Fracture Control 101

A Primer for Spaceflight Project Managers

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Why?

- **Minimize** confusion about Fracture Control
- **Answer** frequently asked questions
- **Reduce** the perceived burden of the process
- **Knowing** is half the battle! With a little background, Fracture Control is a simple process for most projects

Outline

- **Introduction, Definition, Implementation, FAQs, common misconceptions**
  - **Adapted from "JSC 25863C, FRACTURE CONTROL PLAN FOR JSC SPACE-FLIGHT HARDWARE" (payloads and GFE)**
- **Fracture control for composites**
- **Fracture control for pressure vessels**
- **Examples of fracture control value**
- **Summary**

Introduction

- **Fracture Control addresses:**
  - In flight hardware under **cyclic loading**
  - The propagation of **pre-existing** flaws or crack-like defects
  - Fabrication, testing, transportation, handling, and service life

- **Fracture Control prevents:**
  - **Catastrophic structural failures** due to the existence or propagation of flaws

- **Fracture Control implementation is:**
  - **Mandatory** to ensure safety of the **manned** space systems
  - **Optional** to ensure **mission success** for **unmanned** systems at the discretion of the Program/Hardware Manager

Introduction

- **Fracture Control does not:**
  - Replace other applicable requirements for flights such as Vibration testing, Strength, Fatigue, M&P, etc.

- **Fracture Control does not:**
  - Compensate for poor design, analytical errors, misuse, or poor quality

- **There are no differences between:**
  - In-house, commercial of the shelf (COTS), contractor-provided hardware as to when Fracture Control is required

Fracture Control: What is it?

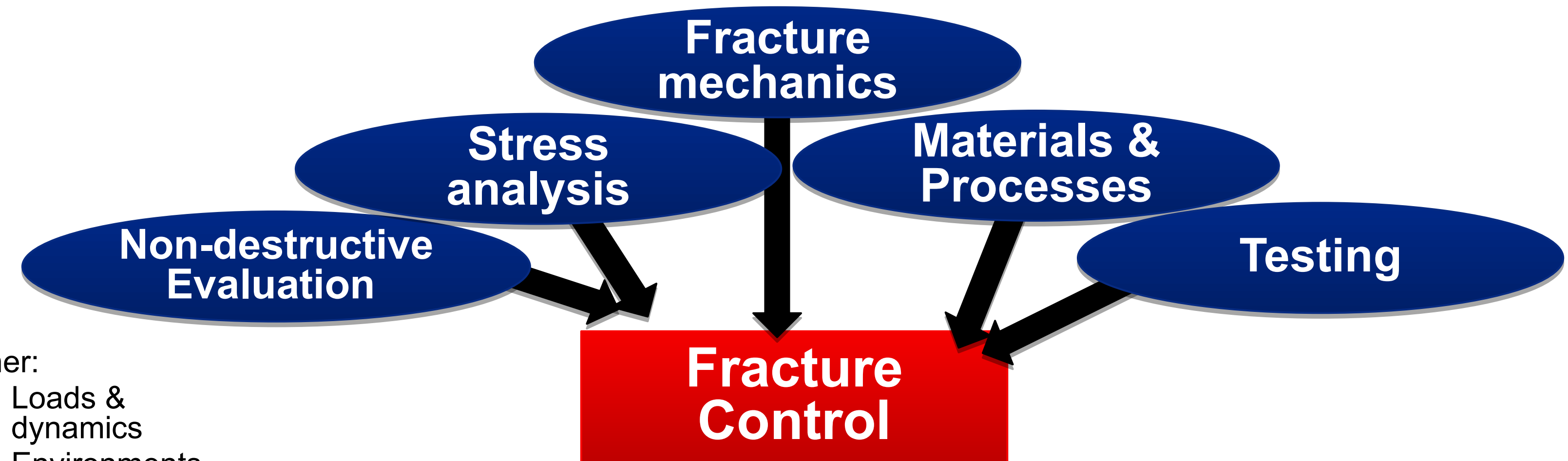
Static Strength

- **Design load x FS < Allowable**
- One load cycle
- Nominal material state (pristine)

Organization or project may invoke fracture control

Service Life

- Accounts for pre-existing and/or accumulated damage in load carrying capacity
- Defines strength with damage present
- Determines safe interval of operation



Other:

- Loads & dynamics
- Environments
- Operations

Board of experts from each technical discipline

(rare that one person is an expert in all categories)

Fracture-related MRBs need this multi-disciplinary perspective for proper disposition

Implementation

NASA-STD-5019…

1. Classify parts and identify those that are "fracture critical"

for fracture critical parts…

2. Perform Non-destructive evaluation (NDE) or proof test to screen for defects

3. Demonstrate damage tolerance by analysis or testing

Easier said than done!

- Most energy for fracture control implementation is spent on cases where steps 2 or 3 are impractical or impossible
- Need to determine an alternate but risk-neutral approach to implement

Hardware classification

- If failure of a part/component creates a catastrophic hazard, the part is fracture critical
  - NASA requires consideration of the worst case scenario
  - Do not need to consider "stacking failures" except for emergency systems
- If failure of a part/component is **clearly** not a catastrophic hazard no further Fracture Control assessment is required beyond documentation of the rationale
- If the answer is **"maybe"** or **"yes"**, hardware may be classified as non-fracture critical (NFC) if it can be shown to meet one of the following categories:
  - Exempt
  - Low released mass
  - Contained
  - Fail-safe
  - Low-risk part
  - Non-hazardous leak before burst (NHLBB) pressurized lines, fittings & components
  - Sealed container

Defect screening

- Non-destructive Evaluation
  - Why? Defects may grow during service life even if the defect is “ok” in the beginning
  - Techniques
    - Ultrasonic
    - Dye penetrant
    - X-ray/X-ray CT
    - Eddy current
    - Thermography
  - Allowable defect size
    - Size determined to survive 4 lives if present from the start
    - What if flaw size acceptability is unknown? FC org. will asses available information including stress analysis, hazards, M&P considerations, legacy hardware, test data, and use SME experience

- Proof test
  - Overload part by a designated factor
  - “Prove” part is good because it will never see that load again
  - “Exercise” potential leaks
  - Sometimes fracture analysis can show that a critical defect in a part will fail and be revealed during proof test
  - Post-proof, defects may be more detectable by NDE

Fatigue vs. Fracture Mechanics Life

Fatigue Life Assessment	Fracture Mechanics Life Assessment (Damage Tolerance)
Under jurisdiction of NASA Structural requirements	Under jurisdiction of NASA Fracture Control requirements
Loading is cyclic	Loading is cyclic
Material is pristine (Does not account for pre-existing and/or accumulated damage/flaws)	Material has an inherent/pre-existing flaw/crack. NDE inspection type(s) and sensitivity establish initial crack size used in the analysis
Crack initiates at geometric discontinuity or other stress risers (typically occurs at peak stress location	Pre-existing crack propagates in the part
~ 80% of total cycles is used in crack nucleation, ~ 20% is crack propagation	100% cycles are used in crack propagation
Less conservative than fracture mechanics life assessment	More Conservative than fatigue life assessment
Typical assessment tools: Miner’s Rule, NASGRO	Typical assessment tool: NASGRO

Fracture Control vs. Fracture Mechanics

Keep Perspective with Other Disciplines:

- Fracture mechanics is an engineering discipline/tool which may be applied to low-risk and fracture critical parts

- Please Remember that

  Fracture Control ≠ Fracture Mechanics

Design and certification methodology	*Technical discipline related to crack growth*

Who Makes a Catastrophic Hazard Call at JSC?

- Fracture Control of the hardware must implement the required rigor based on the 'hazard' criticality evaluation and agreement by the **Project and Safety organizations**

- The Fracture Control organization does not normally determine the criticality of a failure on given hardware, but is available to both the **Project and Safety organizations** for consultation in such determinations and does have the prerogative to question classifications

Assumptions and Guidelines for Fracture Control

- **All individual structural parts contain flaws, damage, or crack-like defects**

- **The use of NDE techniques does not negate the above assumption.** If no flaws are detected during inspection, it is assumed undetectable flaws exist and the probable upper bound flaw size established by the appropriate NDE technique may be used for analysis.

- All space flight hardware will be of good design, certified for the application, acceptance tested as required, and manufactured and assembled using high quality processes - *baseline assumption for fracture control*

- In the event there exists hardware that was previously flown without full Fracture Control, it should be assessed prior to subsequent re-flight using an appropriate Fracture Control approach

- Metallic parts are fabricated from materials that demonstrate high fracture toughness ($K_{Ic}/F_{ty} > 0.33 \sqrt{in}$)

Good Design Practices for Fracture Control

- **Design parts with redundancy** – Avoid single point failures in joints and structures
- **Design parts so they can be inspected** – Avoid fracture critical welds that are not inspectable from both sides
- **Minimize processes that tend to be crack prone** – Such as welding, custom forging, casting and additive manufacturing
- **Use well characterized standard aerospace materials** – With known strength, fatigue, and fracture properties

When to Invoke Fracture Control?

- EARLY!!!!!

- Especially if there are fracture critical parts and Fracture Control is a potential design driver (damage tolerance, proof test, NDE)

- Create Fracture Control plan in parallel or shortly after system requirements baseline
  - Fracture control plan drives NDE, test programs, and system design!
  - Flag unintended oversight gaps related to contract and allocated resources

Fracture Control Problem Areas

Last Minute Documentation of Fracture Control:

- **Defeats the purpose of Fracture Control**
- Any hardware changes required are very expensive (time and money)
- Inspections and Fracture Control certification may not have been completed and *may not be possible after coatings are applied and hardware is assembled*
- Drives up “overhead” cost for fracture control organization
- **Contractors/Vendors have little motivation to participate once they have delivered the hardware**

Responsibilities of the Project

- Ensure compliance with project/program Fracture Control
- **Generate Fracture Control Plan that is compliant with NASA-STD-5019**
- **Generate Fracture Control Summary Report (FCSR)**
- Include Responsible Fracture Control Authority in PDR/CDR loop
- Build in Fracture Control disposition to MRB process

Responsibilities of Fracture Control organization

- **Create, review, and approve Fracture Control Plan**
- Verify compliance of Fracture Control requirements
- Present and assess off-nominal cases in the Fracture Control Board (FCB)
- Implement efficient work practices
- **Create and review Fracture Control Summary Report (FCSR)**
- **Flag and elevate risks as needed**

Fracture Control Milestones

- ***Preliminary Design Review (PDR) or Phase I Safety Review***
  - Fracture Control Plan (compliant with NASA-STD-5019)
  - Preliminary part classification (drives test, analysis, and NDE activities)
  - Damage Threat Assessment (DTA) & Impact Damage Protection Plan (IDPP) for composites
  - Damage Control Plan (DCP) for Composite Overwrap Pressure Vessels (COPV)

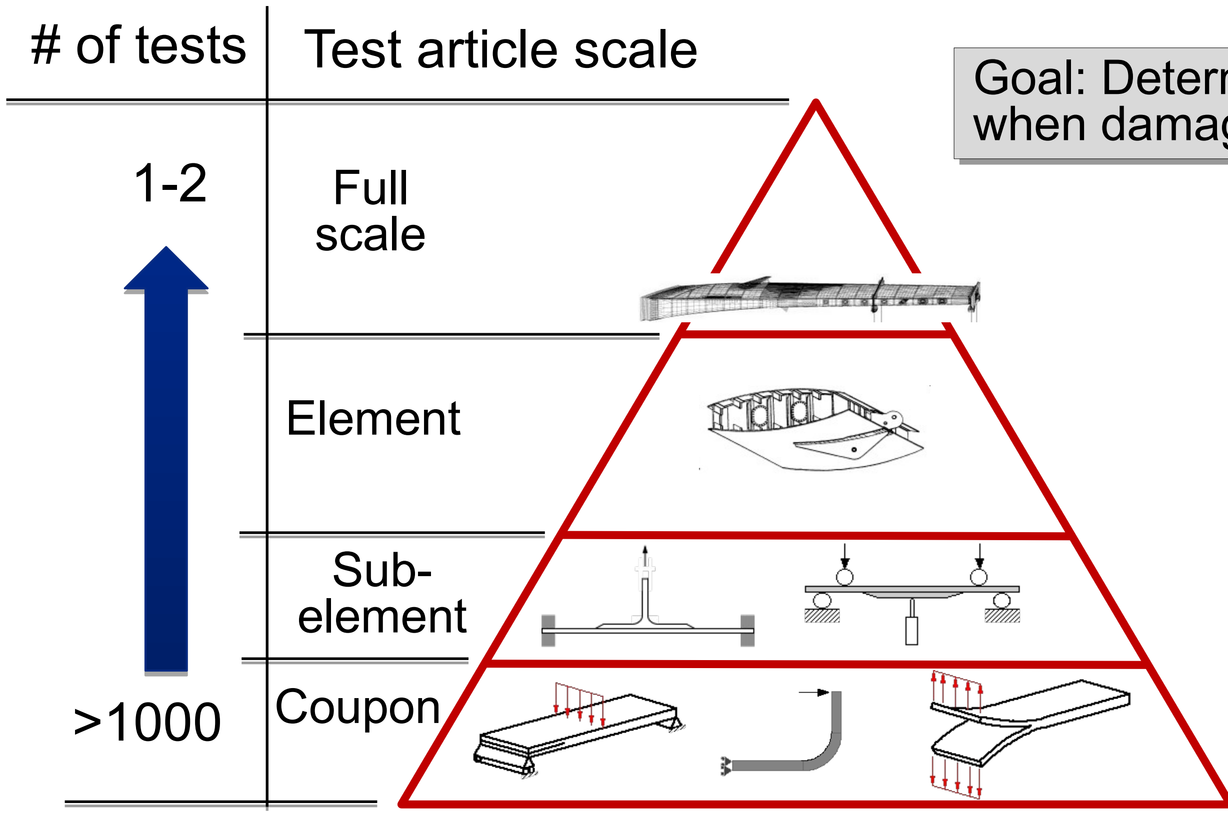
- ***Critical Design Review (CDR) or Phase II Safety Review***
  - Fracture Control status
  - Fracture control plan updates
  - Finalized classification of parts

- ***Certification or Phase III Safety Review***
  - Fracture Control Summary Report (FCSR)

Fracture Control: Composites

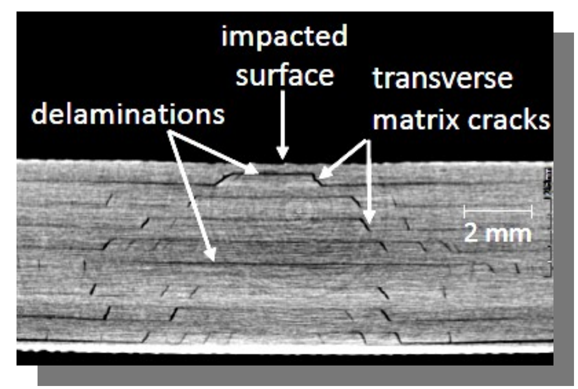
How is fracture control implemented for composite spacecraft & aircraft structures?

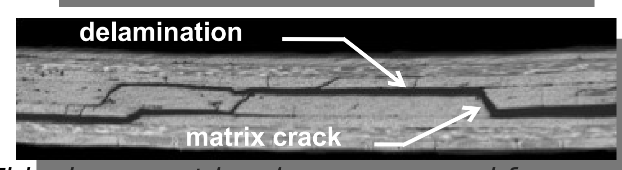
Building Block Approach



Goal: Determine reduced strength when damage is present

Impact damage examples





Composites vs. Metallic

Metallic	Composite
1. Classify parts and identify those that are fracture critical	1. Perform Damage Threat Assessment and create Impact Damage Protection Plan
for fracture critical parts… ↓	↓
2. Perform Non-destructive evaluation (NDE)	2. Classify parts and identify those that are fracture critical and NFC low risk
↓	↓
3. Demonstrate damage tolerance	3. Perform Non-destructive evaluation (NDE) on all parts
	↓
	4. Demonstrate damage tolerance on fracture critical and NFC low risk parts by tests
	↓
	5. Perform proof test on fracture critical and NFC low risk parts (required, but not by fracture control)

Pressure Vessels – Lesson Learned

- Pressure Vessels (PV)
  - Numerous PV failures & manufacturing quality issues occurred in Apollo, Viking, & Shuttle
  - The reaction was the genesis of fracture control and fracture mechanics methods for tank assessments
  - See "History and Qualification of All-Metal Pressure Vessels at NASA", Dr. Lorie Grimes-Ledesma, NESC Academy
- Introduction of fracture mechanics into the design improved safety and reliability
  - Margin and proof test alone were not enough to prevent failures due to cracking
  - Non-Destructive Inspection and process controls techniques are needed
- NASA pressure vessel lessons learned served as the genesis of fracture control at NASA and also the genesis of requirements used by USAF, DoE, and throughout industry
- "Exercise discretion when considering the elimination, because of cost savings, of any quality-control documentation requirements or testing of pressure vessels." - *Glenn Ecord, Manned Spacecraft Center, 1972.*

Summary

- Fracture control mitigates hazards related to catastrophic structural failures due to the existence or propagation of flaws
- It is multi-disciplinary and inherently requires collective expertise
- Pressure vessels have a history, requirements were created for a reason
- Composites are expensive, be prepared and plan for testing!
- Most energy for fracture control implementation in a project is spent on
  - Alternate risk-neutral approaches if requirement is impractical or impossible
  - Recovering from early design choices that did not consider fracture control requirements
  - Recovering from early planning activities that did not allocate project resources
- Implement fracture control EARLY
  - Last minute documentation of fracture control defeats the purpose of fracture control
  - Late implementation results in perpetual crisis/recovery mode for fracture control inflating costs unnecessarily and reducing hazard mitigation

Additional charts from original Shoeb presentation on JSC fracture control plan are included in backup and include topics such as:

- Part classification categories
- Tailored approaches for specific hardware types
- Fracture control summary report

Presentation Copy Request

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Backup

JSC 25863C,
FRACTURE CONTROL PLAN FOR JSC SPACE-FLIGHT HARDWARE

DISTRIBUTION IS UNLIMITED

See Page 2 of this Presentation for Export Control Compliance

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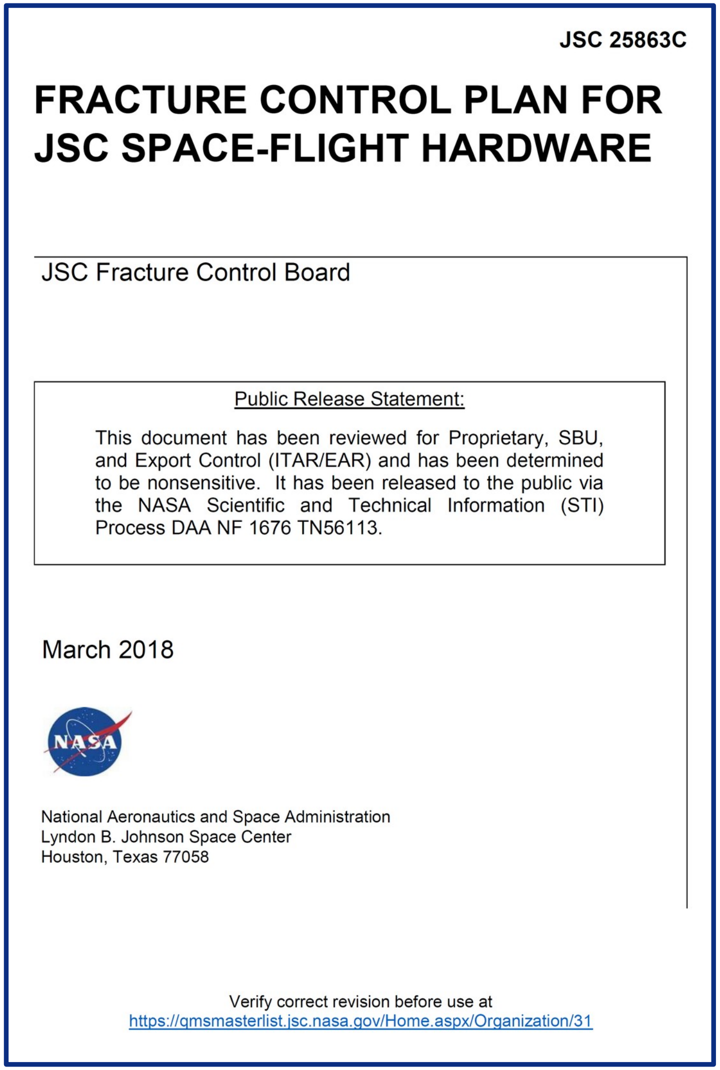


Non-Fracture Critical (NFC) Hardware

- If failure of a part/component is **clearly** not a catastrophic hazard no further Fracture Control assessment is required ***(Project, Safety Organization and FCM must agree with no-catastrophic hazard call)***

- If the answer is **"may be"** or **"yes"**, hardware may be classified as non-fracture critical if it can be shown to meet one of the following categories:
  - Exempt hardware
  - Low released mass
  - Contained
  - Fail-safe
  - Low-risk part:
    - Structural part (metallic and composite)
    - Fastener
  - Non-hazardous leak before burst (NHLBB) pressurized lines, fittings & components
  - Sealed container

NFC – Exempt Hardware

- **Exempt** hardware typically includes **non-structural** items such as:
  - Insulation blankets, switches, sensors
  - Enclosed electrical circuit components/boards, electrical connectors
  - Pins, tangs, lock wire, etc. used for fastener back-off prevention
  - Wire bundles, seals, etc.

NFC – Low Released Mass

- **Launch/Landing:**
  - Release of the component will not cause a catastrophic hazard
  - Mass of the released part must be less than 0.25 lbs *(Use of this option requires prior approval of FCM, SRP and Program/Vehicle Office)*

- **On-orbit (IVA):**
  - Release of the component will not cause a catastrophic hazard *(Project, Safety Organization and FCM must agree with no-catastrophic hazard call)*

- **On-orbit (EVA):**
  - Any released mass external to the International Space Station (ISS) and other manned spacecraft is considered catastrophic unless shown otherwise

NFC – Contained

- Structural failure of the part would not result in a catastrophic event
- The part confined in a container or housing, or otherwise positively restrained from free release
- Typical electronic boxes (radios, cameras, recorders, personal computers, and similar close-packed and enclosed hardware) can be regarded contained without further assessment

NFC – Fail-Safe (Metallic Materials)

- The structure can withstand redistributed loads with a ultimate factor of safety (FOS) of 1.0 on limit load after one failure
- Failure of the part would not significantly alter the dynamic response of the hardware
- Redundancy against catastrophic failure shall be re-verified between missions:
  - For a fail-safe structure that is re-flown and
  - For on-orbit structures subject to fatigue analysis of fail-safe condition
- Fasteners made of Titanium alloys require prior approval of the FCM
- All rivet applications shall meet fail-safe requirements

NFC – Fail-Safe (Composite Materials)

Additional requirements (in addition to metallic fail-safe from previous slide) for composite/bonded fail-safe structure:

- A minimum ultimate FOS of 1.15 on limit load is needed instead of 1.0
- The structural models and analytical methodology will be test-verified for the intact/nominal configuration
- All fail-safe composite/bonded structures shall be subjected to the Damage Threat Assessment (DTA) and Damage Control Plan (DCP)

NFC – Low-Risk Consideration

- **Limited to metallic structures using conventional manufacturing and process control (Additive manufactured metallic materials are excluded)**

- A classification developed for flight hardware that meets:
  - Large structural margin
  - Material processing requirements
  - Fatigue

- Intent to reduce numbers of fracture critical parts

- **Does not apply to:**
  - Pressure vessels
  - Habitable module
  - Pressurized lines, fittings, and components containing a hazardous fluid
  - High-energy rotating equipment

NFC – Low-Risk Metallic Part

- Ultimate FOS > 3.33 on un-concentrated tensile stresses
- Demonstrate $K_{Ic}/F_{ty} > 0.33\ \sqrt{in}$
- Inspect raw material using suitable NDE (such as ultrasound) for internal defects
- Aluminum alloy shall not be loaded in the short transverse (ST) direction if dimension is greater than 3″ to ensure good ductility in parts.
- Shall be Table I material per MSFC-STD-3029, Guidelines for the Selection of Metallic Materials for Stress Corrosion Cracking Resistance in Sodium Chloride Environments
  - Table II and Table III materials require Materials Usage Agreement (MUA)
- Perform NDE for cracks welding, forging, casting, quenching heat treatments and additive manufacturing that is sensitive to cracking

NFC – Low-Risk Metallic Part (contd.)

- Meet $S_{max} < F_{tu}/[(4(I\text{-}0.5\ R)]$
  - Where S_{max} is the local concentrated stress, and R is the ratio of minimum stress to maximum stress ($\sigma_{min}/\sigma_{max}$) in a fatigue cycle

or,

- A conventional fatigue analysis (e.g., Miner's rule) using:
  - FOS of 1.5 on alternating stress
  - Scatter factor of 4 on service life

or,

- A fracture mechanics durability analysis using NASGRO:
  - Initial crack of 0.005″
  - FOS of 1.5 on alternating stress
  - Scatter factor of 4 on service life

or,

- A fracture mechanics durability analysis using NASGRO:
  - Initial crack of 0.025″
  - FOS of 1.0 on alternating stress
  - Scatter factor of 4 on service life

NFC – Low-Risk Fastener

- **Does not need to meet 30% limit load to ultimate tensile strength ratio**
- **Fastener will be in a local pattern of two or more similar fasteners**
- Demonstrate $K_{Ic}/F_{ty} > 0.33 \sqrt{in}$
- Inspect raw material using suitable NDE (such as ultrasound) for internal defects
- Shall be Table I material per MSFC-STD-3029
  - Table II and Table III materials require MUA
- Shall meet NASA-STD-6008, NASA Fastener Procurement, Receiving Inspection, and Storage Practices for Spaceflight Hardware or equivalent
- Fasteners shall have rolled threads. Cut threads will require prior approval of FCM
- Ti-6Al-4V, cp-Ti, and other titanium alloys require prior approval of the FCM
- Shall use **fatigue rated fasteners** or **meet fatigue analysis** including torque/preload with no joint gapping

NFC – NHLBB Consideration

- Non-Hazardous Leak-Before-Burst (NHLBB)
  - Leakage resulting in a non-catastrophic hazard
  - Demonstrate LBB failure mode
    (stable crack for 2c = 10t under uniform tension for metallic material)

- The components shall not have coatings, barriers, or other means that prevent or inhibit leakage through a flaw

- The leak is automatically detected and further pressure cycling is prevented, or there is no re-pressurization

- NHLBB categorization does not apply to:
  - Habitable structures and enclosures
  - Hazardous Fluid Container (HFC)
  - Pressurized lines, fittings and components containing a hazardous fluids

NFC – Sealed Container

- Leakage resulting in a non-catastrophic hazard

- If container is pressurized to 22 psia or less and E (Energy) < 14,240 ft-lb:
  - Demonstrate leak-before-burst (LBB) design
  - No further assessment is required

- If container is pressurized in between 22 psia and 100 psia, E < 14,240 ft-lb:
  - Demonstrate LBB design
  - Ultimate FOS of 2.5 on MDP or greater, or proof test to a minimum of 1.5 X MDP

- Containers with pressure exceeding 100 psia or contained energy exceeding 14,240 ft-lb shall be treated as pressure vessel per Section 6.2.1 of JSC 25863C

- System supports and brackets meet Fracture Control

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

NFC – Lines, Fittings & Components

- Loss of pressure in the system shall not result in a catastrophic event
- Demonstrate leak-before-burst (LBB) design
- Proof and leak test shall be performed in accordance with structural and pressure system requirements
- Lines, fitting and components that are built to commercial standard and containing non-hazardous fluids, having less than 100 psia internal pressure and less than 1000 ft-lb energy may be acceptable without further assessment with the prior approval of FCM
- System supports and brackets are evaluated per Fracture Control and may or may not require NDE depending on their individual Fracture Control classification

NFC – Shatterable Components and Structures

- Shatterable components showing positive protection to prevent fragments greater than 50 μm from entering the cabin environment can be treated as non-fracture critical (contained) per Section 4.8.5 of NASA-STD-5018, Strength Design and Verification Criteria for Glass, Ceramics, and Windows in Human Space-Flight Applications

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

NFC – Bellows

- Contain non-hazardous fluid and loss of pressurization will not be a catastrophic hazard

- Fracture Control implementation for non-fracture critical bellows shall require coordination with the FCM

NFC – Low Energy Rotating Machinery

- Does not present a catastrophic hazard
- Kinetic energy is less than 14,240 ft-lb
- Shrouded or enclosed fans [less than 8000 rpm and 8″ diameter], electric motors, shafts, gearboxes, recorders, conventional pumps, and similar devices is acceptable without further assessment
- The mounts and brackets for rotating machinery will be addressed as standard structure for Fracture Control
- Guidelines for containment analysis of rotating equipment are given in Appendix B of NASA-HDBK-5010, Fracture Control Implementation Handbook for Payloads, Experiments, and Similar Hardware

NFC – Batteries

- NFC Batteries shall meet **one** of the following:
  - Sealed container requirements (Section 6.1.6 of JSC 25863C)
  - Pressurized Lines, Fittings, and Components requirements (Section 6.1.7 of JSC 25863C)
  - **JSC 20793, Crewed Space Vehicle Battery Safety Requirements**

NFC – Tools/Mechanisms

- A single-point failure shall not result in catastrophic hazard

- Shall meet the requirements for low-released mass (Section 6.1.1 of JSC 25863C), or are contained (Section 6.1.2 of JSC 25863C) during all phases of the mission

- Fracture Control requirements on tool/mechanism are applied independently of any mechanism fault tolerance requirements per ES4-07-031, Fracture Control of Mechanisms (also documented in Appendix D of JSC 25863C)

NFC – Composite Part

- Shall meet **one** of the followings:
  - Low released mass (Section 6.1.1 of JSC 25863C)
  - Contained (Section 6.1.2 of JSC 25863C)
  - Fail-safe (Section 6.1.3 of JSC 25863C)
  - Strain of the part will be below the no-growth threshold strain

- The part will be assessed for Damage Threat Assessment (DTA) and Damage Control Plan (DCP)

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

Fracture Critical Parts

- **Fracture critical parts includes:**
  - Habitable Module
  - Pressure Vessel
  - Hazardous Fluid Container
  - Pressurized lines, fittings and components containing a hazardous fluids
  - High-energy rotating equipment
  - Any remaining structural hardware that does not fit the categories of non-fracture critical in **Slide # 8** of this presentation

- Those parts/components identified as **fracture critical** must be shown to be **damage tolerant by analysis or test** with a scatter factor of 4 on service life

- **NASGRO** is an approved computer code for damage tolerant analysis of NASA hardware

Input for NASGRO Safe-life Analysis

- Initial flaw screened by NDE or proof test
- Crack case models
- Materials properties
- Stress analysis
- Load spectrum

- Note: **Safe-life** and **damage tolerance** are synonymous in NASA's space flight terminology. This is NOT true in general.

Fracture Critical Note on Engineering Drawings

- The engineering drawings must identify whether a part is fracture critical or not
- For fracture critical parts, the type of NDE or proof test requirements must be called out on the drawing
- FCM is available for consultation with any question on fracture critical note on the drawing

Pressure Systems

- **Pressure Systems** Include:
  - Pressure Vessels (fracture critical by definition)
  - Lines, Fittings & Components (that contain a fluid whose release would be a catastrophic hazard, shall be fracture critical)

- LBB is the **preferred design practice** for pressure system (although LBB may not be adequate in meeting Fracture Control requirements in cases)

Pressure Systems (contd.)

- All welds in fracture critical pressure system shall have post-proof surface and volumetric NDE to screen for cracks
- If post-proof NDE is not feasible, a Process Control program may be used for welds in pressure system with the approval of FCM. Section 5.2.1.4 of NASA-HDBK-5010 shows an example of Process Control
- Venting hazardous fluids through relief devices is not allowed unless vented overboard
- A pressurization history log shall be maintained for all pressure vessels

Pressure Vessel Definition

- Pressure vessel is defined as a container designed primarily for pressurized storage of gases or liquids and meet one of the following:
  - Contains stored energy of 14,240 ft-lb or greater based on adiabatic expansion of a perfect gas; or
  - Stores a gas that will experience an maximum design pressure (MDP) greater than 100 psia
  - Contains a gas or liquid in excess of 22 psia that will create a catastrophic hazard if released

[The pressure ceiling in the last item of this FCP is slightly higher from the definition in AIAA S-080/81 to make it consistent with Hazardous Fluid Container (HFC) section]

Maximum Design Pressure (MDP) Definition

- MDP is the highest pressure occurring from maximum relief pressure, maximum regulator pressure, maximum temperature or transient pressure excursions and be **two fault tolerant**

- Safety factors, proof factors and leak check factors are applied to MDP

- Safety factors and proof factors are provided per applicable safety and structural requirements documents

Metallic Pressure Vessels

- Metallic pressure vessels shall comply with the latest revision of ANSI/AIAA Standard S-080 with the following tailoring:
  - MDP shall be substituted for all references to Maximum Expected Operating Pressure (MEOP)

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

Composite Overwrapped Pressure Vessels (COPVs)

- COPVs shall comply with the latest revision of ANSI/AIAA S-081 with the following tailoring:
  - MDP shall be substituted for all references to MEOP
  - LBB of the metallic liner may not be required when sufficient damage tolerance (safe-life) is demonstrated with prior approval of the FCM
  - The peak strain in the composite at MDP shall be less than or equal to 50% of the design ultimate composite strength or prior approval of FCM is required
  - Mounting of the pressure vessel via clamps or straps must be approved by the NASA pressure vessel technical discipline authority
  - A DCP shall be submitted to FCM. A DCP template is shown in JSC 66901

ANSI/AIAA S-081B-2018, Space Systems Composite Overwrapped Pressure Vessels (COPVs)

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

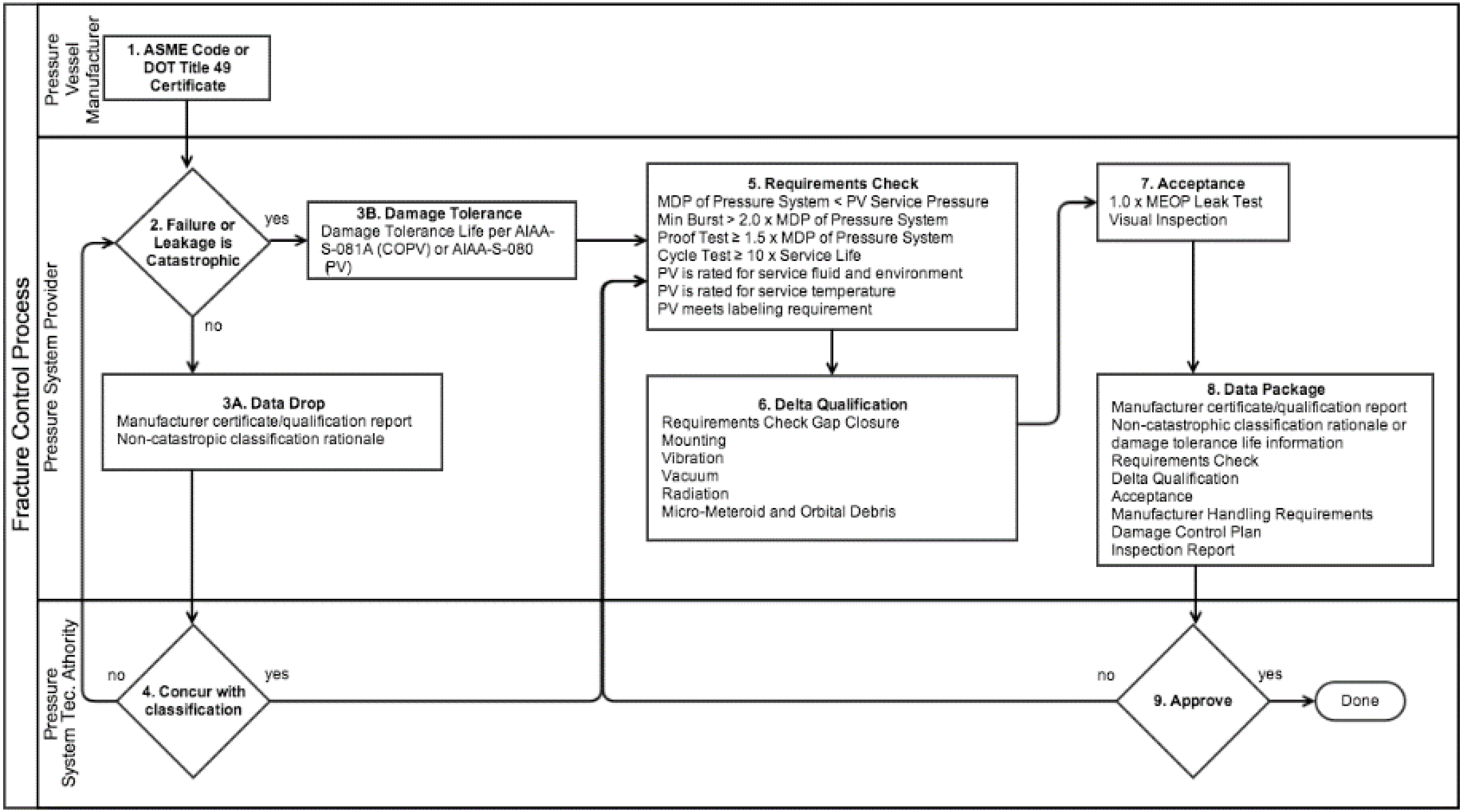
GFE and Payloads only

ASME Code and DOT Title 49 Pressure Vessels

- Provide the manufacturer’s certificate/qualification/life cycle test report and non-catastrophic classification rationale
- Use of American Society for Mechanical Engineers (ASME) Code or Department of Transportation (DOT) Pressure Vessels where leakage is catastrophic requires prior approval of the RFCM
- MDP is maintained at or below the rated pressure
- The pressure vessel will be rated for the internal and external fluids and for temperature environments by the hardware developer or manufacturer DOT, ASME recertification shall be kept
- Hardware manufacturer shall retain ASME or DOT certification for the life of the pressure vessel.
- A DCP is be generated for the COPV per JSC 66901 template
- Mounting of the pressure vessel via clamps or straps must be approved by the NASA pressure vessel technical discipline authority

GFE and Payloads only

ASME Code and DOT Title 49 Pressure Vessels



GFE and Payloads only

ASME Code and DOT Title 49 Pressure Vessels

- Provide the following information for metallic PV and/or COPV:

Parameter	PV/COPV
Pressure Vessel Specification	
Manufacturer Name	
Manufacturer Part Number	
Dimensions, inches	
Liner Material	
Fiber Material	
Fiber Resin	
Qualification Temperature Range, °F	
Operating Temperature Range, °F	
Operating Fluid	
Fill Pressure, psig	
MDP (including temp. excursion), psig	
Manufacturer Rated Pressure, psig	
Proof Pressure, psig	
Design FOS at Manufacturer Rated Pressure	
Actual Burst Pressure, psig	
Service Life, cycles or years	
Reinspection Interval, years	
Current PV/COPV Cert Expiration Date	

- *Provide a copy of the PV/COPV drawing from the manufacturer.*

Fracture Critical Bellows and Flexhoses

- Release of the fluid would result in catastrophic hazard
- Fracture Control implementation for fracture critical bellows shall require coordination with the fracture control organization
- A DCP is recommended for fracture critical Bellows and Flexhoses
- JSC "Additional Measure of Robustness" (AMOR) provides additional guidance

Fracture Critical Pressurized Lines, Fittings, and Components

- These items shall be considered fracture critical if they contain hazardous fluids or if loss of pressure would result in a catastrophic hazard
- They shall be proof tested to a minimum of 1.5 x MDP and leak tested at a minimum pressure of 1.0 x MDP to demonstrate no leakage above the required threshold set forth by the Project
- If tested to bullet above, damage tolerance analysis is not required for fracture critical pressurized lines, fittings, and components
- Volumetric and surface inspection of fracture critical fusion joints shall be made after proof testing
- Custom-made lines, fittings, and components require prior approval of FCM

GFE and Payloads only

Hazardous Fluid Container (HFC)

- HFC shall meet one of the following criteria:
  - The HFC is fracture critical and shall be damage tolerance against rupture and leakage
  - Volumetric and surface inspection of fracture critical fusion joints shall be made after proof testing
  - Containers shall meet pressure vessels requirements per Section 6.2.1 of JSC 25863C when internal pressure is greater than 22 psia
  - Integrity against leaks shall be verified by test at 1.0 X MDP with no leakage above the required threshold set forth by the Project

    or,
  - **Levels of Containment (LOC) may be used to mitigate the leakage. The individual levels of containment in the LOC approach are not "fracture critical" and Fracture Control measures need not be applied when the LOC approach is used as documented in ES4-02-050, Levels of Containment Guidelines for Payloads Utilizing Hazardous/Toxic Materials (Appendix C)**

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

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

Habitable Module

- **Habitable module may require hardware specific Fracture Control Plan (FCP) by PDR/Phase I to meet Fracture Control requirement**
- All habitable modules designed to support human life are classified as fracture critical
- The pressure shell/enclosure shall be shown to be a damage tolerance design
- The pressure shell/enclosure shall require pre-proof and post-proof NDE to screen for cracks
- Integrity against leaks shall be verified by test at 1.0 X MDP to demonstrate no leakage above the required threshold set forth by the Project

High-Energy Rotating Machinery

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

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

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

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

Fracture Critical Fasteners

- Fasteners that do not meet fail-safe or low-risk criteria will be treated as fracture critical and shall meet the following criteria:
  - The raw material shall be inspected using suitable NDE (such as ultrasound) for internal defects. Otherwise, prior approval of the FCM is required
  - Fasteners shall be fabricated from Table I material per MSFC-STD-3029; otherwise MUA is needed
  - Fasteners are fabricated, procured, and inspected in accordance with NASA-STD-6008 or an equivalent specification
  - Fasteners less than 3/16 in (0.48 cm) diameter will generally be avoided or require prior FCM approval
  - Shall meet $K_{Ic}/F_{ty} > 0.33 \sqrt{in}$
  - Ti-6Al-4V, cp-Ti, and other titanium alloys require prior approval of FCM

Fracture Critical Fasteners (Contd.)

- Fasteners shall have rolled threads. Cut threads will require prior approval of FCM
- Fasteners will meet appropriate preloads with no joint gapping
- Fasteners will be NDE inspected by the eddy current method. Alternate NDE methods will require prior approval of the FCM
- Damage tolerance analysis will assume a flaw size in the thread root, shank, and head/shank transition consistent with NDE sensitivity or proof test level and a service life factor of 4 with SF of 1.0 on load
- Inserts used in conjunction with fracture critical fasteners will be proof load tested to a minimum factor of 1.2 x limit load after installation
- After inspection or testing, fracture critical fasteners will be stored and controlled to keep them isolated from other fasteners
- Custom-made fasteners require prior approval of FCM

Fracture Critical Shatterable Components and Structures

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

Fracture Critical Tools/Mechanisms

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

- Fracture critical springs require prior approval of FCM

Fracture Critical Batteries

- Batteries not meeting the criteria of Section 6.1.12 of JSC 25863C **(shown in Slide # 49)** shall be classified as fracture critical

- Fracture critical batteries shall meet the requirements of pressure vessel (Section 6.2.1 of JSC 25863C)

Single-Event or Expendable Fracture Critical Components

- Single-event fracture critical components (such as pyrotechnic components) or expendable fracture critical components shall meet the followings:
  - The hardware is metallic
  - The component is not subject to any other significant fatigue loading beyond acceptance and/or normal proto-flight testing (if any) and transportation
  - The single-event loading involves a single-cycle or multiple-cycles with rapidly decaying subsequent cycles
  - It possesses a margin of 1.4 on fracture toughness

- These parts are acceptable without the need of damage tolerance assessment

Flaw Screening for Fracture Critical Parts

- **NDE:**
  - NDE screening per NASA-STD-5009 (90% probability and 95% confidence interval)
- **Proof Testing:**
  - FCM prior approval shall be required for flaw screening by proof testing
- **Process Control**
  - FCM prior approval shall be required for flaw screening by process control

Methodology for Assessing Fracture Critical Metallic Hardware

- **Damage Tolerance Analysis:**
  - The latest version of NASGRO is an approved analysis tool
  - Other computer programs or analytical tool shall require prior approval of FCM

- **Damage Tolerance Testing**
  - Testing program shall require prior approval of the FCM

- **Fleet Leader Testing**
  - Fleet leader testing program for fracture critical component requires prior approval of the FCM

Material Selection and Properties

- Materials will comply with NASA-STD-6016, Standard Materials and Processes Requirements for Spacecraft and Metallic Materials Properties Development and Standardization (MMPDS)

- Factors affecting materials properties:
  - Effect of service temperature and environment
  - Product form
  - Material orientation

- **Additive manufactured (AM) or 3D-printed materials in structural application require prior approval of the FCM**

Fracture Mechanics Material Properties

- The da/dN vs. ΔK and K_{1c} will correspond to the temperature and environments of the flight hardware for damage tolerance analysis using NASGRO

- Modification of the NASGRO material parameters shall be approved by the FCM

- Retardation effects on crack growth rates needs prior approval of FCM

Loading Spectrum

- A load spectrum shall be developed for **fatigue and damage tolerance assessment**
  - The load spectrum shall include the load (mechanical, thermal, pressure, etc. and environments during ground, flight, orbital and planetary phases) and the number of cycles or duration
  - Both cyclic and sustained loads that the part will experience should be considered
  - Effects of residual stresses and preloads must be considered

Methodology for Assessing Fracture Critical Composite/Bonded Structure

- **Proof Testing:**
  - Require prior approval of FCM
  - Flight hardware shall be proof tested to a minimum of 1.2 x limit load
  - The proof test will be conducted in the service temperature and environments of the flight hardware
  - Proof test loads shall be < 80% of the ultimate strength of the structure
  - For multi-mission components and structures need purposeful inspection or test for signs of damage in between flights
  - The structure shall be protected from inadvertent damage by appropriate DTA and DCP

- **Damage Tolerance Analysis/Testing:**
  - JSC 25863C is not adequate
  - Require project-specific Fracture Control Plan (FCP)

Detected Cracks in Fracture Critical Hardware

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

Tracking of Fracture Critical Parts

- All fracture critical must have:
  - Certification of compliance (COC) to material standards
  - Serialization of the parts
  - MUA (whenever is needed)
  - Type of NDE and the NDE acceptance criteria on drawings

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

What is in a Fracture Control Summary Report (FCSR)?

- FCSR should contain sufficient information to verify that all fracture requirements have been met.

  FCSR should include:

- **Non-Fracture Critical**
  - Identification and Rationale for acceptance

- **Fracture Critical**
  - List of fracture critical parts
  - NDE inspections performed
  - Results of damage tolerant analyses
  - Fracture assessments including MUA, if needed
  - Note of any deviations or discrepancies

- **Pressure Systems**
  - MDP of system
  - Safety Factors
  - Proof Factors
  - Proof tests conducted
  - Inspections
  - LBB / Safe-life assessments

- Supporting detailed documentation such as drawings, analyses, test, inspection, etc., will be made available for review if requested

  [Section 8.0 of JSC 25863C for details]

Fracture Critical vs. Criticality 1 Categorization

- **Fracture critical and Criticality 1 categorization are not synonymous**
- **Fracture Critical** - A part whose structural failure due to the presence and/or propagation of a pre-existing flaw causes a catastrophic hazard
- **Functional Criticality** (Reliability Term) - Criticality 1 is based on functional criticality and is defined as functional failure that could result in loss of life and vehicle (NSTS 22206D). It is determined based on a Failure Modes and Effects Analysis (FMEA) done on a hardware item. Structural failure is not a failure mode that is considered under a FMEA

Fracture Critical vs. Criticality 1 Categorization (Contd.)

- **Recall** - Fracture critical and Criticality 1 categorization are not synonymous

Wide Band Micro-TAU in Orbiter MPS Location

- **Functional Criticality:** Criticality 3/3 hardware
- **Fracture Control:** Structural failure is a catastrophic hazard and Fracture Control has been implemented accordingly

Quick Disconnect Breakout Box (QDBB)

- **Functional Criticality:** Criticality 1SR hardware
- **Fracture Control:** Contains no structural hardware

Summary of the Presentation (Contd.)

- Hardware may be classified as either non-fracture critical or fracture critical
- **Non-fracture critical hardware includes:**
  - Exempt
  - Low released mass
  - Contained
  - Fail-safe
  - Low-risk structural part
  - Low-risk fastener
  - NHLBB pressurized lines, fittings and components
  - Sealed container
- **Fracture critical parts includes:**
  - Habitable module
  - Pressure vessel
  - Hazardous fluid container
  - Pressurized lines, fittings and components containing a hazardous fluids
  - High-energy
  - Any remaining structural hardware that does not fit the categories of non-fracture critical

Summary of the Presentation

- Consider Fracture Control early in the design phase:
  Include ES4/Fracture Control in PDR/CDR loop

- **Project Responsibilities:**
  - Implementing Fracture Control on the hardware
  - Compilation of FCP and FCSR

- Project must submit a cert request to JETS/Certification coordinator for JSC integrated hardware

- **FCM Responsibilities:**
  - Review Flight hardware
  - Verify compliance of Fracture Control requirements
  - Approval of FCSR
  - Issue Fracture Control certification