Additive Manufactured Human-rated Spacecraft Structures:
Certification Challenges

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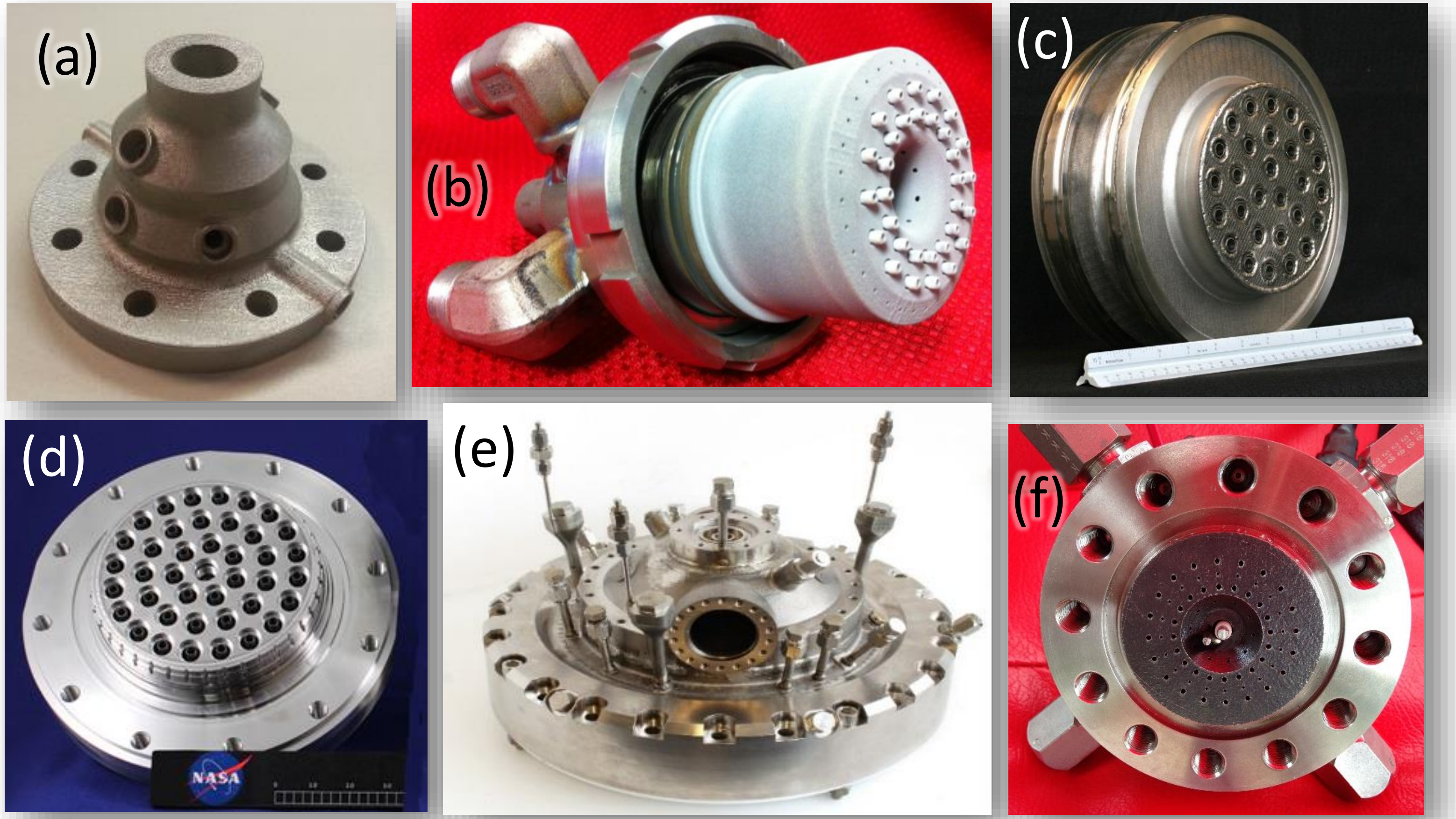
CONTENTS

BACKGROUND: NASA AM EXAMPLES

Examples of Rocket Engine Components Produced at NASA MSFC [1]

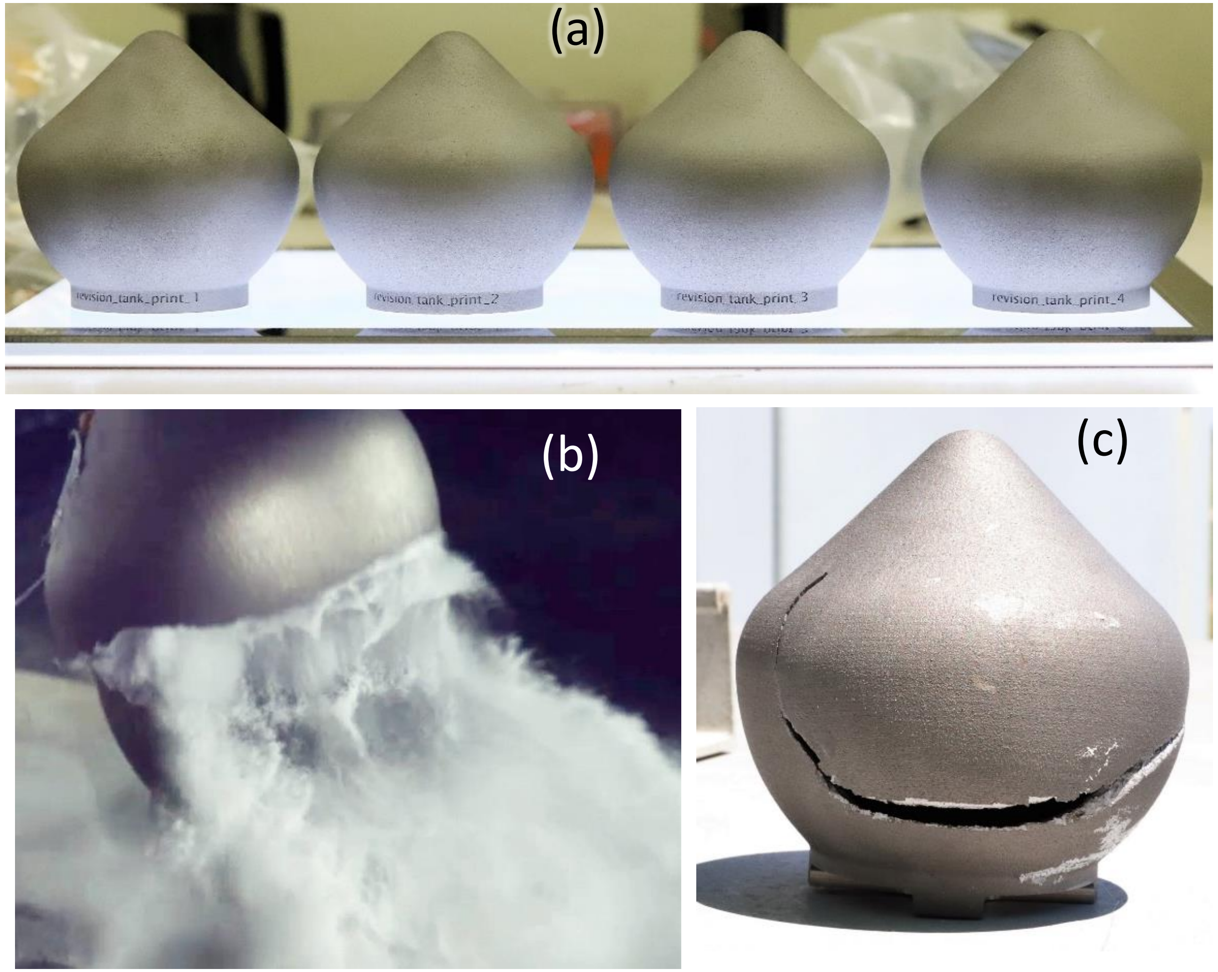


(a) 100# LOX Propane Injector tested 2013
(b) 1.2K LOX Hydrogen tested 2013
(c) 20K LPS Subscale tested 2013,
(d) Methane 4K Injector tested 2015,
(e) LPS 35K Injector tested 2015,
(f) CH4 Gas Generator Injector tested 2017.

[1] P. Gradl, S.E. Greene, C. Protz, B. Bullard, J. Buzzell, C. Garcia, J. Wood, K. Cooper, J. Hulka, R. Osborne. Additive Manufacturing of Liquid Rocket Engine Combustion Devices: A summary of process developments and Hot-Fire Testing Results. 54th AIAA/SAE/ASEE Joint Conference, Cincinnati, OH, 2018.

BACKGROUND: NASA AM EXAMPLES

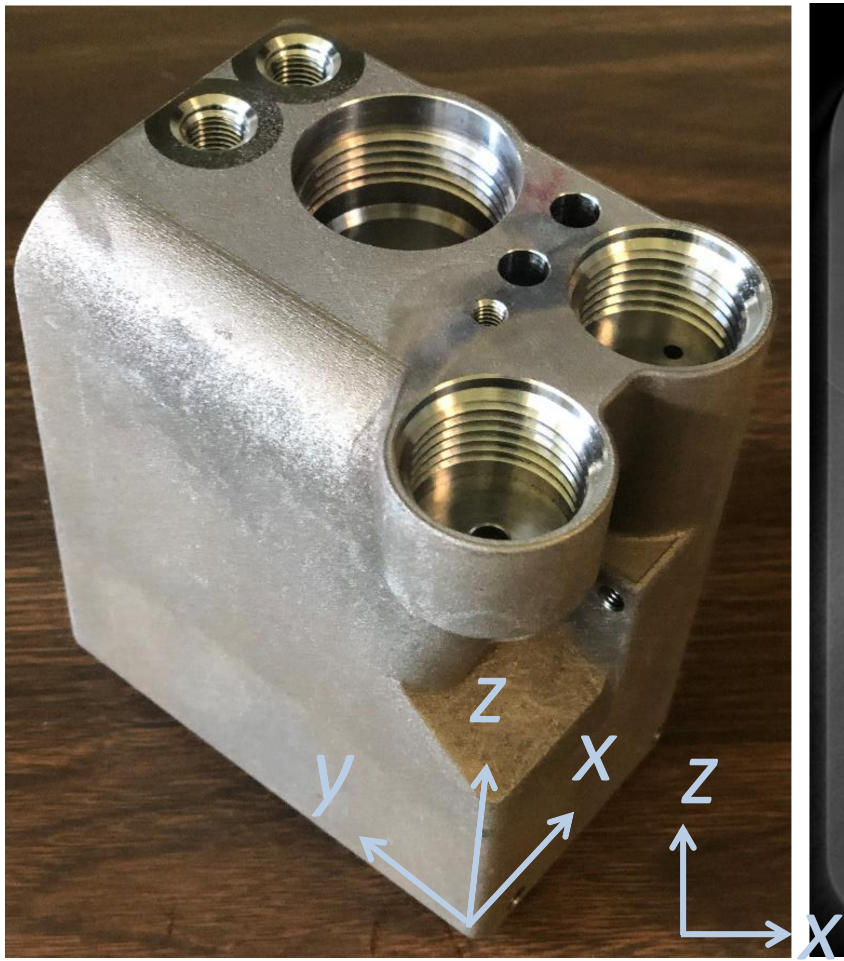
Pressure vessel produced at NASA JSC

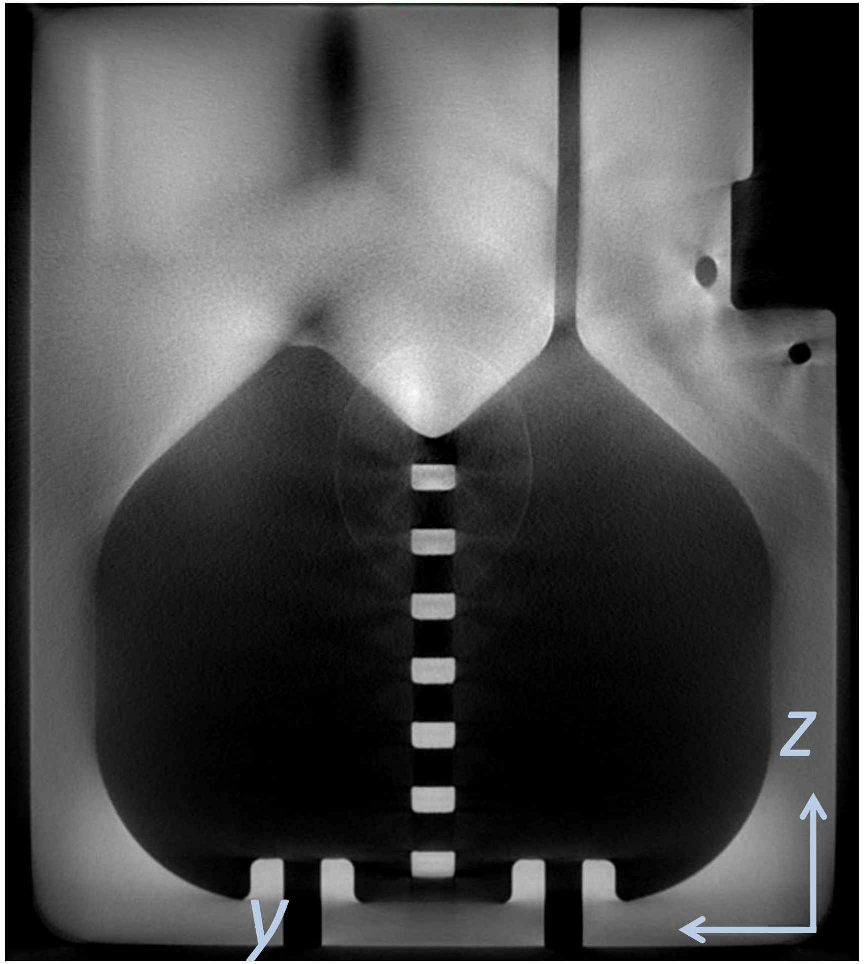


(a) test coupons
(b) burst test failure
(c) test coupon after burst test

BACKGROUND: NASA AM EXAMPLES

"Tankifold" produced at NASA JSC





BACKGROUND: FRACTURE CONTROL

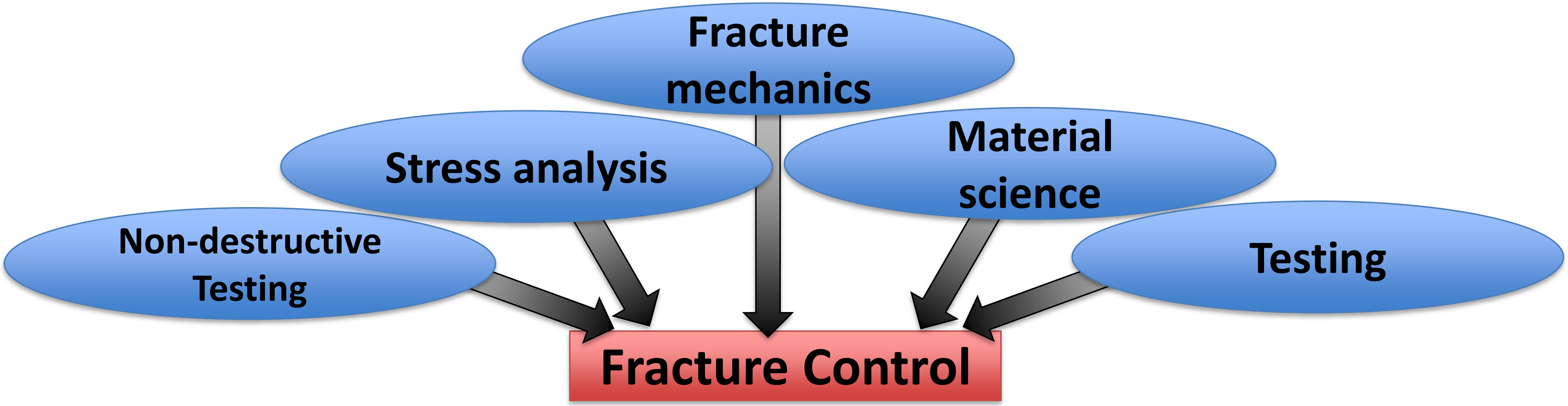
Static Strength

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

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
- Determine safe interval of operation



Board of experts from each technical discipline

BACKGROUND: FRACTURE CONTROL

Implementation of fracture control

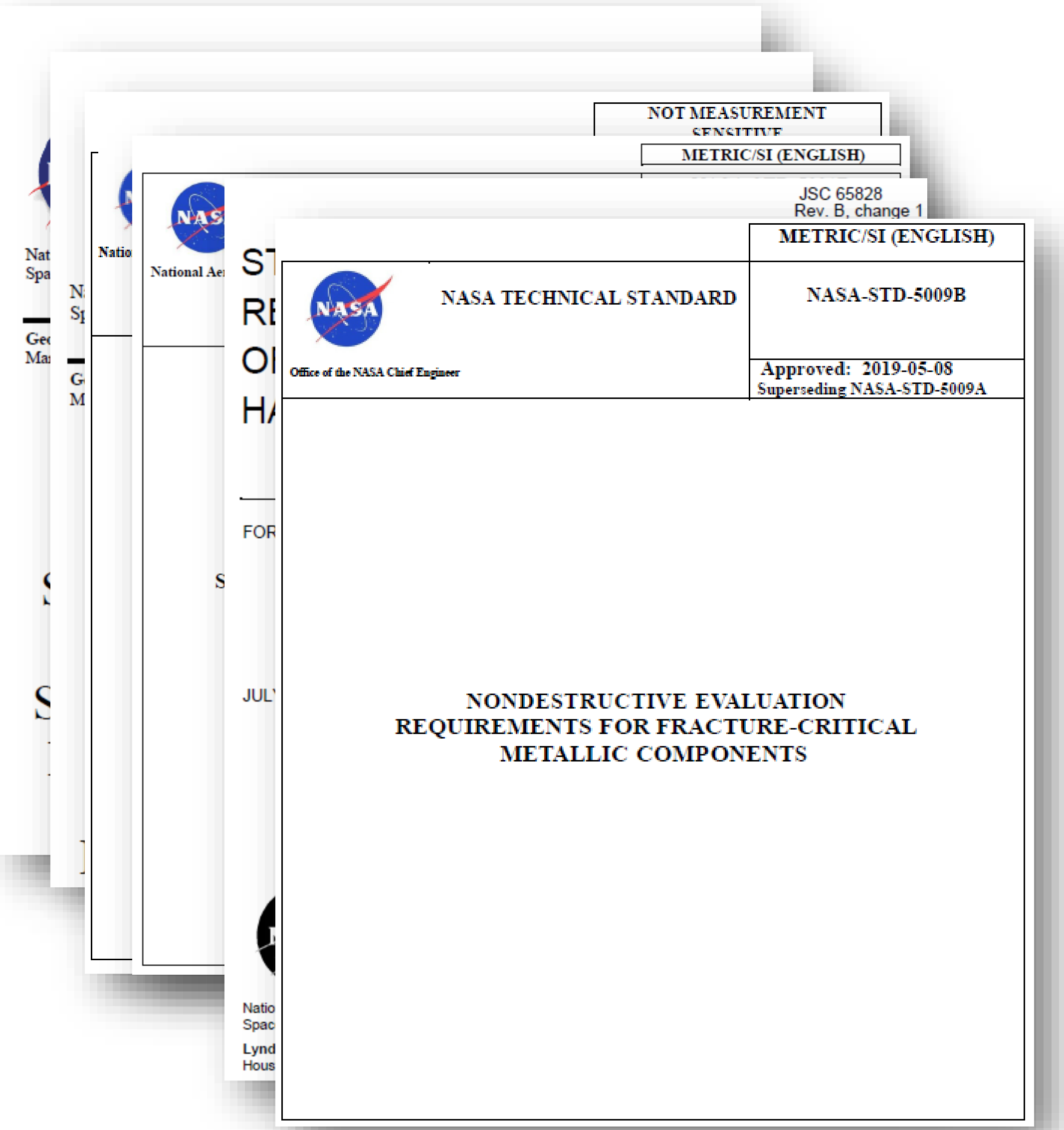
- Classify parts and identify those that are “fracture critical”
  - *for fracture critical parts…*
- ↓
- Perform Non-destructive evaluation (NDE)
- ↓
- Demonstrate damage tolerance

Questions to Address Today:

1. What gaps exist in current NASA standards related to implementation of fracture control on additive manufactured (AM) parts?

2. What AM-specific challenges exist in fracture control implementation and how can the intent of existing standards be met?

BACKGROUND: EXISTING STANDARDS


METRIC/SI (ENGLISH)

NASA TECHNICAL STANDARD

Office of the NASA Chief Engineer

NASA-STD-5009B

Approved: 2019-05-08
Superseding NASA-STD-5009A

NONDESTRUCTIVE EVALUATION REQUIREMENTS FOR FRACTURE-CRITICAL METALLIC COMPONENTS

- MSFC-STD-3716 Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals
- MSFC-SPEC-3717 Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes
- NASA-STD-5019 Fracture Control Requirements for Spaceflight Hardware
- NASA-STD-5001 Structural Design and Test Factors of Safety for Spaceflight Hardware
- JSC 65828 Structural Design Requirements and Factors of Safety for Spaceflight Hardware
- NASA-STD-5009 Nondestructive Evaluation Requirements for Fracture-Critical Metallic Components

Discipline	NASA Requirement Gap
"M&P"	Non-metallic materials
"M&P"	Other AM techniques
Fracture Control	Implementation of Fracture Control
Structures	Structural Certification
NDE	Detectable flaw size

FRACTURE CONTROL IMPLEMENTATION

✓ Classify parts and identify those that are "fracture critical"

for fracture critical parts…

X Perform Non-destructive evaluation (NDE)

X Demonstrate damage tolerance

- Technology is immature
- Tools are immature
- Test methods immature
- Standards are immature

Fracture Control Certification Methodology (FCCM)

FCCM-1: Damage Tolerance Fracture Analysis

FCCM-2: Damage Tolerance Simulated Service Life Test

FCCM-3: Proof Test

Assumptions

- Process control: consistent and repeatable properties
- Accurate material and fracture properties available

Disclaimer: FCCMs should not be interpreted as proposed requirements, early drafts of requirements, or pre-approved by NASA to meet NASA-STD-5019.

FRACTURE CONTROL IMPLEMENTATION

FCCM-1: Damage Tolerance Fracture Analysis

- When to use
  - Test-validated fracture analysis tool is available
  - NDE can find Critical Initial Flaw Size at all locations of concern (90% reliability, 95% confidence)
- Summary
  - Perform damage tolerance flaw growth analysis
  - Assume minimum detectable flaw size at worst case location and orientation
  - Pressurized hardware: proof test and leak check according to FCCM-3
- Comments
  - Not appropriate if NDE cannot find CIFS
  - Option: CIFS can be increased locally by adding material to fall within NDE capability

FRACTURE CONTROL IMPLEMENTATION

FCCM-2: Damage Tolerance Simulated Service Life Test

- When to use
  - NDE cannot support FCCM-1
  - Fracture analysis tools unavailable
- Summary
  - Full-scale/flight-like part containing intentional defects subjected to flight load spectrum
  - Success criteria: no defects grow to cause a catastrophic hazard (i.e., structural failure, critical leak)
  - Initial defects correspond to CIFS at all locations of concern
  - May need ability to "pre-crack"
- Comments
  - Defect growth should be quantified
  - Fracture analysis may be calibrated with test data and applied elsewhere

FRACTURE CONTROL IMPLEMENTATION

FCCM-3: Proof Test

- When to use
  - Simple load or test fixture can replicate flight loading
  - NDE and/or fracture analysis cannot support FCCM-1
  - “Low duty cycle” applications
- Summary
  - Proof test enveloping flight limit load by a predetermined factor at all locations
  - Suggested proof factor: $proof\ factor = burst\ factor \times \frac{1.5}{2.0}$
  - Perform fracture analysis to verify CIFS is screened by proof test at all locations
  - Perform post-proof NDE
- Comments
  - Option: Increase CIFS locally by adding material so that it is screened by proof test

DESIGN FOR AM FRACTURE CONTROL

- Include fracture control considerations in AM design approach
  - Design for Non-fracture critical: Failsafe[1]
    - Multiple redundant load paths
  - Design for similar to NFC: Low Risk[1,2]
    - Combined stresses < 30% Ultimate Strength
    - Infinite fatigue life
  - Design for proof testing
    - Include test fixturing and/or load application features in part
    - Machine features off after proof test
  - Design for NDE
    - Iterate on design to provide CIFS that NDE can find at all locations
- AM design and optimization algorithms can include fracture control goals

[1]NASA-STD-5019 (Fracture Control Requirements for Spaceflight Hardware)

[2]Note: MSFC-STD-3716 prohibits a NFC: Low Risk classification per NASA-STD-5019 on any AM part

CLOSING REMARKS

- NASA Standards have gap regarding implementation of fracture control
  - New requirement needed??
  - Guidance/handbook sufficient??

- Implementation of fracture control on AM parts to meet intent of existing NASA standards
  - Fracture Control Certification Methodology-1: Damage Tolerance Fracture Analysis
  - Fracture Control Certification Methodology-2: Damage Tolerance Simulated Service Life Test
  - Fracture Control Certification Methodology-3: Proof Test

- Design for AM Fracture control

- Next Steps at NASA
  - Discuss fracture control implementation internally and with industry
  - Release AM fracture control guidance

WHAT COULD YOUR ROLE BE?

- Material Science Research
- Hardware design and analysis
- Hardware testing
- Hardware certification
- Project management
- Create Industry Standards