground Handling		X			X			
Static/Proof Test	X	X					X	
Vibration Test		X	X					
Acoustic Test				X				
Thermal Vacuum Test						X	X	
Transportation		X	X	X	X	X		
Launch/Ascent		X	X	X			X	X
On Orbit		X	X		X	X	X	
Descent		X	X			X	X	X
Landing		X				X	X	X
Contingency Landing/Aborted Mission		X				X	X	

Assessments of damage tolerance for components have to include impact loads and damage from mission environments, including, but not limited to, credible impacts from failed parts, MMOD, EVA inadvertent contacts (kick loads), and EVA tool impact hazards. Note that for composite hardware, impact damage is a significant concern. Impact damage assessment to composite or bonded hardware is addressed in section 7.4.

For the analyst, trying to assemble the load spectrum can be daunting, especially early in programs when all the ground activities and even the number of missions may be still under discussion. The analyst and Program Manager have to work together *early* in the program to define the expected number of missions, possible number of aborts, modes of transportation, etc., so that an appropriate service life and anticipated load spectrum can be established for use in service life safety assessments and design.

After establishing the appropriate loading events for a particular part, the most critical locations of the part should be identified based on the location of the maximum level of local stress and cyclic stress ranges. Other critical locations might be those previously exposed to residual stresses (heat affected zones, weld fillers) or those that are exposed to harsh environments during operation (such as high temperatures or corrosive fluids) where material fatigue and fracture resistance properties are reduced.

The next step is to derive the maximum and minimum stresses at a critical location for all the appropriate loading events for damage tolerance analyses. One approach is to use the net section stress calculation along the expected crack path (usually assumed along the maximum principal stress direction) based on strength of material principles as outlined in NASGRO® User Manual, Appendix B, without a crack or an epsilon factor. Using this approach, the stress profile is separated into an axial stress component with two bending components for implementation in the standard NASGRO® stress intensity solutions. For complex parts where finite element results are obtained that may include stress concentrations and stress gradients, the stress profile can be applied as a user input for the univariant or bivariant nonlinear stress distribution along a crack plane for implementation in the more applicable NASGRO® stress intensity solutions.

The principal stresses are the recommended stresses to be used to define the minimum and maximum fatigue crack growth spectrum. To simplify the work, some analysts employ the von Mises stresses in their analysis claiming it is more conservative. This is not always the case but depends highly on the three-dimensional stress state at that location. Using the von Mises stress for fatigue crack growth analyses needs to be verified on a case-by-case basis to demonstrate conservatism.

For a simple load spectra, the rainflow counting algorithm per ASTM E1049-85, Standard Practices for Cycle Counting in Fatigue Analysis, can be used to establish the number of cycles and stress ranges. For a more complex loading history that includes random load types, more advanced methods are needed to estimate the cycle counts. An acceptable industry standard for narrow band random vibration processes is to assume that the probability distribution of the stress reaching a certain level during a time period at a certain frequency follows a Rayleigh probability distribution and the total number of cycles is simply the product of the event time duration and the natural frequency. Alternatively, NASGRO® User Manual, Appendix H, Loading Spectra for Acceptance Vibration Tests, provides methods to estimate an equivalent cycle count at the maximum stress level for various types of vibrations tests. On occasion, a payload launch spectrum is provided by the vehicle owner at a certain location in the payload bay based on actual flight data correlations, as seen in Table 7.3-2, Example of Payload Launch Load Spectrum.

Table 7.3-2 —Example of Payload Launch Load Spectrum

Load Step	Cycles per Flight	Cyclic Stress % of Limit Value	
		Minimum	Maximum
1	3	-100	100
2	2	-90	90
3	3	-80	80
4	3	-70	70
5	3	-60	60
6	9	-50	50
7	17	-40	40
8	540	-30	30
9	1,050	-20	20
10	9,420	-10	10
Total	11,050		

A simple example of the events that may comprise one lifetime for a fracture critical preloaded fastener experiencing ten handling loads, 4K miles truck transportation and 12K miles air transportation and a single launch is shown in Figure 7.3-1, Load Spectrum Example for a Single Launch. In this example, four events are included in one lifetime. Event 4 would include all the loads associated with a launch.

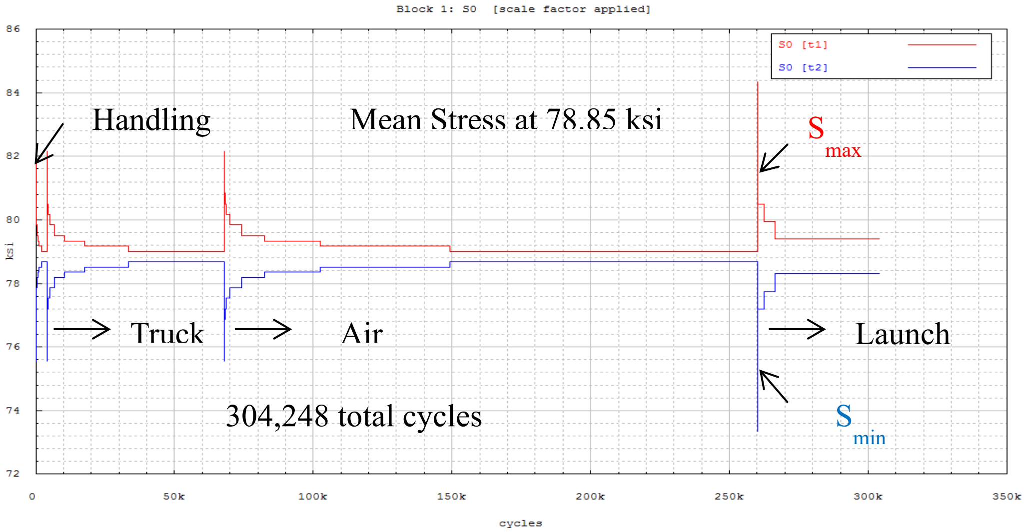


Figure 7.3-1—Load Spectrum Example for a Single Launch

7.3.2 Assessment by Analysis (NASA-STD-5019A, Section 7.3.2)

NASA-STD-5019A:
7.3.2 Assessment by Analysis

Satisfy the following to perform assessment by analysis to meet requirement [FCR 12] section 7.3.b in this NASA Technical Standard:

a. Assume that the initial flaw that could be present and undetected in the part is the size and shape that is not screened by NDE, proof test, or process control and is in the worst location and orientation.

b. Use analysis methods and computer programs that are approved by the RFCB, e.g., NASGRO®, for predicting flaw growth, life, and critical flaw sizes.

Note that when the available analysis ability to simulate crack growth is invalid, assessment by test (section 7.3.3 in this NASA Technical Standard) is required.

c. Establish that the assessed parts survive 4 lifetimes without failure (hazardous leak or fracture instability) by analyses that assess all applicable effects causing crack growth as a result of cyclic loadings.

(1) If the loading sequence of high/low loads is unknown, then damage tolerance analysis is to show that the stress intensity at limit load is less than the critical stress intensity factor or residual strength at the end of 4 lifetimes.

(2) If the service lifetime is a single event or the fatigue crack growth is small relative to the critical crack size (initial and critical cracks are of similar size), the analysis is to establish one of the following:

A. Reserve capability against fracture by meeting either a lower bound critical stress intensity factor or residual strength at the end of 4 lifetimes.

B. A factor of 1.4 on critical stress intensity factor or residual strength after 1 lifetime.

Assessments of metallic alloys that are susceptible to crack growth because of SLC or EAC during the service life are addressed in item 7.3.2.f below.

d. Use flaw growth rates that are greater than or equal to the average values without implementing retardation effects on flaw growth rates in the damage tolerance analysis.

e. Use critical stress intensity factor and cyclic threshold stress intensity range (ΔK_{th}) values that are less than or equal to the average values.

f. For metallic alloys susceptible to EAC or SLC or both, satisfy all of the following:

(1) Use the lower bound value of stress intensity factor threshold for assessment of EAC (K_{EAC} or K_{IEAC} as appropriate) and SLC if the material exhibits these behaviors in the application conditions.

(2) Show that the applied stress intensity factor related to the largest service load is smaller than the lower bound stress intensity factor thresholds determined in item (1) above at the end of 4 lifetimes.

Requirement 7.3.2.f is intended to preclude susceptible metallic alloy flight hardware from experiencing time-dependent, i.e. da/dt, crack growth.

g. If NASGRO® is used:

(1) B_k is either set to zero, or B_k is set such that K_c at the part thickness is less than or equal to the K_{Ic} value.

(2) Values of B_k resulting in $K_c > K_{Ic}$ require further understanding of the constraint condition for the crack situation and may be used with approval of the Technical Authority or RFCB.

h. Use fracture properties subject to all of the following:

(1) From sources or testing that are approved by the RFCB.

(2) Representative of the material process condition.

(3) Representative of weakest material orientation in the part (unless material orientation is fully traceable throughout the design and service life).

i. If material data needed for the damage tolerance assessment are not available, one of the following is to be accomplished:

(1) Obtain the data by material testing.

(2) If the source of the data to be used is from the literature, conduct an assessment to show that conservative results are obtained using that available data.

Section 8.1 in this NASA Technical Standard specifies flaw screening methods. The damage tolerance assessment is to address flaws that are not screened by the screening method applied to the flight hardware.

The NASGRO® computer program is an approved analysis tool for the damage tolerance life assessment of metallic spaceflight hardware. Other computer programs or analysis methods are acceptable with prior approval by the RFCB. The NASGRO® material database contains *fracture mechanics properties for several materials that can be used with concurrence from the RFCB.*

Standard NASA damage tolerance analyses are deterministic, and experience has shown these deterministic methods to be adequate. The probabilistic method uses knowledge (or assumptions) of the statistical variability of the damage tolerance variables to select criteria for achieving an overall success confidence level. Any proposed use of probabilistic damage tolerance analysis or criteria to meet fracture control requirements is considered an alternative approach as described in section 10 in this NASA Technical Standard and is approved by the RFCB on a case-by-case basis.

This is the second of three sections imposed by FCR 12 in section 7.3 that imposes requirements for assessing damage tolerance of fracture critical metallic parts. The purpose of these requirements is described in section 7.3 guidance which is copied below:

Damage tolerant assessment used as the basis for acceptance of a fracture critical metallic part establishes all the following:

- *The relevant critical failure mode for the part is identified.*
- *The appropriate load spectra are applied.*
- *The appropriate initial flaw size in a worst-case orientation based on the screening method implemented, in the worst location, is used.*
- *Conservative material data and analysis methods are used.*
- *One of the following (each of which is detailed in this section) is established:*
  - *The part has a minimum service life factor of 4.*
  - *The part is single loading event hardware and has a factor of 1.4 on critical stress intensity factor or residual strength.*

Section 7.3.2 utilizes the loading spectra generated per the requirements in section 7.3.1 in NASA-STD-5019A as discussed in this Handbook. Section 7.3.2 in NASA-STD-5019A imposes requirements on damage tolerance life assessments performed for metallic hardware using analysis methodology. Section 7.3.3 in NASA-STD-5019A imposes requirements for assessment performed by test, which is always an option. There are situations where assessment by analysis is not feasible. In that event, the assessment has to be performed by test.

The determination of the critical fracture locations and damage tolerance service lifetime of hardware may require multiple damage tolerance assessments. Hardware may have multiple types of catastrophic failure modes caused by inadequate damage tolerance or multiple similar failure modes at different locations. The type, size, and shape of initial flaws at each location have to be defined based on the method(s) used to screen the hardware for cracks. Each location should also be characterized in terms of the static and cyclic loading-induced stress states, the fracture strength, and the damage tolerance lifetime. Different initial assumptions of defect shapes and sizes may be needed at each location for these initial screening assessments to determine the most critical locations, defect sizes, and shapes. The results from these assessments determine the worst location, initial flaw characteristics, and the damage tolerance lifetime of the hardware.

For example, a structure may have welds in multiple locations in different members that could have initial defects. Damage tolerance analyses will be needed of the locations with the largest defects, largest applied stresses, the longest cyclic loadings, and the lowest fracture toughness or residual strength to determine which location is the most critical for the applied loads and defines the hardware damage tolerance lifetime. The summary of these assessments that documents the worst cases that define the damage tolerance service lifetime should be supplied as part of the required damage tolerance documentation provided in the Fracture Control Summary Report as specified by [FCR 24] in section 9.1.3.

Guidance in this section in NASA-STD-5019A that is applicable to these damage tolerance assessments is copied below.

Section 8.1 in this NASA Technical Standard specifies flaw screening methods. The damage tolerance assessment is to address flaws that are not screened by the screening method applied to the flight hardware.

The NASGRO® computer program is an approved analysis tool for the damage tolerance life assessment of metallic spaceflight hardware. Other computer programs or analysis methods are acceptable with prior approval by the RFCB. The NASGRO® material database contains fracture mechanics properties for several materials that can be used with concurrence from the RFCB.

Standard NASA damage tolerance analyses are deterministic, and experience has shown these deterministic methods to be adequate. The probabilistic method uses knowledge (or assumptions) of the statistical variability of the damage tolerance variables to select criteria for achieving an overall success confidence level. Any proposed use of probabilistic damage tolerance analysis or criteria to meet fracture control requirements is considered an alternative approach as described in section 10 in this NASA Technical Standard and is approved by the RFCB on a case-by-case basis.

NASA-STD-5019A, Item 7.3.2.a

Item 7.3.2.a of NASA-STD-5019A defines the first step in the fracture control assessment, which is to identify the worst initial flaw size, shape, location, and orientation that is not screened by the method(s) selected to screen for flaws in the hardware. There are three screening methods which could be used: NDE, proof test, or process control. NDE for metallic parts is discussed in section 8.1.1 in this Handbook. Proof testing to define initial flaw size is discussed in section 8.1.3 in this Handbook. Process control is discussed in section 8.1.4 in this Handbook. Analyses may also be needed for assessment of detected flaws, which is discussed in section 8.1.5 in this Handbook.

The flaws should be assumed to be the worst-case size, location, shape, and orientation to be the most critical flaw in the damage tolerance analyses of the hardware. Examples of a surface crack, an edge crack, and a buried crack are shown and described in section 8.1.1 in this Handbook that discusses NDE for metallic fracture critical parts. The Standard NDE flaw types and the reliably detectable crack size and shape for Standard NDE methods are specified in NASA-STD-5009.

The crack plane used for the damage tolerance assessment is the plane described by the crack length and depth with respect to the applied loadings. The orientation causing the minimum damage tolerance life may be one that is perpendicular to the maximum principal stress in the part at the crack location. In damage tolerance assessments, the assumption is made that a crack may exist anywhere in the hardware with an NDE detectable size, orientation, and shape that causes the hardware to have the lowest damage tolerance life. Multiple assessments will be needed to determine the type and characteristics of cracks in the hardware that result in the minimum damage tolerance life.

The sensitivity of NDE methods specified in NASA-STD-5009 provides data for a range of crack (a/c) aspect ratio end points that vary from 1.0 to 0.2. Flaws with different a/c aspect ratios have been reported to sometimes have a worst case at an intermediate a/c value that depends upon the combined effects of tension and bending stress fields. Studies illustrating this situation are reported in a paper titled "Some Observations on Damage Tolerance Analyses in Pressure Vessels" [58th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 9-13 Jan. 2017, Grapevine, TX; https://doi.org/10.2514/6.2017-0887]. A range of a/c values should be assessed to determine the worst-case flaw and damage tolerance lifetime for the applied stresses. The a/c aspect ratio values should be selected to bound the range of detectable crack aspect ratios specified in NASA-STD-5009 for the NDE method used to screen for cracks. To evaluate the effect of the aspect ratio, the a/c endpoints and at least three intermediate aspect ratios should be assessed. If there is a steep gradient in lifetime results for the sampled a/c aspect ratios, additional a/c values should be computed to define the worst-case situation.

NASA-STD-5019A, Item 7.3.2.b

Item 7.3.2.b of NASA-STD-5019A requires analysis methods to be used that are approved by the RFCB, such as NASGRO®, for predicting flaw growth, life, and critical flaw sizes. NASGRO® is the primary program that is expected to be utilized for fracture analyses of flight hardware. The program module for predicting fatigue crack growth is "NASFLA" using the "linear-elastic" analysis option based on LEFM. The program capabilities are described in the Main Reference Manual. It performs failure checks as the cracks grow as described in section 2.1.5, yielding checks as discussed in section 2.1.6; and it transitions from a surface or embedded crack to a through crack as crack growth occurs. It has a large library of crack geometries illustrated by sketches in the program graphical interface and manual section 2.2 that compute stress intensity factor and crack growth rates for the input stress spectrum. The program has a material database with crack growth rate data for common metallic flight hardware materials. Also, proprietary data can be input into NASGRO® for assessments. The user may manually input all the data each time or save an example in a file that can be edited to modify the input data. Other program modules can compute the stress intensity factor for a particular geometry, a critical crack size, and sustained stress crack growth for glass materials. Additional programs included are a boundary element module for computing stress intensity factors and a module to predict fatigue crack initiation.

In addition to the LEFM-based analysis modules, NASGRO® has fracture analysis capability that includes plastic material response for some of the most recent crack geometry models such as SC30. A list of the available crack configurations with this capability is given in the beginning of Appendix X on "Alternative Failure Criteria." These modules can assess situations involving plasticity such as the Plastic Limit Load (PLL), and the Failure Assessment Diagram (FAD). Use of these modules for assessment of LBB is described in sections 6.1.4c and 6.2.4a in this Handbook.

The NASGRO® NASFLA program also has an J integral analysis option for a few crack geometry cases if the "elastic-plastic" elasticity option is selected, but it is rarely used. For situations with significant plasticity, robust J integral-based Finite Element Analysis programs are commonly available (e.g., ABAQUS, ANSYS). This analysis technology may be used with the approval of the RFCB. The J integral data obtained from test specimen may or may not be appropriate transferrable quantities for assessment of a structural application. The more plasticity that is involved, the more complex the situation becomes for assessment of a structure.

Section 3.2, Definitions, in NASA-STD-5019A discusses the critical stress intensity factor and fracture parameters. It cites ASTM E2899. This standard addresses the transferability issue of test data obtained from surface cracked, laboratory-scale specimens intended to provide understanding of surface cracks in structures. When the applicability of specimen test data to structures is in question, a specialized test that replicates the essential aspects of a structural application may be needed as cited in guidance in this section.

Note that when the available analysis ability to simulate crack growth is invalid, assessment by test (section 7.3.3 in NASA-STD-5019A) is required.

NASA-STD-5019A, Item 7.3.2.c

Item 7.3.2.c in NASA-STD-5019A is a broad statement of the requirement to demonstrate a safety factor of 4 on the damage tolerance life without failure (hazardous leak or fracture instability) by analyses that assess all applicable effects causing crack growth as a result of cyclic loadings. The factor of 4 applies in general, including items 7.3.2.c(1) and 7.3.2.c(2)A, but not 7.3.2.c(2)B, which has unique requirements.

A hypothetical example is shown in Figure 7.3-2, Case c – Applied K and K_c Data vs. Lifetimes. In the figure, the applied K is shown increasing with the numbers of lifetimes which may occur due to crack growth. The example also shows representative material fracture toughness stress intensity factor K_c data as the rectangle symbols. (These example data are plotted for ease of reading the plot at a fraction of one lifetime, but they represent specimen data without crack growth effects, i.e., they would correctly be plotted at zero lifetime on the ordinate axis.) The item 7.3.2.c requirement is the applied K at 4 damage tolerance lifetimes should not exceed the allowable K_c value, which is specified in item 7.3.2.e to be the <u>average</u> of the data for the critical stress intensity factor, Kc. For the example plot, the average K_c may be estimated to be about the 1.14 ordinate, which is more than the applied K at 4 lifetimes, which satisfies the requirements in items 7.3.2.c and 7.3.2.e.

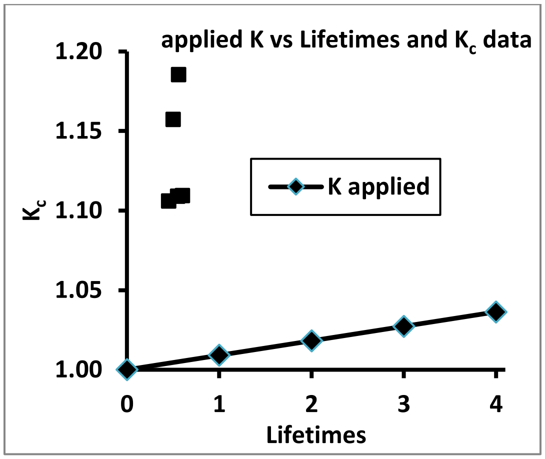


Figure 7.3-2—Case c: Applied K and K_c Data vs. Lifetimes

Additional requirements are imposed in item 7.3.2.f as flagged in the guidance.

Assessments of metallic alloys that are susceptible to crack growth related to SLC or EAC during the service life are addressed in item 7.3.2.f below.

These additional requirements are imposed if the hardware material is susceptible to EAC or SLC, or both. In that situation, either of the EAC or SLC requirements imposed in items 7.3.2.f(1) and 7.3.2.f(2) may be the controlling (i.e., lowest) material damage tolerance quantity that should not be exceeded by the applied K at 4 lifetimes to avoid failure. In the plot example above, suppose the value of applied K at 4 lifetimes is 1.04 in the plot scaling. Then, the lower bound stress intensity factor thresholds of EAC and SLC behavior would have to be smaller than the 1.04 value of the applied K at 4 lifetimes.

NASA-STD-5019A, Item 7.3.2.c(1)

Item 7.3.2.c(1) of NASA-STD-5019A specifies an approach to ensure the damage tolerant life assessment result will be conservative when loading sequences are unknown. If the sequence of high/low loads is a well-defined sequence for the lifetime of the part, the last cycle of the loading spectrum may be used to assess crack stability. If the loading spectrum sequence of high/low loads is variable or unknown, this item requires use of the loading spectrum limit load to assess fracture. The crack size used is the final size after four lifetimes of crack growth. A conservative approach is to always use the limit load to assess fracture of the final crack size. The fracture strength may be computed using the critical stress intensity factor when LEFM is applicable. If LEFM is not applicable, the guidance appearing after item 7.3.2.b notes the residual strength should be determined from tests, which should use cracked specimen simulating the final crack size fracture condition.

NASA-STD-5019A, Item 7.3.2.c(2)

Item 7.3.2.c(2) of NASA-STD-5019A addresses conditions where the service lifetime is a single event or the fatigue crack growth is small relative to the critical crack size for fracture. This is a relative statement. Since no bounds specify when item 7.3.2.c(2) does or does not apply, these situations should be evaluated when performing fracture control assessments, especially those with small increases of the initial crack size at the end of four lifetimes.

The item 7.3.2.c(2) requirement is to establish that either item 7.3.2.c(2)A or 7.3.2.c(2)B is satisfied.

NASA-STD-5019A, Item 7.3.2.c(2)A

Item 7.3.2.c(2)A of NASA-STD-5019A requires the fracture assessment to show fracture does not occur for the following condition. The fracture assessment should compute the final crack size for an initial crack size increased by 4 lifetimes of crack growth. As noted in item 7.3.2.c(1), if the loading spectrum sequence of high/low loads is variable or unknown, a conservative approach should be used by applying the limit loading experienced during the lifetime to the final crack size to predict critical stress intensity or residual strength after 4 lifetimes. This fracture condition is referred to here as the item 7.3.2.c(2)A critical fracture value. The item 7.3.2.c(2)A requirement is to show the c(2)A critical fracture value is less than or equal to the lower bound critical stress intensity factor or residual strength of fracture data described in item 7.3.2.c(2). Notice that item 7.3.2.c(2)A is comparing to a lower bound critical stress intensity factor or residual strength, which is less than the average value criteria that is imposed in item 7.3.2**.**e. In the example "Case c" plot, the lower bound would have an ordinate value of about 1.10, i.e., less than the lowest K_c data.

NOTE on lower bounds: A lower bound value should be based upon a sufficient number of specimen tests to sample the amount of scatter in the fracture property. Comparison of the lower bound to all test data should show that scatter of the fracture data does not, and likely will not, result in a smaller critical fracture value. For a normal statistical distribution, the "Empirical Rule" states 95% of the data will fall within two standard deviations, and 99.7% of the data will fall within three standard deviations. A value defined by the mean less two standard deviations will be close to a lower bound, while a value determined by the mean less three standard deviations will ensure a lower bound is obtained, provided there is enough data for this statistics rule to be meaningful. Statistical analysis of test data as it is accumulated for additional samples may assist in identifying if a lower bound value has been obtained.

NASA-STD-5019A, Item 7.3.2.c(2)B

Item 7.3.2.c(2)B of NASA-STD-5019A requires the fracture assessment to show that fracture does not occur for the following conditions. The initial crack size is increased by only 1 lifetime of crack growth to the predicted final crack size. (Note: The 1 lifetime is a unique requirement that is only applicable for item 7.3.2.c(2)B assessment, which applies the 1.4 multiplier as compensation.) Per item 7.3.2.c(1), if the loading spectrum sequence of high/low loads is variable or unknown, a conservative approach should be used by applying the limit loading experienced during the lifetime to the final crack size to predict critical stress intensity or residual strength after 1 lifetime. This value is multiplied by a factor of 1.4 to compute the item 7.3.2.c(2)B value of critical stress intensity factor or residual strength. This c(2)B value should satisfy item 7.3.2.e, meaning it should be less than or equal to the average value of the material critical stress intensity factor or residual strength.

NASA-STD-5019A, Item 7.3.2.d

Item 7.3.2.d of NASA-STD-5019A imposes requirements on assessments to use damage tolerance flaw growth rates that are greater than or equal to the average values without implementing retardation effects on flaw growth rates in the damage tolerance analysis.

NASA-STD-5019A, Item 7.3.2.e

Item 7.3.2.e of NASA-STD-5019A imposes requirements on assessments to use damage tolerance critical stress intensity factor and cyclic threshold (ΔK_{th}) that are less than or equal to the average values.

NASA-STD-5019A, Item 7.3.2.f(1)

Item 7.3.2.f(1) of NASA-STD-5019A imposes requirements on metallic alloys susceptible to EAC (K_{EAC} or K_{IEAC} as appropriate) or SLC, or both, that requires assessments to use a lower bound value of stress intensity factor threshold of EAC and SLC if the material exhibits these behaviors in the application conditions. Item 7.3.2.c(2)A has a "NOTE on lower bounds" that discusses the number of tests and relevant statistics when determining lower bound values.

NASA-STD-5019A, Item 7.3.2.f(2)

Item 7.3.2.f(2) of NASA-STD-5019A requires assessments to show the applied stress intensity factors for the largest service loading is smaller than the lower bound stress intensity factor thresholds of EAC and SLC behavior at the end of 4 lifetimes.

NASA-STD-5019A, Item 7.3.2.g(1)

Item 7.3.2.g(1) of NASA-STD-5019A is a specific requirement imposed on use of the NASGRO® program due to particular aspects of that program. It states if NASGRO® is used, either set the material fitting parameter Bk to zero, or set Bk such that the Kc (i.e., the stress intensity factor at the part thickness) is less than or equal to the plane strain fracture toughness K_{Ic}. The reason for this requirement is that Bk is a fitting parameter to a data set that may not conservatively represent the variation of fracture toughness of the material thickness.

NASA-STD-5019A, Item 7.3.2.g(2)

Item 7.3.2.g(2) of NASA-STD-5019A states that if values of Bk result in the Kc (i.e., the stress intensity factor at the part thickness) being greater than the plane strain fracture toughness, K_{Ic}, the situation may be used with approval of the delegated Technical Authority or RFCB. This issue is related to the comment in g(1) above that the Bk is a fitting parameter that may or may not represent the material fracture toughness at the part thickness. A conservative value of Bk would limit the toughness to the plane strain fracture toughness. Thin materials are known to exhibit elevated toughness due to the lack of thickness constraint, and the Bk parameter may result in a program-computed thickness toughness Kc that could be representative of the actual toughness of the part thickness. To utilize the increased toughness, it is assumed the reviewers, i.e., the delegated Technical Authority or RFCB, would want to see test data for the material part thickness that establishes the Kc value being used is representative of the part fracture situation.

NASA-STD-5019A, Item 7.3.2.h

Item 7.3.2.h of NASA-STD-5019A requires the fracture properties used in the damage tolerance assessment are to satisfy all of the requirements in h(1), h(2), and h(3).

NASA-STD-5019A, Item 7.3.2.h(1)

Item 7.3.2.h(1) of NASA-STD-5019A requires the fracture properties to be obtained from sources or by testing that is approved by the RFCB.

NASA-STD-5019A, Item 7.3.2.h(2)

Item 7.3.2.h(2) of NASA-STD-5019A requires the fracture properties to be representative of the material process condition in the part.

NASA-STD-5019A, Item 7.3.2.h(3)

Item 7.3.2.h(3) of NASA-STD-5019A requires the fracture properties to be representative of the weakest material orientation in the part. This presumes the material has an intrinsic anisotropic characteristic such that there is a weak and strong material orientation.

NASA-STD-5019A, Item 7.3.2.i

Item 7.3.2.i of NASA-STD-5019A requires when the damage tolerance assessment does not have needed material data, the needed data have to be obtained by either item i(1) or i(2).

NASA-STD-5019A, Item 7.3.2.i(1)

Item 7.3.2.i(1) of NASA-STD-5019A requires the needed material data to be obtained by material testing.

NASA-STD-5019A, Item 7.3.2.i(2)

Item 7.3.2.i(2) of NASA-STD-5019A states when an assessment needs material data and it is obtained from available literature, an assessment has to be conducted to show that conservative results are obtained using that available material data.

7.3.3 Assessment by Test (NASA-STD-5019A, Section 7.3.3)

NASA-STD-5019A:
7.3.3 Assessment by Test

Perform assessment by test according to the following to satisfy requirement [FCR 12] section 7.3.c in this NASA Technical Standard:

a. Provide the approach and rationale to the RFCB for approval before implementation.

b. Document the approved approach in the FCP.

c. Perform the test(s) with initial flaws in the worst location and orientation.

d. Establish by testing that the components survive 4 lifetimes, including section 7.3.2.c.(1) and 7.3.2.c.(2) requirements in this NASA Technical Standard, without failure (leak or fracture instability).

Testing may be supplemented by analyses that, in conjunction or augmented by test correction factors, assess all applicable effects causing increased crack growth.

e. Test in conditions that account for the service environments.

f. A sufficient number of tests is performed to establish a representative result considering variability of material damage tolerance data.

The approved approach is to be documented in the FCP. Formal documentation in the FCP facilitates in-depth technical review and approval. Testing of coupons and pre-flawed structural elements representative of the flight hardware damage tolerance condition may be an acceptable approach to establish damage tolerance for metallic fracture critical parts. Together, the testing and any supplemental analyses are to establish that equivalent section 7.3.2 requirements in this NASA Technical Standard are met.

Flight hardware that has complex structures, loadings, or materials with crack growth characteristics that are difficult or not amenable for damage tolerance assessment by analysis may satisfy damage tolerance requirements by testing. The testing should demonstrate the applicable damage tolerance requirements specified in this section are satisfied as stated in the guidance in this section that is copied below.

> *Testing may be supplemented by analyses that, in conjunction or augmented by test correction factors, assess all applicable effects causing increased crack growth.*

NASA-STD-5019A, Item 7.3.3.a

Item 7.3.3.a of NASA-STD-5019A requires the approach and rationale to be provided to the RFCB for approval before implementation. Detail documentation on all aspects of the proposed testing approach, rationale, goals, loading methods, test measurements, inspections, and expected results should be submitted to the RFCB for approval. There will likely be a need for iteration on the approach and testing details. This exchange process should begin early in the hardware development schedule to provide time for information exchange and maturation of test details. Analyses may also be needed to ascertain the proposed approach will be likely to obtain all the necessary data to certify the hardware.

NASA-STD-5019A, Item 7.3.3.b

Item 7.3.3.b of NASA-STD-5019A requires the detailed approach, testing plan, measurement plans, inspections before and after testing, and test data evaluation plans, including pertinent details listed in item 7.3.3.a should be described in the approved approach and documented in the FCP.

NASA-STD-5019A, Item 7.3.3.c

Item 7.3.3.c of NASA-STD-5019A requires the test(s) to be performed as planned with documentation of the initial flaws in the worst locations and orientation. Examples of a surface crack, an edge crack, and a buried crack are shown in section 8.1.1 in this Handbook that includes discussions on NDE for metallic fracture critical parts. The Standard NDE flaw types and the reliably detectable crack size and shape for Standard NDE methods are specified in NASA-STD-5009.

If there is inability to adequately analyze the test hardware to predict the worst flaw locations and orientations, multiple tests may be needed. Issues that surfaced when performing the testing should be described and assessments provided as to whether they affected the test results.

NASA-STD-5019A, Item 7.3.3.d

Item 7.3.3.d of NASA-STD-5019A requires the testing to satisfy item 7.3.2.c(1) and 7.3.2.c(2) requirements which are discussed in section 7.3.2 in this Handbook. Per the section 7.3.2.c requirement, the testing has to demonstrate that four (4) damage tolerance lifetimes are achieved and also show that the hardware can still perform required functions with no failure of the hardware. The additional 7.3.2.c(1) requirement is imposed if the loading sequence of high/low loads is unknown. In that case, the hardware has to be able to show the stress intensity factor at limit load is less than the critical stress intensity factor or residual strength at the end of 4 lifetimes. Additionally, item 7.3.2.c(2) requirement applies if the service lifetime is a single event or the fatigue crack growth is small relative to the critical crack size. In that event, the hardware has to satisfy either c(2)A or c(2)B. The c(2)A requirement is to show reserve capacity against fracture at the end of 4 lifetimes by not exceeding either a lower bound critical stress intensity factor or residual strength. The c(2)B requirement is to demonstrate a factor of 1.4 on critical stress intensity factor or residual strength after 1 lifetime. All these cited aspects are discussed more completely in section 7.3.2.c items. Also, a fictitious example is provided in section 7.3.2.c with a plot that is used to discuss all these requirements.

NASA-STD-5019A, Item 7.3.3.e

Item 7.3.3.e of NASA-STD-5019A requires the hardware test to occur in conditions that account for the service environments. For example, if the hardware service lifetime environments include exposure at low temperatures, the testing should be performed in that environment. If that requirement is not feasible, and if low temperatures affect the material damage tolerance capability, the testing should be adjusted to account for effects of the service environment on the stress intensity factor or residual strength. Determining the needed adjustments would require material test data representative of the service environment temperature using specimen representative of the hardware and any pertinent other factors that are identified from assessments of test data.

NASA-STD-5019A, Item 7.3.3.f

Item 7.3.3.f of NASA-STD-5019A requires a sufficient number of fracture or residual strength tests be performed so as to establish and quantify variability exhibited by the material damage tolerance quantities. To accomplish this, there has to be a sufficient quantity of damage tolerance test data to establish the variability of the hardware material.

There is additional guidance text in section 7.3.3 after section 7.3.3.f that is pertinent and is copied below:

> *The approved approach is to be documented in the FCP. Formal documentation in the FCP facilitates in-depth technical review and approval. Testing of coupons and pre-flawed structural elements representative of the flight hardware damage tolerance condition may be an acceptable approach to establish damage tolerance for metallic fracture critical parts. Together, the testing and any supplemental analyses are to establish that equivalent section 7.3.2 requirements in this NASA Technical Standard are met.*

7.4 General Approach for Fracture Critical Composite or Bonded Hardware Assessment (NASA-STD-5019A, Section 7.4)

NASA-STD-5019A:

7.4 General Approach for Fracture Critical Composite or Bonded Hardware Assessment

[FCR 13] Each fracture critical composite or bonded part that is not of a specific hardware type as described in section 7.2 in this NASA Technical Standard and is not approved by the RFCB as appropriate for an optional approach as described in section 7.5 in this NASA Technical Standard shall comply with all of the following items:

a. Develop a DTA by complying with section 7.4.1 in this NASA Technical Standard.
b. Develop an IDMP by complying with section 7.4.2 in this NASA Technical Standard.
c. Develop an RTD by complying with section 7.4.3 in this NASA Technical Standard.
d. Develop loading spectra by complying with section 7.4.4 in this NASA Technical Standard.
e. Perform damage tolerance tests on coupons by complying with section 7.4.5 in this NASA Technical Standard.
f. Perform damage tolerance tests of hardware elements by complying with section 7.4.6 in this NASA Technical Standard.
g. Perform strength and life assessments by complying with section 7.4.7 in this NASA Technical Standard.
h. Perform damage tolerance tests of full-scale flight-like hardware by complying with section 7.4.8 in this NASA Technical Standard.
i. Evaluate anomalies discovered during any portion of the BBA by complying with section 7.4.9 in this NASA Technical Standard.

[Rationale: Fracture critical parts need activities performed to understand the sensitivity of the part if a flaw or damage is present. These activities can range from a direct assessment of the part's capability with a flaw or damage to acceptance tests that establish the part has sufficient capability to a combination of activities that provides information deemed sufficient to mitigate the risk of failure caused by undiscovered flaws.]

Use of an alternative approach requires unique rationale and approval by the RFCB as described in section 10 [FCR 26] in this NASA Technical Standard. The approaches in this requirement are the preferred approaches if followed completely.

Damage tolerance assessment of composite or bonded hardware uses a BBA that includes testing, analysis, and certification. The testing includes material-allowable coupons, structural elements, subcomponents, components, and appropriate full-scale article testing. The tests are performed to evaluate relevant critical failure modes for loads that are representative of the hardware loading spectra and may include LEFs. The test elements develop assessment capability for credible damage levels as determined by the process steps resulting in the RTD. Such a BBA links multiple length scales and accounts for the effects of structural and material parameter variability.

Damage tolerance analysis of composite or bonded hardware is generally considered insufficiently developed to certify flight hardware without the support of a test program and the BBA. However, when a test-verified analysis approach exists and is applicable, an analysis approach that minimizes some of the testing detailed below may be submitted to the RFCB for consideration and approval. The assessment establishes that the spaceflight hardware meets all the criteria for life, strength, and damage tolerance detailed in these subsections. The details of the assessment are documented in the FCP.

The steps used in a damage tolerance assessment of composite or bonded hardware by incorporating the BBA and damage threat mitigation activities are detailed in the sections cited below:

a. The initial three steps (sections 7.4.1 through 7.4.3 in this NASA Technical Standard) establish the critical damage states. There is likely an interaction between these three elements as flaw detection and impact damage protection/detection strategies are developed and implemented on the flight hardware. The final RTD is used in the certification of the flight hardware. Note that there may be credible damage conditions that occur at any point during service life, including during the mission.

b. Concurrent with these first steps is development of the loading spectra determination (section 7.4.4 in this NASA Technical Standard) that affects the criticality of the remaining damage determined by the RTD.

c. The next four steps (sections 7.4.5 through 7.4.8 in this NASA Technical Standard) establish the structural response to the damage by both analysis and test at increasing levels of geometric complexity. There is also an interaction between these tests and the determination of critical damage states needed to develop the RTD.

d. Finally, discrepancies between the anticipated and observed test responses to damage initiation or growth are reconciled in accordance with section 7.4.9 in this NASA Technical Standard.

In practice, there will be iteration between and among these various steps.

BBA as described in this section is a comprehensive approach. Developers may have alternative approaches better suited to their hardware. These approaches and their rationale should be discussed with the RFCB.

Note: FCR 13 is defined in Table 1 in NASA-STD-5019A as “approaches and activities for composite or bonded parts not covered by 7.2 or 7.5.” To understand what types of hardware FCR 13 pertains to, it is important to first understand what hardware is addressed in sections 7.2 and 7.5. Section 7.2, “Established Approaches for Specific Fracture Critical Hardware Types,” includes items such as metallic pressure vessels, COPVs, other pressurized components, habitat modules and volumes, rotating hardware, fasteners, shatterable components and structures, tools, mechanisms, tethers, and batteries. Section 7.5, Optional Approaches for Fracture Critical Parts, covers single-event fracture components, high-cycle fatigue components, proof test approach for composites or bonded hardware, fleet leader testing, and hazardous fluid containers. For all fracture critical composite or bonded hardware that is not covered under sections 7.2 or 7.5, activities to address the requirements in items 7.4.a through i in NASA-STD-5019A are performed. These sections present guidelines for a building block approach (BBA) procedure. Detailed discussion and guidance on items (a) through (i) are found in sections 7.4.1 through 7.4.9 in this Handbook. A general overview of the BBA is given in the following paragraphs.

The BBA is a phased test program with the ultimate goal of certifying a structure for flight. A BBA inherently includes allowables development for the materials used as well as analysis calibration. The structure of the BBA is illustrated in Figure 7.4-1, Building Block Approach Summary. While the full BBA program should be planned and scoped at the start of the effort, by nature, the required tests and test specimens can evolve as the test program matures. The types of properties and behavior for which information should be gathered in a BBA program include:

- Static strength
- Constant amplitude fatigue
- Spectrum fatigue
- Stability
- Durability and damage tolerance
- Effects of defects

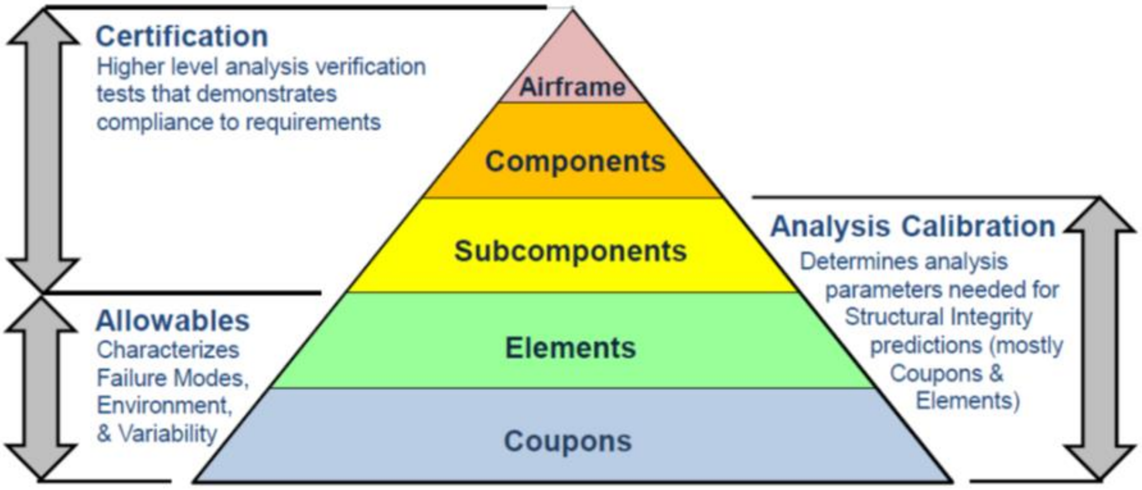


Figure 7.4-1—Building Block Approach Summary

The initial activity in the BBA consists of coupon testing to generate generic material properties (see bulleted list in previous paragraph) for acreage areas of a structure with near constant stress/strain (see section 7.4.5 in this Handbook). Coupon testing does not include evaluation of any structural features or elements such as joints or irregular geometry. Rather, test specimens are at the laminate or sandwich level (i.e., not an investigation of lamina or constitutive material properties). Structural features are included at the element level. This phase of the BBA may consist of up to thousands or tens of thousands of individual test specimens. The total number of specimens is proportional to the number of different materials used in the program. Structural features are not included in this phase but at the element level instead.

Ideally, all coupon-level material properties and allowables should be known early in the hardware design/certification process. In practice, the first phase of the BBA can necessitate a large amount of time and resources; it is not practical to complete this phase up front. To still enable a hardware design to proceed, preliminary data may be obtained early on from which the design is based. This data should be confirmed by completion of the BBA later. An example of this is gathering strength allowables from open-hole compression tests early in a BBA program and temporarily using the open-hole strengths not just for writing margins at open holes but also for damage tolerance. Damage tolerance and strength allowable testing still needs to occur. Until that happens, the structural design assumes the open hole data will be bounding. In this example, if damage tolerance test results later showed lower strength values than the open-hole tests, a redesign may be necessary if the new lower strength allowables yield negative structural margins.

In addition to generation of material properties, the coupon testing phase of a BBA is ideal for investigating manufacturing development and fatigue spectrum truncation. Manufacturing development should be investigated early on, especially concerning novel or high-risk techniques. Fatigue spectrum truncation may be useful at later stages of the BBA where a single test may be, relatively speaking, much more critical and expensive to prepare and perform. An investigation to understand manufacturing development and/or the consequences of spectrum truncation is best performed early in the BBA program and in the relatively lower-stakes and cheaper coupon tests.

The next phase in a BBA consists of element testing (see section 7.4.6 in this Handbook). Element test specimens consist of structural features, including bolted/bonded joints, stiffened panels, sandwich ramps, etc. The goals of element testing may be similar to those of coupon testing; only the test articles are more complex. A BBA program may have an order of magnitude of fewer element tests than coupon tests.

Following the elements test phase is the testing of sub-components, components, and full-scale flight-like hardware (see section 7.4.8 in this Handbook). These phases of the BBA are not explicitly called out with this exact terminology in NASA-STD-5019A, but the intent is a continued evaluation from the element tests of increasingly complex structures using fewer and fewer tests as complexity increases. Sub-component test specimens may consist of structural assemblies that are major load transfer points. Component test specimens include large pieces of the vehicle such as an airfoil/wing or a fully assembled heat shield. In terms of satisfying the NASA-STD-5019A requirements, it may be appropriate to consider sub-component and component tests within section 7.4.9 full-scale/flight-like hardware. Additionally, it may be that there are only one or two test specimens at the full-scale level. The overall cost of a BBA is generally driven by the component and full-scale tests.

Analysis may be utilized to differing degrees in a design and certification process. Application of analysis in a BBA is discussed throughout section 7.4 in this Handbook. The coupon, element, and sub-component phases of the BBA are best suited for analysis calibration. The coupon tests are well suited for validating the basic fundamental material/damage models within an analysis methodology. The element and sub-component tests are well suited for applying those fundamental techniques to more complex structures and again validating that they yield accurate predictions. Analysis calibration may be performed on the larger scale tests as well; but, due to model complexity, any insight gained from poor predictions may be limited.

As stated in the introductory guidance for section 7.4 in NASA-STD-5019A, if approved by the RFCB, alternative approaches for fracture control may be permitted. Examples of scenarios where an alternative approach may be desired for composite or bonded hardware include:

- Standard NDE techniques are difficult or impossible to perform due to complex geometry or due to the nature of the material system,
- Failure modes/damage configuration according to sources identified in the DTA are extremely difficult or impossible to create in a test specimen,
- Service environment and loadings are extremely difficult or impossible to recreate on a test specimen in a laboratory setting,
- There is a specific need for incorporating an analysis model to understand damage tolerance capabilities/behavior (for example, determining the mode mixity of a delamination and using that information to judge the applicability of a Mode I toughness), and
- A material system requires testing/characterization above and beyond that which is specified in section 7.4 in NASA-STD-5019A

Alternate approaches may include use of analysis for which there is guidance already stated in section 7.4 in NASA-STD-5019A:

> *"Damage tolerance analysis of composite or bonded hardware is generally considered insufficiently developed to certify flight hardware without the support of a test program and the BBA. When a test-verified analysis approach exists and is applicable, an analysis approach that minimizes some of the testing detailed below may be submitted to the RFCB for consideration and approval. The assessment establishes that the spaceflight hardware meets all the criteria for life, strength, and damage tolerance detailed in these subsections. The details of the assessment are documented in the FCP."*

Damage tolerance analysis should not be used to replace the need for tests (note that some testing is always required, as specified in NASA-STD-5001); analysis can potentially be used in combination with testing to reduce the number of tests and improve the efficiency of the overall design/certification process. The utility of analysis models in empirically focused composite certification efforts may include the following:

- Preliminary design of damage tolerance test coupons (e.g., a parametric study investigating coupon geometry and embedded flaw position to maximize the applicability of the test to a known damage scenario),
- Preliminary damage tolerance analysis of hardware to get a high-level/first-order understanding of the criticality of damage or a suspected failure mode (follow-on testing or model validation would be required to confirm the preliminary findings),

- Simulation of damage tolerance of a flaw that could be developed in flight when inspection and/or repair is not possible (this could be performed using a previously test validated model),
- Damage tolerance analysis of an environment or loading condition that is not possible to recreate in a test laboratory nor with a demonstration test in a remote location,
- Damage tolerance analysis of a flaw or damage configuration identified in the DTA that is difficult or not possible to recreate in a test laboratory,
- Replacement of some number of specimen configurations in a test program (the model would need to be test validated on other specimens of a similar configuration and applied conservatively; see section 6.2.5 in this Handbook for further discussion on test validation),
- Supplementing an empirically obtained argument for damage tolerance that is lacking BBA validation, provided the analysis capability has been demonstrated to be comprehensive and applicable,
- Preliminary analysis of full-scale testing to bound expectations,
- Reduction in the number of tests using the rationale that the model predicts a consistent failure mode, that it has been determined by additional specimen test results that confirm this assumption, and the analysis provides comprehensive evaluation of the structure and failure modes, and
- Improve the understanding of observed test results.

Validating a model using test data is paramount to applying analysis tools to damage tolerance requirements in NASA-STD-5019A. Promotion and re-creation of failure in a test that mimics that which is expected in a real damage event for a flight part is especially important when using a test for model validation. Generally, a model will include a capacity to simulate a limited number of failure modes (i.e., sometimes only one failure mode such as delamination). If a test is being used to validate a model, the test specimen has to fail according to the same failure mode that is being predicted and used as the failure metric in the model. Key features to account for in a validation test should include aspects of the problem that are confirmed or suspected to influence results such as irregular hardware geometry, a particular material interface, ply orientation, the nature of loading (e.g., normal vs. shear), the expected failure mode, etc.

The attributes of a model that may need to be validated include predictions related to linear elastic stiffness, material strength, critical energy release rate, material micro-structure, and progressive damage behavior. Additionally, details of the model configuration such as mesh size, element type, numerical technique, etc., should be validated. Once a model is validated, model configuration features such as mesh size and element type should not be altered and applied to new problems without a new validation of the altered model configuration. If a model is flawed such that it cannot be shown to be accurate via test data but it can be *proven* to be conservative, it may still be valid for use in a residual strength demonstration and margin writing.

Generally, in failure prediction in composites, care should be taken regarding use of stress-based material strengths that are input as model parameters. Stress-based damage simulation in composites can be challenging due to the possibility of in-situ strength where constitutive material strength can depend on geometric material configuration attributes such as ply thickness or adhesive bond thickness. Energy-based or micro-mechanical damage simulation methods may avoid challenges/complications related to in-situ strength.

Two potentially useful examples related to model validation are shown below:

- Example 1: A validation test is configured such that shear stress is applied on a flaw located on a flat interface between two specific materials. This test may be leveraged to validate the model for simulation of a range of shear stress magnitudes and initial flaw geometries.
- Example 2: A model predicts a part to fail by delamination *at the same load level* as a test, but the test specimen fails due to fiber breakage. This is *not* a valid test to use for model validation unless the model is modified to also simulate fiber breakage.

Model parameters that should be studied in a verification/validation exercise include:

- Mesh sensitivity on stiffness, strength, and prediction of significant fracture modes if a fracture analysis is being performed (i.e., prove that the mesh size is within a range of sizes where the model predicts consistent values for stiffness, strength, and significant fracture modes);
- Linear-elastic stiffness (i.e., prove that the model is producing results that match test data in the linear-elastic range of deformation);
- Strength (i.e., prove that the failure prediction method and the necessary material inputs, such as critical energy release rate, critical stress concentration factor, or ultimate strength are such that damage initiation is accurate or conservative compared to a test);
- Depending on the scope of the analysis, confirm that the prediction methodology and associated material inputs are valid for both damage onset and for continued growth;
- Develop some data or rationale supporting the use of the model for predicting damage onset/growth along all material orientations;
- Temperature related effects; and
- Detailed description of the scope for which a fatigue simulation is valid (i.e., what R-ratio?, what mode-mixity?, what material orientations?, load sequencing?, etc.)

While some analysis techniques may be mature enough and reliable enough to implement as permitted in NASA-STD-5019A guidance (preceding section 7.4.1), the following recommendations may assist the analyst and the RFCB during evaluation of an analysis-based alternate approach:

- Predicting damage formation from a pristine structure can be inherently more difficult and case specific than predicting damage onset from a preexisting flaw.
- Fatigue simulations for composites are less mature than quasi-static. Composite fatigue simulation models are usually heavily reliant on load/structure-specific test data and as a result can be limited in scope as a predictive tool.
- The field of damage simulation in composite materials is evolving. Among the more mature and time-tested fracture analysis techniques for composites that may offer the

most confidence with their use are the Virtual Crack Closure Technique (VCCT), cohesive zone, and J-integral.

As stated above in the introductory section 7.4 guidance describing implementation of sections 7.4.1 through 7.4.3 in NASA-STD-5019A, these three sections should be performed in parallel. Multiple iterations may be required before all requirements in each of these sections are satisfied. For example, developing the DTA in section 7.4.1 is contingent upon developing the RTD flaw size in section 7.4.3. Since the RTD flaw size is founded upon information in the DTA, sections 7.4.1 and 7.4.3 have to be in agreement with one another; but neither can be developed independently. Furthermore, later sections such as 7.4.5 through 7.4.8 in NASA-STD-5019A offer guidance on testing necessary to complete requirements in sections 7.4.1 through 7.4.3. These sections establish the interaction of sections 7.4.1 through 7.4.9 in NASA-STD-5019A, i.e., they are not to be completed in a chronological order.

7.4.1 Damage Threat Assessment (NASA-STD-5019A, Section 7.4.1)

NASA-STD-5019A:
7.4.1 Damage Threat Assessment

Develop a DTA according to the following to satisfy requirement [FCR 13] section 7.4.a in this NASA Technical Standard.

a. Provide information for residual strength sensitivity to impact damage and manufacturing flaws based on test data.

b. Define and quantify the flaws from any source that may occur to the hardware during its service life.

NASA-STD-5019A, Item 7.4.1.a

Quantified damage tolerance capabilities are required to be determined for hardware containing impact damage or a manufacturing flaw. Statistically relevant empirical data should be generated to obtain both material-level and part-level strength knockdowns considering impact damage and manufacturing flaws as identified according to this requirement. Such a test program may include different impact energy levels, impactor tip geometries, types of manufacturing flaws, acreage regions of a structure, and structural features of interest. This test program should encompass demonstration that the structure will tolerate the RTD flaw as defined in section 7.4.3 in NASA-STD-5019A. Much of this activity is also addressed in guidance that is provided in sections 7.4.5 through 7.4.8 in this Handbook. Additionally, while it is not a requirement of this section, a fatigue evaluation as described in section 7.4.7 in this Handbook may be seen as one necessary component of the residual strength sensitivity assessment.

Note that, while section 7.4.1.a in NASA-STD-5019A requires residual strength sensitivity to be determined based on test data, analysis may still play a role. If employed effectively, use of analysis to help satisfy this requirement may reduce the extent of necessary testing (see sections 7.4 and 7.4.5 in this Handbook).

If test determined strength allowables with the RTD flaw are insufficient for the design, fracture control requirements are not met. In this scenario, barring a change in design or loads, one course of action is to attempt to decrease the RTD flaw size by improving damage mitigation measures in the IDMP (see section 7.4.2). See sections 7.4.5 through 7.4.8 in this Handbook for more information on damage tolerance testing.

NASA-STD-5019A, Item 7.4.1.b

Note that service life is defined in NASA-STD-5019A as the “time interval for a part beginning with manufacture and extending throughout all phases of its specified mission usage. The period of time or number of cycles that includes all relevant loadings, conditions, and environments encountered during this period that will affect flaw growth, including all manufacturing, testing, storage, transportation, launch, on orbit, descent, landing, and if applicable, post-landing events, refurbishments, retesting, and repeated flights until the hardware is retired from service.” Sources of flaws that may occur during service life include service loads (mechanical or thermal) that are near or exceed the material strength, impact, hygrothermal loading resulting from prolonged exposure to moisture, cryo-pumping, internal sandwich core over pressurization (especially when using unvented core), or manufacturing anomalies.

Manufacturing anomalies that can be the source of flaws include:

- Trapped air due to insufficient debulking or vacuum pressure.
- Foreign object debris (inclusions).
- Inadvertent contact or tool/equipment drops.
- Faulty or improperly stored material.
- Uncontrolled resin flow leading to resin filled sandwich core or “dry” laminates.
- Human error related to laying up process.
- Post-cure residual stress due to layup configuration that exceeds material strength.
- Coefficient of thermal expansion (CTE) mismatch between constitutive materials or cure tooling.
- Insufficient potting at sandwich core splices or inserts.
- Insufficient resin degassing before infusion.
- Feature locations prone to fabrication complications (for example, (1) ply drop-off areas where resin-rich regions can form or (2) geometric discontinuities in a laminate structure such as a tight radius where the plies may not fully consolidate).

The types of flaws that can arise from these sources include, but are not limited to:

- Voids/delaminations in monolithic laminates.
- Voids/poor bonding in sandwich core splices.
- Poor bonding between sandwich core and facesheet.
- Excessive porosity in monolithic laminates.

- Poor bonding between plies of differing material (i.e., such as metal-polymer composites).
- General susceptibility for flaws at feature locations such as open holes; complex geometry; changes in layups, or inserts, ply drops, pad ups, etc.
- “Dry” monolithic laminates where resin has flowed away during cure.
- Foreign object debris contamination.

Sources of impact to a composite structure during the service life may include, but are not limited to, the following:

a. Fabrication
    - Stand impact.
    - Hand tool drop or swing.
    - Cart/lift rolling impact.
    - Power tool drop or swing.
    - Hand tool ricochet.
    - Crane hook drop or swing.
    - Torque wrench slip.
    - Fastener drop.
    - Impingement during movement in shop or assembly area (i.e., “bumping” hardware into a stationary object during transportation).
    - Computer numerical control (CNC) tool impacts.
    - Clamp/assembly jig damage.
    - Inspection probe impact.
    - Scaffolding installation.
    - Ceiling debris impact.

b. Ground Transportation
    - Road debris during transportation.
    - Vandalism (gun shots) during transportation.
    - Vehicle vibration.
    - Vehicle crash (e.g., auto accident, barge run aground).
    - Hail.
    - Bird strike.

c. Flight
    - Micro-meteoroid.
    - Orbital debris.
    - Astronaut EVA kick load.
    - Astronaut internal kick load.
    - Astronaut EVA hand tool impact.
    - Astronaut EVA power tool impact.
    - Launch debris (thermal protection system, ejected structures).

This list of potential sources of impact damage is not intended to be comprehensive, and designers/analysts should think carefully about additional damage sources to include in their DTA. Several impact sources listed may be relevant in-service life phases other than the phases where they are shown. Additionally, it is possible that the hardware configuration during fabrication may be more vulnerable to damage than after structural assembly is complete. Care should be taken to account for differing levels of vulnerability and different threat environments throughout the different stages of hardware assembly. An example of this is a structural panel on the outer mold line of a spacecraft that is protected from direct impacts during flight by bonded thermal tiles. During fabrication, before the thermal tiles are installed, the panel is more vulnerable to impact damage. The DTA should take this into account when identifying what impact threats exist during specific phases of hardware fabrication.

Flaw detection strategies should be employed to the greatest extent that is practical at all stages of hardware life. During and immediately after fabrication, parts can be NDE inspected using techniques that include X-ray computed tomography, ultrasonic, florescent penetrant (see section 4.2.4.2 in NASA-STD-5009), thermal imaging, visual inspection, and manual tapping. Section 8.1.2 in this Handbook contains further information and guidance on NDE requirements. Flaw mitigation strategies should be discussed in and implemented according to an IDMP as described in section 7.4.2 in this Handbook.

The following is an outline for an example DTA:

1. Introduction
    a. Background/Context.
    b. Purpose.
    c. Scope.
2. References/Applicable Documents
3. Damage Threat Assessment Methodology
    a. DTA Task 1 – Identify credible impact damage sources and impact energies.
        (1) Consider all composite parts at all locations in the structure and through all phases of service life.
        (2) Impact energy may be estimated based on any of the following: tests, potential energy calculations for dropped items, kinetic energy calculations for moving objects, or simulation.
        (3) DTA Task 1 will also provide input for developing the IDMP in section 7.4.2 in NASA-STD-5019A.
        (4) Note that threats that are credible and unmitigated post-proof NDE should not result in insufficient strength margins.
    b. DTA Task 2 – Characterize impact damage size(s) and residual strength(s)
        (1) Consider multiple impact energies covering all identified credible threats.
        (2) Consider multiple impactor geometries.
        (3) Consider multiple locations on structure.

(4) Characterize damage size as a function of items bi through biii.
(5) Determine NDE detection capabilities using planned methods (including visual inspection) and identify the damage sizes that have to be included as credible threats.
(6) Plan residual strength tests (compression tests are commonly used as a bounding type of test; the test type may be chosen to suit the actual structure loading if compression is not part of the design space).
(7) Consider all material configurations (some material configurations may be enveloped by other tests).
(8) Consider environmental and fatigue effects (this may involve use of a limited set of coupons selected to bound many other material configurations).
(9) Consider use of damage simulation to reduce the amount of testing in (6) – (8) (see section 7.4 in this Handbook).

c. DTA Task 3 – Determine manufacturing flaw types and sizes

(1) Note that many manufacturing flaw types and sizes may be bounded by impact damage threats.
(2) Plan to include residual strength tests with embedded manufacturing flaws.
(3) Consider use of damage simulation to reduce the amount of testing in item d.ii (see section 7.4 in this Handbook).

d. Perform all necessary testing and simulations

(1) Determine statistically generated damage tolerance strength knockdown factors for each material configuration tested.
(2) Evaluate if RTD is within structural capabilities; if not, then the structure does not meet fracture control requirements.

4. Summary

a. Critical damage sources.
b. DTA methodology.
c. Residual strength conclusions.

7.4.2 Impact Damage Mitigation Plan (NASA-STD-5019A, Section 7.4.2)

NASA-STD-5019A:
7.4.2 Impact Damage Mitigation Plan

Develop an IDMP according to the following to satisfy requirement [FCR 13] section 7.4.b in this NASA Technical Standard.

a. Define, document, and implement impact protection and/or detection strategies that are used for the flight hardware to diminish targeted damage threats identified by the DTA.

b. Prescribe when and how impact protection and/or detection strategies are to be used for flight hardware to mitigate credible damage or threats.

NASA-STD-5019A, Item 7.4.2.a

The IDMP should prescribe protection and detection strategies for all threats that are identified in the DTA. Part of this effort includes establishing reporting rules and procedures for damage that is discovered or caused accidentally by personnel. Damage that is discovered or caused by accident should already be included in the DTA; if not, expand the DTA to include the newly discovered and any related damage sources.

For each threat identified in the DTA, a mitigation strategy should be developed in the IDMP. Some common mitigation strategies applicable to the manufacturing and assembly phases of hardware development include the following:

- Use of protective covers for hardware when it is not being worked on, and when it is being transported.
- NDE milestones, including visual inspections at opportune times.
- Identify energy cutoff levels (based on technical data) that can be controlled by prescribed actions, such that associated DTA threats are decreased below the level of concern.
- Special quality control measures that are demonstrated to diminish or otherwise control targeted threats identified in the DTA.

Mitigation strategies for threats that may occur during flight may be addressed by sizing structure according to damage tolerance strength knockdowns determined per item 7.4.1.a requirements in NASA-STD-5019A.

NASA-STD-5019A, Item 7.4.2.b

The mitigation and inspection strategies defined per the requirement in this section should be tied to specific program or manufacturing milestones such as post-cure, post-assembly, pre-test, pre-launch, etc., when the strategy implementation can be verified.

7.4.3 Residual Threat Determination (NASA-STD-5019A, Section 7.4.3)

NASA-STD-5019A:
7.4.3 Residual Threat Determination

Develop an RTD according to the following to satisfy requirement [FCR 13] section 7.4.c in this NASA Technical Standard.

a. Define the worst-case credible flaw conditions that are shown to be tolerated by the hardware through analysis and test, considering all applicable flaw detection and mitigation strategies that are implemented for the flight hardware.

b. Encompass all possible worst-case credible damage conditions, except the threats that are mitigated by NDE evaluations, the IDMP, and the threats where risk is accepted by the program or project.

c. Document the damage states the program or project has chosen to exclude from the design.

The RTD helps identify flaws or damage conditions that are not screened by a combination of inspection, protection, and detection strategies.

Although inspection techniques meeting the 90 percent detectability level with 95 percent confidence called for in NASA-STD-5009 for metals are generally not available for composite or bonded materials, the RTD damage detection levels are to be set to produce a similar level of reliability as expected from metallic fracture critical parts.

For re-flight hardware, the inspections to be performed between flights are to be defined.

The residual threat determination involves defining the worst-case credible (WCC) flaw that could be expected to occur and be tolerated by the hardware. To achieve this, the RTD has to occur in parallel with the requirements in sections 7.4.1 and 7.4.2 in NASA-STD-5019A. Additionally, assessment of the flaws as required by this section and section 7.4.1 in NASA-STD-5019A occurs per guidance contained in sections 7.4.5 through 7.4.8 in NASA-STD-5019A.

NASA-STD-5019A, Items 7.4.3.a and b

Section 7.4.3.a in NASA-STD-5019A necessitates that analysis and test need to demonstrate tolerance of the WCC flaw in flight hardware. The WCC flaw is one that is quantified by a combination of sections 7.4.1 (DTA) and 7.4.2 (IDMP) in NASA-STD-5019A, may be expected to occur during the service life, and is included in the set of credible damage conditions after applying requirement 7.4.3.b. Additionally, the WCC flaw is one that is positioned and oriented such that growth is most likely to occur based on the structure, material, and loading. The criterion for tolerance of the WCC flaw is defined according to section 7.4.7 in NASA-STD-

5019A. Full-scale flight hardware damage tolerance testing will include WCC flaws based on the RTD (see section 7.4.8 in this Handbook).

Test configurations may range from simple coupons representative of structural areas with near uniform stress/strain (see section 7.4.5 in NASA-STD-5019A) to full-scale hardware (see section 7.4.8 in NASA-STD-5019A) with flight load combinations applied. A small coupon may be sufficient if the RTD flaw geometry, local stresses, and failure mechanisms are well understood in the full-scale part and easily replicated on a smaller scale. Damage complexity due to things like irregular hardware geometry, high or uncertain local stress gradients, failure mechanisms that are not well understood, or complex structural assemblies may drive the need for a full-scale hardware test specimen. A test configuration has to recreate the physical attributes of the RTD flaw, and it has to promote failure in the manner that is expected in a real damage event for that hardware.

Note the following two scenarios that highlight some of the nuances of requirements in this section:

- Scenario 1: A flaw under consideration that the flight hardware cannot tolerate is defined within the DTA, cannot be mitigated by the IDMP, and ***is*** NDE detectable. This flaw cannot qualify as the WCC because it is detectable by NDE. Fracture control requirements may not be violated by this flaw because it is detectable by NDE.
- Scenario 2. A flaw under consideration that the flight hardware cannot tolerate is defined within the DTA, cannot be mitigated by the IDMP, and ***is not*** NDE detectable. While this flaw may qualify as WCC, it would prevent fracture control requirements from being met unless the flaw could be shown to be non-credible and/or NDE capability is improved such that the flaw is detectable.

NASA-STD-5019A, Item 7.4.3.c

If waivers have been applied to damage states identified in the DTA that cannot be mitigated by the IDMP or by NDE, these should be approved and documented as specified in section 7.4.3.c in NASA-STD-5019A. In addition, if the hardware mission includes re-flight, the guidance at the end would be applicable. The guidance provided at the end of section 7.4.3 in NASA-STD-5019A is copied below to help clarify the meaning and implementation of this section.

> *"The RTD helps identify flaws or damage conditions that are not screened by a combination of inspection, protection, and detection strategies.*
>
> *Although inspection techniques meeting the 90 percent detectability level with 95 percent confidence called for in NASA-STD-5009 for metals are generally not available for composite or bonded materials, the RTD damage detection levels are to be set to produce a similar level of reliability as expected from metallic fracture critical parts.*
>
> *For re-flight hardware, the inspections to be performed between flights are to be defined."*

7.4.4 Loading Spectra (NASA-STD-5019A, Section 7.4.4)

NASA-STD-5019A:
7.4.4 Loading Spectra

Establish that all the loads and the number of cycles or duration during the service life of the part at the appropriate environment are included to develop loading spectra to meet requirement [FCR 13] section 7.4.d in this NASA Technical Standard.

Development of the loading spectra includes all the applicable loads listed in section 7.3.1 in this NASA Technical Standard and all other applicable loads such as those related to environment effects on composite or bonded materials.

Note that section 7.3.1 in NASA-STD-5019A (Loading Spectra) requires the effects of impact loads and damage to be included. This encompasses all possible WCC damage events, except the threats that are mitigated by NDE evaluations, the IDMP, and the threats where risk is accepted by the program or project. Specific impacts and associated damage states should be based on the DTA developed in section 7.4.1 in this Handbook. As the load spectra should constitute a worst-case scenario, structural loads resulting from credible impacts and any subsequent resulting change in loading due to damage (i.e., due to a different structural response) should be considered.

7.4.5 Damage Tolerance Tests of Coupons (NASA-STD-5019A, Section 7.4.5)

> **NASA-STD-5019A:**
> **7.4.5 Damage Tolerance Tests of Coupons**
>
> *Damage tolerance tests on coupons are performed with the applicable environments to generate strength-based and a life-based database.*
>
> Perform damage tolerant coupon tests according to the following to satisfy requirement [FCR 13] section 7.4.e in this NASA Technical Standard:
>
> a. Perform damage tolerance tests that represent flight hardware materials, manufacturing methods, and layups.
>
> b. Perform damage tolerance tests that contain induced flaws and damage that encompass the worst-case credible-flaw conditions as determined by the RTD.
>
> c. Perform damage tolerance tests that represent the modes of failure expected in the flight hardware.
>
> d. Perform tests in a quantity sufficient to define design values for the relevant critical failure modes, e.g., residual strength, fatigue, using the B-basis statistical techniques as defined in CMH-17-1G or an equivalent approach approved by the RFCB.
>
> e. Develop or use coupon data to establish the sensitivity of residual strength to impact and manufacturing damage as determined in the DTA in accordance with section 7.4.1 in this NASA Technical Standard.
>
> *Note that sufficient quantities of data are also necessary for use in computing the Weibull shape parameters used in determining the LEF, as described in CMH-17-1G.*

This section is focused on testing of coupons. In this context, “coupon” can be defined as a test specimen representative of the material configuration at the laminate or sandwich layup level and should not include any geometric structural features. Furthermore, coupons are representative of acreage areas of a structure with near uniform stress/strain. This section is invoked by the requirement in section 7.4.1 in NASA-STD-5019A to assess damage tolerance and residual strength. Note, while it is not a requirement of this section, a fatigue evaluation as described in section 7.4.7 in this Handbook may be seen as one necessary component of a damage tolerance and residual strength assessment.

The data generated by coupon level tests are intended to be applied in a general sense to any structure that is composed of the same material, built with the same processes, provided that the structure does not warrant a dedicated feature/element level test (see sections 6.2.5 and 7.4.6 in this Handbook). In cases where a dedicated element level test is warranted, data obtained from coupons such as strength or an assessment of damage tolerance should not be used for writing margins or final design.

NASA-STD-5019A, Item 7.4.5.a

All flight hardware material configurations (i.e., material types, laminate layups, sandwich layups, etc.) and manufacturing methods should be included in the damage tolerance assessment testing. Test coupons should be manufactured by means as similar to those of flight hardware as possible, including use of the same facilities, processes, personnel, equipment, and tooling. One means of accounting for all material configurations and manufacturing methods is to actually build test specimens that cover each and every possible combination. Some alternative approaches that may be more efficient are listed below:

- Streamlined test programs where data obtained from testing certain material configurations (i.e., layups) are said to bound other specific cases. For example, if a technical rationale can be generated by testing results or by analysis that strength allowables for Layup A are conservative if applied to Layup B, then it is acceptable to use test-obtained Layup A allowables to write margins on Layup B and skip extensive Layup B testing (after demonstrating it is conservative to do so). One analysis method that could be applied to generate this rationale is a first ply failure strength assessment using classical laminate theory.
- A test-verified analysis approach where testing is performed to validate an analysis method and that analysis method is subsequently used in place of required additional tests. For example, in a finite element model a fracture mechanics failure method is successfully correlated with strength testing of Layup A. That finite element model then could be used in place of a test to predict the strength of Layup B provided that:

    - The model is not significantly altered from its test-validated state (i.e., mesh size, element type, failure criterion, etc.).
    - Layup B is similar in nature and structural design to Layup A such that no difference in failure mode or general structural response is expected.
    - Layup A and Layup B consist of the same constitutive material types and experience similar structural loadings.
    - A rationale is documented that justifies the material strength and/or toughness values used in each model (the analyst may decide that critical energy release rate should differ between models if, for example, delaminations are growing along different material orientations and fracture behavior is known/suspected to differ as a result).

NASA-STD-5019A, Item 7.4.5.b

See comments in section 7.4.5.a in this Handbook for guidance. See section 7.4.1.a in NASA-STD-5019A for the requirement that RTD flaws be evaluated in the DTA. See section 7.4.3 in NASA-STD-5019A for definition of the RTD flaw.

NASA-STD-5019A, Item 7.4.5.c

Evidence or rationale should be provided to prove that damage tolerance tests performed in this section as required by section 7.4.1.a in NASA-STD-5019A should be representative of the expected failure modes in flight hardware. If analysis is used, the analysis models should predict the same failure modes seen in flight hardware and validation tests. If additional failure modes are present, the analysis model should be able to simulate them. Analyses that do not simulate damage mechanisms observed in testing are not considered reliable subsequent to the initiation of those failure modes. For example, a model may be used with confidence to simulate delamination growth as observed in testing until a structural instability occurs in the test that the model cannot predict well. In this case, the model may be considered reliable up until the instability event. Furthermore, the model may even be capable of predicting the instability point but not the subsequent damage formation. Prediction of the instability point, in this scenario, may still be considered reliable if verified by the test.

NASA-STD-5019A, Item 7.4.5.d

Note that CMH-17-1G, Volume 1, section 2.2.5, specifies the use of a minimum of 18 specimens for determination of B-basis values. Analysts also may consider testing up to three batches of material production where, for a given B-basis property being determined, specimens from at least two different batches are used.

NASA-STD-5019A, Item 7.4.5.e

The main goal of the coupon damage tolerance testing is to determine strength reduction sensitivity of a material to impact damage. For a given material system, this assessment may include consideration of parameters such as impact energy, impactor geometry, impactor mass, impactor velocity, and impact damage size/extent. Damage size/extent is often used as the metric to study strength sensitivity against due to the fact that it has a fairly consistent relationship with strength that is independent of the nature of a specific impact event (which can be hard to predict). Whatever metric is chosen to study strength sensitivity, several values (recommend 3-4 minimum) can be chosen to include in a test matrix to generate a strength curve. If the curve shows a clear trend and fits the available data well, then it may be utilized in ranges where test data was not gathered.

7.4.6 Damage Tolerance Tests of Hardware Elements (NASA-STD-5019A, Section 7.4.6)

> **NASA-STD-5019A:**
> **7.4.6 Damage Tolerance Tests of Hardware Elements**
>
> *Damage tolerance tests on hardware elements, subcomponents, and components are representative of the flight designs and have induced RTD determined flaws.*
>
> Perform damage tolerance tests of hardware elements according to the following to satisfy requirement [FCR 13] 7.4.f in this NASA Technical Standard:
>
> a. Include both residual strength and life-based testing.
>
> b. Perform tests sufficient in number to guide the design and provide confidence that the tests performed in accordance with section 7.4.8 in this NASA Technical Standard encompass the worst-case credible conditions, locations, and orientations.
>
> *Note that spectrum truncation is allowed for structural-level testing (components and full-scale hardware) with supporting coupon test data.*

Element level testing should consist of test specimens greater in structural complexity than in the coupon testing. Examples of some common hardware elements that may require a dedicated damage tolerance test are:

- Bonded joints.
- Bolted joints.
- Locations containing complex geometry.
- Skin-stringer configuration.
- Cutouts or openings.
- Sandwich core ramp-downs.
- Laminate ply ramp-downs.

The exact definition of an element test may vary by project and, in some cases, may include more substantial structures than those listed above.

NASA-STD-5019A, Item 7.4.6.a

Structural elements should be tested to assess both strength and life. See section 7.4.7 in this Handbook for more detail. An aspect of the element strength and life assessments to keep in mind is that this exercise is partially performed to build confidence that the eventual full-scale/flight-like test will be successful (see section 7.4.8 in this Handbook). Because the elements tested represent features of concern in the flight-like test specimen, the dedicated element testing is directly relevant to the design and preparation of the flight-like test.

NASA-STD-5019A, Item 7.4.6.b

Testing as specified in this section should be used to determine the nature of flaws that are included in the full-scale damage tolerance tests that are required in section 7.4.8 in NASA-STD-5019A. Before fabrication of hardware element test specimens, an assessment should be performed to determine what the WCC conditions, locations, and orientations are (this will also help with the RTD in section 7.4.3 in NASA-STD-5019A). The assessment may be performed based upon a stress analysis, limited pathfinder tests, more comprehensive tests that account for the nature of the origin of the RTD flaws, or by fracture analysis. A fracture analysis may be advantageous in that a parametric study can be performed that evaluates many potential initial damage conditions and identifies the worst-case scenario relative to the others. Note that in this type of analysis application where a fracture model is being used to design a test configuration and predictions are being compared against one another to identify relative differences, dedicated experimental validation of the model may not be necessary. On the other hand, if a fracture model is being used to replace or supplement test data that will be used to support structural certification, experimental validation is required.

7.4.7 Strength and Life Assessments (NASA-STD-5019A, Section 7.4.7)

NASA-STD-5019A:
7.4.7 Strength and Life Assessments

Assessment of the flight article should be developed that is supported by analysis of the coupon and hardware element testing with RTD determined flaws present at any location and orientation.

Perform strength and life assessments according to the following to satisfy requirement [FCR 13] 7.4.g in this NASA Technical Standard:

a. Perform analysis to establish that the B-basis residual strength after 1 service lifetime is sufficient to support DUL, after which the hardware will perform as intended.

b. Establish that the hardware performs as intended after experiencing a B-basis number of spectrum loading service lifetimes followed by one DLL cycle.

Note that the service life factor in analysis is the full B-basis number of lives, because the additional lives can be assessed without significant additional cost. One can therefore consider that no LEF is used or equivalently LEF=1.

This section is applicable to activities described in sections 7.4.5, 7.4.6, and 7.4.8 in NASA-STD-5019A. See comments in section 7.4.6 in this Handbook for a description of an analysis methodology to limit testing by investigating RTD flaw location and orientations. Additionally, this section should help interpret the test results obtained according to sections 7.4.5 and 7.4.6 in NASA-STD-5019A to prepare for a successful full-scale/flight-like test as described in section 7.4.8 in this Handbook.

NASA-STD-5019A, Item 7.4.7.a

The criteria for demonstrating that certain initial flaws can be tolerated after one service life follows: Whatever test is performed to evaluate a state of damage, it should demonstrate that after one service life, the B-basis strength is sufficient to support DUL. The load spectrum should provide a B-basis level of reliability (0.90). A DUL strength assessment is required after flaw growth, if any, associated with one life.

One approach that can be taken to satisfy this requirement is performing all quasi-static testing to design ultimate load. To take this approach, a rationale has to be developed (based on testing or test-validated analysis) that demonstrates that had the quasi-static tests been subjected to a full-load spectra corresponding to one service life, no significant flaw growth would have been observed; and the B-basis strength capacity would not have been reduced below the DUL.

NASA-STD-5019A, Item 7.4.7.b

In addition to the DUL assessment after one service life, further confidence is necessary that there will be no issues related to capability to perform all critical functions with requisite strength after the fatigue cycling and the DUL loading.

Fracture control requirements in NASA-STD-5019A, section 7.3, for metallic parts require a demonstration of four service lifetimes. Composites and bonded materials tend to exhibit higher scatter in fatigue and additional service lives are usually required to show the same level of reliability. To demonstrate confidence to provide the required life in a statistical manner, while performing a minimal amount of fatigue testing, the following approach is recommended: Using equation 12.6.3.3(a) in CMH-17, volume 3, section 12.6.3.3, set the load enhancement factor (LEF) = 1.0 and solve for N using a reliability of 0.90. N may then be used as the “B-basis number of spectra loading service lifetimes” that the hardware is required to be demonstrated to survive. Following the B-basis fatigue cycling, the hardware has to then survive a quasi-static applied DLL. See section 7.4.8.e in this Handbook for a more detailed description of the LEF.

7.4.8 Damage Tolerance Tests of full-Scale Flight-Like Hardware (NASA-STD-5019A, Section 7.4.8)

NASA-STD-5019A
7.4.5 Damage Tolerance Tests of full-Scale Flight-Like Hardware

Perform damage tolerance tests of full-scale flight-like hardware according to the following to satisfy requirement [FCR 13] section 7.4.h in this NASA Technical Standard:

a. Induce flaws into test hardware as specified by the RTD in the worst credible location and orientation.

b. Perform NDE on test hardware before test to verify that the RTD flaws have been imposed and to record any flaws in addition to those imposed.

c. Account for the effects of environments and flight hardware structural conditions to simulate performances throughout the specified service lifetime. If tests are not performed in the operational environment, test levels are adjusted via an ECF.

d. Establish ultimate load capability in the test hardware after a minimum of 1 service lifetime loading.

e. Subject the test hardware to a minimum of 4 service lives of spectrum loading with appropriate LEF necessary to establish B-basis reliability followed by 1 DLL cycle.

More than 4 lifetimes of testing may be performed to reduce the LEF.

f. Establish that the test hardware does not experience structural failures and is capable of performing its design function after both spectrum service life testing and DUL testing and 7.4.8.e above).

(1) Determine primarily by assessment.

Functional or other tests may also be used. Note that items 7.4.8.a through f may be satisfied with one test article or may involve more than one test article as appropriate. The RFCB should be consulted for further understanding of what is expected to satisfy item 7.4.8.f, e.g., no structural failure or burst, no catastrophic leak caused by flaws, no catastrophic mechanical malfunctions.

(2) Perform NDE as part of this assessment.

NASA-STD-5019A, Item 7.4.8.a

The manner and aspects of flaws introduced into the test hardware depends on the origins and causes of the flaws identified by the RTD. Modeling, testing, and analyses that supported the development of the RTD may all contribute to the plan for introduction of flaws in full-scale test hardware. See notes in section 7.4.6.b in this Handbook on how an analysis approach may be leveraged to streamline this evaluation.

Note that the common practice of inclusion of thin films in a composite to simulate an initial delamination can result in a higher toughness at the flaw than if it were a sharp natural crack. A preferable option if feasible to introduce initial flaws in a test article is to try to recreate the damage event. A common example of this is use of a portable spring-loaded impactor. If use of thin films is the only option, efforts should be taken to use as thin a film as possible (i.e., less than 10 microns if possible).

NASA-STD-5019A, Item 7.4.8.b

Test specimens should receive an NDE inspection before testing. Note that the pre- and post-test NDE techniques should be equivalent in resolution and ability to find flaws. Ideally, the same technique is used in both cases. Some common NDE methods used in composite testing are X-ray computed tomography, ultrasonic inspection, visual, and flash thermography imaging.

NASA-STD-5019A, Item 7.4.8.c

Thermal conditions are the most common environmental factors necessary for accounting purposes. This includes hot and cold conditions. Other environmental factors that may necessitate testing are chemical exposure, extreme multi-faceted load conditions such as the re-entry environment on a heat shield, vacuum, and humidity. Note that, if a non-vented sandwich core configuration is utilized, the effects of vacuum, trapped moisture, and changing thermal conditions should receive special attention to minimize the risk of an unintended facesheet-core disbond due to internal over-pressurization.

Certain environmental tests may envelope others. For example, if coupon test data performed according to the requirements in section 7.4.5 in NASA-STD-5019A showed that fracture toughness of a system is lower for colder temperatures, evaluation of the full-scale test article in a hot environment may be minimal or unnecessary (note, this is just an example related to consideration of toughness; there may be other factors driving the need for a hot test).

NASA-STD-5019A, Item 7.4.8.d

In some cases, it may be impossible or infeasible to recreate a flight load spectrum in a test. The spectrum applied in the test should constitute a worst-case scenario within the bounds of the load spectra in terms of promoting damage growth at the locations where initial flaws are located. These same guidelines apply to the subsequent quasi-static test where DUL is determined.

NASA-STD-5019A, Item 7.4.8.e

The method described in section 7.4.7.b in this Handbook may be used to satisfy section 7.4.8.e in NASA-STD-5019A (recall, LEF = 1.0 and the number of lives necessary to demonstrate B-basis reliability is calculated and implemented in the test program). Alternatively, if the number of lifetimes to test is desired to be set at the minimum value of four in this case, the LEF can be calculated using equation 12.6.3.3(a) in CMH-17, volume 3, section 12.6.3.3. Note this will give an LEF that results in a B-basis (0.90) level of reliability. The LEF equation and a deeper explanation of its application are given in Equation 3.

The LEF is a factor to be applied to a load spectrum to ensure a desired level of reliability is obtained by the test results. The LEF is calculated using:

$$LEF = \frac{\left[\Gamma\left(1+{}^{1}/_{\alpha_L}\right)\right]^{\alpha_L/\alpha_R}}{\left[\frac{-\ln(\lambda) N^{\alpha_L}}{\chi^2_\gamma(2n)/2n}\right]^{1/\alpha_R}} \qquad \text{Equation 3}$$

where

α_L= Weibull shape parameter of the fatigue life distribution
α_R= Weibull shape parameter of the residual strength distribution
λ = reliability required, 0.90 for B basis, 0.99 for A basis
γ = confidence level, 0.95 for both A and B basis
N = test duration in lifetimes
n = sample size, i.e., the number of test articles tested
Γ = the gamma function
$\chi_\gamma^2(2n)$ = the value of the chi-squared function with 2n degrees of freedom at a probability of γ

Among other things, the LEF is a function of the number of service lives, N, included in a test. In the case of section 7.4.8.e in NASA-STD-5019A, N = 4, at a minimum. This means that the LEF can be equal to 1.0 if the number of service lives tested increases. This is the approach recommended previously in section 7.4.7.b in this Handbook.

The Weibull shape parameters need to be determined experimentally and are a description of the statistical distribution of strength and life (see CMH-17, Volume 1, section 8.4.1). The Weibull shape parameter, α, is such that a higher shape parameter, corresponds to less data scatter. The Weibull shape function is given by the Weibull distribution equation 4 where *p* is the probability that a value *X* is less than or equal to another value *x:*

$$p(X) = e^{-\left(\frac{x}{\beta}\right)^{\alpha}} \qquad \text{Equation 4}$$

where β is the scale factor. The shape parameters are determined by iteratively curve fitting a Weibull distribution to at least 5 data points (i.e., data points in this case are experimentally determined values for strength and life). Typical values of α_L and α_R for composites are 1.25 and 20.0, respectively.

Following application of four service lives with the LEF included, the hardware has to survive a quasi-static DLL. Note that this requirement for full-scale, flight-like hardware is more specific than described in section 7.4.7.b due to the fact that demonstration of four service lives is required.

7.4.9 Evaluate Flaws or Damage that Occurs During BBA Testing (NASA-STD-5019A, Section 7.4.9)

> **NASA-STD-5019A:**
> **7.4.9 Evaluate Flaws or Damage that Occur During BBA Testing**
>
> Evaluate flaws or damage occurring during BBA testing according to the following to satisfy requirement [FCR 13] section 7.4.i in this NASA Technical Standard:
>
> a. Evaluate unexpected flaws or damage, significant or unusual flaw growth, and any new failure modes observed.
>
> b. Address any concerns raised by the evaluation by assessment, test, retest, or redesign as appropriate.
>
> c. Include RFCB involvement with all assessments and evaluations.

NASA-STD-5019A, Item 7.4.9.a

The purpose of this requirement is to ensure the nature of unexpected damage behavior is understood and establish that a new or unknown threat does not exist. The term "evaluate" is used to encompass whatever procedure is undertaken to achieve this goal such as analysis or additional tests.

NASA-STD-5019A, Item 7.4.9.b

When the evaluation is performed, if an unexpected flaw or other critical aspect is found that affects the structural integrity of the hardware, additional actions are needed. If the aspect is determined to pose a threat that was previously not included in the DTA, then the DTA, the IDMP, and the RTD will need to be revised. Additional testing, analyses, or redesign may also be needed to achieve compliance with the requirements in NASA-STD-5019A.

NASA-STD-5019A, Item 7.4.9.c

As stated in this requirement in NASA-STD-5019A, provide the RFCB with descriptions and opportunities for involvement with all assessments, evaluations, analysis, and testing that affect or demonstrate compliance with requirements.

7.5 Optional Approaches for Fracture Critical Parts (NASA-STD-5019A, Section 7.5)

NASA-STD-5019A:
7.5 Optional Approaches for Fracture Critical Parts

[FCR 14] Each fracture critical part that is not of a specific hardware type as described in section 7.2 in this NASA Technical Standard and is approved as appropriate for one of the following optional approaches by the RFCB shall comply with one of the following items:

a. Single-event fracture critical components comply with section 7.5.1 in this NASA Technical Standard.

b. HCF components comply with section 7.5.2 in this NASA Technical Standard.

c. Proof test approach for composite or bonded hardware complies with section 7.5.3 in this NASA Technical Standard.

d. Fleet leading testing approach complies with section 7.5.4 in this NASA Technical Standard.

e. Hazardous fluid containers for payloads and experiments comply with section 7.5.5 in this NASA Technical Standard.

[Rationale: Parts that comply with this requirement have had sufficient activities performed to establish adequate risk mitigation of failure caused by the presence of a flaw or crack-like defect and are approved by the RFCB.]

Use of an alternative approach requires unique rationale and approval by the RFCB as described in section 10 [FCR 26] in this NASA Technical Standard.

Section 7.5 in NASA-STD-5019A lists five optional established approaches for assessment of a fracture critical part that is not any of the hardware types addressed in section 7.2 and is approved by the RFCB for assessment in one of the five optional established approaches.

The sections are based on NASA experience for each hardware type. The FCR 14 "shall" requirement in NASA-STD-5019A imposes all the details of a selected section 7.5 classification upon the flight hardware.

[Rationale: Parts that comply with these requirements have had sufficient activities performed to establish adequate risk mitigation of failure caused by the presence of a flaw or crack-like defect and are approved by the RFC.]

These are the preferred approaches if completely implemented. An alternative approach may be feasible if it is approved by the RFCB and satisfies all the requirements in section 10 in NASA-STD-5019A.

NASA-STD-5019A, Item 7.5a

Section 7.5.a in NASA-STD-5019A imposes section 7.5.1 requirements upon single-event fracture critical parts.

Fracture critical components with a single-event life loading history, such as pyrotechnic components, may be shown acceptable by demonstrating a factor of 1.4 on critical stress intensity factor instead of a factor of 4 on life, if all of the conditions in this section apply and are satisfied.

NASA-STD-5019A, Item 7.5.b

Item 7.5.b in NASA-STD-5019A imposes section 7.5.2 requirements upon high-cycle fatigue components.

Fracture critical components operating in a potential HCF environment may be shown acceptable by establishing no HCF flaw growth. Examples of these are 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.

NASA-STD-5019A, Item 7.5.c

Item 7.5.c in NASA-STD-5019A imposes section 7.5.3 proof test approach requirements upon composite or bonded hardware.

Proof test, as an optional approach, is a category available on a limited-use basis. Use of this classification should include the RFCB early in the program. The proof test classification is usually limited to payload or secondary structures. These structures should have well-defined load paths, loads, and boundary conditions. The proof test should adequately load all appropriate members and sections of the structure, where necessary both in tension and compression (load reversal). In cases where shear and/or compression dominate, the proof test approach may not be appropriate because of delamination growth under these load conditions. If proof test does not adequately replicate operational conditions, this may not be an applicable approach.

NASA-STD-5019A, Item 7.5.d

Item 7.5.d in NASA-STD-5019A imposes section 7.5.4 fleet leader testing requirements upon hardware that can be characterized by a fleet leader assessment.

NASA-STD-5019A, Section 7.5.5

Section 7.5.5 in NASA-STD-5019A imposes section 7.5.5 requirements upon payloads and experiments that satisfy the requirements for classification as hazardous fluid containers.

The hazardous fluid containers category is limited to payload and experiment applications at conditions defined in requirements in section 7.5.5. This hardware type is not part of a pressurized system nor is it intended to transfer stored fluid as part of a pressurized system.

7.5.1 Single-Event Fracture Critical Components (NASA-STD-5019A, Section 7.5.1)

NASA-STD-5019A:
7.5.1 Single-Event Fracture Critical Components

Fracture critical components with a single-event life loading history, such as pyrotechnic components, may be shown acceptable by demonstrating a factor of 1.4 on critical stress intensity factor instead of a factor of 4 on life, if all of the following conditions apply.

For single-event fracture critical components, satisfy the following items 7.5.1.a, 7.5.1.b, 7.5.1.c, and either 7.5.1.d or 7.5.1.e (as appropriate for the material and situation) to meet requirement [FCR 14] section 7.5.a in this NASA Technical Standard:

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

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

c. The evaluation, whether by analysis or testing, and any deviations from the prescribed approaches in this section are coordinated in advance with and approved by the RFCB.

d. Metallic components are shown by analysis to satisfy a minimum factor of 1.4 on critical stress intensity factor.

The margin is be computed as:

$$\text{Margin on Critical Stress Intensity Factor} = \frac{critical\ stress\ intensity\ factor}{(1.4\ \times K_{applied})} - 1$$

where the:

critical stress intensity factor is usually represented as the plane strain fracture toughness, K_{Ic}*, or a parameter such as* K_{JIc} *with approval of the RFCB.*

e. Both non-metallic components and metallic components satisfy the requirements of this section by using process controls that ensure the flight hardware will be represented by tests conducted on identical samples that establish the following:

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

(1) Tests include a flaw in the worst location and orientation in the test articles.

(2) Apply either approach A or B below to establish the components are acceptable:

   A. Use this approach when loads are known and can be readily applied to test articles.

      i. The test load is at least 1.4 times the maximum expected flight load.

      ii. The flaw size is at least as large as the detectable sizes in NASA-STD-5009 (RTD for composite or bonded hardware, as described in section 7.4.3 in this NASA Technical Standard) for the inspection method applied to the flight hardware.

   B. Use this approach when loads are not well characterized or are difficult to apply.

      i. The flaw size is at least twice as large in all dimensions as the detected sizes in NASA-STD-5009 (twice as large as the RTD for composite or bonded hardware as described in section 7.4.3 in this NASA Technical Standard) for the inspection method applied to the flight hardware.

      ii. The load application is to simulate worst-case flight conditions.

      iii. A sufficient number of articles are tested to ensure the test conditions approach the maximum flight conditions.

Section 7.5.1 in NASA-STD-5019A imposes fracture control requirements upon fracture critical components which have a service lifetime that is essentially a single event, such as a pyrotechnic component. An example is described in the NASA Newsletter: Pyrotechnic Device Evaluation, Testing and Analysis/Propellants and Aerospace Fluids (Describes capabilities at the NASA White Sands Test Facility), last updated August 6, 2017 (https://www.nasa.gov/centers/wstf/testing_and_analysis/propellants_and_aerospace_fulids/pyrotechnic_device_evaluation.html which states:

> Commonly used in launch vehicles, tactical missiles, cargo and parachute deployment, and payload release mechanisms, a pyrotechnic device is a one-time use type of cutter. Activated by an electric signal, a small explosive charge within the device fires creating a high-speed, shearing effect that severs electrical circuits, opens or closes a valve, or releases and separates bolted connections and joints.

Introductory guidance in this section is copied below.

> *Fracture critical components with a single-event life loading history, such as pyrotechnic components, may be shown acceptable by demonstrating a factor of 1.4 on critical stress intensity factor instead of a factor of 4 on life, if all of the following conditions apply.*

Requirements in this section are imposed as specified by the following statement:

> For single-event fracture critical components, satisfy the following items 7.5.1.a, 7.5.1.b, 7.5.1.c, and either 7.5.1.d or 7.5.1.e (as appropriate for the material and situation) to meet requirement [FCR 14] section 7.5.a in NASA-STD-5019A.

NASA-STD-5019A, Item 7.5.1.a

Item 7.5.1.a of NASA-STD-5019A requires the loading event to be a single cycle or a single cycle that includes rapidly decaying subsequent cycles. When the pyrotechnic component is activated, the impulsive force may be a single loading spike, or it may be followed by decreasing loadings as the impulsive loading decays due to dampening. Both situations are treated as a single-event loading since the rapidly decreasing loadings will have minor effects on crack growth and fracture after the peak loading. If a component design results in repetitive similar magnitude impulsive loading events, it may not be suitable to assess the component with only the requirements in this "single-event" classification. In that situation, the RFCB should be consulted for guidance on developing an appropriate fracture control approach.

NASA-STD-5019A, Item 7.5.1.b

Item 7.5.1.b of NASA-STD-5019A requires the component not to experience any other significant loads. If rapidly decaying initial loadings occur, per item 7.5.1.a they do not violate the 7.5.1.b requirement. This item 7.5.1.b prevents the component from being exposed to other significant structural loads before or after the component has been activated. One way to evaluate whether other loadings exceed this requirement could be a damage tolerance analysis that demonstrates other loadings do not affect the structural strength of the critical section before the component is activated. This item 7.5.1.b also applies after the activation of the component. The remaining structure should not be expected to perform structural functions, unless that aspect was included as part of the qualification and certification of the component.

NASA-STD-5019A, Item 7.5.1.c

Item 7.5.1.c of NASA-STD-5019A specifies aspects of the damage tolerance assessment evaluation that is performed to demonstrate the component meets the requirements in this section of NASA-STD-5019A. Item 7.5.1.c requires the evaluation to be performed by analysis or testing and be approved by the RFCB. It also requires any deviations from the assessment approaches specified in section 7.5.1 to be coordinated in advance with the RFCB, and the completed assessment to be approved by the RFCB.

NASA-STD-5019A, Item 7.5.1.d

Item 7.5.1.d of NASA-STD-5019A applies the section 7.5.1 requirements to metallic single-event fracture critical components when this approach is appropriate for the situation. The requirements that have to be demonstrated by analysis are to show a minimum factor of 1.4 on the critical stress intensity factor of the component before activation. Guidance in this item describing the analysis details is copied below.

> *The margin is be computed as:*
>
> $$\text{Margin on Critical Stress Intensity} = \frac{critical\ stress\ intensity\ factor}{(1.4\ \times K_{applied})} - 1$$
>
> *where the:*
>
> *critical stress intensity factor is usually represented as the plane strain fracture toughness,* K_{Ic}*, or a parameter such as* K_{JIc} *with approval of the RFCB. Note that the margin should be greater than zero.*

NASA-STD-5019A, Item 7.5.1.e

The requirements in item 7.5.1.e of NASA-STD-5019A may be applied to both non-metallic and metallic components when the approach is appropriate for the situation. Since item 7.5.1.d is only for metallic components, item 7.5.1.e is the only approach available for non-metallic components.

This item requires process controls to be in place that ensure that all flight components will be identical, such that testing of representative components will be applicable to the components designated as flight hardware. Guidance in this section copied below clarifies the use of testing:

> *Tests may be used in situations where the applied loads are difficult to determine, the material properties are uncharacterized, or other factors make the damage tolerance analyses difficult.*

NASA-STD-5019A, Item 7.5.1.e(1)

Item 7.5.1.e(1) in NASA-STD-5019A specifies that a component test article has to have a flaw that is located in the most critical, i.e., the worst location and orientation. This item describes testing of "test articles" which means more than one test article is to be tested. If testing of two components demonstrates a significant difference in the test results, then requirement 7.5.1.e that imposes process controls has not been satisfied. In that case, actions should be pursued to identify root causes of the variability in the tested components, and the process controls should be improved and demonstrated to satisfy requirements in 7.5.1.e and 7.5.1.e(1).

NASA-STD-5019A, Item 7.5.1.e(2)

Item 7.5.1.e(2) of NASA-STD-5019A imposes either approach 7.5.1.e(2)A or 7.5.1.e(2)B to establish the components are acceptable as flight hardware. Note both the A and B approaches rely on test articles meeting the requirements for process-controlled hardware as described in item 7.5.1.e(1).

NASA-STD-5019A, Item 7.5.1.e(2)A

Item 7.5.1.e(2)A of NASA-STD-5019A requires the approach specified in items 7.5.1.e(2)A items i and ii shown below to be applied when the flight loads acting on the components are known and can be readily applied to the test articles.

NASA-STD-5019A, Item 7.5.1.e(2)Ai

Item 7.5.1.e(2)Ai of NASA-STD-5019A requires the test load to be at least 1.4 times the maximum expected flight load. When determining the test load, variability in the flight load assessment should be taken into account, such that the test load is assured of being at least 1.4 times the maximum expected flight load.

NASA-STD-5019A, Item 7.5.1.e(2)Aii

For metallic components, item 7.5.1.e(2)Aii requires the flaw size in the test articles to be at least as large as the detectable NDE sizes specified in NASA-STD-5009 for the inspection method applied to the flight components.

For composite or bonded hardware, this item requires the flaw size in the test articles to be representative of the RTD flaw size that is determined as specified in section 7.4.3 in NASA-STD-5019A.

NASA-STD-5019A, Item 7.5.1.e(2)B

Item 7.5.1.e(2)B of NASA-STD-5019A specifies the approaches detailed in items 7.5.1.e(2)Bi, 7.5.1.e(2)Bii, and 7.5.1.e(2)Bii are to be applied when the activation loads are not well characterized or are difficult to apply.

NASA-STD-5019A, Item 7.5.1.e(2)Bi

For metallic test articles, item 7.5.1.e(2)Bi specifies the flaw size in the test articles is to be at least twice as large in all dimensions as the detectable NDE size specified in NASA-STD-5009 for the inspection method applied to the flight components.

For composite or bonded test articles, this item specifies the flaw size in the test articles is to be at least twice as large as the RTD flaw size determined as described in section 7.4.3 in NASA-STD-5019A.

NASA-STD-5019A, Item 7.5.1.e(2)Bii

Item 7.5.1.e(2)Bii of NASA-STD-5019A specifies the test load application is to simulate the worst-cast flight conditions. This means the simulation is to encompass the worst-case situations and conditions during flight when the component is to be activated.

NASA-STD-5019A, Item 7.5.1.e(2)Biii

Item 7.5.1.e(2)Biii in NASA-STD-5019A specifies a sufficient number of articles should be tested to ensure the test conditions approach the maximum flight conditions. These conditions should encompass the worst-case situations that could affect the performance of the component during flight.

7.5.2 High-Cycle Fatigue Components (NASA-STD-5019A, Section 7.5.2)

NASA-STD-5019A:
7.5.2 High-Cycle Fatigue Components

Fracture critical components operating in a potential HCF environment may be shown acceptable by establishing no HCF flaw growth. Examples of these are 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.

Satisfy the following for HCF Components to meet requirement [FCR 14] section 7.5.b in this NASA Technical Standard:

a. Use a value for fatigue crack growth threshold that has been approved by the RFCB.

b. Assume the initial NDE flaw size in the worst location and orientation.

c. Propagate the flaw (by analysis or test) for 4 times the required design life using the low-cycle loads.

d. Use the final flaw size from the calculations or test data in 7.5.2.c (above) as the initial flaw size in calculating the stress intensity factor (metallic components) or total strain (composite or bonded components) related to the HCF environment.

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

  (2) The composite or bonded component is acceptable if the calculated net section strain (or stress) is below the no-growth threshold strain (or stress) for the composite or bonded material with RTD determined flaws.

All items 7.5.2.a through 7.5.2.d are typically performed analytically. Items 7.5.2.b and 7.5.2.c may be performed by test.

Section 7.5.2 in NASA-STD-5019A imposes fracture control requirements upon fracture critical components operating in an HCF environment. In this situation, crack growth should not be permitted to occur due to the high-cycle loadings, because the resulting crack growth per cycle would rapidly increase the initial crack size to a point where the component fractures. The maximum size defect that is exposed to the HCF loadings has to be less than the size where the HCF loading can cause fatigue crack growth.

These components may also experience a limited number of other types of loads which are not HCF loads. For example, a turbine or compressor blade may experience loadings due to centrifugal force, static pressures from fluids acted upon by the blade, or loadings transferred to the blade through its supports from adjacent blades. If these loadings are low occurrence, such as starting or stopping loadings, they may cause only small amounts of growth of small cracks in the blade during its service lifetime. The small crack growth due to these large loadings should not cause preexisting flaws to increase in size to a point where the HCF loadings exceed the fatigue crack growth threshold.

The introductory guidance copied below clarifies the hardware types that are addressed by this section:

> *Fracture critical components operating in a potential HCF environment may be shown acceptable by establishing no HCF flaw growth. Examples of these are 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.*

The guidance at the end of this section describes methodologies that are expected to be utilized to satisfy the requirements in this section.

> *All items 7.5.2.a through 7.5.2.d are typically performed analytically. Items 7.5.2.b and 7.5.2.c may be performed by test.*

NASA-STD-5019A, Item 7.5.2.a

To implement fracture control of HCF components per the requirements in this section, the fatigue crack growth threshold has to be available for the material in the operational environments. The fatigue crack growth threshold should have been established by crack growth testing using specimen that are representative of the component crack growth properties.

The testing establishing fatigue crack growth threshold for metallic components should use fracture specimen with initial crack sizes and/or shapes that represent or are an upper bound of the NDE detectable crack size plus the crack growth resulting from the requirements specified in item 7.5.2.c. (As an aid to understanding 7.5.2.c, see item 7.5.2.d that utilizes the results from item 7.5.2.c). The metallic specimen fatigue crack growth threshold testing should be based on loadings that create stresses and crack growth conditions that are representative of those associated with the HCF stresses in the component hardware. Also, the testing should be performed in environments that simulate or bound the conditions experienced by the component hardware during its damage tolerance service lifetime. A successful testing result defining the threshold should demonstrate no crack growth occurs when exposed to at least the number of cycles or the time duration the components experience at the HCF stress levels during at least 4 damage tolerance service lifetimes.

For composite or bonded components, the no-growth threshold strain (or stress) should be established by tests on specimen that are representative of the components with the NDE detectable crack size, plus the crack growth as specified in item 7.5.2.c, in environments that simulate or bound those encountered during the component damage tolerance lifetime.

The process to establish the component threshold for fatigue crack growth should be documented and the threshold value be approved by the RFCB.

NASA-STD-5019A, Item 7.5.2.b

Item 7.5.2.b of NASA-STD-5019A requires the initial flaw that is assessed to be detectable by NDE and located in the worst-case location and orientation. The worst-case should be selected based on effects of the component loadings and environments on crack growth in the component.

NASA-STD-5019A, Section 7.5.2.c

Item 7.5.2.c of NASA-STD-5019A requires demonstration by analysis or testing that the worst-case initial NDE flaw survives a damage tolerance service life that is at least 4 times the required design life of the low-cycle loads. The "low-cycle" loads are presumed to be larger, infrequent loads, which are not HCF loadings. These are discussed in an introductory paragraph before item 7.5.2.a.

NASA-STD-5019A, Item 7.5.2.d

Item 7.5.2.d of NASA-STD-5019A requires the final flaw size from the calculations or test data as specified in item 7.5.2.c to be used in assessments as specified in either item 7.5.2.d(1) or 7.5.2.d(2), according to the material type. The assessments are to evaluate the stress intensity factor for metallic components, or the total strains for composite or bonded components, for operations in the HCF loading environment.

NASA-STD-5019A, Item 7.5.2.d(1)

Item 7.5.2.d(1) of NASA-STD-5019A states the metallic component is acceptable with the flaw specified in section 7.5.2.d if the calculated HCF stress intensity factor is below the stress intensity factor threshold for the metallic material that was established as discussed in item 7.5.2.a.

NASA-STD-5019A, Item 7.5.2.d(2)

Item 7.5.2.d(2) of NASA-STD-5019A states the composite or bonded component is acceptable with the flaw specified in section 7.5.2.d if the calculated net section strain (or stress) is below the no-growth threshold strain (or stress) for the composite or bonded material that was established per item 7.5.2.a.

In addition, there is another requirement in item 7.5.2.d(2) that has not yet been discussed. The additional requirement is assessment of the risk of failure of the composite/bonded component due to growth of RTD flaws. The assessment will need to evaluate the effects of both the HCF and the low-cycle loads on the RTD flaws in the operational environment and demonstrate the effects of these flaws are also below the no-growth threshold strain (or stress) of the composite or bonded component.

RTD flaws are discussed at a high level in item 7.4.c. A DTA is required of composite/bonded hardware as specified in section 7.4.1 in NASA-STD-5019A. If the flaws identified by the DTA are not mitigated by an IDMP per requirements in section 7.4.2, they form the basis of flaws identified as RTD flaws as specified in section 7.4.3 in NASA-STD-5019A.

7.5.3 Proof Test Approach for Composite or Bonded Hardware (NASA-STD-5019A, Section 7.5.3)

NASA-STD-5019A:
7.5.3 Proof Test Approach for Composite or Bonded Hardware

Proof test, as an optional approach, is a category available on a limited-use basis. Use of this classification should include the RFCB early in the program. The proof test classification is usually limited to payload or secondary structures. These structures should have well defined load paths, loads, and boundary conditions. The proof test should adequately load all appropriate members and sections of the structure, where necessary both in tension and compression (load reversal). In cases where shear and/or compression dominate, the proof test approach may not be appropriate because of delamination growth under these load conditions. If proof test does not adequately replicate operational conditions, this may not be an applicable approach.

Satisfy the following for the proof test approach for composite or bonded hardware to meet requirement [FCR 14] section 7.5.c in this NASA Technical Standard:

a. Proof test the flight article to 1.2 times the limit load using one of the following:

Conduct the proof test in the appropriate environment.

Adjust the test loads using a coupon or hardware element test verified ECF.

b. Perform pre-proof and post-proof NDE, including special visual inspection if necessary, on the hardware.

c. Repair or replace hardware with indications of flaw growth or initiation that are discovered during proof test or with post-proof NDE.

Repeat the proof test to 1.2 times the limit load for repaired hardware.

Perform pre-proof and post-proof NDE, as well as special visual inspection if necessary, on the repaired regions.

d. Define the threats that may cause flaws from any source that may occur to the hardware during its service life, considering all applicable flaw detection and mitigation strategies that are implemented for the flight hardware.

e. Develop and implement an IDMP for the hardware that assures a complete record of hardware impact or damage status and mitigates the risk of undetected damage from the threats identified in 7.5.3.d (above) for the period between post-proof NDE and launch.

f. Establish that the largest remaining residual threat after post-proof NDE through the remainder of the service life can create damage no larger than the flaw size screened by NDE.

g. Repeat the proof test, repair, or replace the hardware as described in 7.5.3.a through 7.5.3.c (above) if any incidents of impact or other damage occur after post-proof NDE and before launch.

h. For re-flight hardware, repeat the proof test approach activities in items 7.5.3.a through 7.5.3.g in this NASA Technical Standard before the hardware is re-flown.

Proof test loads should be limited to less than 80 percent of ultimate strength of the structure for the appropriate mode of failure, e.g., tension, compression, and shear. Structures with an ultimate safety factor of 1.5 or greater will preclude exceeding 80 percent of ultimate strength when using a test factor of 1.2. Note that the full DTA activities of section 7.4.1 in this NASA Technical Standard are not required. However, test data describing capability relative to damage or flaws will likely be necessary to assist with disposition of any flaws discovered during pre-proof NDE. Test data for capability relative to damage or flaws may also be necessary to develop NDE criteria for reportable flaws. The relevant capability is dependent on the failure mode of concern, e.g., compression-after-impact strength, delamination growth, or other. Proof tests are usually performed in the operational environment, or the test levels are adjusted via an ECF.

The composite or bonded structure should be designed so that accompanying metallic parts do not experience detrimental yielding during the proof test.

General

The proof test approach for composite and bonded structures is an alternative to the damage tolerant approach for composite and bonded structures. The building block approach (see NASA-STD-5019A, section 7.4, FCR 13) is replaced with an approach that requires a substantial proof load be applied to each flight structure. This can dramatically reduce the cost to fly hardware, but this can also result in weight increases; and it locks the program into performing a proof test each time a flight article is to be used.

Proof testing is a very specific and detailed approach with highly prescribed activities that include identification of threats and development of an IDMP. The proof test will generally take the form of a static load test, a spin test, or a pressure test. More than one type or a combination of tests may be needed to fully proof the item. In some cases, a vibration test that sufficiently encompasses the hardware flight/operational loads may suffice.

Limited Application

The proof test approach is generally limited to payloads with well-defined load paths and boundary conditions or to hardware that does not lend itself to normal damage tolerant methods discussed in this Handbook. In special cases, small hardware items for which the design details are not fully known but the items themselves or similar ones have a successful history of safe operation may be accepted by proof test. Applicable hardware generally should be single use or should be proof tested between each mission.

RFCB Approval

The hardware developer should present detailed test plans to the RFCB for approval prior to implementing the proof test approach.

NASA-STD-5019A, Item 7.5.3.a

Proof Test

The proof test should be performed to a level of at least 1.20 times the limit load and/or MDP as applicable. This proof test factor is thought to be sufficient to screen for any flaw that might be a catastrophic hazard at the limit load. Given a design ultimate factor of safety of 1.5 or above, this would reduce the proof load to be at or below 80 percent of the ultimate strength. This limitation is intended to avoid the possibility of damage induced by the proof test.

ECF

Because the environment can affect the mechanical response of structures to loading, it is essential to conduct the proof test in the appropriate environment. An acceptable alternative is the use of an ECF that correctly accounts for the differences of mechanical response between the flight environment and the proof test environment.

The ECF is derived from coupon or hardware testing, and it is used to “calibrate” the damage tolerance behavior in the test environment to be equivalent to that in the flight environment. The environmental correction is not just restricted to temperature, and it should include all environmental aspects that would cause a deviation of material response between the flight environment and the proof test environment. As an example, if the residual strength at flight temperature is half of that for the proof test, then the proof test ECF should be two so that the proof test affects the material equivalently to a proof test load that would be performed at the flight temperature.

Calibration

A comparative analysis of proof test versus operation stress/strain should be performed to provide confidence that the proof test loading is adequate.

NASA-STD-5019A, Item 7.5.3.b

Detected Flaws

Any hardware with indications of growth or new flaws caused by the proof test should be repaired or replaced, and the proof test and NDE should be repeated after any repair.

NDE

Pre- and post-proof NDE are required. The proof test load magnitude (1.2 times the limit load) combined with the pre-test and post-test NDE is used in lieu of damage tolerance testing to provide assurance that the hardware does not contain flaws of concern. The proof test approach does not require damage tolerance testing to understand sensitivity of the hardware to defects. The hardware should be inspected post-proof to establish that there were no failures during proof and that the hardware is capable of performing its function. The intent is to provide assurance that no new flaws are created by the test and no existing flaws grow due to the test.

NASA-STD-5019A, Items 7.5.3.c, d, e, f

DTA, IDMP, and RTD

The full DTA activities of section 7.4.1 in NASA-STD-5019A are not required. Test data describing structural capability relative to damage or flaws will likely be necessary to assist with disposition of any flaws discovered during pre-proof NDE, and test data for structural capability relative to damage or flaws will likely be necessary to develop NDE criteria for reportable flaws. The relevant capability is dependent on the failure mode of concern, e.g., compression-after-impact strength, delamination growth, or other.

To perform the DTA, define any impact damage threats posed to the hardware by estimation, brainstorming, or other appropriate means. This effort is intended to help identify elements needed for the IDMP. Some threats may be more credible than others and may warrant extra effort to assure protection from impact damage.

Implement an IDMP. The IDMP is intended to provide assurance of two items:

1. Awareness of any impact damage that occurs or could occur. This approach could include multiple means such as isolation of hardware, impact sensing film or sensors, video monitoring, and human monitoring.

2. Avoidance of impacts for threats deemed to be too severe or likely. This approach can include a greater reliance on hardware protection and operational constraints as the primary mitigation activities.

Perform the RTD. Identify those damage threats that are not adequately addressed by the IDMP. The largest residual threat after post-proof NDE is to be no larger than the flaw size screened by

NDE. This is a prescriptive approach that requires a particular way to implement the IDMP to define the RTD flaw size. The IDMP should have some combination of protection, operational constraints, damage detection, additional NDE, or monitoring such that any damage larger than the NDE size is assured to be discovered either by knowledge of the impact event or discovery of the damage site.

7.5.4 Fleet Leader Testing (NASA-STD-5019A, Section 7.5.4)

> **NASA-STD-5019A:**
> **7.5.4 Fleet Leader Testing**
>
> Satisfy the following for fleet leader testing to meet requirement [FCR 14] section 7.5.d in this NASA Technical Standard:
>
> a. Provide the approach and rationale to the RFCB for approval before implementation.
>
> b. Document the approved approach in the FCP.
>
> *In cases where loading conditions are poorly defined, a ground test fleet leader program that allows use of the hardware may be feasible.*

The Fleet Leader Testing classification is intended for use with hardware where complex and combined environments may not be well understood or where a prediction of the response to the environments may not be reasonable. The situation may preclude the use of a fracture analysis, discrete fracture test, or increased proof test levels to provide a reasonable understanding of defect sensitivity. An example could include liquid engine propulsion system components where combined loading such as significant thermal transients, pressure, and flow-induced vibrations exist.

NASA-STD-5019A, Item 7.5.4.a

Requirement 7.5.4.a of NASA-STD-5019A recognizes that there are no standard methods that have been in consistent use for classifying hardware with fleet leader testing. The requirement provides the option to propose an approach using hardware test information as part of the fracture control rationale for mitigation of failure due to potential flaws. Although the approach is not specifically envisioned to include hardware testing with induced flaws, such an approach would provide a more thorough understanding of hardware defect sensitivity. Fleet leader testing should provide a sample representation of hardware performance, leading to a level of understanding for hardware sensitivity to defects inherent to the materials and manufacturing processes used.

An example approach could include hardware testing of multiple flight-like units with an increase in operational cycles and increases in environmental or load severity (where possible/practical) such that multiple units have test history that bounds the intended hardware usage. The number of units tested and level of bounded hardware operational cycles deemed to be necessary may be different depending on hardware type and mission needs. Discussion with the RFCB is necessary prior to implementation.

The approach should also address how hardware testing provides risk mitigation for fracture critical hardware, including a discussion of any other activities being performed for the hardware. Relevant topics include:

- Hardware sensitivity to defects.
- Flaw screening.
- Appropriate selection and usage of materials and manufacturing processes.
- Traceability of materials and hardware, serialization, handling, and loads or usage activities.

NASA-STD-5019A, Item 7.5.4.b

The RFCB-approved approach should be documented in the FCP for use in fracture control implementation activities.

7.5.5 Hazardous Fluid Containers for Payloads and Experiments (NASA-STD-5019A, Section 7.5.5)

NASA-STD-5019A:
7.5.5 Hazardous Fluid Containers for Payloads and Experiments

The hazardous fluid containers category is limited to payload and experiment applications at conditions defined in requirements below. This hardware type is not part of a pressurized system nor is it intended to transfer stored fluid as part of a pressurized system.

Satisfy the following for hazardous fluid containers for payloads and experiments to meet requirement [FCR 14] section 7.5.e in this NASA Technical Standard:

a. The container is limited to an MDP of 152 kPa (22 psi, 1.5 atm) and a maximum volume of 0.05 m^3 (1.76 ft^3).

b. An analysis is to show a positive margin against burst when a factor of 2.5 on MDP is used.

c. Perform proof test to 1.5 MDP.

d. Establish that no damage or detrimental deformation exists after the proof test.

e. Establish damage tolerance against rupture and leak by satisfying sections 8 and 9 in this NASA Technical Standard for all materials, section 7.3 in this NASA Technical Standard for metallic parts, section 7.4 in this NASA Technical Standard for composite or bonded parts, and by test or analysis as approved by the RFCB for other materials.

f. In addition to section 8 requirements in this NASA Technical Standard, perform an NDE inspection of all fusion joints in the container after proof test to determine acceptable conditions both on the surface and within the fusion joint.

g. Perform a leak test to 1.0 times the MDP.

In instances where NDE is not feasible, the manufacturer may employ a process-control program that assures the quality of the uninspectable welds and obtain approval of the RFCB.

Proof tests are usually performed in the operational environment, or the test levels are adjusted via an ECF.

Inertial load effects (including attach points) may necessitate additional assessments beyond the items in this category.

The introductory guidance is copied below. If the hardware being considered for this classification does not satisfy the aspects cited in the guidance, the hardware is not suitable for this classification.

The hazardous fluid containers category is limited to payload and experiment applications at conditions defined in requirements below. This hardware type is not part of a pressurized system nor is it intended to transfer stored fluid as part of a pressurized system.

NASA-STD-5019A has the following definitions of hazardous fluids and a hazardous fluid container which distinguish hardware that can be assessed by this fracture critical classification. Refer to section 3.2 in this Handbook or in NASA-STD-5019A for other relevant definitions such as catastrophic hazard.

Hazardous Fluid: For fracture control, a fluid the release of which would create a catastrophic hazard. These types of fluids may include liquid chemical propellants, liquid metals, biohazards, and other highly toxic liquids or gases. The release of such fluids 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 the release of which would cause a catastrophic hazard and that is not classified as a pressure vessel.

If the above definitions do not apply to the fluid and hardware being considered for this classification, the hardware cannot be classified as section 7.5.5 hardware.

The hardware may be evaluated to determine if it satisfies requirements for classification per section 6.1.4 for NFC Sealed Containers. That classification may be appropriate if the hardware is not part of a pressure system, is not a pressure vessel, does not contain a hazardous material, and loss of pressure or fluid from the container does not result in a catastrophic hazard.

Otherwise, hardware that is a fracture critical part has to satisfy the fracture critical requirements as discussed in section 7.1 in this Handbook.

NASA-STD-5019A, Item 7.5.5.a

Item 7.5.5.a of NASA-STD-5019A specifies the maximum container fluid pressure and volume. The MDP limit is 152 kPa (22 psi, 1.5 atm), and the maximum volume is 0.05 m^3 (1.76 ft^3).

The MDP is defined in section 3.2 in this Handbook for human-rated hardware. It is the highest possible operating pressure considering maximum temperature, maximum relief pressure, maximum regulator pressure, and, where applicable, transient pressure excursions. MDP for human-rated hardware is a two-failure-tolerant pressure, i.e., it will accommodate any combination of two credible failures that will affect pressure. Some programs have defined MDP as a two-fault-tolerant pressure.

For example, when pressure regulators, relief devices, and sources of pressure increase such as compressor systems or heaters are used to control pressure, collectively the system should be two-fault tolerant to prevent the system pressure from exceeding the MDP of the system. This means the MDP pressure limit, whether a steady or a transient pressure, is the maximum that can be reached after any combination of two credible failures that affect pressure.

NASA-STD-5019A, Item 7.5.5.b

Item 7.5.5.b of NASA-STD-5019A requires a structural analysis of the pressurized structure to be performed. Note this is not a damage tolerance analysis that is addressed in item 7.5.5.e. The analysis should utilize "A" basis material data and determine the burst pressure of the flight hardware. The item 7.5.5.b requirement is the predicted burst pressure should be larger by a positive margin than 2.5 times the MDP.

NASA-STD-5019A, Item 7.5.5.c

Item 7.5.5.c of NASA-STD-5019A requirement is to perform a pressure proof test to 1.5 times the MDP. Relevant guidance in this section is copied below.

Proof tests are usually performed in the operational environment, or the test levels are adjusted via an ECF.

NASA-STD-5019A, Item 7.5.5.d

Item 7.5.5.d of NASA-STD-5019A requirement is to establish that no damage or detrimental deformation exists after the proof test. One way to demonstrate this requirement has been met could be to measure the dimensions of the container before and after the proof test and shown them to be unchanged. Another could be to apply a strain-sensitive coating to the outside surface and verify the coating does not indicate detrimental deformation occurred during the proof test.

NASA-STD-5019A, Item 7.5.5.e

Item 7.5.5.e of NASA-STD-5019A requires the hardware to satisfy all the requirements in sections 8 and 9 in NASA-STD-5019A. This means the hardware should be subjected to flaw screening per section 8.1 and subsections according to the material type. It should also satisfy the material requirements in section 8.2 on traceability for fracture control and in section 8.3 on material selection and usage. Fracture control documentation is required as specified in section 9.1 and verification as specified in section 9.2.

Relevant guidance in this section is copied below.

In instances where NDE is not feasible, the manufacturer may employ a process-control program that assures the quality of the uninspectable welds and obtain approval of the RFCB.

In addition, the hardware is to satisfy all the damage tolerance requirements in NASA-STD-5019A according to the material type per section 7.3 for metallic parts, or section 7.4 for composite or bonded parts, and by test or analysis as approved by the RFCB for other materials.

NASA-STD-5019A, Item 7.5.5.f

Item 7.5.5.f of NASA-STD-5019A imposes an additional requirement beyond the section 8 requirements in NASA-STD-5019A, which is to perform an NDE inspection of all fusion joints in the container after the proof test. The criteria imposed is the NDE should confirm acceptable conditions both on the surface and within the fusion joint. Acceptable conditions mean there are no defects or cracks detected within or on the surface of the joints.

NASA-STD-5019A, Item 7.5.5.g

Item 7.5.5.g of NASA-STD-5019A requires a leak test be performed with a maximum pressure equal to 1.0 times the MDP. There has to be no leakage from any part of the container surfaces or joints from the pressure test.

Lastly, this section contains the following guidance.

Inertial load effects (including attach points) may necessitate additional assessments beyond the items in this category.

The above guidance is addressing the need to assess the container and the supports for all dynamic and inertial loading interactions between the container and the supports. For example, a crack in the container could result in fracture of an integral bracket leading to complex failure scenarios. Similarly, a crack in a bracket that is integral to the container may affect the container structural integrity.

8. FLAW SCREENING, TRACEABILITY, AND MATERIAL SELECTION

This section provides guidance and interpretations of numbered and titled material from NASA-STD-5019A.

NASA-STD-5019A:
8. FLAW SCREENING, TRACEABILITY, AND MATERIAL SELECTION

[FCR 15] All fracture critical parts shall be screened for flaws with methods and techniques identified in the FCP.

[Rationale: An understanding of the flaws or damage types to be screened and the methods to be used is necessary to assure adequate fracture control implementation.]

NDE is the primary method used for screening flaws for fracture critical parts. Proof test of the flight article may be used to screen for flaws in special cases, especially for glass elements. Visual inspection is an NDE method that is frequently used for inspecting composite or bonded parts for damage, in addition to other NDE methods. Visual inspection is also used for inspecting optical elements for flaws, often in addition to proof testing. In some cases, process control may be allowed as a method for establishing an upper bound on flaw sizes that may be present in the part.

As explained in section 1.4 in NASA-STD-5019A, FCR stands for a Fracture Control Requirement that is imposed by NASA-STD-5019A. FCR 15 imposes the overarching requirement that all fracture critical parts have to be screened for flaws. The reasons for this requirement, and methods of screening for flaws, are provided by the rationale and guidance in section 8.

The following guidance in section 7.1 is also pertinent:

In addition to assessments discussed in the subsequent subsections, fracture critical parts are subject to flaw screening, traceability, and material selection requirements in accordance with section 8 in the NASA Technical Standard.

There are additional NDE considerations as NASA looks to establish permanent and sustainable outposts in the moon and beyond. For long term or reusable hardware, structures, and systems (e.g., ISS, SpaceX Crew module, Gateway, human habitats), NDE inspections need to be scheduled to detect for flaws during operation throughout service life, especially at high-stress regions. For these types of hardware, fracture critical parts need to be inspected throughout their service life to identify crack initiation and propagation to ensure safety and preclude catastrophic hazard. Other considerations are the cases of mission profile changes or when DLL differ from measured operational loads affecting service life. Scheduled inspection would be documented in an NDE Plan.

8.1 Flaw Screening (NASA-STD-5019A, Section 8.1)

NDE is the primary method for screening flaws in fracture critical parts. NDE is discussed in section 8.1.1 of NASA-STD-5019A for metallic parts and in section 8.1.2 of NASA-STD-5019A for composite or bonded parts.

Two other methods of screening for flaws may be used if their use is approved by the RFCB. They are section 8.1.3 that describes screening of flaws by proof testing and section 8.1.4 that discusses screening of flaws by process controls.

8.1.1 NDE for Metallic Parts (NASA-STD-5019A, Section 8.1.1)

NASA-STD-5019A:
8.1.1 NDE for Metallic Parts

[FCR 16] Metallic fracture critical parts screened with NDE shall have inspections performed in accordance with NASA-STD-5009 and include the following for flaw screening by NDE:

a. Apply sufficient flaw inspection methods to the flight hardware to screen flaws larger than or equal to the size and shape that are evaluated in the hardware damage tolerance assessment.

b. In addition to NDE for flaw screening of other regions of fracture critical parts, perform post-proof test NDE at critical welds and other critical locations identified in the FCP for all parts that are proof tested as a part of acceptance, i.e., critical hardware locations not screened for specific flaws with the proof test.

[Rationale: This cites NASA-STD-5009 *and reduces the potential for redundant or conflicting requirements.]*

It is expected that fracture critical parts have surface and volumetric inspections unless there is rationale that it is not necessary. The need for internal (volumetric) inspection depends on application and materials characteristics such as thickness, product form, and other factors. Internal inspection requirements and methods should be determined early in the design process so that proper flaw screening is accomplished.

According to NASA-STD-5009, the flaw sizes and shapes that are evaluated in the hardware damage tolerance assessment are based on 90-percent probability of detection with 95-percent confidence (90/95 or better) flaw detection capability.

If one NDE method cannot adequately examine a part, additional NDE methods may be needed. If there are multiple types of flaws or complex geometry to assess, additional NDE may be needed. If there is uncertainty about which NDE methods or results for a particular *part are to be used to define flaws for the damage tolerance assessment, conservative choices are to be made.*

NDE activities and damage tolerance assessment activities should be coordinated to assure flaw screening occurs in the way intended.

As explained in section 1.4 in NASA-STD-5019A, FCR stands for a Fracture Control Requirement that is imposed by NASA-STD-5019A. FCR 16 requires metallic parts to be screened with NDE that is performed in accordance with NASA-STD-5009 which defines and specifies requirements imposed on Standard NDE and Special NDE.

NASA-STD-5019A, Item 8.1.1.a

Item 8.1.1.a of NASA-STD-5019A requires application of sufficient NDE methods to screen all regions of the metallic fracture critical part for flaws larger than or equal to the size and shape that are evaluated in the hardware damage tolerance assessment which is specified in section 7.3.2 for assessment by analysis or 7.3.3 for testing. The damage tolerance assessment begins at each location in the hardware with the NDE detectable flaw size, then computes flaw growth for all the damage tolerance service lifetime loadings. The assessment applies the damage tolerance requirements specified in section 7.3.2 or 7.3.3. The assessment should demonstrate no failure of the hardware occurs before the end of the required damage tolerance service lifetime.

The NDE methods should be able to reliably detect flaws of the types and sizes that are specified in Table 1 or 2 for Standard NDE in NASA-STD-5009. (References to NASA-STD-5009 are meant to refer to the latest version of that standard.)

NDE Detectable Flaw Types and Descriptions

Several flaw types are shown below in Figure 8.1-1, Types of Flaws (from NASA-STD-5009). The types include a surface crack, corner crack, embedded crack, and a through crack. The corner and through crack may occur at a hole, which is also shown in the figure. The through crack may occur at the edge or interior of a plate, with corresponding crack lengths as shown in the figure. There are many other geometries where cracks may occur, as in the many examples addressed by the NASGRO® computer program. These flaw types suffice to illustrate the crack dimensions that relate to the reliably detected flaw sizes specified in Table 1 or 2 for Standard NDE in NASA-STD-5009.

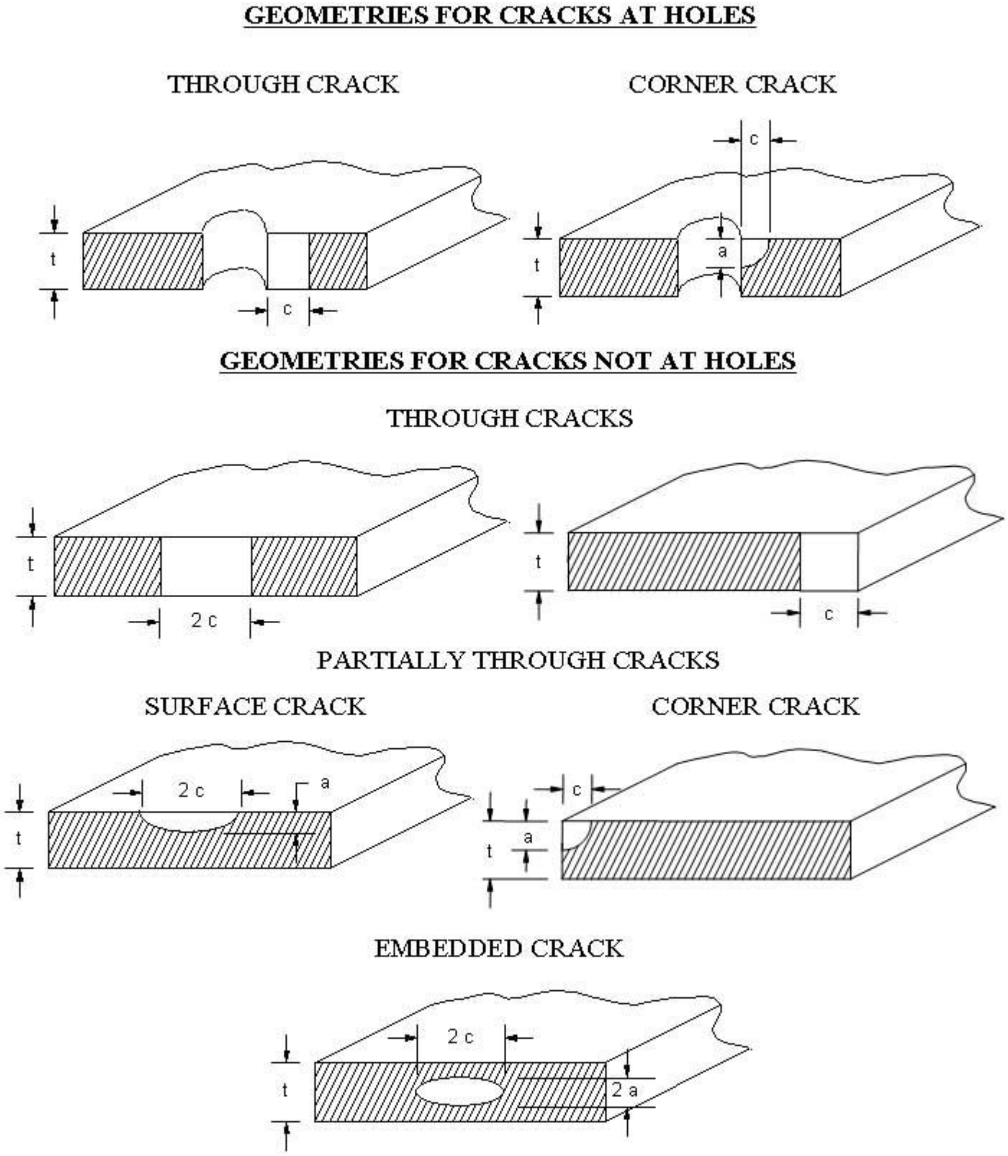


Figure 8.1-1—Types of Flaws

The surface crack geometry may be described as a half-ellipse in a surface of a plate, with the dimension of one-half of the minor and major axes denoted by the symbols a and c, respectively. The total surface crack length is then 2 times c, and the depth is the dimension. In the figure, the crack is shown centered in the plate, but in practice it is unlikely to be centered. In this example and others, there are additional dimensions needed for damage tolerance assessments that do not appear in the figure. Two examples of corner cracks are shown in the figure, which have a surface length of c and depth of a. Three types of through cracks are also shown, which have a length of "c" if they are associated with other boundaries such as the edge of a plate or a hole, and a length of "2c" if the crack is not associated with other geometry. An embedded elliptical-shaped crack in the figure is described by the total width of the minor axis as 2 times a, and the total length of the major axis as 2 times c.

The numerical value of the ratio a/c of these flaws is frequently referred to as the crack aspect ratio and may also be referred to as the flaw shape. The orientation of the plane where stresses are specified for damage tolerance stress intensity calculations is the plane described by the crack length and depth.

The NDE detectable crack sizes listed in NASA-STD-5009B, Tables 1 and 2, for surface cracks are identified in the tables as crack type "PTC," which is stated in a footnote to mean "Partly through crack (Surface Crack)" and is labeled "Surface Crack" in the above figure. Other crack types in the Tables are "Through" meaning a through crack, "Corner" meaning a crack at an edge of a hole or a corner, and "Embedded" meaning an elliptical crack in the interior of the part. The cracks shown above are idealized crack geometries for flaws that could exist in the part that are reliably detectable by the NDE method. Sufficient NDE methods have to be applied to screen all regions of the part for flaws.

Note the above cited reliably detected cracks are not actual cracks that were found to exist in the part. If NDE of the part reports actual cracks, the assessment of those cracks has to follow the requirements in section 8.1.5 in NASA-STD-5019A, as discussed in section 8.1.5 in this Handbook.

In addition to Standard NDE, Special NDE methods may also be available if the capability has been certified as specified in NASA-STD-5009. If special NDE may be needed and the capability is not already available and certified, the need should be identified and included in the FCP discussion of the planned NDE for the part.

Tables 1 and 2 in NASA-STD-5009B specify the reliably detectable crack sizes for Standard NDE that are to be used for damage tolerance assessments with the specified NDE methods, part thicknesses, crack types, and crack dimensions "a" and "c." These tables do not list the value of the ratio of a/c. The a/c values for the data in these tables were computed and found to be mostly in the range from 0.2 to 1.0, with a few exceptions for particular crack types and NDE methods.

An important conditional note in NASA-STD-5009B, section 4.2.3, discusses the basis for the detectable flaw sizes in the Standard NDE tables, identifies situations where the flaw sizes in these tables may not be applicable, and describes actions to be taken in that event.

Damage Tolerance Assessments and NDE

Requirements for damage tolerance assessments performed by analysis are described in section 7.3.2 in NASA-STD-5019A and are discussed in section 7.3.2 in this Handbook. The crack analysis program NASGRO® has models for many crack model types, including the types of cracks shown in Figure 8.1.1. The requirements for damage tolerance assessment by testing are described in section 7.3.3 in NASA-STD-5019A and are discussed in section 7.3.3 in this Handbook.

As discussed in sections 7.3.2 and 7.3.3 in this Handbook, damage tolerance assessments are performed based on the assumption that a crack may exist anywhere in the hardware with an NDE detectable size, orientation, and shape. All regions of the hardware have to be inspected by NDE. Then, damage tolerance assessments are performed for the hardware that are based on an assumed initial NDE detectable flaw at each unique location. The assessment then evaluates the applied loading-induced stresses upon the flaw to predict crack growth in the hardware and the damage tolerance lifetime. A particular crack growth assessment defines the damage tolerance service life for an initial flaw in that particular location in the hardware. Multiple flaw locations should be assessed to determine the worst location that produces the lowest damage tolerance service life. The flaw size at location(s) that cause the lowest damage tolerance service life establish the damage tolerance service life capability of the hardware.

A discussion is provided in section 7.3.2.a in this Handbook on the effect of the crack aspect ratio, a/c, on the damage tolerance life. The discussion cites a reference that reports the minimum life for the same applied loadings may be a crack with aspect ratio that is between the a/c aspect ratios of 1.0 and 0.2, depending on the applied stresses. As noted above, the values of a/c that are shown in NASA-STD-5009, Tables 1 and 2, are mostly for a/c range of 1.0 to 0.2. In addition to evaluating the detectable crack a and c values shown in NASA-STD-5009, Tables 1 and 2, two or three intermediate values of a and c should be assessed to search for the minimum damage tolerance life of a flaw with a worst-case a/c aspect ratio for the applied stresses and part geometry.

Screening for Cracks

In general, the types of manufacturing processes used to produce the part should be characterized by metallurgical studies that establish the types of flaws that may be present at processing steps and where inspections can be effective in reducing the size and number of defects in finished parts. The example flaws may also be useful to evaluate the effectiveness of NDE methods in finding and characterizing likely flaws.

Appropriate NDE methods and techniques should be selected and applied for inspection of the hardware with consideration of part geometry, capabilities of the NDE methods and the probable types of cracks. Some NDE methods are briefly discussed in the following list:

- Penetrant inspection testing can provide a sensitive detection method for the location of surface flaws on hardware parts that are machined or formed from plates, forgings, or spinning. To obtain the required reliability of crack detection with penetrant testing, etching is generally needed to ensure cracks that were open to the surface but were closed off by polishing or machining operations, are exposed so the penetrant can enter the crack.
- Eddy current inspection may be useful. Probes can have specialized shapes to be compatible with hardware geometry. Examples of the hardware with radii may be needed with known cracks in them to calibrate the eddy current probes and detection equipment.

- Radiography may be useful for inspection of welds for typical volumetric flaws. For crack detection, the method sensitivity depends on the orientation of the x-ray beam and the plane of a crack. The most contrast on the sensor/film occurs when the x-ray beam and the crack are in the same plane, i.e., when the crack is not at an angle to the beam.
- Ultrasonic inspection methods may be used for detection of surface cracks and interior cracks. Different types of ultrasonic probes and ultrasonic waves are used for these examples. An inspection test article may be needed with example flaws in it to validate the method capability and reliability.
- Magnetic particle testing may be useful to detect surface flaws for hardware made from ferritic materials.

There are many other NDE methods which are not listed, and the listed descriptions are not comprehensive; each one is a very short synopsis. A combination of the above and other NDE methods may be needed depending on the hardware manufacturing processes, the hardware geometry, material, and the size and types of cracks that have to be reliably detected.

Additive Manufacturing Metallic Parts

Parts fabricated by AM are susceptible to both conventional metallic flaw types as well as flaw types specific to the AM process. The potential AM-specific flaws may include laminar cracks and tears along build planes, separation of the part from support structures, and geometric distortion. It is unknown at this time if the Standard NDE flaw sizes in NASA-STD-5009 are applicable to AM-fabricated parts. All inspections of AM-fabricated parts should meet the conditions for Special NDE as defined in NASA-STD-5009. Demonstration studies would need AM parts with intentional flaws for evaluating the reliability of NDE methods. The flaws would need to be situated in the most challenging locations and positions to characterize the worst-case situation for NDE detection of the flaws.

NASA-STD-5019A, Item 8.1.1.b

Item 8.1.1.b of NASA-STD-5019A requires application of post-proof NDE screening for flaws at critical locations and critical welds. These critical regions are to be identified in the FCP for all parts that are proof tested as part of their acceptance requirements. Section 8.1.1b also states critical hardware regions are all locations that are not screened for flaws with the proof test.

Damage tolerance assessments will be needed to determine the part locations and critical welds that are to be screened by post-proof NDE. The assessments will need to satisfy the requirements in section 7.3.2 or 7.3.3 in NASA-STD-5019A as discussed in this Handbook.

First, assessments will need to determine the critical initial flaw size that is detected by NDE and provide the needed damage tolerance service lifetime in the welds and in the other regions of the part. This flaw size is represented by the symbol A_{NDE}. Its value is expected to be different throughout the part locations and the welds. Since the flaw may be a surface or a corner crack, it may have different values at the crack depth, a, and surface, c positions.

Next, damage tolerance assessments will need to determine the flaw size that is screened by the proof test in the welds and in the other regions of the part. This flaw size is represented by the symbol $A_{\mathbf{proof}}$. Its value also is expected to be different throughout the part locations and the welds, and it also may have different values at the crack depth, a, and surface, c positions. Since the proof loading is a larger loading, it is expected the $A_{\mathbf{proof}}$ values will be smaller than the $A_{\mathbf{NDE}}$ values at the same physical location in the part; but it could vary due to fatigue crack growth affecting $A_{\mathbf{NDE}}$ that is not considered when computing $A_{\mathbf{proof}}$.

Item 8.1.1.b can then be explained as a requirement that all welds and other locations in the hardware where either of the $A_{\mathbf{proof}}$ two values are larger than the corresponding $A_{\mathbf{NDE}}$ two values have to be inspected by post-proof test NDE that screens for the $A_{\mathbf{NDE}}$ flaw sizes.

Note that any detected flaws in the part should be assessed per the requirements of section 8.1.5 in NASA-STD-5019A as discussed in this Handbook.

One reason for this requirement is the proof-test loading may cause a critical flaw to be more open after the proof loading so it is easier to detect with NDE. Also, the proof test loading may cause growth of a flaw causing it to have a smaller damage tolerance service lifetime.

There may be an option to avoid performing the $A_{\mathbf{proof}}$ damage tolerance assessments if the NDE that is required for the $A_{\mathbf{NDE}}$ flaw screening was also applied throughout all regions, both the welds and all other locations of the part, after the proof test. If this approach is feasible and planned, it should be documented in the FCP that is approved by the RFCB.

Additional Considerations for Additively Manufactured Parts

Because of the nature of AM parts which are process-dependent, refer to NASA-STD-6030, Additive Manufacturing Requirements for Spaceflight Systems, section 4.8, for additional NDE considerations.

8.1.2 NDE for Composite or Bonded Parts (NASA-STD-5019A, Section 8.1.2)

NASA-STD-5019A:
8.1.2 NDE for Composite or Bonded Parts

NDE activities for composite or bonded materials requirements apply to fracture critical and NFC parts. Because of the potential sensitivity to impact damage and flaws for these types of materials, additional activities are necessary for NFC parts in accordance with [FCR 9] 6.3.c in this NASA Technical Standard.

[FCR 17] For composite or bonded materials, the hardware developer shall:

a. Provide the NDE methodology and rationale in the FCP.

b. Perform flaw screening by NDE on all composite or bonded part regions, except for the following:

(1) No NDE is required for NFC low-released mass parts.
(2) No NDE is required for NFC contained parts.

c. For hardware that is proof tested as part of acceptance, perform pre-proof and post-proof test NDE at critical joints, discontinuities, and other critical locations identified in the FCP for all hardware, i.e., critical hardware locations not screened for specific flaws with the proof test.

[Rationale: There are no NDE standards available that are applicable to the wide variety of non-metallic materials and forms in use and the different NDE methods required for their inspection. The approach for NDE of other materials needs to be documented and fully explained within the FCP.]

Inspection of composite or bonded parts is to meet the intent of MIL-HDBK-6870, Nondestructive Inspection Program Requirements for Aircraft and Missile Materials and Parts, as required in NASA-STD-6016.

Hardware should receive post-proof NDE unless a special RFCB approval has been granted.

Generally, the NDE approach and rationale for all materials should address which indications rise to the level of a reportable flaw. For signal-based methods, such as ultrasonic inspections, NDE acceptance criteria are usually necessary to discern whether the signal responses warrant nonconformance reporting. All damage indications from visual inspection are reportable. Workmanship standards for visual inspection should define acceptance criteria, e.g., porosity, surface texture, geometric contours. NDE acceptance criteria may be developed by analysis with supporting coupon test data for the appropriate material type. Prior approval should be obtained from the RFCB when visual inspection is used as a flaw-screening technique for fracture control. Screening of a low-risk part with NDE should be *considered when it is plausible for that part to be reclassified as a fracture critical part. A part may need to be reclassified when it is plausible for that part to be accepted for flight with out-of-tolerance dimensions or nonstandard material properties.*

[FCR 17] imposes requirements for NDE of composite or bonded hardware in items 8.1.2a, b, and c that are discussed below.

[Rationale: There are no NDE standards available that are applicable to the wide variety of non-metallic materials and forms in use and the different NDE methods required for their inspection. The approach for NDE of other materials needs to be documented and fully explained within the FCP.]

The rationale explains there are no established NDE standards for this application that can be cited. The NDE approach would be defined by the hardware developer and would consider items such as: 1) developing standards with engineered flaws to meet the orientation of the component and expected defect zones, 2) defining POD requirements, 3) defining flaw types expected, and 4) determining the part inspect-ability for the NDE methodology employed. The approach for accomplishing the NDE of these parts should be fully documented in the FCP which has to be developed and maintained per section 4.1, Fracture Control Plan, and the [FCR 1] requirements that include approval of the FCP by the RFCB. In some programs the hardware developer generates a separate NDE Plan that accompanies the FCP. In such cases, the aforementioned approach may be documented in the NDE Plan.

The following introductory guidance clarifies NDE is required for fracture critical hardware and also for NFC composite or bonded materials due to their sensitivity to impact damage and flaws:

> *NDE activities for composite or bonded materials requirements apply to fracture critical and NFC parts. Because of the potential sensitivity to impact damage and flaws for these types of materials, additional activities are necessary for NFC parts in accordance with [FCR 9] 6.3.c in this NASA Technical Standard.*

The fracture critical section 7.2.6, Fracture Critical Pressurized Structures, also imposes requirements for composite or bonded hardware. These requirements are specified in items d and e with associated guidance that are copied below for reference.

Item 7.2.6.d states:

"For composite or bonded pressurized structures, provide the damage tolerance approach and rationale to the RFCB for approval before implementation."

Item 7.2.6.e requires:

"For composite or bonded pressurized structures, perform post-proof NDE as described in section 8.1.2 in the NASA Technical Standard."

Section 7.2.6 guidance states:

"For composite or bonded pressurized structures, the requirements in section 7.4 in NASA-STD-5019A are a good starting point as a fracture control approach but will need enhancement to provide adequate protection against catastrophic hazard."

Other relevant guidance in this section is copied below.

Inspection of composite or bonded parts is to meet the intent of MIL-HDBK-6870, Nondestructive Inspection Program Requirements for Aircraft and Missile Materials and Parts, as required in NASA-STD-6016.

Note that MIL-HDBK-6870 is a general guidance book and not a requirements document. However, it is widely used in the aerospace industry as guidance for NDE for composite and bonded materials.

Following guidance discussion on section 8.1.2 requirements, relationship between section 7.4 requirements in NASA-STD-5019A and this section is presented. Composite or bonded hardware typically has more complex crack growth and failure modes than those exhibited by metallic materials, NDE is an integral part of assessing this type of hardware. Section 8.1.2 and section 7.4 are closely linked as NDE is central to supporting section 7.4 requirements. A discussion describing how the two sections are linked with regard to NDE methods for composite or bonded parts is provided at the end of this section.

NASA-STD-5019A, Item 8.1.2.a

Item 8.1.2.a of NASA-STD-5019A requires the NDE methodology and rationale to be documented in the FCP that is approved by the RFCB as noted above.

NASA-STD-5019A, Items 8.1.2.b, b(1), and b(2)

Items 8.1.2.b, b(1), and b(2) of NASA-STD-5019A require NDE screening to be performed on all composite or bonded part regions, with the exception that no NDE screening is required for parts classified as either 6.2.1, NFC Low Released Mass, or 6.2.2, NFC Contained parts. Failure of parts in these classifications do not usually present additional risks.

An additional consideration is discussed in the following guidance on NDE of low-risk parts:

> *Screening of a low-risk part with NDE should be considered when it is plausible for that part to be reclassified as a fracture critical part. A part may need to be reclassified when it is plausible for that part to be accepted for flight with out-of-tolerance dimensions or nonstandard material properties.*

Guidance in this section on NDE methods states:

> *For signal-based methods, such as ultrasonic inspections, NDE acceptance criteria are usually necessary to discern whether the signal responses warrant nonconformance reporting. All damage indications from visual inspection are reportable. Workmanship standards for visual inspection should define acceptance criteria, e.g., porosity, surface texture, geometric contours. NDE acceptance criteria may be developed by analysis with supporting coupon test data for the appropriate material type. Prior approval should be obtained from the RFCB when visual inspection is used as a flaw-screening technique for fracture control.*

NASA-STD-5019A, Item 8.1.2.c

Item 8.1.2.c of NASA-STD-5019A requires pre-proof and post-proof test NDE of critical locations of hardware that is proof tested as part of the acceptance requirements when the proof test does not screen the critical locations for flaws. The critical locations are identified as critical joints, discontinuities, and other critical locations that are identified in the FCP which are not screened for specific flaws by the proof test.

Relevant guidance in this section is copied below:

> *Hardware should receive post-proof NDE unless a special RFCB approval has been granted. Generally, the NDE approach and rationale for all materials should address which indications rise to the level of a reportable flaw.*

Relationship between Section 8.1.2 and Section 7.4

Section 7.4, General Approach for Fracture Critical Composite or Bonded Hardware, in this Handbook defines how fracture control is implemented on fracture critical composite and bonded parts. Section 8.1.2 and section 7.4 are closely linked as NDE is central to supporting section 7.4 requirements. The following is a discussion describing how the two sections are linked.

As described in section 7.4.1, a DTA should “define and quantify flaws from any source . . . during its service life.” The DTA should be one of the first activities performed in implementation of fracture control to composite or bonded parts. An IDMP is a follow-on activity describing how each identified threat in the DTA is mitigated. The hardware has to be able to survive any of the threats that cannot be mitigated and are credible. NDE is a valid method for mitigating threats; though to use it in this manner, it should be quantifiably reliable to a level approximately equivalent to the analogous 90% detectability with 95% confidence requirement for metallic parts. For example, mitigation of low-velocity impacts using NDE may be best performed via external visual inspection that searches for barely visible impact damage or via techniques that can discover internal delaminations such as ultrasonic or thermography.

Following the DTA and IDMP, section 7.4.3 then calls for developing an RTD. The RTD is defined in section 7.4.3.a as “the worst-case credible flaw conditions that are shown to be tolerated by the hardware through analysis and test, considering all applicable flaw detection and mitigation strategies . . ..” Section 7.4.3.b then goes on to state: “Encompass all possible worst-case credible damage conditions, except by threats that are mitigated by NDE evaluations . . ..” By using NDE in the IDMP to mitigate threats defined in the DTA, the flaw size and type in the RTD is commonly based on the capability of the NDE method that is used. The NDE used to satisfy section 8.1.2 should be the same that is used in developing the RTD.

Note that BVID as defined in the aircraft industry may be inappropriately large for spaceflight applications. Barely visible damage and critical defect size need to be established by means of IDMP and RTD with appropriate inspections.

Sections 7.4.5, 7.4.6, and 7.4.8 describe much of the activity needed to determine the RTD. The NDE sets a threshold defining what unmitigated threats are undetectable and credible to exist. Specifically, NDE of composite or bonded parts may define several items, including:

a. Which identified threats can be mitigated;
b. What damage size can be found; and
c. To what extent there are multiple credible damage sizes, types, and locations.

The RTD development takes all of this into consideration and then determines which of these credible damages is worst case and ultimately provides evidence through testing and/or analysis that the worst-case credible damage is survivable. Sections 7.4.5, 7.4.6, and 7.4.8 call for damage tolerance testing of test articles that represent flight hardware ranging in scale from material coupons to full-scale flight-like test articles. The NDE technique used in the damage tolerance testing to quantify flaws in these tests should be the same NDE that is used to satisfy requirements in section 8.1.2. Otherwise, it may be difficult to argue that the NDE used for 8.1.2 is appropriate.

If a composite or bonded part has geometry or specific material non-homogeneity such that the NDE capability is not consistent at all locations or for all flaw types, this should be accounted for in the NDE procedure. For example, NDE of a sandwich composite may have differing capability in detecting a core face sheet disbond and a disbond internal to the face sheet only. In this scenario, a credible flaw size is dependent on flaw type and development of the RTD should include assessment to determine which of these two credible flaw types is “worst case” from a damage tolerance perspective. If there is not a clear answer to this question, it may be that both flaws are included in the RTD and two different NDE methods (or two levels of capability of the same method) are needed. This scenario also assumes that both flaw types were identified in the DTA. If this is the case, all NDE processes used to support the RTD testing should also be performed on flight hardware to satisfy section 8.1.2.

Item 7.4.8.b and section 7.4.9 require evaluation of initial flaws and damage that occurs during damage tolerance assessment of test articles. Again, the same NDE techniques used to satisfy section 8.12 should also be used to satisfy item 7.4.8.b and section7.4.9. This is particularly important to verify that failure modes are as expected and that the NDE technique can detect all failure modes of interest.

Note that NDE can be used to mitigate risks as discussed, but NDE only mitigates threats that may have occurred up to the point in time that the NDE is performed. A common example is performing post-proof test NDE. Both the NDE and the proof test cannot mitigate threats that occur later in service life. Another common example is only performing NDE of a composite panel after manufacturing and before shipment. This NDE, provided it is of sufficient quality and reliability, may be said to mitigate threats present during the manufacturing phase prior to shipment. If an optional approach, proof test approach, or programmatic risk acceptance is used such that section 7.4 is followed only in part or not at all, the NDE used to satisfy section 8.1.2 has to be of sufficient quality to satisfy section 8.1.2 and also to support whatever fracture control methodology is used. Regardless of activity performed to satisfy section 7.4, a minimum interpretation of section 8.1.2 should be to perform NDE of composite or bonded parts after fabrication but before integration. (Performing NDE after integration may be acceptable if there is still full physical access needed to perform the NDE.)

Composites Inspection

At the time this Handbook was written, there appeared to be no NASA standards on composites inspection methodology, capabilities, or defect detection reliability available. The applicable requirements are stated in section 8.1.2 in NASA-STD-5019A by FCR 17, which imposes the following requirements. In section 8.1.2.a, the requirement is to “provide the NDE methodology and rationale in the FCP.” In section 8.1.2.b, the requirement is to “perform flaw screening by NDE on all composite or bonded part regions” (with the exceptions in items 8.1.2.b(1) and (2).

Also, section 4.1 in NASA-STD-5019A imposes requirements on the FCP, including section 4.1.c that requires the FCP “Specifies fracture controls that are established to mitigate the risk of catastrophic failure caused by flaws throughout the service life of the hardware,” and section 4.1.d “Has approval by the RFCB.” Also, if tailoring of NASA-STD-5019A requirements is necessary, section 1.3 in NASA-STD-5019A states: “Tailoring shall be approved by the responsible delegated Technical Authority in accordance with NPR 7120.5, NASA Space Flight Program and Project Management Requirements.” Requirements for composites inspection need to be stated in the FCP, adhere to the above requirements, and be approved by the RFCB unless the requirements are tailored and approved by the responsible delegated Technical Authority.

Inspection of composites is an evolving technology accompanying the development of composite fracture critical structures. The inspection methods should be capable of detecting the identified RTD defects that could prevent the parts from accomplishing the required damage tolerance lifetime. To demonstrate the NDE methods are valid, they should be shown to be capable of reliably detecting the RTD defects that may exist in the flight part. Descriptions and studies of NDE capability to reliably detect flaws representative of the RTD defects should be documented in the RFCB-approved FCP.

Inspection of fracture critical parts should include a comprehensive visual inspection. Additional NDE methods may be applied if the visual inspection capability is not sufficient to reliably detect all the RTD flaws that may exist in the part. Additional NDE methods may include standard ultrasonic testing, phased array ultrasound testing, air coupled ultrasound testing, thermography, shearography, and other evolving methods. To facilitate use of multiple NDE methods on the part, regions or zones of the part may be identified as areas where additional NDE method(s) should be applied. Use of particular NDE methods for zones in the part would need to be shown to be valid by testing the NDE method for the identified zone and demonstrating it can reliably detect a typical RTD flaw in that zone.

NDE methods may be categorized as deterministic or statistical depending on their demonstrated capability to detect RTD flaws as discussed below. Brief discussions of both methods are provided below followed by two examples of procedure specifications.

An NDE method is deterministic if it is demonstrated to be capable of detecting all possible RTD flaws equal to or larger than the RTD flaw size with a contrast-to-noise ratio (CNR) of 2.5 to 1 or better. Contrast means the difference of the digital value in a specific region compared to the average digital value in a neighboring region. The CNR is the contrast in the specific region divided by the standard deviation of the contrast of a neighboring region. In addition, demonstration of capability requires the RDT flaws to be larger than 10% of the screen with the resolution of the inspection system at normal inspection settings.

An NDE method is statistically acceptable if it has the capability to detect RTD representative flaws with at least a 90% probability of detection at a 95% confidence level. False calls of defects (false positives) are not allowed. The test should meet the intent of MIL-HDBK-1823, Nondestructive Evaluation System Reliability Assessment.

The NDE method(s) used should be deterministic or statistically acceptable at finding all RTD flaws. Reference standards that are either from actual hardware or manufactured to simulate RTD flaws of a smaller size than the RTD flaw(s) should be used to verify inspection capability.

Personnel performing inspection should be qualified and certified for the NDE procedure to an equivalent of Level II in accordance with NAS410, NAS Certification and Qualification of Nondestructive Test Personnel. If the NDE method used is statistical the inspector should demonstrate capability to detect RTD flaw(s) with at least a 90% probability of detecting the RTD flaw(s) at a 95% confidence level.

Hypothetical Example: Inspection of Fiber-reinforced laminate composite parts

1. **Assumptions**: Scanning ultrasonic inspection is used on the part and a plan view of the part is generated with color coding of the inspection results (C-scan) scanning. Frequently zero-degree longitudinal wave mode is used. If other techniques are used small changes to the requirements may be needed. Assumes square pixels i.e., scan step equals index step.

The capability of 90% probability of detection at 95% confidence of RTD flaws or deterministic capability should be verified. RTD flaws may be delaminations, foreign material, crushed or gaps in core for honeycomb, or other flaws. Noise is measured in the surrounding area of the flaw as standard deviation of the signal response. Ultrasonic attenuation may be used to screen for excessive porosity in laminated parts as a cursory check without calibrated technique.

2. **Reference Standard Requirements**: NDE reference standards shall be representative of the part and shall have known size representative flaws (programmed delaminations or disbonds) at various depths (z coordinate) and spatial (x, y coordinates) locations. Representative flaws in the laminate sections shall be located at minimum 3 depths providing adequate coverage for flaws within the laminate thickness. Typically, in laminates, flaws should be on nearside, middle, and farside. Nearside and farside flaws may be between ply 2-3 from the respective nearside and farside laminate surface. For thinner laminate thicknesses, where more than 2-3 plys of separation between flaw depths is not possible, less than three depths of flaws may be used. Representative disbonds shall be located on both sides of (film or paste) adhesive for bonded parts. Pull tabs may be used for core structures. The representative flaws shall be spaced so that they do not overlap in x- y coordinates. Flaws used for validation of NDE procedure may be located on a single or several physical test standards.

3. **Flaws Used for Validation and/or Calibration/Standardization**: Both target and sub-target flaws shall provide adequate and uniform flaw detectability (indication size and signal response). Flaws with out-of-family flaw indications caused by either bonding of flaw partially or wholly shall not be used in the validation.

4. **NDE Procedure Validation Requirements**

If the deterministic capability is to be satisfied, then:

> CNR shall be ≥ 2.5. Minimum 40 pixels shall be used for noise measurement, and at least when viewing the defect standards for every simulated defect it will be at least as large as 10% of the imaging screen for the c-scan used.
>
> Adequate statistical capability requires a probability of detection (POD) study be performed. The required 90% probability of detection at 95% confidence level requires at a minimum 29 RDT flaws for each method. The POD has to meet the intent of MIL-HDBK-1823.

8.1.3 Proof Test (NASA-STD-5019A, Section 8.1.3)

NASA-STD-5019A:
8.1.3 Proof Test

[FCR 18] If proof testing is used as the flaw screening technique for fracture critical parts, the approach shall be documented in the FCP with rationale establishing that it is an applicable approach that has been approved by the RFCB.

[Rationale: Proof test may be used for flaw screening. However, few parts, materials, and applications lend themselves to a simple proof test strategy. Environmental effects, temperature, test fixture, inertial loads, and other complexities require careful consideration before accepting proof as the sole method for flaw screening. If proof test is used for flaw screening, an understanding of the planned approach and anticipated effectiveness needs to be approved by the RFCB and documented in the FCP.]

Proof test should not be used as the only flaw screening method for composite or bonded hardware.

The flaw size used in the life assessment should adequately account for flaw growth during the proof test. To establish that the assessment is valid, sufficient test data should be obtained using pre-flawed specimens that are representative of the part configuration, material conditions, and screened flaw and show the amount of growth of all crack fronts during the proof test from all sources, including stable tearing, and both EAC and SLC if applicable, have been conservatively bounded.

When it is judged that a proof test is appropriate to screen hardware for flaws, the proof test should occur at the in-service temperature and environment. If this is not feasible, an ECF can be used as approved by the RFCB. Upper bound critical stress intensity or residual strength should be used when establishing an analytically predicted flaw size screened by proof test.

Note that a proof test is required for acceptance in accordance with NASA-STD-5001 (or program-specific requirements), with a minimum proof test factor, depending upon whether a prototype or proto-flight verification approach is followed and the type of material used.

Section 8.1.3 in NASA-STD-5019A describes the NASA fracture control requirements imposed upon proof testing if it is used for flaw screening. Requirement [FCR 18] specifies the proof test approach should be documented in the FCP, with rationale that establishes it is an applicable approach, and the approach has to be approved by the RFCB.

The reasons for these requirements are provided in the Rationale which is copied below:

> *[Rationale: Proof test may be used for flaw screening. Few parts, materials, and applications lend themselves to a simple proof test strategy. Environmental effects, temperature, test fixture, inertial loads, and other complexities require careful*

> *consideration before accepting proof as the sole method for flaw screening. If proof test is used for flaw screening, an understanding of the planned approach and anticipated effectiveness needs to be approved by the RFCB and documented in the FCP.]*

The Rationale advises a proof test may be proposed for flaw screening, but it may be very difficult to implement in complex situations. The Rationale cites a number of cases where applying a proof test loading may not be meaningful when fracture is controlled by loading or environmental effects that would be difficult or impossible to simulate with a proof test.

Discussion for composite or bonded hardware damage tolerance assessments

Guidance in this section regarding proof testing and composite or bonded hardware states:

Proof test should not be used as the only flaw screening method for composite or bonded hardware.

Composite or bonded hardware typically has more complex crack growth and failure modes than those exhibited by metallic materials. The method of performing damage tolerance assessments in NASA-STD-5019A for composite or bonded hardware relies upon the BBA as discussed in section 7.4 in this Handbook. This methodology is a test-based approach that may include a proof test as one of the assessment tools used in characterizing hardware damage tolerance capabilities under loadings. For example, there may be options to include proof testing as a screening tool for some types of defects, which may then be evaluated for residual strength. The proof test would best be performed in combination with NDE before and after the proof test to quantify the resulting damage and flaw sizes. Also, life testing may follow the proof test and NDE to assess the effects on damage tolerance lifetime. The proof test results would not be expected to provide a quantifiable damage tolerance life prediction unless that was established by a comprehensive assessment involving proof testing, NDE, and damage tolerance life testing.

Discussions for Metallic Hardware Damage Tolerance Assessments

The discussions in the following paragraphs presume the metal is not at risk of failure during the damage tolerance service lifetime due to either SLC or EAC for the maximum crack size, loadings, and the fluid environments experienced during the service lifetime. If the material is at risk of failure due to EAC or SLC, it is not an acceptable material for the service application.

Assessment Calculation Differences

Item 7.3.2.a in NASA-STD-5019A states: "Assume that the initial flaw that could be present and undetected in the part is the size and shape that is not screened by NDE, proof test, or process control and is in the worst location and orientation." Assessment aspects to be used with these three ways of defining the initial flaw are discussed in the items below that are numbered (1), (2), and (3).

1. In this case, the initial flaw is determined by the NDE sensitivity as specified in section 8.1.1 in NASA-STD-5019A. When following this requirement, also follow the section 7.3.2 damage tolerance lifetime assessment requirements in NASA-STD-5019A, including section 7.3.2.e that states: "Use critical stress intensity factor and cyclic threshold stress intensity range (ΔK_{th}) values that are less than or equal to the average values."

2. In this case, the assessment is based on the proof test screened initial flaw when computing the damage tolerance service life. Guidance in section 8.1.3 in NASA-STD-5019A states to use upper bound material toughness values when establishing a predicted flaw size that is screened by a proof test. Item 7.2.1.e(4)Bi discussion in this Handbook provides a "Note on lower bounds" that identifies relevant statistical measures defining lower bounds that also applies to determining an upper bound. Notice that the item 7.3.2.e requirement to use critical stress intensity factor values that are less than or equal to the average values should not be followed. It is superseded for proof testing by the section 8.1.3 guidance to obtain a more conservative result. All the other requirements in section 7.3.2 have to be used, including the item 7.3.2.e requirement to use cyclic threshold stress intensity range (ΔK_{th}) values that are less than or equal to the average values.

An upper bound material toughness value will cause prediction of a larger flaw resulting from the proof test screening. A larger flaw causes a larger stress intensity factor at a given stress loading and more rapid crack growth, which is a more conservative approach for this life prediction assessment. Depending on the material capability to exhibit stable crack extension under load, NDE and testing may also be advised as explained in the later headings titled Discussions of Fracture of Ductile Metal Materials and Discussion of NDE Combined with Flaw, material characterization, and proof test.

3. In this case, the initial flaw size is based on manufacturing process control. Refer to section 8.1.4 in NASA-STD-5019A for requirements and guidance for the initial flaw size determination. Note section 8.1.4 in NASA-STD-5019A does not address determination of the critical stress intensity factor but does require documentation in the FCP, with rationale establishing the approach is applicable, and be approved by the RFCB. The approach documented in the FCP should discuss the damage tolerance lifetime basis, including the reasons for selection of the material toughness values used in the proposed assessment. The relevance and effects of using the value specified in item 7.3.2.e. as discussed above in paragraph (1) as contrasted with an upper bound value as discussed above in paragraph (2) should be included in discussions of the proposed approach, with recommendations for the RFCB consideration.

Discussion for Brittle Metal Materials

Proof testing may be a viable approach for parts made of brittle materials whose crack tip fracture conditions can be characterized by a single parameter such as stress intensity factor. If the proof loading induces stress distributions that are similar to what the part experiences during its service lifetime, the proof test screens for cracks in the part at the proof loading, which is larger by some factor than the service life loadings. The predicted crack size and aspect ratio at the end of the hardware damage tolerance lifetime should not exceed the crack stress intensity factor that is screened by the proof test.

Discussion for Brittle and Ductile Metal Materials

Some assumptions that appear conservative may be non-conservative. For example, presuming residual stresses in metallic hardware are large uniform tensile stresses causes cracks screened by applied proof loadings to be smaller than if the analysis assumed none or compressive residual stress. When the resulting smaller cracks are assessed for the service lifetime loadings, they may not grow rapidly. If residual stresses are assumed to be null or compressive, larger cracks are predicted to survive the proof loading. These larger cracks may grow faster during the service cyclic loadings. Depending on the number of service cycles and the magnitude of the load cycles, the larger cracks may be worst case. If the worst case is not assessed, the hardware reliability is decreased and may result in a failure during the service lifetime.

Discussion of Fracture of Ductile Metal Materials

Proof testing of hardware made from ductile materials can cause sufficiently large pre-existing cracks to grow due to the proof test. The proof loading may not be large enough, or the resulting crack may not be large enough, to cause failure during the proof test. The crack growth due to the proof test may cause lower reliability of the hardware in service than if no proof test was performed. The larger crack could reduce the hardware tolerance for extreme loading conditions, and/or it may grow to a size that would cause a failure during the damage tolerance service life.

For ductile metals, the critical crack size for fracture may not be controlled by a parameter such as stress intensity factor. Conditions controlling growth at the crack tip may depend upon many factors such as the material thickness, nearness of the crack tip to surface boundaries, the opportunities for failure due to a shear band triggered by the flaw, or prior loadings that left residual plastic strain fields that affect the crack. EPFM tools have been developed to help assess some of these situations, but those tools may not be applicable; or if they are applicable, they may be difficult to apply to complex shapes and loadings in flight hardware. An elastic plastic parameter that is calibrated by tests in a metal plate with a crack that is encompassed by elastic material may not apply to a crack in the same material in a thin plate, or if the crack approaches an edge or other boundary where local plasticity becomes important. In other words, the transferability of a fracture prediction parameter from a test specimen to flight hardware may be complex and perhaps beyond the ability of available analysis tools.

Discussion of NDE Combined with Flaw, Material Characterization, and Proof Test

For critical metallic hardware applications where NDE by itself is unable to demonstrate the level of required structural integrity, an approach may be applicable that has been used for important metallic flight hardware. The method applies a proof test after NDE, tests, and assessments have established the proof test will improve hardware reliability. To accomplish this goal, the proof test should not increase the risk of leaving a critical flaw in the structure. Relevant guidance in this section is the following:

> *The flaw size used in the life assessment should adequately account for flaw growth during the proof test. To establish that the assessment is valid, sufficient test data should be obtained using pre-flawed specimens that are representative of the part configuration, material conditions, and screened flaw and show the amount of growth of all crack fronts during the proof test from all sources, including stable tearing, and both EAC and SLC if applicable, have been conservatively bounded.*
>
> *When it is judged that a proof test is appropriate to screen hardware for flaws, the proof test should occur at the in-service temperature and environment. If this is not feasible, an ECF can be used as approved by the RFCB. Upper bound critical stress intensity or residual strength should be used when establishing an analytically predicted flaw size screened by proof test.*

This approach requires defining the largest initial flaw sizes at each critical location in the hardware. The flaw size is based on two criteria:

1. The size is established that may be missed by the initial NDE inspection. That flaw size is compared to the flaw size that could be produced by the manufacturing processes.

2. The worst-case initial flaw sizes and shapes are then used in experimental fracture tests which should be performed at the worst-case environmental conditions the hardware will experience as noted in the above-cited guidance. The test goals are to define upper bounds of the amount of crack growth that are expected to develop for the worst-case initial flaw condition for each of the hardware locations of concern. This requires an extensive experimental testing program that requires many specimen components, or simulated-component specimen, that conservatively model the component material, the expected pre-existing flaws, the fracture constraint conditions around the flaw, and produces data that quantifies the amount of crack growth that is to be expected in the hardware due to the proof test. The experimental testing may also define the amount of crack extension that results in failure of the test article, which is to be avoided. This approach requires a significant investment in testing and analyses. The process produces hardware that demonstrates a very high reliability. A variation of the described approach is to perform another NDE inspection of the hardware after the proof test to confirm crack growth was as expected, and no critical cracks are likely to exist in the flight hardware.

The above discussions also illustrate that hardware may need to be screened for critical flaws by NDE prior to conducting proof tests that are used to validate structural strength of the hardware. Proof tests are mandated as cited in the following guidance in this section.

> *Note that a proof test is required for acceptance in accordance with NASA-STD-5001 (or program-specific requirements), with a minimum proof test factor, depending upon whether a prototype or proto-flight verification approach is followed and the type of material used.*

If critical size flaws are discovered during a pre-proof test NDE screening, there may be an opportunity to repair the regions with flaws before the proof test makes them larger or fails the part. If post-proof test NDE is also performed, it may be able to discover critical size flaws that were opened and/or enlarged by the proof test. If critical flaws are detected, the part could be disqualified from service, thereby preventing a failure during the service lifetime. Or, if detected critical flaws could be repaired, the hardware may be approved for service.

Refer to section 8.1.5, Detected Flaws, in this Handbook for discussion of the requirements regarding detected flaws in flight hardware.

8.1.4 Process Control (NASA-STD-5019A, Section 8.1.4)

NASA-STD-5019A:
8.1.4 Process Control

[FCR 19] If process controls are used to establish bounds on flaw sizes in fracture critical parts, the approach shall be subject to the following:

a. The approach is documented in the FCP.
b. The rationale establishing that the approach is applicable is documented in the FCP.
c. The FCP is approved by the RFCB.

[Rationale: Use of process control information to define flaws or damage that could be in the part is an unusual approach. An understanding of the approach and supporting information need to be approved by the RFCB and documented in the FCP.]

Process control rationale to bound flaw sizes submitted for RFCB approval should include documentation on why this approach is being applied, an overview of the hardware, and evaluation that the approach is adequate for fracture control. Descriptions of the relevant manufacturer’s experience base, process control during manufacture, inspection results, and subsequent life of the component, all component testing, and summary arguments should be included.

Process control may be used to establish damage tolerance of a fracture critical part if the requirements in this section are satisfied. It is not the typical way damage tolerance assessments are accomplished. The usual ways are by inspection processes that screen for cracks of the size reliably detected by the inspection methods used as discussed in section 8.1.1 of NASA-STD-5019A for metallic parts, section 8.1.2 of NASA-STD-5019A for composite or bonded parts, and section 8.1.3 of NASA-STD-5019A for proof test screening of flaws.

To use process control as the basis for flaw screening, the manufacturing project process that produces the part should be extremely well controlled and have demonstrated capability to produce hardware with initial flaw or damage sizes that do not exceed the critical initial flaw or damage sizes. The critical initial flaw or damage sizes are those that cause failure of the part before it achieves the required damage tolerance service lifetime. Demonstration the manufacturing process is sufficiently controlled may entail significant development effort.

Requirements, rationale, guidance, and discussions provided in this section are cited and discussed below.

[FCR 19] If process controls are used to establish bounds on flaw sizes in fracture critical parts, the approach shall be subject to the following:

[Rationale: Use of process control information to define flaws or damage that could be in the part is an unusual approach. An understanding of the approach and supporting information need to be approved by the RFCB and documented in the FCP.]

This section provides the following description of aspects to be provided in the approach and rationale that are to be documented in the FCP per requirement items a and b.

> *"Process control rationale to bound flaw sizes submitted for RFCB approval should include documentation on why this approach is being applied, an overview of the hardware, and evaluation that the approach is adequate for fracture control. Descriptions of the relevant manufacturer's experience base, process control during manufacture, inspection results, and subsequent life of the component, all component testing, and summary arguments should be included."*

NASA-STD-5019A, Items 8.1.4.a, b, and c

Item 8.1.4.a of NASA-STD-5019A requires the approach to be documented in the FCP. Item 8.1.4.b requires the rationale establishing that the approach is applicable is also documented in the FCP. Item 8.1.4.c requires the FCP to be approved by the RFCB.

A document that describes the approach for manufacture of a fracture critical part with initial flaw size based on process control is the process control specification, which should be part of the submittal for the FCP. The specification lists all the manufacturing steps that have to be performed to produce the part. Each critical manufacturing step procedure in the specification should include monitoring of controls affecting the quality of process step aspects. The step procedure should include part measurements and/or inspections that provide quantitative evaluations of the step success by comparing part aspects against acceptance and rejection criteria. The inspections should evaluate aspects of the part that control part performance and reliability. The inspections also provide accountability and sign-off as the part progresses from step to step.

The documentation submitted in the FCP may demonstrate the approach will be essentially the same as a process control specification that is already providing flight hardware that has satisfied all flight certification requirements, including damage tolerance. Alternatively, the approach may be a significant modification of an existing process specification to satisfy significantly different requirements for the flight hardware. In that event, the risks introduced by the modifications and methods proposed to control the risks should be identified. If an entirely new process control is being proposed, the background experience base that will be utilized to develop and certify the process control should be described.

The scheduling of inspections during the process should be based on a trade-off between inspection cost, part rework cost, and loss due to scrap. The inspection details and scheduling are more critical in a fracture critical part because there may not be many options for rework of the hardware. If rework of the hardware is planned if it fails a process inspection point, the repair activity should be included in the development of the process specification.

The hardware produced by the process control specification should satisfy all the requirements levied on the hardware such as performance, strength, and most importantly, the damage tolerance capability. The specification should identify the critical process steps that should be performed correctly to produce the part with the required attributes. If the manufacturing process invokes subsidiary process control specifications, these should be described and supplied if requested by the RFCB reviewers.

The most critical aspects for fracture control are effects of process steps upon damage and defect flaw size that defines damage tolerance performance of the fracture critical part. The size of damage or flaws in the part should be quantified. If the flaw size is determined by an NDE method that has limited capability, the size may be confirmed by a more rigorous form of NDE, or destructive inspection, or relevant testing that is approved by the RFCB. The damage tolerance strength of the part with the probable upper bound flaw or damage size should be determined by assessment. The assessment may be performed by analysis if the analysis methodology is relevant or by tests as specified in NASA-STD-5019A. The size of the damage or defect flaw of a fracture critical part should be documented with the part identification used for fracture control traceability per section 8.2 in NASA-STD-5019A. If there are multiple fracture critical parts being assessed, the exposure of each part to each process step should be tracked.

If determination of the size of damage or flaws that control the damage tolerance of the part is not feasible without destructive inspection, an approach should be devised that reliably establishes the minimum damage tolerance capability of a significant number of parts manufactured to the process control specification. In a situation like this, the approach for ensuring the probable lower bound damage tolerance capability of these parts will satisfy the damage tolerance lifetime requirement should be included in the FCP.

A lower bound may be determined from a statistical analysis of the data for a significant number of parts. The number of parts needed to provide the lower bound capability should be addressed in the process specification approach in the FCP.

Also, whenever a change is made to the process, such as modified process equipment or other factors are changed that could affect the damage tolerance performance of the part, precautions should be taken. The precautions include increasing the frequency of the process control specification inspections and additional testing of parts produced with the modified process.

An Example

A hypothetical example is provided of process control specification items for metal parts using welding fabrication. This example is not an actual welding process control specification, and it does not include aspects addressed by other applicable sections in NASA-STD-5019A, including 8.2, Traceability for Fracture Control; 8.3, Material Selection and Usage for Fracture Critical Parts; and 9, Fracture Control Documentation and Verification, which are discussed in their sections in this Handbook.

For metal parts with welding fabrication, the following are a sample of possible items to be addressed in a welding process specification. Actual welding process control specifications should have more aspects and details than this abbreviated example. Also, inspection points are not listed in this example but should be placed in the welding process step procedures to confirm readiness to perform welding and includes pre- and post-welding inspections that ensure the part was ready and was manufactured per the process control specification:

- Weld design – the part welding design using qualified weld joints and procedures selected for the part welds by the responsible welding engineer; it includes specified weld depth of penetration and permitted variability.
- Welding procedure specification – the written qualified welding procedure that provides direction for making the part weld(s).
- Essential variables – welding variables that are controlled for each part weld and, if changed, alter the quality of the weld; they are confirmed before welding the part.
- Procedure qualification records – recorded variables and data during welding of test samples, including the number and frequency of the test samples.
- Certified welder – welder qualified to perform welding per the welding procedure specification.
- Weld inspectors – requirements, including accreditation and assigned duties.
- Renewal of qualifications – period of time or other measure when certified welders, weld inspectors, and the welding procedure are to be requalified.
- Detailed manufacturing steps implementing the welding procedure specification.
- Requirements on materials used for the part, the qualification weldments, and welding expendables.
- Number and types of qualification samples representing part welds.
- Detailed tests to be performed on welded samples with acceptance/rejection criteria.
- Number and location of metallographic samples, evaluation procedures, and criteria.
- Specification of porosity limitations on size and distribution.

NOTE on Determination of Lower Bound of Data

A lower bound value should be based upon a sufficient number of test data to sample the amount of scatter in the measurement property. Comparison of the lower bound to all data should show that scatter of the data does not, and likely will not, result in a lower bound value. For a normal statistical distribution, the "Empirical Rule" states 95% of the data will fall within two standard deviations, and 99.7% of the data will fall within three standard deviations. A value defined by the mean minus two standard deviations may be close to a lower bound, while a value determined by the mean minus three standard deviations will be more likely to provide a lower bound, provided enough data exist and this statistics rule is meaningful. Statistical analysis of data as it is accumulated for additional samples may assist in identifying if a lower bound has been obtained.

8.1.5 Detected Flaws (NASA-STD-5019A, Section 8.1.5)

NASA-STD-5019A:
8.1.5 Detected Flaws

[FCR 20] Spaceflight hardware with detected flaws that is used for flight without being repaired or replaced shall have a specific detailed assessment approach documented with rationale in the FCP that contains the following:

a. An assessment approach of metallic parts by analysis is to include the following items in addition to the items in section 7.3.2 in this NASA Technical Standard:

(1) Upper bound flaw size.
(2) Upper bound crack growth rate.
(3) Lower bound critical stress intensity factor or residual strength.
(4) Lower bound cyclic fatigue crack growth threshold stress intensity range (ΔK_{th}).

b. An assessment approach for composite or bonded parts with detected flaws is to include the following items:

(1) The approach and rationale provided to the RFCB for approval before implementation.

(2) Documentation of the approved approach in the FCP.

[Rationale: An understanding of the approach and methodology to accept detected flaws, which accounts for variability in the assessment, is necessary to assure adequate fracture control implementation.]

For reportable detected flaws in composite or bonded parts, a similar worst-case analysis approach to that used for metal parts may not be available. Any proposed analysis approach is to be test verified with a similar damage configuration and approved by the RFCB.

Note that the detailed assessment approach may be by damage tolerance test if approved by the RFCB.

The normal fracture control process is carried out with the assumption that the part contains a flaw in the worst-case location and orientation. The assessment of the assumed flaw includes typical fracture properties and an assumed flaw size. However, when flaws are detected in a part that is planned for use in flight, an assessment is performed using bounding flaw sizes, material properties, loads, and boundary conditions.

Fracture critical parts with reportable NDE indications are to be assessed by a process approved by the Technical Authority to determine whether the indication is a flaw.

Fracture critical parts with detected flaws are to be assessed with an approach that satisfies [FCR 20] and then evaluated by the Technical Authority to determine whether the part is acceptable to use as is or if the part is to be repaired or replaced. If the part is to be repaired, the repair process is to be an established, proven process that has been approved for this purpose by the Technical Authority.

Pressure vessels and COPVs should not be flown with detected flaws, e.g., see sections 7.2.1 and 7.2.2 in this NASA Technical Standard. If an exception is sought, it is to satisfy section 10 in this NASA Technical Standard as an alternative approach that is deviating from these established procedures and needs approval by the Technical Authority and the RFCB.

The RFCB should be notified of the intent to fly the flawed part when it is not feasible to repair or replace the part.

Section 8.1.5 in NASA-STD-5019A describes the NASA fracture control requirements imposed by [FCR 20] upon spaceflight hardware when a flaw is detected.

The first step is an assessment to confirm if the NDE indication is a flaw that could affect the strength, function, or damage tolerance capabilities of the hardware. If the nature of the indication is not well defined, it should be treated as a flaw and subjected to a comprehensive evaluation as required in this section's rationale and the guidance copied below.

> *[Rationale: An understanding of the approach and methodology to accept detected flaws, which accounts for variability in the assessment, is necessary to assure adequate fracture control implementation.]*
>
> *Fracture critical parts with reportable NDE indications are to be assessed by a process approved by the delegated Technical Authority to determine whether the indication is a flaw.*
>
> *Fracture critical parts with detected flaws are to be assessed with an approach that satisfies [FCR 20] and then evaluated by the delegated Technical Authority to determine whether the part is acceptable to use as is or if the part is to be repaired or replaced. If the part is to be repaired, the repair process is to be an established, proven process that has been approved for this purpose by the delegated Technical Authority.*
>
> *Pressure vessels and COPVs should not be flown with detected flaws, e.g., see sections 7.2.1 and 7.2.2 in this NASA Technical Standard. If an exception is sought, it is to satisfy section 10 in this NASA Technical Standard as an alternative approach that is deviating from these established procedures and needs approval by the delegated Technical Authority and the RFCB.*
>
> *The RFCB should be notified of the intent to fly the flawed part when it is not feasible to repair or replace the part.*

If the above cited activities determine the hardware has a flaw affecting its structural integrity, and if the hardware is to be used for flight as-is without being replaced or repaired, [FCR 20] requirements state the hardware should have a specific detailed assessment approach that is documented in the FCP with rationale justifying the use of the part in the flawed condition.

The question may arise as to whether the 90/95 reliability NDE flaw screening size can be used for determining if the hardware can be flown with a detected flaw. The answer is an emphatic "NO." A flaw of the NDE 90/95 detectability size is not expected to be present in parts that are qualified for spaceflight. That assumption becomes invalid when a flaw is found. Relevant guidance in this section is copied below.

> *The normal fracture control process is carried out with the assumption that the part contains a flaw in the worst-case location and orientation. The assessment of the assumed flaw includes typical fracture properties and an assumed flaw size. When flaws are detected in a part that is planned for use in flight, an assessment is performed using bounding flaw sizes, material properties, loads, and boundary conditions.*

The usual damage tolerance assessment requirements do not account for uncertainties and scatter in the actual crack size and material properties that affect damage tolerance life. A larger flaw and/or material property variability may cause failure of a part with a detected flaw before the end of the damage tolerance lifetime computed using usual approaches when no flaw is known to be in the hardware.

The purpose of the requirements imposed by this section in NASA-STD-5019A is to ensure a part with a detected flaw that is approved for flight will have a reduced likelihood of failure during its service lifetime. The assessment requirements for metallic parts are specified in item 8.1.5.a. Composite or bonded parts should address the requirements in item 8.1.5.b. Additional guidance in this section on the assessment options is copied below.

> *Note that the detailed assessment approach may be by damage tolerance test if approved by the RFCB.*

NASA-STD-5019A, Item 8.1.5.a

Item 8.1.5.a of NASA-STD-5019A states an assessment of metallic parts with detected flaw or flaws has to be performed with an analysis approach that includes the following four items: (1) Upper bound flaw size, (2) Upper bound crack growth rate, (3) Lower bound critical stress intensity factor or residual strength, and (4) Lower bound cyclic fatigue crack growth threshold stress intensity range (ΔK_{th}), in addition to the requirements in section 7.3.2 in NASA-STD-5019A.

The requirements in section 7.3.2 that are applicable to the assessment are all the content in section 7.3.2 except item 7.3.2.a, which is not relevant since the detected flaw is the target for the assessment. The guidance in section 7.3.2 that is copied below is also applicable and may cause the assessment to be performed by test instead of by analysis.

> "*Note that when the available analysis ability to simulate crack growth is invalid, assessment by test (section 7.3.3 in this NASA Technical Standard) is required.*

If the assessment is to be performed by test, as noted in guidance above, the assessment approach would have to be approved by the RFCB. For assessment by test, section 8.1.5.a requirement (1) would still be applicable to define the initial flaw size to be used in the testing. Also, requirements in section 8.1.5.a(2), a(3), and a(4) would also apply, as discussed below, which means the material used for the test would have to be selected to conservatively bound the qualities addressed by these three requirements.

Alternatively, if material that is representative of the metallic part that also satisfies the requirements discussed in items 8.1.5.a(2), a(3), and a(4) is not available, the following testing approach may be used if approved by the RFCB. The approach is to use the same material as in the hardware but impose increased loadings so as to achieve equivalent conditions affecting crack growth as addressed in the three items 8.1.5.a(2), a(3), and a(4): (1) per item 8.1.5.a(2), the applied loadings have to elevate the crack growth rates in the test so that they simulate those at the upper bound crack growth rates for the material; (2) to satisfy requirement 8.1.5.a(3), the test should demonstrate the lower bound critical stress intensity factor or residual strength is not reached during the required damage tolerant lifetime; and (3) per item 8.1.5.a(4), the applied loadings have to elevate the cyclic fatigue crack growth threshold stress intensity range to be above the lower bound cyclic fatigue crack growth stress intensity range of the material.

Analysis conservatisms to be imposed on assessments, as a minimum, are the requirements specified in section 7.3.2 and in items 8.1.5.a(1), a(2), a(3), and a(4). In some situations where the conditions affecting crack growth and damage tolerance life are difficult to assess and quantify, the RFCB may require some additional conservative factors, as originally discussed in NASA-HDBK-5010 baseline version, section 6.4.1, Crack Size Conservatism. For especially critical applications, the RFCB may require a larger service life factor. To protect against cracks near instability, in addition to use of a lower bound critical stress intensity factor or residual strength as required in item 8.1.5.a(3), the RFCB may require an additional safety factor to provide margin against limit load fracture, which is discussed in item 8.1.5.a(3).

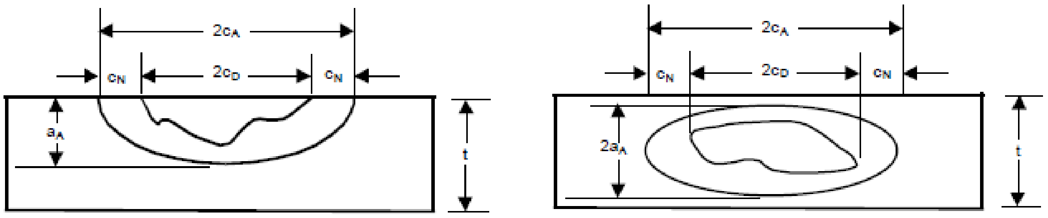
NASA-STD-5019A, Item 8.1.5.a(1)

Item 8.1.5.a(1) of NASA-STD-5019A requires an upper bound size be used for assessment of the detected flaw. The upper bound flaw size is based on the NDE description of the flaw. The upper bound flaw size should have margin for the possibility the NDE may not be able to accurately report the extent of the flaw. For example, the flaw or crack tips may not be planar, or they may have branching or angled cracks that make it difficult to locate the crack tip. The flaw may have originated due to defects in the raw material, or it may have been created during manufacturing processes such as metal forming, welding, or during assembly due to fit-up stresses. The crack tip may be closed due to residual stress or crack closure from prior loadings. The conditions that created the crack may or may not be present in the hardware when NDE is used to determine the size of the crack.

Flaws in ductile metals may grow due to loadings such as proof tests if the part is pressurized hardware. This aspect is discussed in this Handbook in section 8.1.3, Proof Test, Discussion of Fracture of Ductile Metal Materials, and the other paragraphs in that section. If the pressurized hardware is subjected to NDE before the proof test and a flaw was found that was subjected to a qualification proof test, the flaw may have grown by sub-critical crack growth during the proof test. Also, other flaws that were too small to be detected by the NDE screening before the proof test may be opened by the proof test loadings making them more detectable as well as possibly making them larger. Other aspects may also be applicable. The proof loading could cause a residual stress state, as mentioned in the previous paragraph, that causes closure of the crack tip resulting in decreased NDE capability to detect and accurately size the flaw. The potential for ductile tearing during a proof test could exceed the bounds of crack size that are discussed in the next paragraph that addresses NDE size uncertainty. And, if significant ductile tearing could occur in the hardware material and leave the crack closed due to residual stress effects, the increased crack size may not be encompassed by the NDE size uncertainty. In that situation, testing of material cracked samples subjected to bounding loadings combined with NDE of the samples may be needed to determine the maximum size of flaws. Such testing could also be used to define the critical crack size for fracture stress intensity factor or residual strength, as applicable.

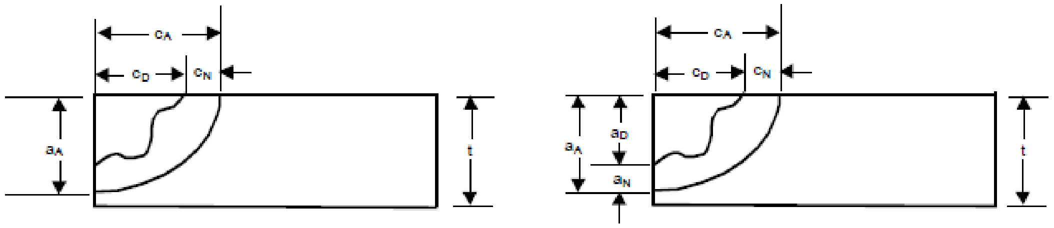
The approach described in NASA-HDBK-5010 baseline version, section 6.4.1, Crack Size Conservatism, provides an upper bound crack size for the assessment. This method assumes the crack size is the NDE reported size plus the NDE uncertainty margin at each crack tip. The NDE uncertainty margin is assumed to be the same as the NDE detectable flaw size capability at the 90% probability of detection with 95% confidence level by the NDE method(s) used to inspect the hardware. These sizes are specified for standard NDE in the current version of NASA-STD-5009, Table I for U.S. customary units (inches) or Table 2 for System International (SI) Units (millimeters). The NDE detectable flaw size capability is shown in these tables in the columns labeled "Crack Dimension, a" and "Crack Dimension, c." The meanings of "a" and "c" for different geometries are shown in Figure 1 of NASA-STD-5009 NDE standard. If "Special NDE" is performed, the NDE detectable flaw size capabilities are those specified by the requirements in section 4.3.3 in NASA-STD-5009.

The upper bound size depends on the type of crack and the crack dimensions as reported by the NDE method used to characterize the crack. Example cracks are shown as sketches labeled "a" through "f" in Figure 8.1-2, Analysis of Crack Sizes for Detected Cracks, that was extracted from NASA-HDBK-5010 baseline version, section 6.4.1, as described below. The procedures begin by selecting the crack sketch that is representative of the detected crack. The upper bound crack size is determined using the NDE detected crack dimensions denoted with subscript "D" in the sketches, and the NDE detectable flaw size uncertainty denoted by dimensions with subscript "N" in the sketches. The crack sizes to be used in the damage tolerance assessments are shown with the subscript "A" in the sketches.



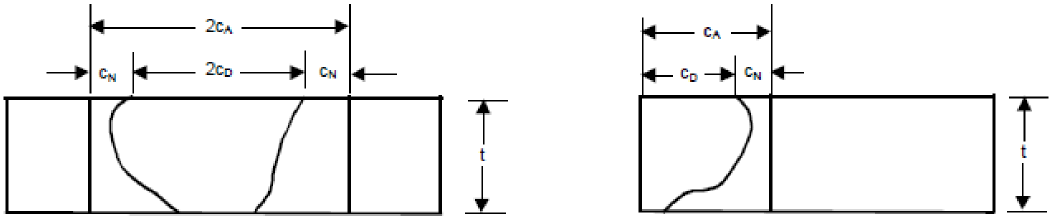
a. Part through surface crack. Depth not detectable.
$a_A = 0.95t$, $2c_A = 2c_D + 2c_N$

b. Embedded crack. Depth not detectable.
$2a_A = 0.95t$, $2c_A = 2c_D + 2c_N$



c. Corner crack. Depth not detectable.
$a_A = 0.95t$, $c_A = c_D + c_N$

d. Corner crack. Depth detectable.
$a_A = a_D + a_N$, $c_A = c_D + c_N$
If $a_A \geq t$, analyze as through edge crack of length c_A



e. Center through crack.
$2c_A = 2c_D + 2c_N$

f. Edge through crack.
$c_A = c_D + c_N$

Definitions

a	Crack depth or half the crack depth
c	Crack length or half the crack length
t	Part thickness

Subscripts

A	Indicates crack dimension used for analysis
D	Indicates detected crack dimension
N	Indicates the capability of the NDE method used to detect the crack

Figure 8.1-2—Analysis of Crack Sizes for Detected Cracks

Sketch "a" is for a part through surface crack found with penetrant NDE. This sketch will be used as an example to describe use of the other five sketches. In sketch "a," the crack length "$2c_D$" is the total surface length that was detected using the NDE penetrant method. The crack half-length, "c_D," has to be increased by the NDE crack length uncertainty "c_N" for <u>each</u> crack half-length. The result is the total surface length to be used for the assessment, "$2c_A$," is equal to the NDE reported total surface length, "$2c_D$," plus twice the NDE length uncertainty, "$2c_N$," as shown in sketch "a." Penetrant NDE inspection cannot determine the crack depth. If penetrant NDE was performed on both the front and back surfaces with no crack indication on the back surface, the crack is confirmed to be a surface crack of unknown depth. In that case, the upper bound crack depth "a_A" to be used in the assessment is assumed to be 0.95 times the thickness, t.

Notice regarding sketch "a" that if the back surface is not inspected with the penetrant NDE, the crack may be a through crack. In that case, the upper bound assessment crack would be a through crack of total length "$2c_A$" equal to "$2c_D$" plus twice the NDE length uncertainty "$2c_N$."

Note also there is a penetrant NDE inspection detectable crack depth capability shown in the NASA-STD-5009 tables. This dimension is a minimum depth for a surface crack to be detected using the penetrant method. This dimension cannot be used to specify the surface crack depth, because penetrant will also give a crack indication for a deeper crack.

For example, suppose a metal plate of thickness 1.02 mm (0.040 in) was found by penetrant inspection of one side of the plate that satisfies NASA-STD-5009 requirements. The NDE reported the part to have a through crack of length "$2c_D$" equal to 7.62 mm (0.300 in). Referring to NASA-STD-5009B, Table 1 data for Penetrant NDE, the detectability flaw size capability for a through flaw in thickness less than 0.050 in is a crack with a "c" half-length dimension in Table 1 of 0.100 in (Table 2 shows 2.54 mm). The crack half-length uncertainty is assumed to be the same as the "c" dimension, i.e., 2.54 mm (0.100 in). Accordingly, the upper bound crack total length to be assessed is computed as "$2c_A$" equals "$2c_D$" plus "$2c_N$." The numerical value of total length "$2c_A$" for the assessment equals 0.300 in plus 2 times 0.100 in, which gives a total length of 0.500 in (7.62 mm plus 2 times 2.54 mm equals 12.70 mm).

If other NDE methods were used to determine the size of the detected crack, the upper bound size would depend upon the NDE reported flaw size and the detectable flaw size capabilities of the NDE method used. For example, if eddy current NDE was performed on both sides, the assessment crack size would be determined using the same approach as for the penetrant inspection but using eddy current detectable flaw size capability in the NASA-STD-5009 tables as the crack uncertainty values; similarly, if magnetic particle NDE was performed on both sides. Ultrasonic inspection from both sides with no other information available on the ultrasonic inspection would also result in the same situation as the penetrant and eddy current methods. It is noted some ultrasonic methods may be able to size the depth of an apparent surface crack when inspecting from only one surface; but unless the method was qualified to the same rigor as the detectable flaw size capabilities per NASA-STD-5009 requirements, the detectable crack depth would be considered to be unknown. In that case, the crack may have to be considered as a through crack unless NDE was also performed on the back surface. Radiographic NDE is a different methodology. The radiographic NDE detectable flaw size capability is a percentage of the thickness.

NASA-STD-5019A, Item 8.1.5.a(2)

Item 8.1.5.a(2) in NASA-STD-5019A requires the damage tolerance assessment to use upper bound crack growth rate in the assessment. Figure 8.1-3, Crack Growth Rates for Detected

Cracks, from the NASA-HDBK-5010 baseline version, section 6.4.1, shows a plot of fatigue crack growth rate da/dN data versus stress intensity range, delta-K, with typical curves drawn through the data. The larger crack growth rate curve is labeled "Upper Bound Growth Curve." This curve that corresponds to the crack growth rate data for the material being evaluated should be used per the item 8.1.5.a(2) requirement.

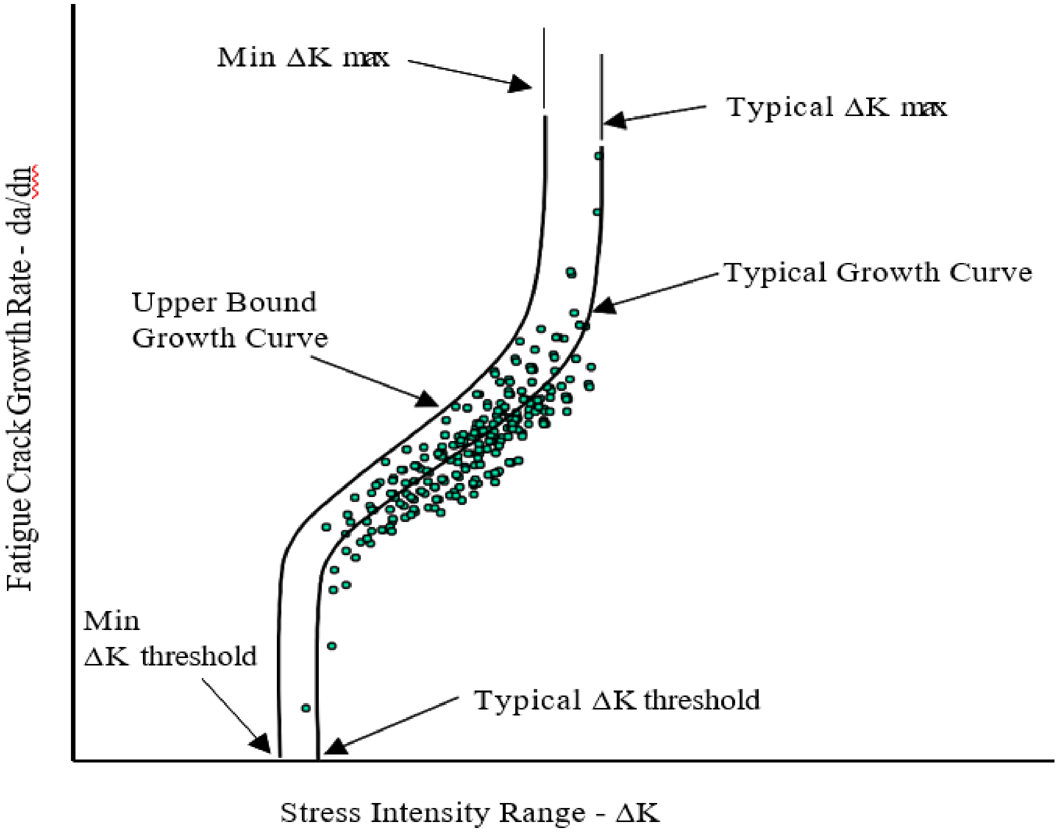


Figure 8.1-3—Crack Growth Rates for Detected Cracks

NASA-STD-5019A, Item 8.1.5.a(3)

Item 8.1.5.a(3) in NASA-STD-5019A requires use of lower bound critical stress intensity factor or residual strength. These data would have to come from test data of several test specimens to define the lower bound value. The statistical determination of a lower bound value of test data is discussed in item 7.2.1.e(4)Bi in this Handbook.

In addition, the following additional safety factor may be imposed by the RFCB for assessments where it is difficult to assess all the uncertainties regarding loadings and material fracture response, especially for conditions of large, applied loadings and/or large crack size such that crack tip conditions approach fracture instability or residual strength conditions. In this situation, the RFCB may require a safety factor of 1.5 against the appropriate fracture criteria of lower bound fracture toughness or residual strength. This safety factor would supplement and be in addition to the requirements specified elsewhere in item 8.1.5.a paragraphs.

NASA-STD-5019A, Item 8.1.5.a(4)

Item 8.1.5.a(4) in NASA-STD-5019A requires the damage tolerance assessment to use lower bound cyclic fatigue crack growth rate threshold stress intensity range (ΔK_{th}) in the assessment. Figure 8.1-3 that is cited in item 8.1.5.a(2) above shows typical fatigue crack growth data and identifies this lower bound as "Min (ΔK_{th}) threshold." Sufficient crack growth rate data for the material being evaluated would be needed per item 8.1.5.a(4) requirement at the threshold region to identify a valid lower bound value to use for the assessment.

NASA-STD-5019A, Item 8.1.5.b

Item 8.1.5.b in NASA-STD-5019A requires an assessment of a detected flaw in composite or bonded parts to include the following two items. The guidance in this section is copied below to assist in understanding the reasons for the requirements imposed in item 8.1.5.b, b(1), and b(2).

> *For reportable detected flaws in composite or bonded parts, a similar worst-case analysis approach to that used for metal parts may not be available. Any proposed analysis approach is to be test verified with a similar damage configuration and approved by the RFCB.*
>
> *Note that the detailed assessment approach may be by damage tolerance test if approved by the RFCB.*

NASA-STD-5019A, Item 8.1.5.b(1)

Item 8.1.5.b(1) in NASA-STD-5019A requires the approach and rationale for the assessment conclusions to be provided to the RFCB for approval before the approach is implemented. Assessment of composite or bonded parts is complex and may require representative and comprehensive testing. By requiring approval from the RFCB before implementing the approach, the assessment approach will have the greatest potential for a successful conclusion.

NASA-STD-5019A, Item 8.1.5.b(2)

Item 8.1.5.b(2) in NASA-STD-5019A requires the approved approach to be documented in the FCP. This is necessary to ensure the assessment details will be available if any additional assessments are needed during the damage tolerance lifetime in case the character or size of the flaw, or the environments, or the lifetime loadings change before the service lifetime of the part is ended.

8.2 Traceability for Fracture Control (NASA-STD-5019A, Section 8.2)

NASA-STD-5019
8.2 Traceability for Fracture Control

Traceability requirements are typically associated only with fracture critical parts, except in the case of NFC composite or bonded parts. Because of the nature of these types of materials, additional activities are necessary for NFC parts in accordance with [FCR 9] section 6.3.d in this NASA Technical Standard.

[FCR 21] Traceability for each fracture critical and NFC composite or bonded part shall be established and maintained by providing a unique serial number (or other method when serialization is not practical) and a complete life history, including load history, impact damage, repair, materials, manufacturing, processing, and environmental exposure.

[Rationale: Traceability is necessary to assure the information used to assess flaw or damage sensitivity, screening, and protection is understood and accurate throughout the service life of the hardware.]

Traceability for NFC composite or bonded parts is somewhat unique relative to metallic parts. While metallic parts usually have a specification for providing minimum properties throughout the part, composite and bonded parts are composed of elements that may have specifications, but the properties after combination of these elements are often unique to the part being produced. These considerations lead to the need for traceability of fracture critical parts and NFC composite or bonded parts as also required in section 6.3 in this NASA Technical Standard.

One of the components of a viable fracture control program is the tracking of fracture critical hardware. For effective fracture control implementation, the group, organization, or person(s) who have the responsibility of damage tolerance activities should be identified. These activities include the implementation of traceability and documentation that show adherence to approved drawings, specifications, plans, and procedures with respect to damage tolerance.

Tracking or other traceability is a key element in establishing damage tolerance, and it is required by NASA-STD 5019, FCR 21, that planning for traceability be included in the FCP. The developer identifies and documents how to accomplish the tracking of information related to damage tolerance for the following:

- Material traceability.
- Serialization of all fracture critical parts and of NFC composite and bonded parts.
- Configuration control.
- Load history.
- Impact damage and repair (e.g., for composite and bonded parts).
- Manufacturing (e.g., for AM and composite and bonded parts).
- Processing (e.g., for AM and composite and bonded parts).
- Environmental exposure.
- Flaw screening.
- Detected cracks.

All fracture critical hardware is subject to traceability, damage tolerance assessment, NDE, and documentation requirements. In addition, some NFC parts, such as composite and bonded parts, are subject to traceability and NDE requirements due to the nature of the manufacturing processes.

General Considerations: Traceability and Documentation

Traceability is maintained on all fracture critical parts throughout their development, including manufacturing, testing, and flight to provide a record that all fracture control processes have been met on each fracture critical part. Serialization is required for fracture-critical components.

Engineering drawings for fracture critical parts contain notes which:

- Identifies the part with the note: "FRACTURE CRITICAL PART."
- Specifies the appropriate NDE technique to be used on the part.
- Specifies that the part be marked with part number and serial number.

All changes in design or process specifications, manufacturing discrepancies, repairs, and finished part modifications of all parts are reviewed by the assigned governing fracture control entity to ensure that fracture control requirements are still met.

A pressure history log is maintained for pressure vessels when vessel life is limited by damage tolerance fracture control requirements. The log, which begins with the proof test or inspection used to define the starting flaw baseline, records pressure cycles, associated environmental conditions, and vessel contents throughout the manufacturing, testing, and flight of the vessel.

Additive Manufactured Metallic Parts

Refer to NASA-STD-6030, section 4.1.2, for serialization of AM parts.

MSFC-STD-3716 specifies several requirements regarding traceability for laser powder bed fusion (L-PBF) parts. The L-PBF manufacturing process is highly process-control sensitive, resulting in uniqueness for each build. MSFC-STD-3716 requires that all L-PBF parts be serialized. Refer to MSFC-STD-3716 for additional requirements, guidelines, and best practices for traceability and serialization of AM parts.

NFC Composite and Bonded Hardware

The properties of composite and bonded parts are unique to the combination of its constituent elements and are process dependent. Due to the variability and uniqueness of this type of manufacturing process, item 6.3.d of NASA-STD-5019 requires traceability for NFC composite or bonded parts. Refer to CMH-17 for additional requirements, guidelines and best practices for traceability and serialization of composite and bonded hardware.

Tracking for Fracture Critical Parts

Materials

All materials used in fracture critical parts have to be traceable by certificate of compliance to material standards or engineering requirements stated on the drawing. Material drawing notes have to be explicit and control the product form, condition, and heat treatment of the material. Processes with consequences for fracture control, such as welding, etching, or plating, have to be controlled and documented.

Design, Analysis, and Hardware Configuration

During the development phase of spaceflight hardware, a system should be in place to assure that delivered fracture critical hardware is as designed and assessed. This program should include sufficient tracking to provide for fracture control assessment of load changes, modifications, or redesigns of fracture critical hardware, and discrepancy reviews (DRs), or equivalent, for anomalies that could affect hardware material fracture characteristics and life.

Load History

The load history should be maintained for fracture critical parts. This history should include load level, number of cycles, and environments in which the loads occurred. The history should cover the entire life of the part as described in section 7.3.1. For multi-mission hardware, the used life of the hardware should be booked against the remaining life so that assessment of flight readiness from a fracture control point of view can readily be made between missions. Explicit data are desirable but not required if conservative estimates of the history can be made. For example, if it is known with certainty that the hardware is not ahead of the original load spectrum, this may be documented with supporting rationale for between flight reviews.

Flaw Screening

A record of part NDE and findings should be maintained by the responsible NDE organization. Inspection records should bear the stamp and/or signature of the inspector. Proof test results should be documented in a report. Engineering drawings and equipment specifications for fracture-critical parts should 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.

8.3 Material Selection and Usage for Fracture Critical Parts (NASA-STD-5019A, Section 8.3)

NASA-STD-5019A:
8.3 Material Selection and Usage for Fracture Critical Parts

Material selection and usage requirements are typically associated with fracture critical parts, except in the case of NFC composite or bonded parts. Because of the nature of these types of materials, additional activities are necessary for NFC in accordance with [FCR 9] 6.3.f in this NASA Technical Standard.

[FCR 22] The selection, processing, and use of materials for all fracture critical and NFC composite or bonded parts shall include the following items, which are documented directly in the FCSR or the items have pertinent documents referenced in the FCSR:

a. Fabricate parts from materials with supplier data certifications.

b. Select materials compatible with NASA-approved Standards and Specifications.

c. Account for the effect of operating conditions on damage tolerance properties.

Examples of conditions that may affect damage tolerance properties are temperature, operating environment (atmosphere, corrosive media), cleaning and/or inspection agents, coatings, proof test fluids, loading spectra, time, temperature, and other environmental exposures and conditions.

d. Design and assess with strength and damage tolerance properties that are generated by tests on samples representative of the flight hardware material, subject to either item (1) or (2) below:

(1) Material is processed to the same thickness, material process condition, and material orientation in the part that result in the worst combination for damage tolerant assessment.

(2) The material process condition and the material orientation are fully traceable throughout fabrication and service life.

Examples of activities that may affect a metallic material process condition include: mill billet hot processes, such as forging, rolling, or other high-deformation processes; metallurgical product operations, including heat treatments; shaping operations, such as rolling, spinning, or drawing; fabrication joining processes, such as welding; and any other operations known to affect the material microstructure, strength, fracture, crack growth, or environment sensitivity properties.

e. Derived strength and damage tolerance data obtained from NASA-approved sources. If data are lacking, data are conservatively bounded or determined by sufficient testing to assess scatter to provide averages with testing approved by the RFCB.

f. Obtain an approved MUA for any materials not developed and qualified in accordance with the requirements of NASA-STD-6016.

g. Include all MUAs in the FCSR.

[Rationale: The specific items related to materials selection and usage are necessary to assure the information used to assess flaw or damage sensitivity is understood and accurate throughout the service life of the hardware.]

NASA-STD-5019A, Items 8.3.a and b

Fracture critical parts should be fabricated from materials with specific verification of applicable supplier data/certifications and obtained from bonded storage or equivalent materials/hardware control. Materials have to be compatible with NASA-approved and industry standards and specifications such as NASA-STD-6016, Standard Materials and Processes Requirements for Spacecraft; MSFC-STD-3716; CMH-17; MSFC-STD-3029; NASA-HDBK-6025, Guidelines for the Specification and Certification of Titanium Alloys for NASA Flight Applications; NASA-STD-6030; etc.

NASA-STD-5019A, Items 8.3.c and d

Several factors should be considered when making a material selection with respect to fracture performance. General considerations and guidelines on the effects of service environment, product form, material orientation, and material processing on fracture properties are discussed below.

General Considerations for Metallics

A practical consideration with respect to material selection is to consider whether fracture properties are available for the material. Generating fracture data can be costly in terms of time and money; given the choice between two equally suitable materials, consideration should be given to whether fracture properties are available. Conversely, selection of a material should not be made simply because fracture properties are available. Clearly, material selection has to be made based on the suitability of the material for the application; just because a material is in the fracture database does not mean that it is necessarily the best material to use.

A general screening criterion for materials selection is to select a material with a plane strain fracture toughness to yield strength ratio such that $K_{Ic}/F_{ty} > 1.66\ \text{mm}^{1/2}$ ($0.33\ \text{in}^{1/2}$). While this is not a mandatory requirement for all fracture critical parts, it is a good practice for material selection. This is a requirement for materials in parts that are to be classified as NFC low risk and fasteners to be classified as NFC low mass. Another general point to consider is that toughness tends to decrease with increase in strength and tends to increase with an increase in ductility. Both strength and ductility parameters are important and should be considered together. For example, for a given material, a process that results in a higher strength, but lower ductility may result in a lower toughness, depending on the extent of the loss of ductility. Although not an explicit fracture control requirement, a good general practice is to maintain a minimum of 3 percent elongation (in 4- or 5-diameter gage length) in the service environment. Factors affecting ductility include temperature, material orientation, and environmental exposure. With respect to temperature, particular attention should be given to the ductile-to-brittle transition temperatures for materials (particularly high-strength steels) to ensure operational environments do not fall below the ductile-to-brittle transition temperature for the material. With respect to material orientation, some materials may have adequate ductility in primary orientations and have significantly less ductility in the short-transverse (through thickness) orientation. This is particularly noticeable in aluminum hardware machined from thick plate product. Reductions in ductility in the short-transverse direction may be as high as 70 percent. As a general guideline, in components fabricated from aluminum plate products greater than 7.6 cm (3 in) in thickness, S-T material properties should be verified if material property data for the S-T orientation are not available. With respect to environmental exposure, other potential causes of low ductility to be considered are environmental embrittlement such as hydrogen exposure in service or related to plating operations, liquid metal embrittlement, and exposure to corrosive environments.

- **Service Environment**

  Environmental factors such as temperature and exposure to harmful media can affect fracture properties. Clearly, material properties that are compatible with the operating environment are necessary for accurate analysis. Literature reviews, handbooks, test data, and experience can be used to evaluate material susceptibility in specific environments. With respect to environmental exposure, a general requirement is the use of materials with a high resistance to stress corrosion cracking, as defined in MSFC-STD-3029A. A material not rated with a high resistance to stress corrosion cracking requires an approved MUA. MUAs, if required, should document the suitability of the alloy for the specific application and should be included in the FCSR. MUAs have to be processed using the forms cited in the applicable documents.

  Note that MSFC-STD-3029A characterizes materials based on performance in sodium chloride (NaCl) environments and should not be used as a blanket measure of material performance in all environments. Materials have to be assessed for specific environmental exposure such as hydrogen embrittlement, liquid metal embrittlement, NaCl environments, environmental gases, corrosive media, compatibility with contained fluids, and any environment where related problems could result in a catastrophic hazard. Also note that data in MSFC-STD-3029A are based on performance of smooth or notched test samples. Test data on stress intensity thresholds for environment-assisted cracking (K_{EAC} or K_{IEAC}) are not provided. Fracture properties that are relevant (or conservative) to the service environment have to be used. Plans to address material performance in specific environments should be addressed in the FCP.

The effects of service temperature on fracture toughness as well as flaw growth rate properties should also be considered. Excursions from the service temperature as well as the sustained operating temperature can affect fracture performance of the material and should be factored into the characterization of the material as needed. For example, an aluminum part that nominally operates at room temperature but experiences brief but periodic service cycles at temperatures near the aging temperature of the material can experience significant degradation of fracture properties during its service life.

- **Product Form**

  Fracture toughness and flaw growth rates will vary with product form. Plate, sheet, forgings, extrusions, and castings for the same alloy generally will exhibit enough variation in properties to warrant data for each product form. In general, castings will exhibit lower properties and more variability than wrought material and need to be carefully considered. Plate material can also exhibit variability in toughness with product thickness and location within the thickness. This can be influenced metallurgically by factors such as through hardenability in steels and the effectiveness of cold working in aluminums. Variability with thickness is also associated with the degree of constraint at the crack front. Care should be taken to ensure that specimens used to determine toughness for a given plate thickness are representative of the plate thickness of the raw stock used to manufacture the hardware and the location within the thickness for thick plate products and are representative (or conservative) with respect to the constraint conditions present in the hardware. For example, if a thin structural membrane is machined from the center of a thick plate, fracture properties for specimens machined from the center of thick plate product should be used in the analysis.

  Welds and brazes can be problematic. Fracture properties for these joints are required if they are used in fracture critical parts requiring damage tolerant analysis. These properties should be representative of the process and geometry used in the hardware.

- **Material Orientation**

  Fracture properties can vary with grain orientation, depending on the degree of anisotropy in the material. In general, for thin plate products, T-L properties (specimen loaded in the transverse direction with the flaw growing in the longitudinal direction) will be the lowest. Off-axis properties, such as those at 45 degrees to the rolling direction, sometimes exhibit the lowest fracture toughness. This should be evaluated in materials where anisotropic behavior is noted. In thick plate products, S-T properties are generally the lowest. This is particularly true in thick plate aluminum. As a general rule, in components fabricated from aluminum plate products greater than 7.6 cm (3 in) in thickness, S-T material properties have to be verified if material property data for the S-T orientation are not available. Properties of the weakest material orientation should be used in the life and strength analysis unless material orientation is fully traceable throughout the design and manufacturing process.

- **Material Processing**

  Material processing can have a large impact on fracture and strength properties. Within a given alloy, many processing factors can affect mechanical behavior directly. Heat treatment, cold working, and plating are common influences. For example, 7075 aluminum heat treated in the T6 condition has a low resistance to stress corrosion cracking; whereas, if it is heat treated to the T73 condition, it has a high resistance to stress corrosion cracking, resulting in large differences in the critical fracture toughness threshold for environment-assisted cracking (K_{EAC} and K_{1EAC}) values for the materials. Similarly, fracture toughness of precipitation-hardened stainless steels varies significantly with the temper condition. It is important to ensure that fracture data are matched to the material process condition of the alloy.

General Considerations for Additive Manufactured Metallic Parts

In general, special care needs to be exercised in the use of the appropriate material properties specific to an additively manufactured part due to the process dependability of these types of materials. Refer to NASA-STD-6030 for additional considerations of AM parts.

MSFC-STD-3716 specifies several requirements for L-PBF parts. The L-PBF manufacturing process is highly process-control sensitive, resulting in uniqueness for each build. MSFC-STD-3716 requires controls for L-PBF parts. Refer to MSFC-STD-3716 for additional requirements, guidelines, and best practices for AM parts.

General Considerations for Composite and Bonded

The properties of composite and bonded parts are unique to the combination of its constituent elements and are process dependent. Due to the variability and uniqueness of this type of manufacturing process, refer to CMH-17 for additional requirements, guidelines, and best practices for material selection for composite and bonded hardware.

NASA-STD-5019A, Item 8.3.e

Material Fracture Mechanics Properties for Damage Tolerant Analysis

Metallics

Guidelines for the values of material properties used in damage tolerant analysis are summarized in Table 8.3-1, Material Properties for Damage Tolerance Assessments. Further explanations and guidelines on property usage follow the table.

Table 8.3-1—Material Properties for Damage Tolerance Assessments

	Property - Value			
Usage	**K_{1c} (K_c)**	**da/dn (da/dt)**	**ΔK_{th}**	**K_{EAC} (K_{1EAC})**
Damage Tolerance life analysis based on NDE	≤ average	≥ average	≤ average	
Flaw size based on proof test	upper bound			
Damage Tolerance life based on proof test	upper bound	≥ average	≤ average	
EAC growth check				lower bound
Damage Tolerance life for detected flaw	lower bound	upper bound	≤ lower bound	
Damage Tolerance life < 1000 cycles	lower bound	upper bound	≤ average	

- When using assumed NDE initial flaw sizes for damage tolerant analysis of ordinary fracture critical parts, the assumed fracture toughness values for predicting flaw instability should be no larger than average or typical values. Fracture properties should be obtained from NASGRO®. Use of properties outside the NASGRO® database should be coordinated with the RFCB. The use of properties outside the NASGRO® database typically requires supporting test data or literature references.
- Fracture properties used in the damage tolerant analysis have to be appropriate for the product form, thickness, and constraint condition. Note that thin parts machined from thick product forms exhibiting lower toughness and ductility may not provide the assumed K_c enhancements based on thickness alone. Also, the constraint conditions associated with test data to determine K_c values may not be consistent with the component. The NASGRO® materials database generally sets B_k, a NASGRO® fitting parameter, to a value in the range 0.5 to 1.0 resulting in significant enhancements to K_{Ic} that are not always supported by test data. The NASGRO® User Manual, section 2.1.4, cautions against using these enhanced toughness values, especially in high-stress/low-cycle fatigue applications. Additionally, the appropriate use of non-zero B_k values requires understanding of the constraint condition for the flaw, which is a function of stress state and geometry. As a result of these observations, it is prudent to set B_k to zero in NASGRO® analysis unless specific data are available to justify a non-zero value.
- Where environmental effects on flaw growth should be considered, as in pressure vessel applications, the lower bound values of K_{EAC} or K_{1EAC} as appropriate should be used in fracture mechanics analysis for the relevant fluid and material combinations.

- Strength and fracture toughness testing of actual representative material may be required for fracture critical parts whose failure clearly results in a catastrophic occurrence and that are fabricated from an alloy having a wide range of fracture toughness for the particular fabrication and heat treatment process used. This consideration is necessary since the required service life factor (a minimum of four) may not envelope materials with wide variations in fracture toughness. As a general guideline, a wide range in fracture toughness may be defined as material exhibiting a range of fracture data with values falling below 20 percent of the average value. In these cases, samples from material out of the same heat lot or out of remnant material used in fabrication of the part should be considered for testing. Assessment of components that fall in this category have to be coordinated with the RFCB.
- Fracture toughness testing should be performed for components with less than 1000 cycle lives when an assumed lower bound value of fracture toughness results in an inadequate life. This provision is required since damage tolerant parts with analytical lives less than 1000 cycles typically have a significant portion of their life in the steep flaw growth rate portion (Region III) of the flaw growth rate curve. Deviations between typical test data and actual material performance in low-cycle count scenarios might not be conservatively covered by the required service life factor (a minimum of four). Test data from representative material are needed in these cases to ensure that appropriate toughness and flaw growth parameters are used in the damage tolerant analysis. Assessment of components that fall in this category should be coordinated with the RFCB.
- It is strongly recommended that all components with less than 1000 cycle lives use documented lower bound toughness values and upper bound flaw growth parameters. As noted above, these components typically have a significant portion of their life in the steep flaw growth rate portion (Region III) of the flaw growth rate curve. Test data are generally sparse and scattered in this region, and the required service life factor may not conservatively envelope variations between actual and typical toughness/flaw growth parameters.
- If a proof test is used for initial flaw screening, upper bound fracture toughness values should be used to calculate the flaw size determined by the proof test. Upper bound values may be determined by multiplying average values by 1.2. This may be used as an estimate of the upper bound values for preliminary evaluation purposes, but more realistic values are required to determine the flaw size screened by proof test. The determination of upper bound values typically requires testing (or supporting test data in the literature). The toughness values used in the proof test assessment should also be representative of the constraint conditions in the hardware, which are a function of geometry and stress state. Simulation of constraint conditions in the hardware may be accomplished by adjusting the B_k value in NASGRO® (recall that it is recommended that B_k be set to zero for standard damage tolerant analysis) or employing more sophisticated stress analysis tools to match the stress state in the vicinity of the flaw. Proof test as a screen for initial flaws should be coordinated with the RFCB.
- Average or larger fatigue flaw growth rate properties are to be used for flaw growth calculations for the NDE initial flaw size approach. Average or smaller fracture toughness values may be used in flaw growth rate equations that model growth rate

approaching instability. Where the fatigue flaw growth data sources are particularly sparse, conservative estimates of the growth rate should be assumed and documented. All flaw growth rate data should correspond to the actual temperature and chemical environments expected or shown conservative with respect to the actual environments.

- When calculating life for flaws screened by proof test, an end-of-service life fracture toughness value consistent with the toughness value used in determining the flaw screened by the proof test should be used. Note if the proof test environment is different from the service environment, that there will likely be differences between the critical toughness value used for the proof test analysis and the critical toughness value used in the service life analysis. It is important to maintain a consistent methodology for determining toughness. For example, suppose a pressure vessel will be proof tested at room temperature but will experience cryogenic service cycles. The test methodology used to determine upper bound toughness values at room temperature to calculate the flaw screened by a room temperature proof test should be consistent with the methodology used to determine upper bound toughness values at the cryogenic service temperature for use in the damage tolerant calculations. In cases where specific data for one temperature is already available, care should be taken that the data are appropriate for the application and that the corresponding data for the other temperature are collected in a similar manner. As noted above, average or larger fatigue flaw growth rate properties may be used for flaw growth in these calculations provided they correspond to the actual temperature and chemical environments expected or are shown to be conservative with respect to the actual environments. Where the fatigue flaw growth data sources are particularly sparse, conservative estimates of the growth rate should be assumed and documented.
- Guidelines for disposition of detected flaws in fracture critical hardware are provided in section 8.1.5. Note that disposition of known flaws should be coordinated with the RFCB.
- NASGRO® models for flaw growth rate and fracture may vary from version to version and may also vary from equations published in the literature. As such, the material parameters (C, n, p, q, etc.) also vary and are not generally interchangeable. Modification of NASGRO® material parameters should be coordinated with the RFCB.
- Material properties for use in elastic-plastic or non-linear elastic (J) models for damage tolerant analysis should be coordinated with the RFCB.

NASA-STD-5019A, Item 8.3.f

Materials not developed and qualified in accordance with the requirements of NASA-STD-6016 require an approved MUA. The suitability of the material for the specific application is documented in an MUA which is included in the FCSR. MUAs have to be processed using the procedure and typical form specified in NASA-STD-6016.

NASA-STD-5019A, Item 8.3.g

All MUAs are to be included in the FCSR.

9. FRACTURE CONTROL DOCUMENTATION AND VERIFICATION

This section provides guidance and interpretations of numbered and titled material from NASA-STD-5019A.

9.1 Fracture Control Documentation (NASA-STD-5019A, Section 9.1)

The fracture control program activities will be documented. This may be very brief, e.g., a short memo for a small, simple program with no fracture critical parts, or it may be several volumes of material for complex hardware with many fracture critical parts such as an advanced payload or launch vehicle stage. A typical fracture control program would generally include the following documentation:

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

The program and the technical/engineering community should review the above list **during program formulation** and work together so that the appropriate data requirements will be levied on the hardware developer. It may be necessary for the Responsible Technical Organization to contact the program to initiate this data requirement definition. In any event, it is best performed early while the program is being formulated.

9.1.1 Fracture Control Plan (NASA-STD-5019A, Section 9.1.1)

> **NASA-STD-5019A:**
> **9.1.1 Fracture Control Plan**
>
> *The FCP developed in compliance of [FCR 1] in section 4.1 in this NASA Technical Standard is part of the documentation.*

The FCP is typically prepared by the hardware developer and describes how fracture control will be met for specific hardware such as a payload, launch vehicle stage, habitable module, propulsion system, an engine, etc. The FCP provides hardware-specific activities and describes the responsibilities for carrying out fracture control per the NASA requirements. Each separate hardware project within a program should have an FCP. The intent of the FCP is to give careful consideration of the hardware to determine the applicable fracture control methodologies specific to the hardware that will mitigate risk of catastrophic hazard. An FCP that generically repeats the NASA requirements does not fulfill the intent of NASA-STD-5019. Examples of FCPs for several types of hardware are provided in Volume 2 of NASA-HDBK-5010.

The initial version of the FCP should be submitted early in the program but no later than the Preliminary Design Review (PDR). Subsequently, the FCP should be updated as the program matures to keep it current with program fracture control intentions. Typically, the FCP should be updated at subsequent major reviews such as PDR, Critical Design Review, etc.

Following is a list of the key elements that should appear in a typical FCP. The format is left to the discretion of the hardware developer:

a. Introduction, including identification of the hardware being addressed by the FCP, identification of the hardware developer, and the objective of the document. The document should contain a clear description of the associated hardware, including a description of the operation of the hardware.

b. Title and hardware developer signature pages.

c. Listing of applicable documents (generic and program specific).

d. A clear, unambiguous description of responsibility by discipline/organization for fracture control implementation within the hardware developer's organization. Also, identification of the inputs/outputs of each organization needed for effective fracture control. For example, if the materials organization was going to provide fracture properties to the analyst, the organizations, the property, material, condition, etc., would be identified here. Typical organizations would include:

(1) Program Office.
(2) Design.
(3) Analysis.
(4) Materials.
(5) Manufacturing.
(6) NDE.
(7) Structural, proof, and environmental damage tolerant testing.
(8) Tracking.
(9) Quality Control.
(10) Documentation/reports planned and responsible parties.
(11) Project Change Boards, RFCB, etc.
(12) Other specific organization/function designated by the hardware developer.

e. Include a preliminary classification of all the hardware for fracture control as exempt, non-fracture critical, and fracture critical. Based on the classification of each part, provide the approach for each part selected from NASA-STD-5019A. See an example of an FCP and FCSR in Volume 2 of NASA-HDBK-5010A. Note that the list of fracture classifications in the FCP and FCSR may not be congruent since the FCP is formulated earlier in the program. For example, in the Space Launch System Multiple Stage Adapter, the hardware fracture classifications were updated in the FCP as the program matured. Language in the FCP may be included to indicate the list is preliminary and as the design matures, the list will be updated, specifying how and where the update list will be maintained (e.g., in the FCSR). The FCSR would identify the final classifications along with the rationale.

f. Activities by discipline/organization to support the disposition and acceptance rationale of parts classified in “e” above. Identify any unusual hardware situations that require special attention. Candidate topics include, but are not limited to:

(1) Program Office: Program definition (e.g., specify the number of missions required of the hardware) and provide resources for fracture control implementation.
(2) Design.

    A. Design approaches used to minimize fracture control issues for this specific hardware (e.g., fail safe, no single-point failure fasteners, minimize stress concentrations, etc.).
    B. Drawings for fracture critical hardware (provide plans to identify fracture critical hardware and specify NDE for fracture critical parts).

(3) Analysis
    A. Specific types of analysis/test approaches to be used on this hardware, e.g., “part x does not lend itself to damage tolerant analysis and will be assessed by damage tolerant test. Test plan to follow in document X.”
    B. Origin/methods of generating stresses for fracture analysis.
    C. Fracture code/other for damage tolerant analysis.

    D. Approach and assumptions for obtaining/generating loading scenario.
    E. Treatment of any flaws found in flight hardware.
- (4) Materials
    - A. Materials selection, certification, and controls.
    - B. Origin and source of material and fracture properties, e.g., NASGRO® material library.
    - C. Anticipated MUAs.
- (5) Manufacturing
    - A. Assuring process compatibility with design specifications.
    - B. Serialization of fracture critical parts.
    - C. Handling of flight hardware.
- (6) NDE: Specific types of NDE, e.g., “only eddy current will be used with certified inspectors.”
- (7) Tests
    - A. Environmental.
    - B. Proof.
    - C. Damage Tolerant.
- (8) Tracking
    - A. Material traceability.
    - B. Configuration control.
    - C. Load history.
    - D. Flaw screening/detected flaws.
- (9) Quality control: Sign off on all hardware and testing certificates of record.
- (10) Documentation: Generation of required fracture control documentation, such as what reports will be generated and at what point in the program.

g. Three-dimensional assembly views of the hardware, along with appropriate project terminology and drawing references, as best as are available at the time the plan is written or updated. Include subassemblies and individual part drawings where needed for hardware functional understanding.

9.1.2 Engineering Drawings (NASA-STD-5019A, Section 9.1.2)

NASA-STD-5019A:
9.1.2 Engineering Drawings

[FCR 23] Fracture critical parts shall be identified on engineering drawings in the notes of the individual part drawing, along with the inspection, serialization, and other pertinent information necessary to maintain traceability of the part and its history of manufacturing and use.

[Rationale: Identification of fracture critical parts on engineering drawings is necessary to assure that the appropriate NDE, serialization, and traceability needs are recognized and implemented.]

The type of NDE and NDE acceptance criteria should be specified.

Detected flaws are assessed in accordance with section 8.1.5 in this NASA Technical Standard.

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

Composite or bonded material epoxies and adhesives should have their shelf life requirements included as part of the engineering drawing notes.

The engineering drawings should identify the parts that are fracture critical in the notes of the individual part drawing, along with the inspection, serialization, and other pertinent criteria. The type of NDE should be specified (eddy current, penetrant, etc.) along with the statement that “all detected flaws, regardless of size, shall be cause for rejection.” Any detected flaws have to be reported for assessment in accordance with section 8.1.5. As applicable, processing or fabrication requirements that would affect fracture properties of a fracture critical part in a given application, including heat treatments, welding requirements and peaking and mismatch allowables, grain direction, etc., should also be specifically called out on the part drawing.

Rationale for including the fracture critical note and NDE requirements include:

a. Notification regarding appropriate NDE is a primary motivation. This includes two steps: (1) Getting a basic drawing together with the core requirements, and (2) When the analysts finish the fracture life assessments to confirm that the part is getting an appropriate screen for sufficient life. Changes to the NDE would be made at this stage. There have been cases where parts that were fracture critical failed to get proper NDE because the fracture critical designation was not evident.

b. The drawing note is the primary configuration-controlled location for documenting the fracture critical classification of the part. There are fracture control and stress analysis reports, but they are generally not controlled to the same degree as the engineering drawings.

c. The note is a primary guide for any assessments that are required during certain types of material review activity. The first question asked (or that is supposed to be asked) when reviewing NDE findings, incidental damage, or such is whether the part is fracture critical or not. The primary source for part information for the material review assessment is the drawing. The fracture critical designation alerts those doing the MR assessment that different use-as-is rules are in place for the part if it is fracture critical. For example, NDE indication sizes should be bounded, material properties are adjusted, etc.

9.1.3 Fracture Control Summary Report (NASA-STD-5019A, Section 9.1.3)

NASA-STD-5019A:
9.1.3 Fracture Control Summary Report

[FCR 24] An FCSR shall be developed by the spaceflight hardware program or project that:

a. Documents the basis for acceptance that all the flight hardware parts have met the fracture control requirements in the approved FCP.

b. Contains detailed information or reference to detailed information for all parts, including results for evaluations, classification, assessments, inspections and other pertinent records, and their disposition for fracture.

c. Documents all assessments, such as analyses and tests, conducted on representative flight hardware used for flight certification.

d. Identifies the flaws and impact damage threats that are accepted on risk by the program authority, i.e., the flaws and impact damage threats for which there is no damage tolerance evaluation.

e. Is approved by the RFCB.

[Rationale: The FCSR contains the information or summarizes and points to the detailed reports necessary to show fracture control compliance of all parts to the requirements in the approved FCP.]

The FCSR may point to other project documentation that is available for review by the RFCB that contains fracture control data relevant to the completion of the FCSR as necessary to avoid duplication of efforts.

The flaws identified in 9.1.3.d (above) may vary from program to program. Examples may include flaws, such as those caused by lightning strikes, system failures, handling mishaps, MMOD impacts, bird impacts, etc.

The hardware developer prepares an FCSR on the total system for review and approval by the RFCB. As a minimum, the following information has to be provided: The FCSR has to provide sufficient information to certify that fracture control requirements have been met:

a. The FCSR should provide sufficient hardware descriptions, including sketches and figures to convey a clear understanding of the hardware elements and their functions.

b. The FCSR gives an accounting of all parts and their disposition for fracture control:

(1) Exempt parts, groups of exempt parts, and types of exempt parts have to be identified (see section 5.2 of NASA-STD-5019 A).
(2) Non-fracture critical parts have to be listed along with their classification and supporting rationale.
(3) Fracture critical parts have to be listed and the bases for their damage tolerance summarized. Fracture critical parts that are limited life have to be identified along with their life limitations.

c. The FCSR identifies the following for all parts except those classified as exempt, low released mass, or contained:

(1) NDE and other inspections carried out on the hardware in support of fracture control.
(2) MUAs.
(3) Discrepancies or deviations from design that affect fracture control.
(4) Flaw detections and their resolutions.

e. A summary discussion of alternative approaches or any special considerations involving fracture mechanics properties, inspections, analysis, etc., not covered by guidelines have to be identified.

Supporting detailed documentation such as drawings, calculations, analyses, test results, data printouts, inspection plans, records, specifications, certifications, reports, procedures, etc., while generally are not included in the FCSR, have to be provided to the RFCB under separate cover, upon request.

The FCSR has to be submitted by the Phase 3 Safety Review for payloads or by the final acceptance review or flight certification for other hardware.

An example of an FCSR is given in Volume 2 of NASA-HDBK-5010.

9.1.3.1 Detailed Information for the FCSR (NASA-STD-5019A, Section 9.1.3.1)

NASA-STD-5019A:

9.1.3.1 Detailed Information for the FCSR

a. The FCSR provides sufficient information to certify that fracture control requirements have been met by assessment results available in detailed damage tolerance assessment reports of analyses and testing. The FCSR summarizes the results and damage tolerance service life, loadings, flaw screening methods, initial flaw sizes used in the assessment, material characteristics, flaw sizes at the end of lifetime, predicted lifetime, and analysis methods used in the assessment.

b. The FCSR provides sufficient hardware descriptions, including sketches and figures, to convey a clear understanding of the hardware elements and their functions.

c. Supporting detailed documentation, such as drawings, calculations, analyses, testing details, test results, data printouts, inspection plans, records, DTA, IDMP, RTD, specifications, certifications, MUAs, reports, procedures, and all other items that establish the fracture control suitability of the flight hardware, is to be provided to the RFCB under separate cover, upon request.

d. The FCSR gives an accounting of all parts and their disposition for fracture control as follows:

(1) Identifies exempt parts, groups of exempt parts, and types of exempt parts.

(2) Lists NFC parts, along with their classification and supporting rationale.

(3) Lists fracture critical parts with a summary of the basis for their damage tolerance.

e. The FCSR identifies the following for all NFC parts requiring NDE, including fail-safe parts, containment enclosures, NHLBB items, low-risk parts, NFC composite or bonded hardware assessed in accordance with section 6.3.1 in this NASA Technical Standard, and fracture critical parts:

(1) NDE and other inspections carried out on the parts.
(2) MUAs.

f. The FCSR identifies inspections and other requirements imposed on re-flight hardware before re-flight.

g. The FCSR includes results from implementation of approved alternative approaches used in accordance with section 10 in this NASA Technical Standard.

A detailed FCSR has to be prepared by the analyst to document the analysis that has been performed to support fracture control. This report should contain sufficient detail to allow reviewers to check and reconstruct all calculations. Hardware descriptions, program requirements, and analysis assumptions should be clearly stated. The following is an outline for items that should be included in the subject report.

a. Preliminaries. The following is a typical list that would normally be included:

(1) Title page.
(2) Signature and approval page.
(3) Table of Contents.
(4) List of Figures.
(5) List of Tables.
(6) List of Appendices
(7) List of Definitions and Acronyms.

b. Fracture control summary list for all non-exempt parts. The list format is optional but should include the part name identification and its classification. Examples of a summary list are given in Volume 2 of NASA-HDBK-5010. A table format is recommended, and some useful information to include along with the required data is:

(1) Part name.
(2) Drawing number.
(3) Material and condition.
(4) Classification (damage tolerant, fail safe, etc.).
(5) Flaw analysis model (NASGRO®SC02, etc., “NA” for parts other than damage tolerant, “Test” for hardware accepted by subsystem test, vibration, or proof for composites).
(6) Drawing thickness.
(7) Initial flaw size (“NA” for parts other than damage tolerant).
(8) Type of NDE (“NA” for parts other than damage tolerant, “proof test” for parts screened by proof test).
(9) Life for damage tolerant parts, margin of safety on ultimate in failed condition for fail-safe parts, weight for low-mass parts.
(10) Reference page number in report for detailed analysis.

c. Introduction. Include things that would help the reviewers understand who the hardware developer is, hardware maturity, and program constraints. State whether there are fracture critical parts or not. Also make clear whether or not there are pressure vessels or fracture critical rotating equipment present.

d. Hardware Description. Include diagrams, sketches, and a written description so that the reviewer has a general idea of hardware operation and function.

e. Program requirements. Include the number of missions, configurations for launch, landing, or on-orbit operations, contingency constraints, ground testing, transportation, availability/accessibility between missions for NDE, etc.

f. Loads. Provide the loads for all mission phases and their source. Construct the general loading scenario. Provide assumptions and rationale.

g. Fracture control analyses (each subsystem and its parts). Summarize the damage tolerant, NHLBB, fail safe, containment, test, etc., analysis and classification rationale for each part on the summary list (Item b above). Put extended analysis and computer runs such as NASGRO® in an appendix. List the stresses and material properties used in the fracture control analysis. Provide sources for each. If the stress analysis is also being performed in the same report, follow the individual part stress analysis immediately with the fracture analysis. Include part-free body diagrams, stress contours as applicable, flaw location and orientation, and flaw model, e.g., TC01 from NASGRO®. List assumptions. Describe any alternate approaches used.

h. Address justification for use of any flight hardware with any detected flaws in accordance with section 8.1.5 in this Handbook.

i. Conclusions. Ideally, the analyst will be able to conclude that the analysis is complete and there are no open issues. Otherwise, summarize the status and provide closure plans for any remaining work.

j. List of References.

k. Appendices. Include detailed analysis, NASGRO® computer runs, test results, inspection sheets, and other supporting data that would interrupt the flow of the body text. In a separate appendix, identify the exempt parts along with rationale for their classification. These parts do have to be identified by individual part number but may be identified be groups, assembly, and or type.

An example of a detailed fracture control analysis report is given in Volume 2 of NASA-HDBK-5010.

9.1.3.2 Other Documentation (NASA-STD-5019A, Section 9.1.3.2)

NASA-STD-5019A:
9.1.3.2 Other Documentation

Other documentation supporting fracture control may be called for in the program data requirements. A summary of any parts with known flaws that were accepted for flight by the Technical Authority and any accompanying RFCB review documentation should be maintained by the program/project configuration data management organization. This includes any discrepancies or deviations from design that affect fracture control, e.g., any flaw detection information with resolution data.

Inspection Report

This report is primarily a compilation of the inspection sheets used by the inspector to record results. The sheets should identify the part name, part number, serial number, material and condition, type NDE and sensitivity level, a sketch of the part showing the area inspected and type of flaw inspected for, the results of the inspection and the inspector’s signature, date, and stamp. Instead of a separate report, these data may be included in an appendix of the detailed fracture control analysis report if available at the time that report is published.

Test Report

If a proof test, damage tolerant test, vibration test, or other test is used to justify damage tolerance compliance, it has to be documented in a report. Data sheets from the vender will suffice for routine proof test of lines, fittings, and pressure vessels. For other tests, the hardware configuration, loading, and test setup have to be documented with sketches and photographs. Actual test loading scenarios and environments have to be recorded and reported. Conclusions as to the acceptability of the hardware based on the test performed should be included in the report in accordance with the criteria established in the detailed fracture control analysis report. Instead of a separate test report, these data may be included in an appendix of the detailed fracture control analysis report if available at the time that the report is published.

Load/Use History

The project is responsible for maintaining a load and use history of fracture critical items for the life of the project. This is especially important if multi-mission limited-life hardware is involved. The report has to track projected use against remaining life for each fracture critical part at appropriate intervals to demonstrate that the hardware is being operated within fracture control requirements.

9.2 Verification (NASA-STD-5019A, Section 9.2)

NASA-STD-5019A:

9.2 Verification

[FCR 25] Verification of adherence of the flight hardware to the fracture control requirements in this NASA Technical Standard shall include all of the following:

a. Written documentation that establishes that each requirement has been met. This documentation describes how the requirement was verified, e.g., test, analysis, inspection. The project is responsible for providing this verification, including assurance that fracture control activities were implemented on the flight hardware before flight and reflight, to the appropriate program management.

b. Approval of the FCP and FCSR by the RFCB, documented by a concurrence memorandum from the RFCB to the applicable project/program office.

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

[Rationale: All requirements need to be verified. The verification is the evaluation and documentation that all requirements have been met. There are many methods of verification, e.g., analysis, test, inspection, each of which should be documented.]

The project is responsible to the appropriate program for the line-by-line review of the verification requirements. The RFCB is responsible for a review of the methodology of the compliance to and verification of the requirements. These are documented in the FCP and FCSR, respectively.

Commonly, the project writes project-specific requirements that are traceable to a higher level standard. This requirements set includes a verification section. In this section, there is a verification requirement for every requirement in the project-specific requirements. This requirement documents how the verification will be done.

The RFCB is to receive the FCP and FCSR in accordance with requirements in this NASA Technical Standard, but, as described above, the RFCB is not the entity that performs the requirement-by-requirement review.

[FCR 25] specifies that verification the flight hardware has satisfied and adhered to the fracture control requirements in the NASA Technical Standard is accomplished by the three items in this section.

Each item in this section contains complete descriptions of the specific requirement(s) and the method of demonstrating compliance with the requirement. Accordingly, the discussions of each item in this section will not repeat the content of items a, b, and c. Instead, a short summary of each item will be provided.

The guidance provided in this section is copied below as it provides explanations of the situations and the usual processes.

> *The project is responsible to the appropriate program for the line-by-line review of the verification requirements. The RFCB is responsible for a review of the methodology of the compliance to and verification of the requirements. These are documented in the FCP and FCSR, respectively.*
>
> *Commonly, the project writes project-specific requirements that are traceable to a higher-level standard. This requirement set includes a verification section. In this section, there is a verification requirement for every requirement in the project-specific requirements. This requirement documents how the verification will be done.*
>
> *The RFCB is to receive the FCP and FCSR in accordance with requirements in this NASA Technical Standard, but, as described above, the RFCB is not the entity that performs the requirement-by-requirement review.*

NASA-STD-5019A, Item 9.2.a

Item 9.2.a of NASA-STD-5019A describes required written documentation in detail that has to be provided, identifies the responsible entity for providing the documentation, and the recipient of the documentation.

NASA-STD-5019A, Item 9.2.b

Item 9.2.b in NASA-STD-5019A specifies the FCP and FCSR have to be approved by the RFCB and documented by a concurrence memorandum from the RFCB to the applicable project/program office.

NASA-STD-5019A, Item 9.2.c

Item 9.2.c in NASA-STD-5019A describes the process to be followed in the event of conflict between the RFCB and the applicable project office regarding the verification of compliance with the fracture control requirements.

10. ALTERNATIVES (NASA-STD-5019A, Section 10)

NASA-STD-5019A:
10. ALTERNATIVES

[FCR 26] If alternative approaches are proposed (rather than meeting any part of the accepted approaches that are prescribed in sections 5, 6, 7, or 8 in this NASA Technical Standard, with the exclusions shown below), the alternative approach shall include all of the following items:

a. Provide an equivalent assurance of mitigating the risk of catastrophic failure from flaws during the service life of the hardware.

b. Have the approval of the RFCB.

c. Meet all the other applicable requirements in this NASA Technical Standard.

d. FCRs 10, 15, 20, 21, and 22 (sections 7.1, 8, 8.1.5, 8.2, and 8.3, respectively, in this NASA Technical Standard) are excluded from alternative approach consideration.

Note that FCR 26 pertains to sections 5, 6, 7, and 8 only; FCRs 1, 2, 3, 4, 5, 23, 24, and 25 are also excluded from alternative approach consideration.

[Rationale: Regardless of the detailed acceptance approach used for each part, the method is to be responsive to NASA NPR directives to mitigate the risk of catastrophic failure related to flaws during the service life of the hardware. If an alternative approach is proposed, its effectiveness is to be established and the approach documented in the approved hardware-specific FCP in accordance with [FCR 1] in section 4.1 in this NASA Technical Standard.

This document contains acceptable methods for fracture control based on NASA's experience base, established approaches, industry standards, or aerospace standards that satisfy the fracture control requirements; therefore, it is advisable to use the methods prescribed in this NASA Technical Standard.

Alternatives to the approaches prescribed in this NASA Technical Standard in sections 5, 6, 7, or 8 may be proposed for a specialized part or application for which the approaches in this NASA Technical Standard are not feasible or effective or for which other viable methods are advantageous. Alternative approaches, accompanied by supporting rationale that establishes that the alternative has comparable rigor to the approaches in this NASA Technical Standard, are presented to the RFCB for review and approval. Approved alternative approaches are to be documented in the specialized FCP for the parts in accordance with [FCR 1] in section 4.1 in this NASA Technical Standard.

The purpose of fracture control is to mitigate the risk of catastrophic failure due to flaws in the absence of failure tolerance. The requirements in NASA-STD-5019 represent approaches which provide risk mitigation for catastrophic failure due to flaws. The approaches provide a system for classifying parts based on criticality to help determine activities needed for risk mitigation. Classification of each part as fracture critical, NFC, or exempt is the key first step. Within the fracture critical and NFC classification topics, specific approaches have developed into categories that provide prescribed activities and evaluations necessary to either remove concern of a catastrophic hazard, develop confidence that a catastrophic hazard is not likely to occur, or perform activities that help mitigate the risk of a catastrophic hazard due to a flaw.

The categories developed for fracture control in NASA-STD-5019 were developed to eliminate or diminish catastrophic hazards for various hardware systems. The prescribed approaches represent a one-size-fits-all approach, which may not always be the most useful or appropriate approach for a particular situation or hardware system.

NASA-STD-5019A, Item 10.a

Alternatives to the prescribed approaches in NASA-STD-5019 can be advantageous for organizations that have other established approaches which provide an equivalent level of risk mitigation. Alternative approaches should address the catastrophic hazards of concern for the part being considered and provide rationale for how those failure mode concerns are either eliminated, deemed unlikely, or mitigated.

Catastrophic Hazards

An overview of examples for common potential catastrophic hazards created by failure due to a flaw includes the following:

- Part failure
  - Loss of load-carrying capability including strength and stability.
  - Excessive energy release due to rupture/burst.
  - Excessive deformation/interference (separate from loss of stability).
  - Loss of critical functional.
  - Creation of debris (impact hazard).
- Fluid leakage
  - Leakage of fluid (hazardous fluid).
  - Loss of pressure (functionality loss).

Part failure under load due to a credible flaw or damage may result in any of the following concerns related to potential catastrophic hazards:

- Loss of structural integrity (inability to support limit load).
- Excessive energy release due to rupture or burst of a pressurized component.
- Damage of the material resulting in loss of structural rigidity leading to excessive deformation.
- Impact of fragments from the part failure upon personnel or critical hardware.

- Failure of a structural part under load causing the part to move and obstruct some critical mechanism or cause a sudden stop of rotating hardware resulting in loading that causes a catastrophic hazard.
- Failure of a part under some lesser loading, thereby changing structural support capabilities and causing a catastrophic failure of a critical structure during a future loading event.
- Inability of a part to perform a critical function (loss of which creates a catastrophic hazard) due to a flaw such as:

    - Failure of a part of the spacecraft propulsion or guidance system,
    - Diminished mechanical capability resulting in malfunction of a critical part due to flaws (e.g., loss of movement in bearing components, loss of pressure sealing capability in hardware for habitable module hatch)

Leakage of fluid from a part under pressure due to a flaw or damage could be a result of growth of the flaw, or damage accumulation resulting in a through-the-thickness condition, or changes of an initial through flaw condition due to service effects, or any other structural failure of a part due to a flaw that creates a leak path or increased permeability of the material. The leakage may cause a catastrophic hazard if the fluid:

- Is a hazardous fluid.
- Leakage reduces pressure below allowable in a habitable module or human-rated enclosure.
- Leakage changes pressure in a volume that exceeds structural allowables.
- Leakage causes loss of critical pressure or fluid supply.
- Leakage plume degrades critical equipment lifetime or transparency of windows (when loss of a national asset is considered).
- Leakage rate is sufficient to impart unacceptable acceleration upon the part or other hardware.

Materials

Different hardware materials and conditions may cause different credible types of failure modes due to a flaw that may affect the hazard assessment. Some common material failure modes are listed below.

Metallic hardware may contain inherent flaws due to common manufacturing processes such as welding, casting, and forging. Flaws may initiate and/or grow due to corrosion, loadings, temperature loadings, creep, surrounding fluids, and other environmental conditions. Multiple flaws may exist in the hardware after manufacturing or may initiate due to service loadings at multiple high-stress locations such as holes. Structural assessment of flaws in thin structures may be difficult to characterize accurately if significant plasticity is present.

Composite/bonded hardware may have loss of structural integrity due to single or multiple flaws or damage. There are conditions that may diminish structural performance of the matrix and/or the fibers due to the manufacturing process such as introduction of foreign object debris, processes resulting in irregularity of the fiber layup, or matrix porosity. During manufacturing and during the service lifetime, environmental conditions can affect the structure due to changing temperatures and humidity. Composite structures may have structural weaknesses or excessive deformation due to design issues from choice of ply details and material allowables if unexpected service loading directions or conditions could credibly affect the strength or stiffness of the hardware.

Equivalent Assurance of Risk Mitigation

Catastrophic hazards should be considered within the framework of fracture control classifications of exempt, NFC, and fracture critical. Some general alternative approach guidelines for each classification are provided below:

Exempt: Limited to nonstructural items or small mechanical parts qualified with rigorous test programs and whose failure clearly does not directly lead to a catastrophic hazard. The approach should provide rationale that clearly demonstrates these situations.

Non-Fracture Critical Parts (NFC) - Establish one of the following to provide rationale that concerns of a catastrophic failure due to a flaw are not credible:

- What activities will be performed that can demonstrate no credible possibility of a catastrophic failure due to a flaw?
    - Example: NASA-STD-5019A, section 6.2.4, NFC NHLBB Pressurized Components
        - This category addresses concerns of structural failure (items 6.2.4.a, c, d, e, and f), concerns of potential fluid hazards (item 6.2.4.b), potential for defects (items 6.2.4.d and g), and basic assurance of re-flight integrity (item 6.2.4.g).
- What activities will be performed that can demonstrate no credible possibility of a flaw in a part to cause failure?
    - Example: NASA-STD-5019A, section 6.2.5, NFC Low-Risk Parts
        - This category of NASA-STD-5019A addresses the likelihood of failure due to a flaw for either a metallic or composite part. For metallic parts, the likelihood of the part having adequate materials that typically do not contain flaws is addressed by items 6.2.5.a(1), (2), and (3). Likelihood of failure is addressed by large structural margins and an assessment for fatigue, items 6.2.5.a(4) and a(5). For composite or bonded parts, this addresses the likelihood of the part having unacceptable flaws via the RTD, in combination with the activities of section 6.3, and basic assurance of re-flight integrity in items 6.2.5.b(1), b(2), and b(3). Likelihood of failure is addressed with ultimate load capability and an assessment for

fatigue concerns, each with an RTD flaw present as identified in items 6.2.5.b(1) and b(2).

Fracture Critical Parts - Establish all the following:

- What activities will be performed to provide understanding of the part's sensitivity to defects?
    - Examples: Life or critical initial flaw size prediction, proof test ≥ 1.5 for some hardware, qualification and acceptance testing for some hardware (e.g., NASA-STD-5017), laboratory fracture testing, hardware testing, other potential hardware developer activities may be a combination of explicit and anecdotal.
- What activities will be performed to understand if any defects are in the part?
    - Examples: NDE, process control data, proof test, other potential hardware developer activities; for some hardware, this includes impact damage protection/detection/inspection strategies.
- How adequate materials and processes are selected and implemented in part design and usage?
    - Identify hardware developer configuration controls and compliance documents used to control materials selection and usage, describe the processes that are in those documents.
- How are materials, loads, handling, and usage activities traceable?
    - Identify and describe processes used to maintain traceability of parts relative to materials, loads, environments, handling, and usage.
- How are detected defects dispositioned?
    - Identify the processes used for determining rejectable indications (i.e., those that rise to the level of a reportable nonconformance) and the assessment approaches (e.g., review boards and analysis/test methodology) for evaluation of the defect relative to reject, repair, or use-as-is.

NASA-STD-5019A, Item 10.b

Item 10.b of NASA-STD-5019A requires approval of the alternative approach by the RFCB. Discussions with the RFCB should occur early and allow for an iterative process to arrive at an acceptable alternative approach that does not impact hardware schedules.

NASA-STD-5019A, Item 10.c

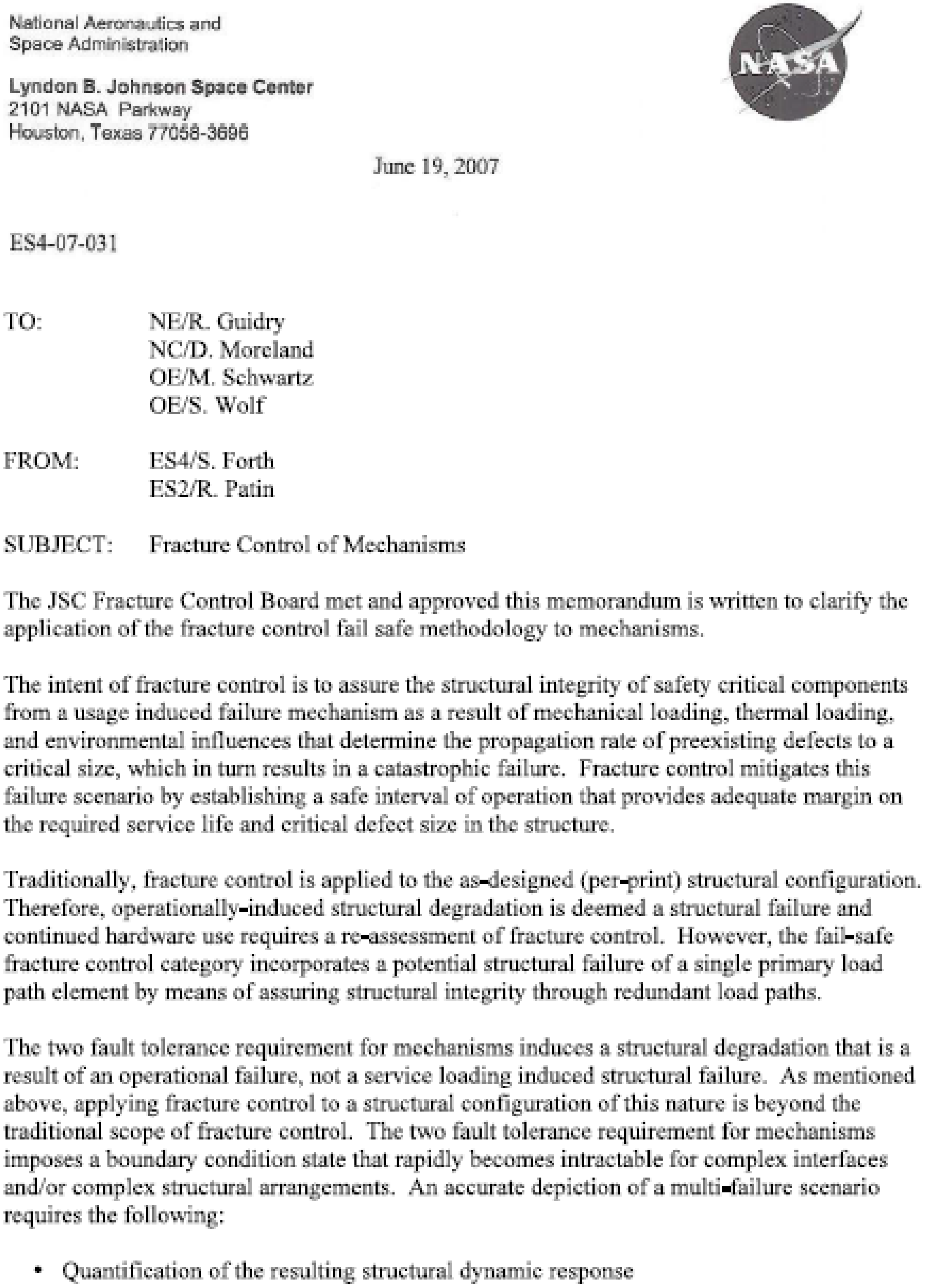
An alternative approach to fracture control may include a more broad-based concept, such as a combined understanding of a part's sensitivity to defects and defect screening approach, or may be very limited to a specific portion of an otherwise completely implemented existing fracture control category. In any case, the other applicable requirements within NASA-STD-5019A have to be met in addition to the items identified in the alternative approach.

NASA-STD-5019A, Item 10.d

The requirements FCR 10, 15, 20, 21, and 22 represent fundamental fracture control concepts within sections 5 through 8 and are not to be modified as part of an acceptable alternative approach.

APPENDIX A: NASA JSC LETTER ES4-07-031

Reference document NASA JSC Letter ES4-07-031 dated 6/19/2007 on Fracture Control of Mechanisms.



National Aeronautics and
Space Administration

Lyndon B. Johnson Space Center
2101 NASA Parkway
Houston, Texas 77058-3696

June 19, 2007

ES4-07-031

TO: NE/R. Guidry
NC/D. Moreland
OE/M. Schwartz
OE/S. Wolf

FROM: ES4/S. Forth
ES2/R. Patin

SUBJECT: Fracture Control of Mechanisms

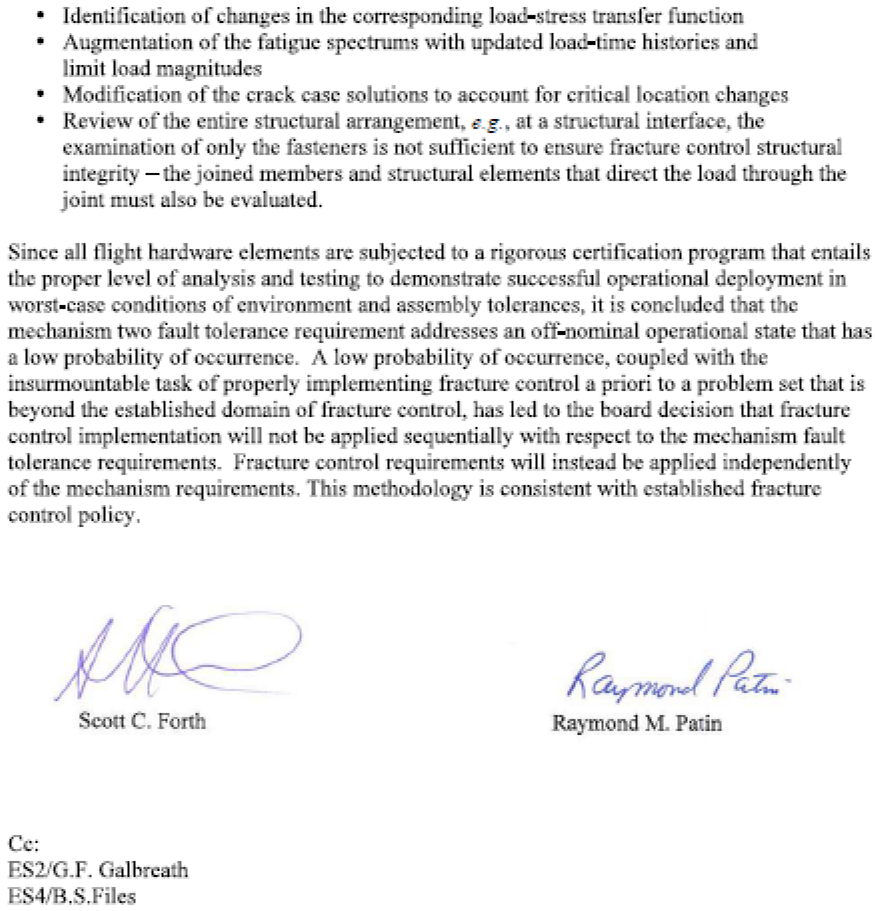
The JSC Fracture Control Board met and approved this memorandum is written to clarify the application of the fracture control fail safe methodology to mechanisms.

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.

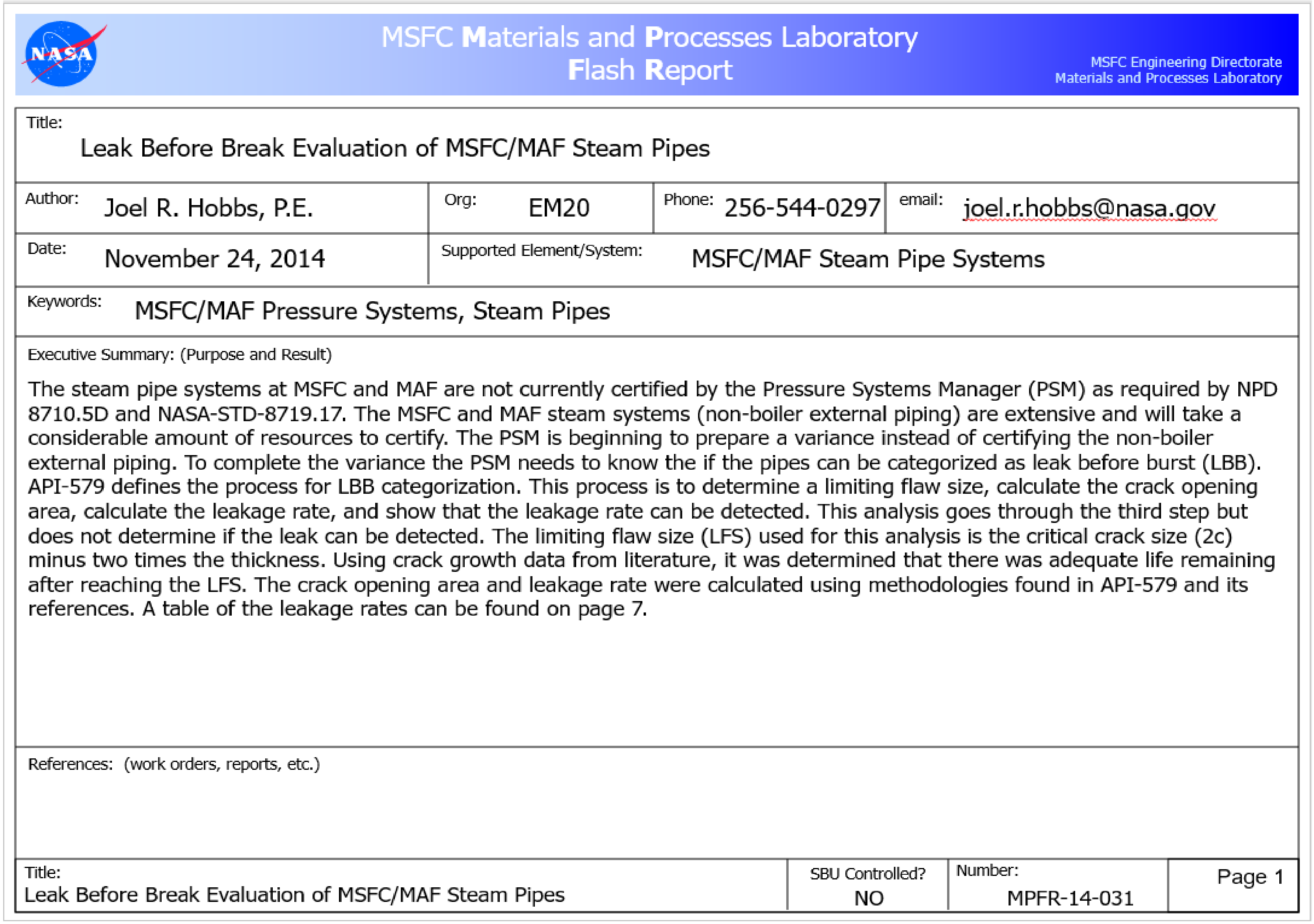
Since all flight hardware elements are subjected to a rigorous certification program that entails the proper level of analysis and testing to demonstrate successful operational deployment in worst-case conditions of environment and assembly tolerances, it is concluded that the mechanism two fault tolerance 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.

Scott C. Forth

Raymond Patin
Raymond M. Patin

Cc:
ES2/G.F. Galbreath
ES4/B.S.Files

APPENDIX B: MPFR-14-031: LEAK BEFORE BREAK EVALUATION OF MSFC/MAF STEAM PIPES



MSFC **M**aterials and **P**rocesses Laboratory
Flash **R**eport

MSFC Engineering Directorate
Materials and Processes Laboratory

Title:
Leak Before Break Evaluation of MSFC/MAF Steam Pipes

Author: Joel R. Hobbs, P.E.
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Phone: 256-544-0297
email: joel.r.hobbs@nasa.gov

Date: November 24, 2014
Supported Element/System: MSFC/MAF Steam Pipe Systems

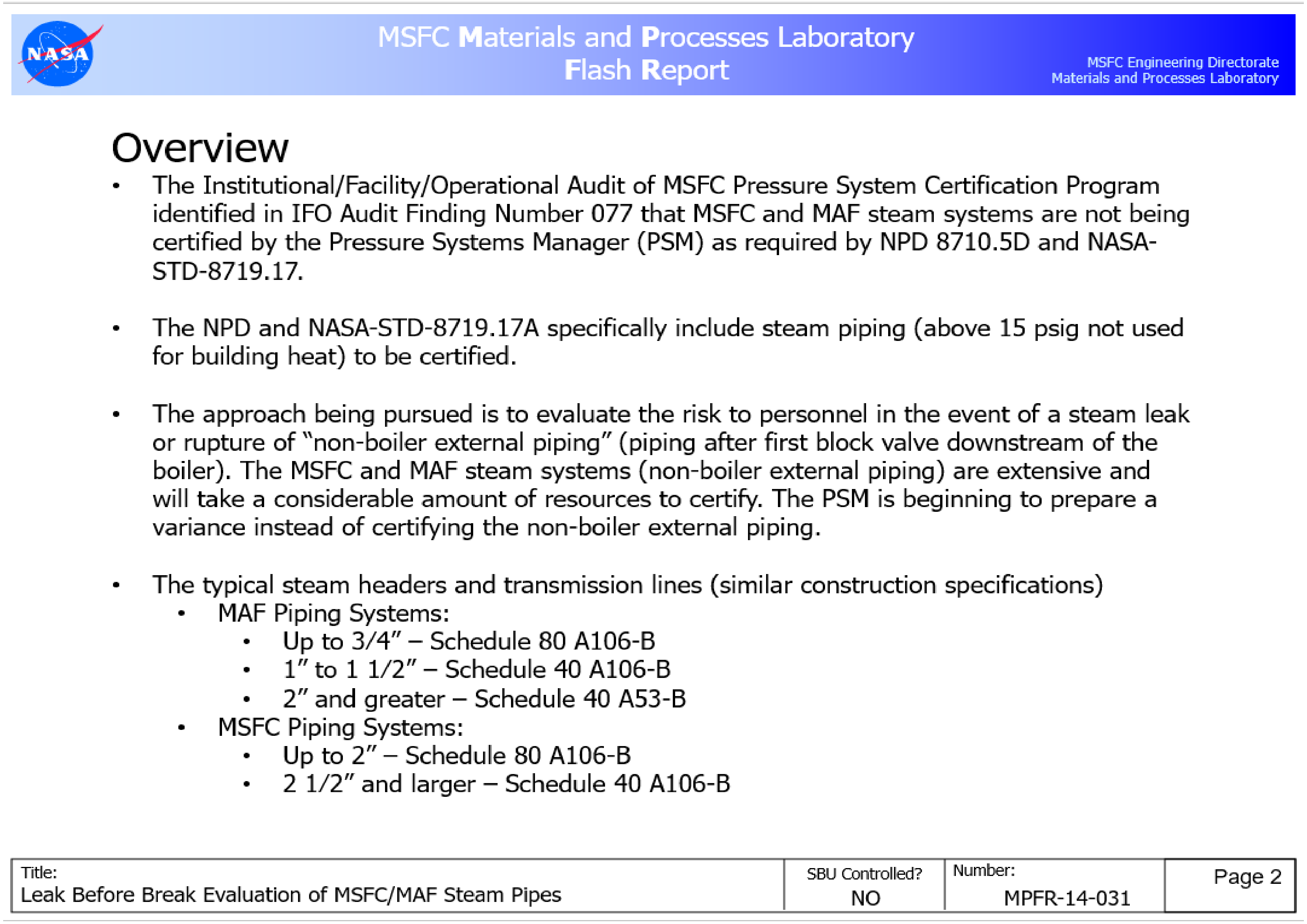
Keywords: MSFC/MAF Pressure Systems, Steam Pipes

Executive Summary: (Purpose and Result)

The steam pipe systems at MSFC and MAF are not currently certified by the Pressure Systems Manager (PSM) as required by NPD 8710.5D and NASA-STD-8719.17. The MSFC and MAF steam systems (non-boiler external piping) are extensive and will take a considerable amount of resources to certify. The PSM is beginning to prepare a variance instead of certifying the non-boiler external piping. To complete the variance the PSM needs to know the if the pipes can be categorized as leak before burst (LBB). API-579 defines the process for LBB categorization. This process is to determine a limiting flaw size, calculate the crack opening area, calculate the leakage rate, and show that the leakage rate can be detected. This analysis goes through the third step but does not determine if the leak can be detected. The limiting flaw size (LFS) used for this analysis is the critical crack size (2c) minus two times the thickness. Using crack growth data from literature, it was determined that there was adequate life remaining after reaching the LFS. The crack opening area and leakage rate were calculated using methodologies found in API-579 and its references. A table of the leakage rates can be found on page 7.

References: (work orders, reports, etc.)

Title:
Leak Before Break Evaluation of MSFC/MAF Steam Pipes
SBU Controlled? NO
Number: MPFR-14-031
Page 1



MSFC Materials and Processes Laboratory
Flash Report

MSFC Engineering Directorate
Materials and Processes Laboratory

Overview

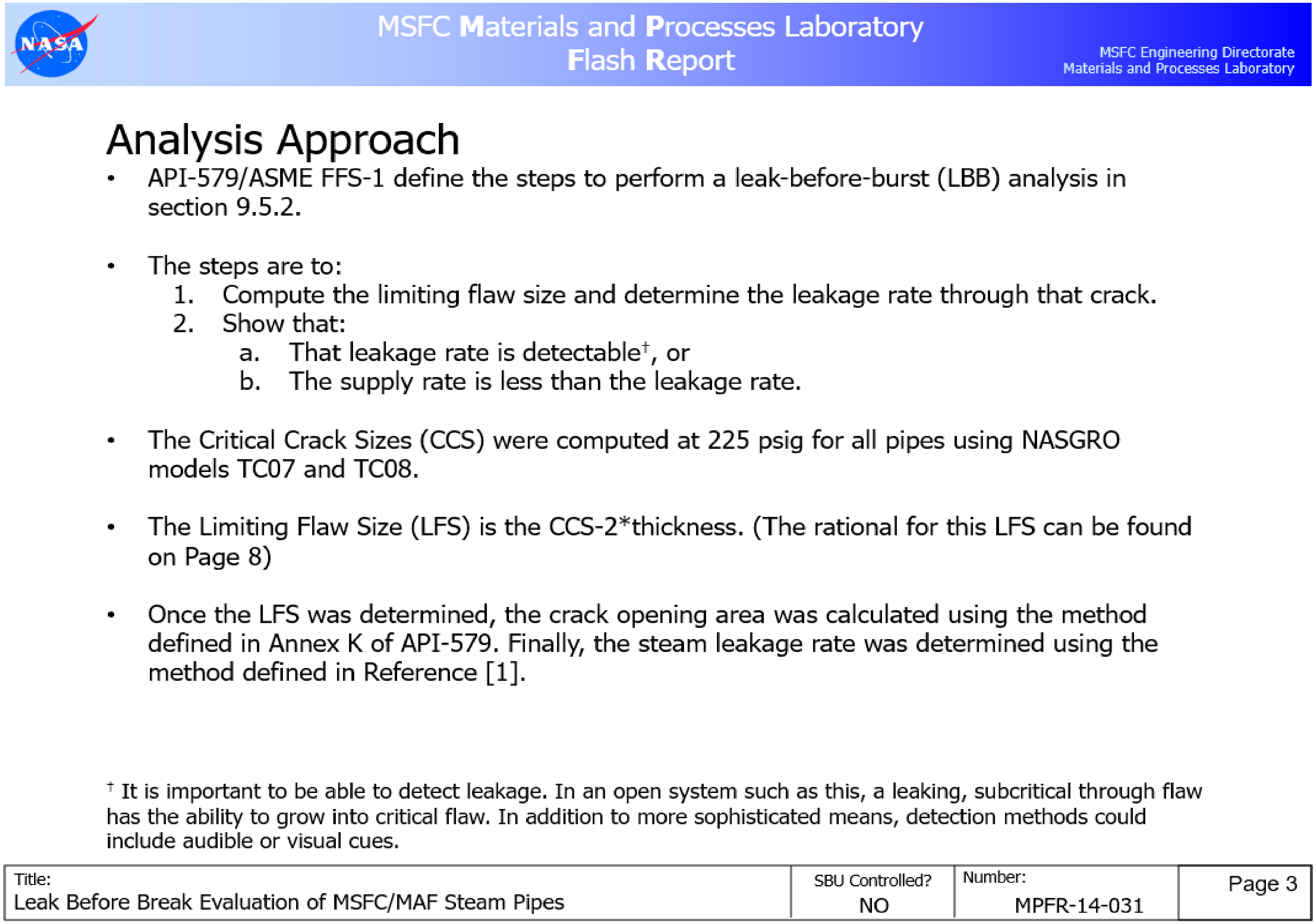
- The Institutional/Facility/Operational Audit of MSFC Pressure System Certification Program identified in IFO Audit Finding Number 077 that MSFC and MAF steam systems are not being certified by the Pressure Systems Manager (PSM) as required by NPD 8710.5D and NASA-STD-8719.17.

- The NPD and NASA-STD-8719.17A specifically include steam piping (above 15 psig not used for building heat) to be certified.

- The approach being pursued is to evaluate the risk to personnel in the event of a steam leak or rupture of "non-boiler external piping" (piping after first block valve downstream of the boiler). The MSFC and MAF steam systems (non-boiler external piping) are extensive and will take a considerable amount of resources to certify. The PSM is beginning to prepare a variance instead of certifying the non-boiler external piping.

- The typical steam headers and transmission lines (similar construction specifications)
  - MAF Piping Systems:
    - Up to 3/4" – Schedule 80 A106-B
    - 1" to 1 1/2" – Schedule 40 A106-B
    - 2" and greater – Schedule 40 A53-B
  - MSFC Piping Systems:
    - Up to 2" – Schedule 80 A106-B
    - 2 1/2" and larger – Schedule 40 A106-B

Title: Leak Before Break Evaluation of MSFC/MAF Steam Pipes	SBU Controlled? NO	Number: MPFR-14-031	Page 2



MSFC **M**aterials and **P**rocesses Laboratory
Flash **R**eport

MSFC Engineering Directorate
Materials and Processes Laboratory

Analysis Approach

- API-579/ASME FFS-1 define the steps to perform a leak-before-burst (LBB) analysis in section 9.5.2.

- The steps are to:
  1. Compute the limiting flaw size and determine the leakage rate through that crack.
  2. Show that:
     a. That leakage rate is detectable[†], or
     b. The supply rate is less than the leakage rate.

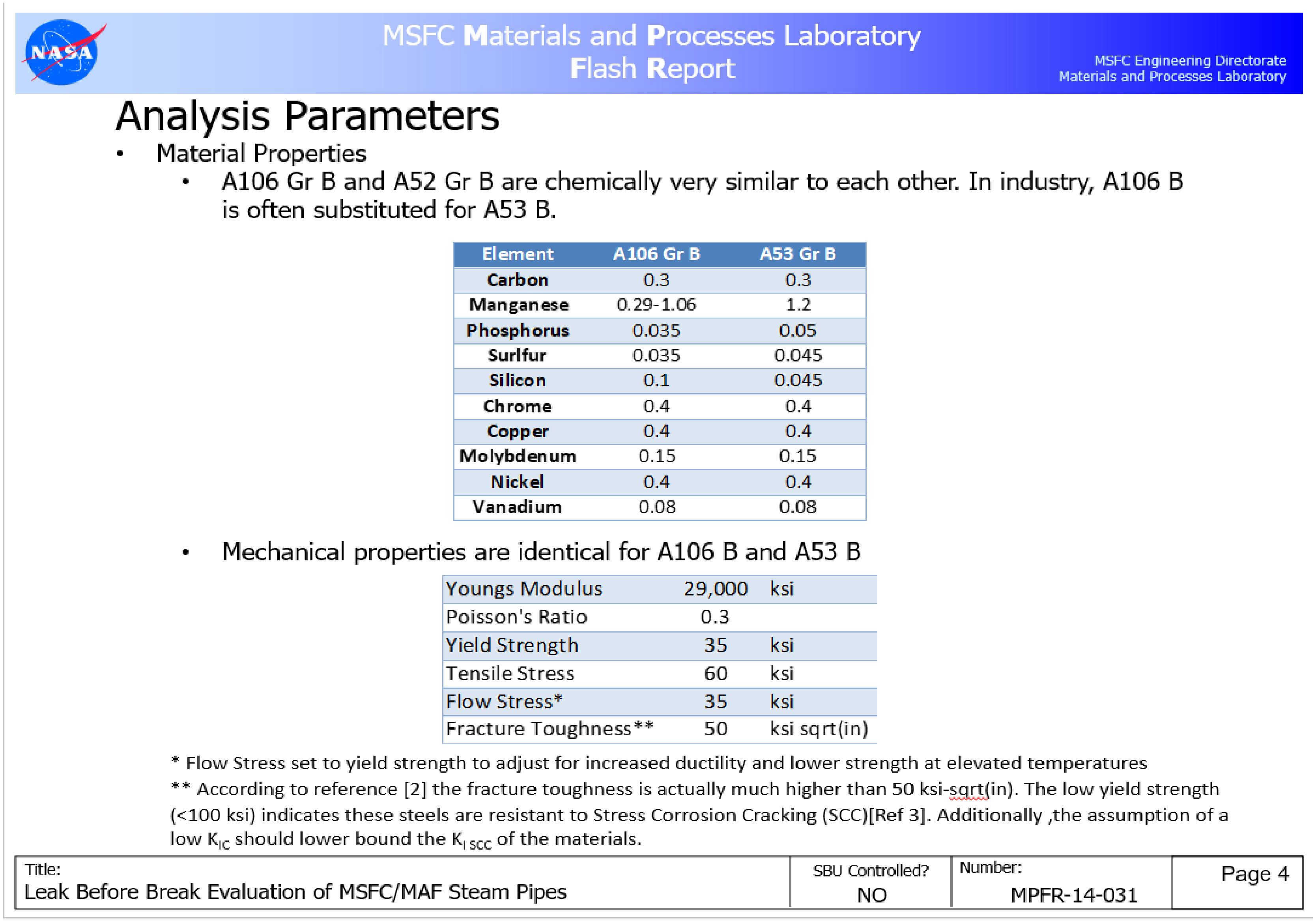
- The Critical Crack Sizes (CCS) were computed at 225 psig for all pipes using NASGRO models TC07 and TC08.

- The Limiting Flaw Size (LFS) is the CCS-2*thickness. (The rational for this LFS can be found on Page 8)

- Once the LFS was determined, the crack opening area was calculated using the method defined in Annex K of API-579. Finally, the steam leakage rate was determined using the method defined in Reference [1].

[†] It is important to be able to detect leakage. In an open system such as this, a leaking, subcritical through flaw has the ability to grow into critical flaw. In addition to more sophisticated means, detection methods could include audible or visual cues.

Title: Leak Before Break Evaluation of MSFC/MAF Steam Pipes	SBU Controlled? NO	Number: MPFR-14-031	Page 3



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Analysis Parameters

- Material Properties
  - A106 Gr B and A52 Gr B are chemically very similar to each other. In industry, A106 B is often substituted for A53 B.

Element	A106 Gr B	A53 Gr B
Carbon	0.3	0.3
Manganese	0.29-1.06	1.2
Phosphorus	0.035	0.05
Surlfur	0.035	0.045
Silicon	0.1	0.045
Chrome	0.4	0.4
Copper	0.4	0.4
Molybdenum	0.15	0.15
Nickel	0.4	0.4
Vanadium	0.08	0.08

  - Mechanical properties are identical for A106 B and A53 B

Youngs Modulus	29,000	ksi
Poisson's Ratio	0.3	
Yield Strength	35	ksi
Tensile Stress	60	ksi
Flow Stress*	35	ksi
Fracture Toughness**	50	ksi sqrt(in)

* Flow Stress set to yield strength to adjust for increased ductility and lower strength at elevated temperatures

** According to reference [2] the fracture toughness is actually much higher than 50 ksi-sqrt(in). The low yield strength (<100 ksi) indicates these steels are resistant to Stress Corrosion Cracking (SCC)[Ref 3]. Additionally ,the assumption of a low K_{IC} should lower bound the $K_{I\ SCC}$ of the materials.

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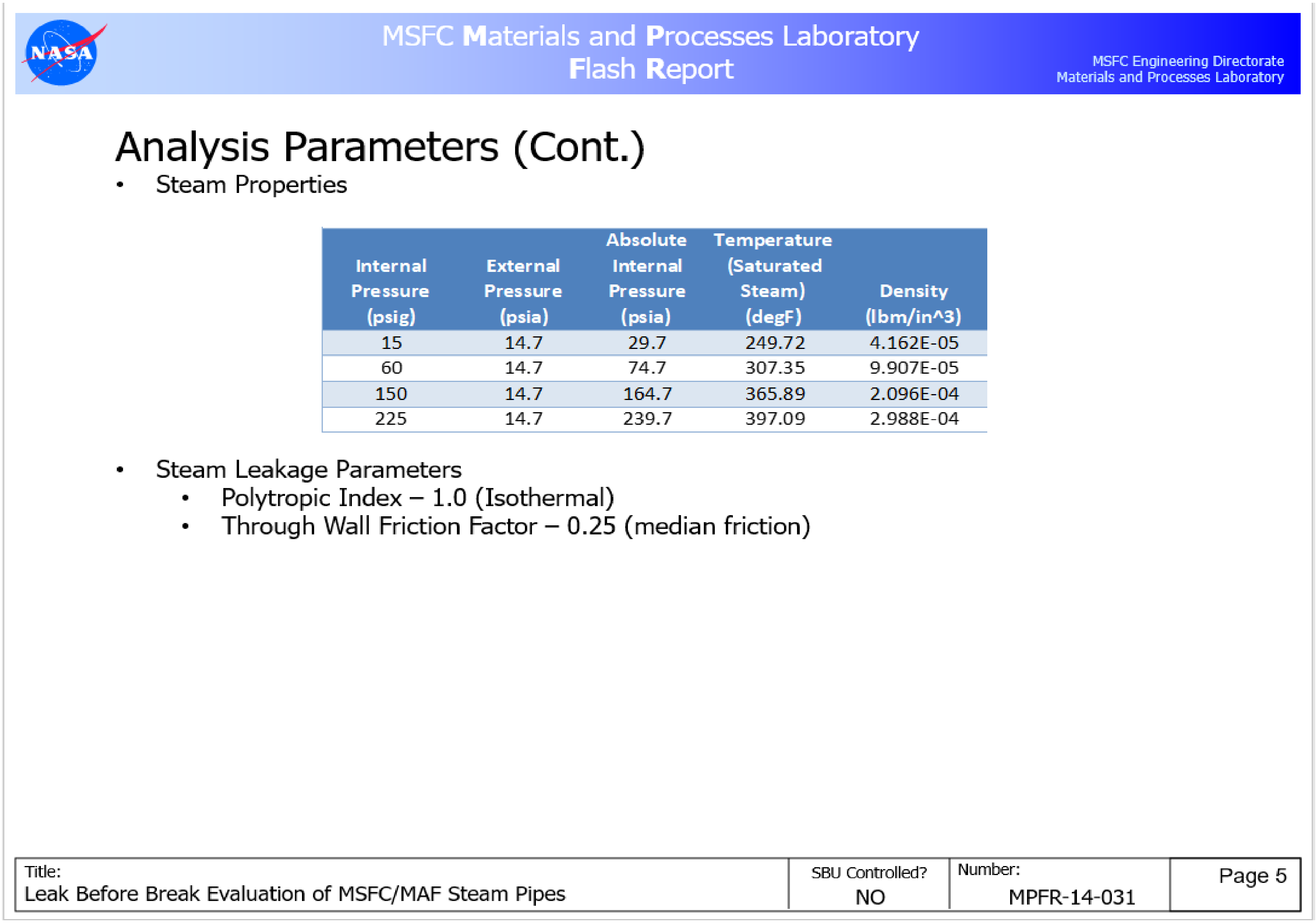

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Analysis Parameters (Cont.)

- Steam Properties

Internal Pressure (psig)	External Pressure (psia)	Absolute Internal Pressure (psia)	Temperature (Saturated Steam) (degF)	Density (lbm/in^3)
15	14.7	29.7	249.72	4.162E-05
60	14.7	74.7	307.35	9.907E-05
150	14.7	164.7	365.89	2.096E-04
225	14.7	239.7	397.09	2.988E-04

- Steam Leakage Parameters
  - Polytropic Index – 1.0 (Isothermal)
  - Through Wall Friction Factor – 0.25 (median friction)

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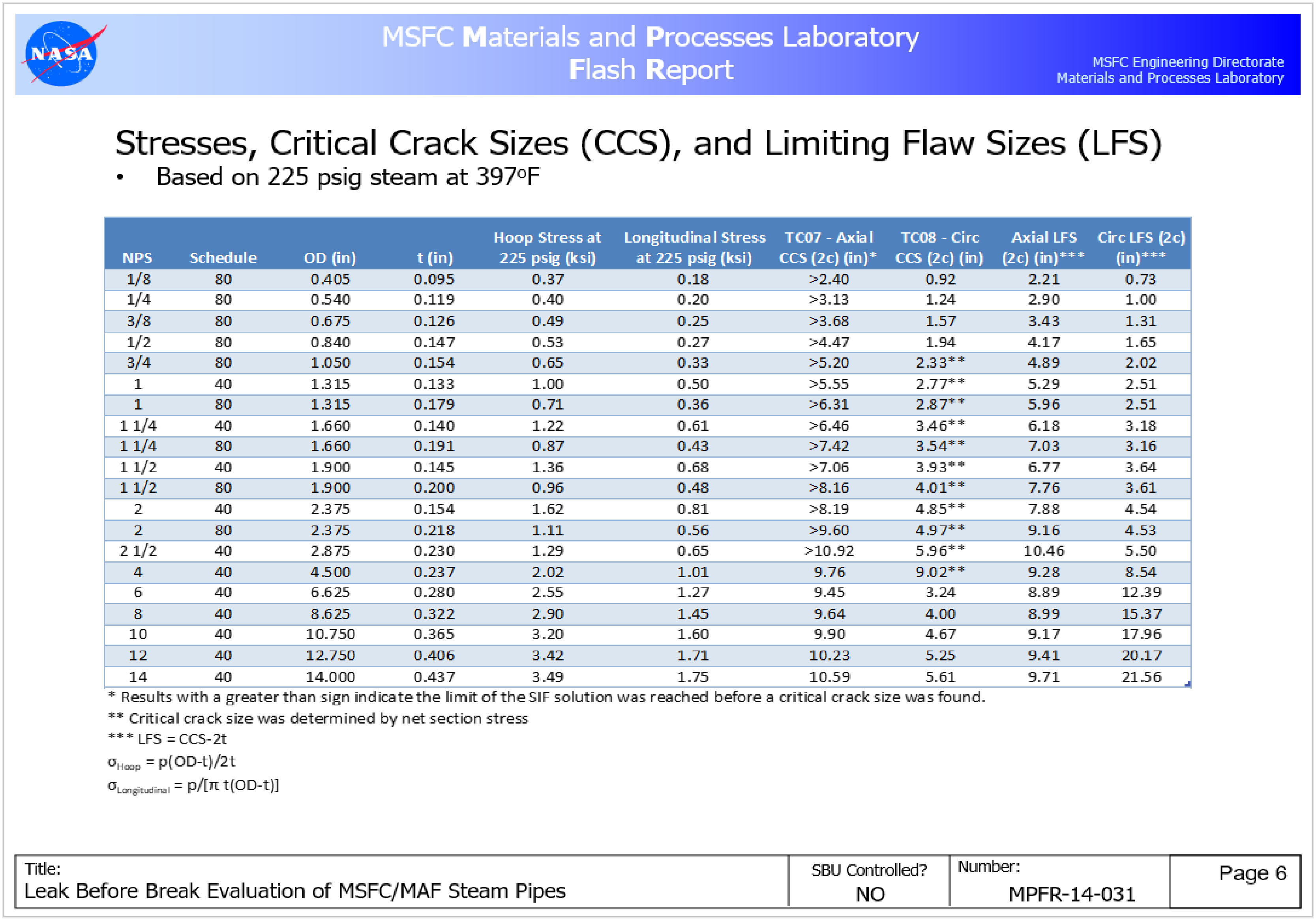

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Stresses, Critical Crack Sizes (CCS), and Limiting Flaw Sizes (LFS)

- Based on 225 psig steam at 397°F

NPS	Schedule	OD (in)	t (in)	Hoop Stress at 225 psig (ksi)	Longitudinal Stress at 225 psig (ksi)	TC07 - Axial CCS (2c) (in)*	TC08 - Circ CCS (2c) (in)	Axial LFS (2c) (in)***	Circ LFS (2c) (in)***
1/8	80	0.405	0.095	0.37	0.18	>2.40	0.92	2.21	0.73
1/4	80	0.540	0.119	0.40	0.20	>3.13	1.24	2.90	1.00
3/8	80	0.675	0.126	0.49	0.25	>3.68	1.57	3.43	1.31
1/2	80	0.840	0.147	0.53	0.27	>4.47	1.94	4.17	1.65
3/4	80	1.050	0.154	0.65	0.33	>5.20	2.33**	4.89	2.02
1	40	1.315	0.133	1.00	0.50	>5.55	2.77**	5.29	2.51
1	80	1.315	0.179	0.71	0.36	>6.31	2.87**	5.96	2.51
1 1/4	40	1.660	0.140	1.22	0.61	>6.46	3.46**	6.18	3.18
1 1/4	80	1.660	0.191	0.87	0.43	>7.42	3.54**	7.03	3.16
1 1/2	40	1.900	0.145	1.36	0.68	>7.06	3.93**	6.77	3.64
1 1/2	80	1.900	0.200	0.96	0.48	>8.16	4.01**	7.76	3.61
2	40	2.375	0.154	1.62	0.81	>8.19	4.85**	7.88	4.54
2	80	2.375	0.218	1.11	0.56	>9.60	4.97**	9.16	4.53
2 1/2	40	2.875	0.230	1.29	0.65	>10.92	5.96**	10.46	5.50
4	40	4.500	0.237	2.02	1.01	9.76	9.02**	9.28	8.54
6	40	6.625	0.280	2.55	1.27	9.45	3.24	8.89	12.39
8	40	8.625	0.322	2.90	1.45	9.64	4.00	8.99	15.37
10	40	10.750	0.365	3.20	1.60	9.90	4.67	9.17	17.96
12	40	12.750	0.406	3.42	1.71	10.23	5.25	9.41	20.17
14	40	14.000	0.437	3.49	1.75	10.59	5.61	9.71	21.56

* Results with a greater than sign indicate the limit of the SIF solution was reached before a critical crack size was found.

** Critical crack size was determined by net section stress

*** LFS = CCS-2t

$\sigma_{Hoop} = p(OD-t)/2t$

$\sigma_{Longitudinal} = p/[\pi\, t(OD-t)]$

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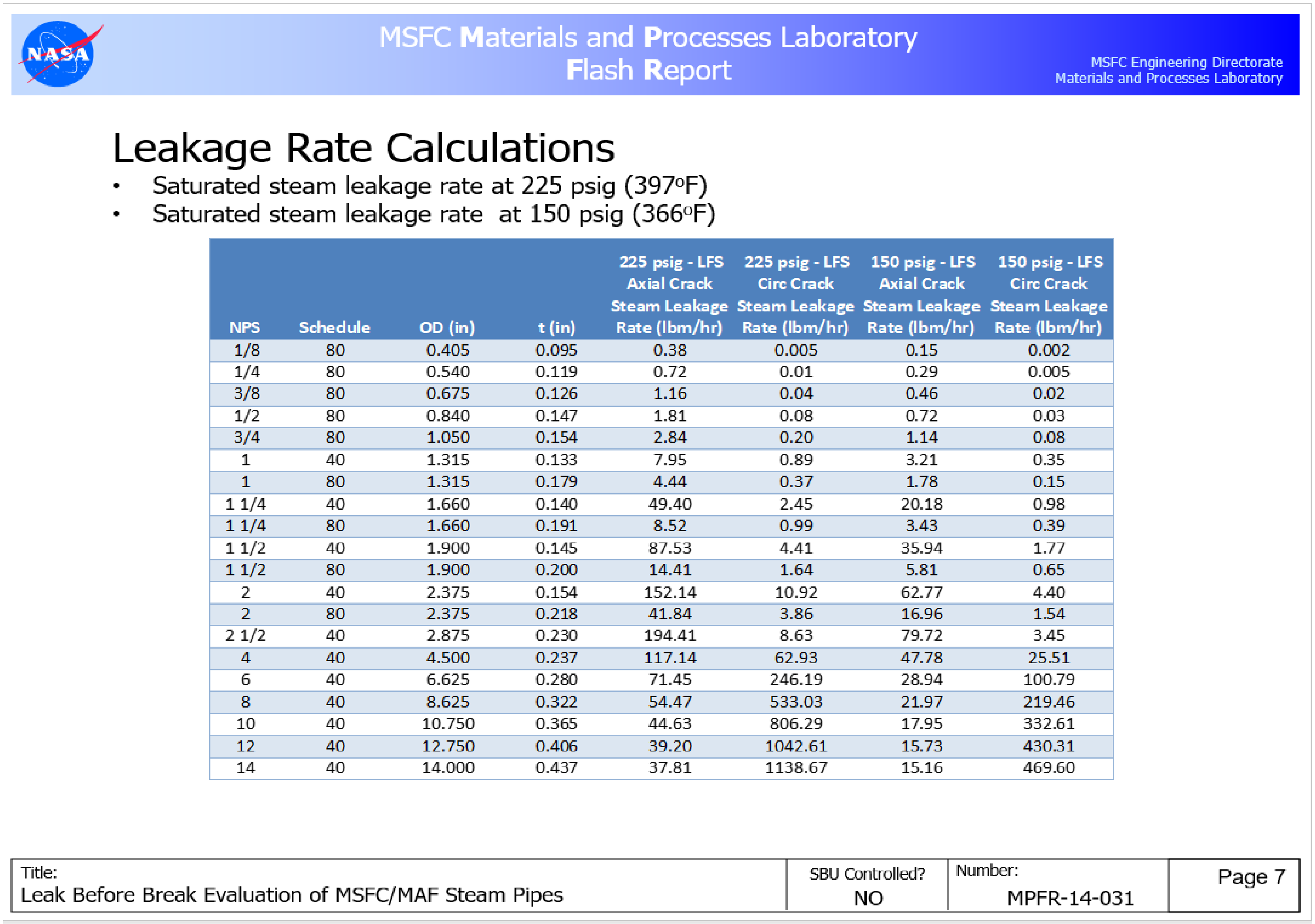

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Leakage Rate Calculations

- Saturated steam leakage rate at 225 psig (397°F)
- Saturated steam leakage rate at 150 psig (366°F)

NPS	Schedule	OD (in)	t (in)	225 psig - LFS Axial Crack Steam Leakage Rate (lbm/hr)	225 psig - LFS Circ Crack Steam Leakage Rate (lbm/hr)	150 psig - LFS Axial Crack Steam Leakage Rate (lbm/hr)	150 psig - LFS Circ Crack Steam Leakage Rate (lbm/hr)
1/8	80	0.405	0.095	0.38	0.005	0.15	0.002
1/4	80	0.540	0.119	0.72	0.01	0.29	0.005
3/8	80	0.675	0.126	1.16	0.04	0.46	0.02
1/2	80	0.840	0.147	1.81	0.08	0.72	0.03
3/4	80	1.050	0.154	2.84	0.20	1.14	0.08
1	40	1.315	0.133	7.95	0.89	3.21	0.35
1	80	1.315	0.179	4.44	0.37	1.78	0.15
1 1/4	40	1.660	0.140	49.40	2.45	20.18	0.98
1 1/4	80	1.660	0.191	8.52	0.99	3.43	0.39
1 1/2	40	1.900	0.145	87.53	4.41	35.94	1.77
1 1/2	80	1.900	0.200	14.41	1.64	5.81	0.65
2	40	2.375	0.154	152.14	10.92	62.77	4.40
2	80	2.375	0.218	41.84	3.86	16.96	1.54
2 1/2	40	2.875	0.230	194.41	8.63	79.72	3.45
4	40	4.500	0.237	117.14	62.93	47.78	25.51
6	40	6.625	0.280	71.45	246.19	28.94	100.79
8	40	8.625	0.322	54.47	533.03	21.97	219.46
10	40	10.750	0.365	44.63	806.29	17.95	332.61
12	40	12.750	0.406	39.20	1042.61	15.73	430.31
14	40	14.000	0.437	37.81	1138.67	15.16	469.60

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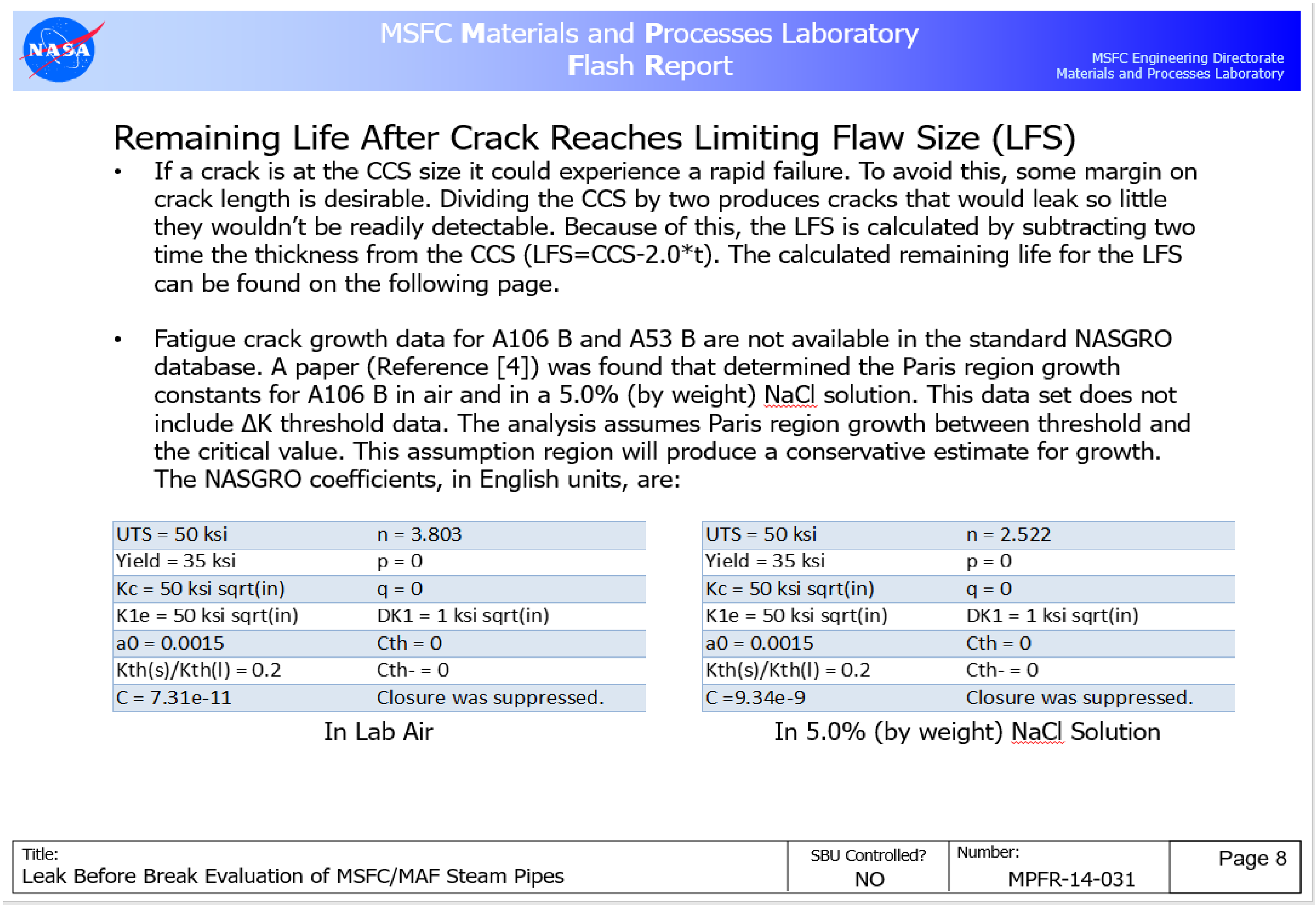

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Remaining Life After Crack Reaches Limiting Flaw Size (LFS)

- If a crack is at the CCS size it could experience a rapid failure. To avoid this, some margin on crack length is desirable. Dividing the CCS by two produces cracks that would leak so little they wouldn't be readily detectable. Because of this, the LFS is calculated by subtracting two time the thickness from the CCS (LFS=CCS-2.0*t). The calculated remaining life for the LFS can be found on the following page.

- Fatigue crack growth data for A106 B and A53 B are not available in the standard NASGRO database. A paper (Reference [4]) was found that determined the Paris region growth constants for A106 B in air and in a 5.0% (by weight) NaCl solution. This data set does not include ΔK threshold data. The analysis assumes Paris region growth between threshold and the critical value. This assumption region will produce a conservative estimate for growth. The NASGRO coefficients, in English units, are:

UTS = 50 ksi	n = 3.803
Yield = 35 ksi	p = 0
Kc = 50 ksi sqrt(in)	q = 0
K1e = 50 ksi sqrt(in)	DK1 = 1 ksi sqrt(in)
a0 = 0.0015	Cth = 0
Kth(s)/Kth(l) = 0.2	Cth- = 0
C = 7.31e-11	Closure was suppressed.

In Lab Air

UTS = 50 ksi	n = 2.522
Yield = 35 ksi	p = 0
Kc = 50 ksi sqrt(in)	q = 0
K1e = 50 ksi sqrt(in)	DK1 = 1 ksi sqrt(in)
a0 = 0.0015	Cth = 0
Kth(s)/Kth(l) = 0.2	Cth- = 0
C =9.34e-9	Closure was suppressed.

In 5.0% (by weight) NaCl Solution

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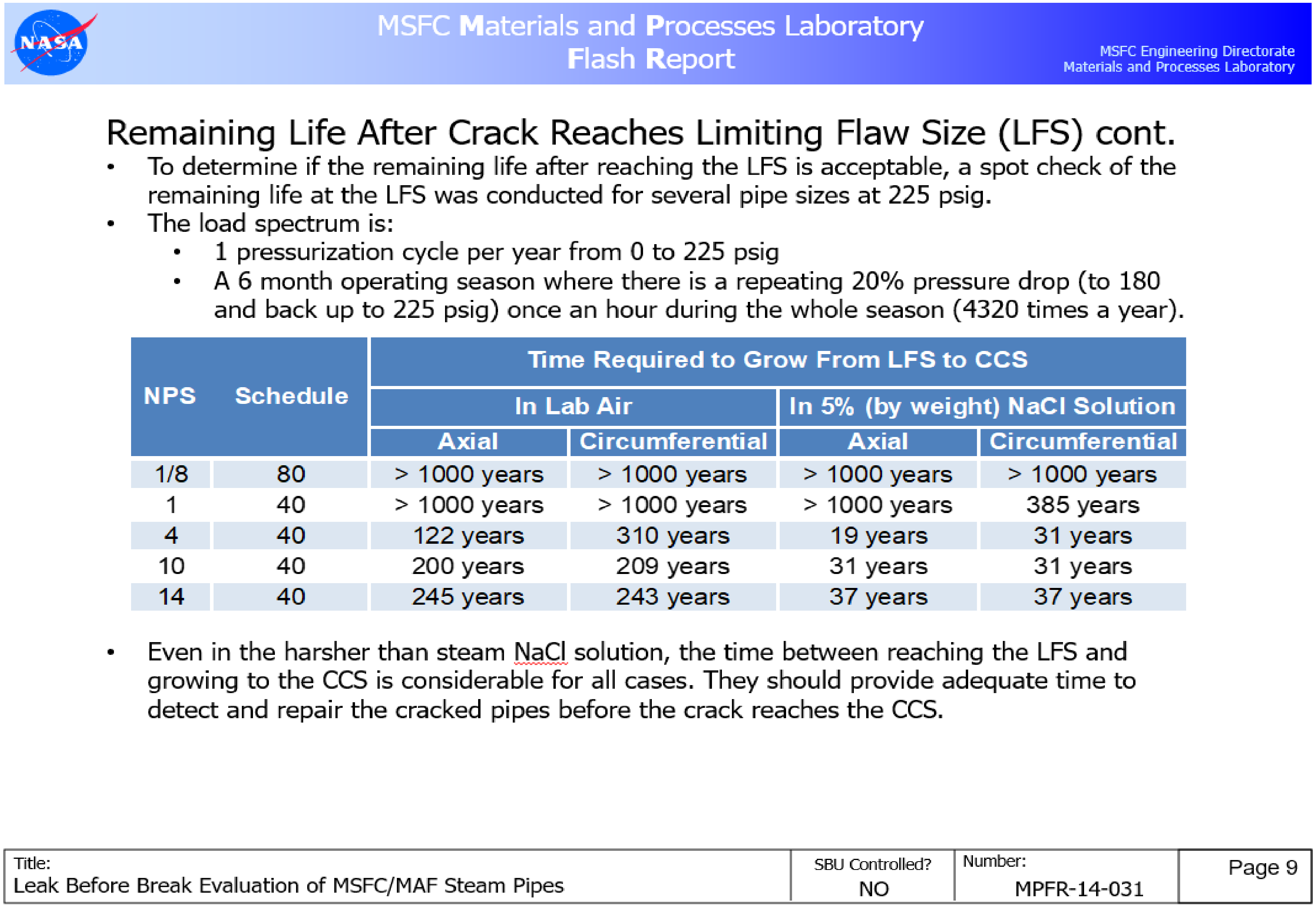

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Remaining Life After Crack Reaches Limiting Flaw Size (LFS) cont.

- To determine if the remaining life after reaching the LFS is acceptable, a spot check of the remaining life at the LFS was conducted for several pipe sizes at 225 psig.
- The load spectrum is:
  - 1 pressurization cycle per year from 0 to 225 psig
  - A 6 month operating season where there is a repeating 20% pressure drop (to 180 and back up to 225 psig) once an hour during the whole season (4320 times a year).

NPS	**Schedule**	**Time Required to Grow From LFS to CCS**			
		In Lab Air		**In 5% (by weight) NaCl Solution**	
		Axial	**Circumferential**	**Axial**	**Circumferential**
1/8	80	> 1000 years	> 1000 years	> 1000 years	> 1000 years
1	40	> 1000 years	> 1000 years	> 1000 years	385 years
4	40	122 years	310 years	19 years	31 years
10	40	200 years	209 years	31 years	31 years
14	40	245 years	243 years	37 years	37 years

- Even in the harsher than steam NaCl solution, the time between reaching the LFS and growing to the CCS is considerable for all cases. They should provide adequate time to detect and repair the cracked pipes before the crack reaches the CCS.

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