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Developing Approaches for Certification of Un-inspectable Fracture Critical AM Components

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Author Bio

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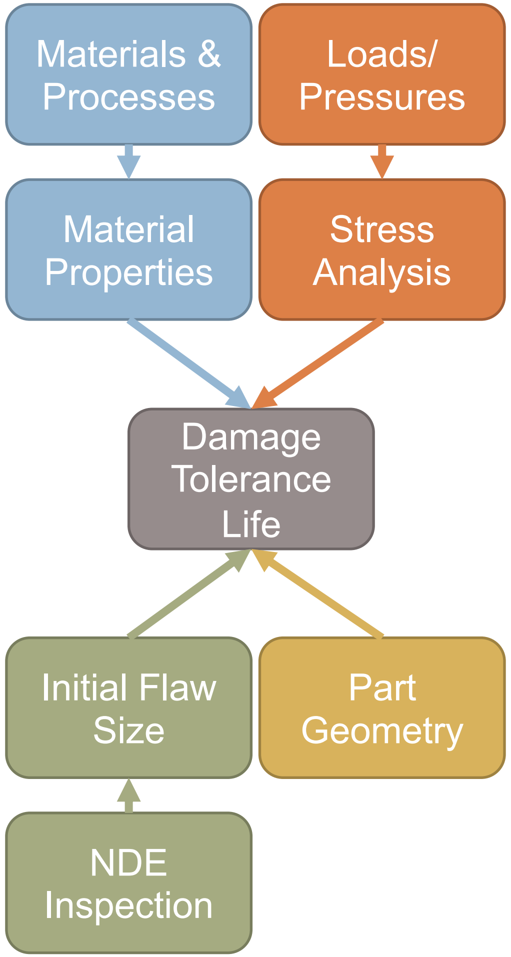
Will Tilson is a Structural Materials Engineer at NASA Marshall Space Flight Center in Huntsville, Alabama. Will is a member of the Damage Tolerance Assessment Team, where he works to ensure the safe operation of critical spaceflight hardware through fracture control and damage tolerance, including AM hardware. Will's interests include fracture mechanics, probabilistic damage tolerance, and AM hardware certification. Prior to joining NASA in late 2019, Will worked as a Test Engineer in the MSFC Mechanical Testing Lab, where he primarily supported fatigue and fracture testing and AM material characterization. Will has a B.S. in Materials Engineering from Auburn University and a M.S. in Mechanical Engineering from the University of Alabama Huntsville.

Introduction

- Human-rated spaceflight hardware is subject to the Fracture Control requirements in NASA-STD-5019, which are intended to control the risk of component failure due to undetected cracks or defects.
  - All hardware in this mission class is classified for Fracture Control – *Exempt*, *Non-fracture Critical*, or *Fracture Critical*
- **Fracture Critical**: A classification that identifies a part where failure due to the presence of a crack is a catastrophic hazard ➔ Pressure vessels, engine components, primary structure, etc.
  - Axiom 1: Material and manufacturing process produce structures and components with cracks or defects.
  - Axiom 2: The presence of a crack or defect of sufficient size reduces the strength and life of the structure.
- **Damage Tolerance**: demonstration that a component can survive the service life (with a safety factor) in the presence of an undetected flaw or damage.
  - Components are manufactured from aerospace quality materials using controlled processes.
  - Components are inspected for damage (cracks, flaws, defects, etc.).
  - Components are shown by test or analysis to be tolerant to undetected flaws.



Introduction

- Fracture Critical AM components have the potential to uniquely challenge existing fracture control approaches:

	AM Materials	Wrought Materials
Material Quality	Material quality is highly process-dependent; variation from machine to machine.	More consistent quality due to small number of dedicated production mills with extensive experience.
Flaws	Flaws are inherent to the process	Flaws are typically rare
Inspectability	Inspectability varies based on component geometry; inspection techniques still under development	Raw stock is commonly fully inspectable, parts generally have high inspectability
Heritage	Little to no experience for critical applications, rapid technological development	Decades of experience

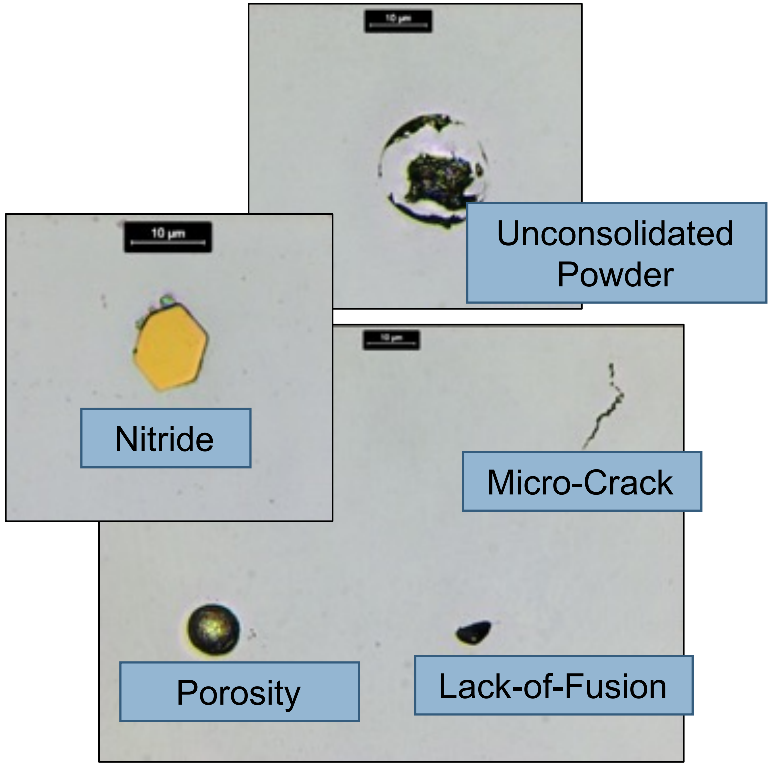
Challenge

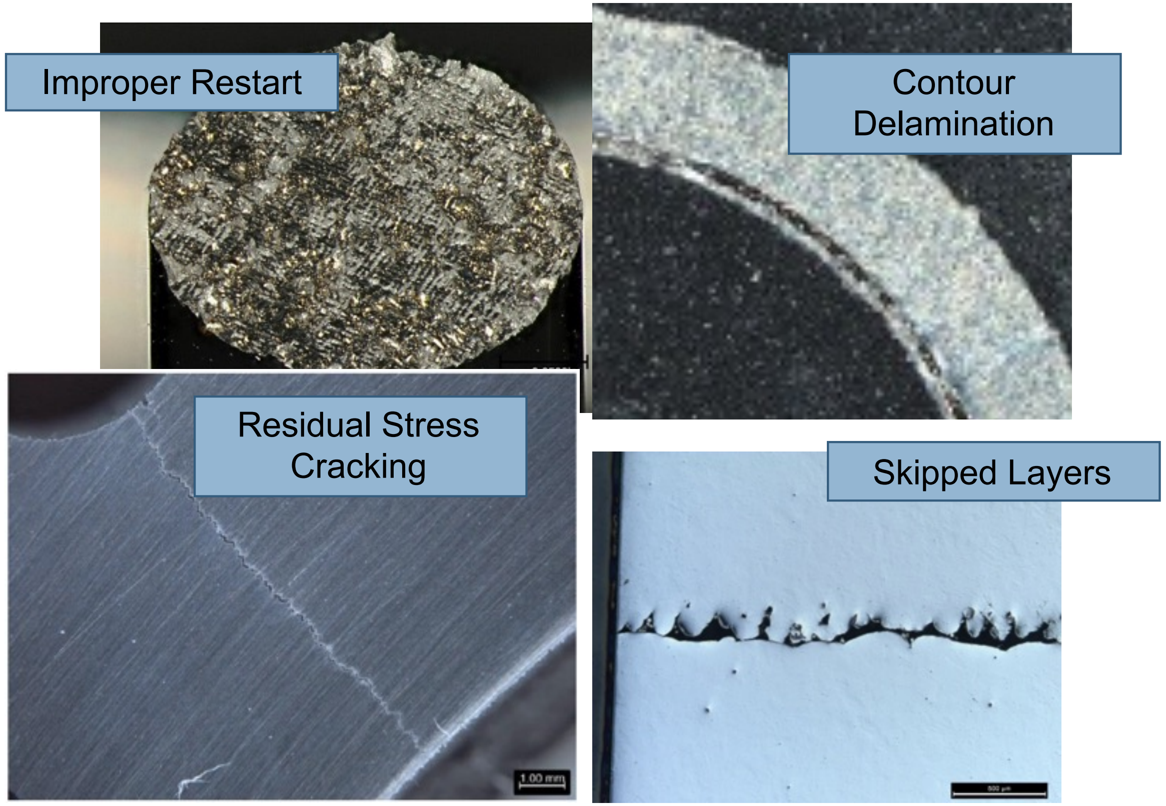
- **Problem:** Fracture Critical AM components with limited or no post-build inspectability may be used for NASA programs.
  - How do we develop Fracture Control rationale for un-inspectable AM components?
  - How do we communicate risk associated with un-inspectable AM components?
- **Approach**: Begin to develop a consistent philosophy for assessing un-inspectable Fracture Critical AM components
  - Complex problem – incremental developments, potential redirection, future adaptations
  - Likely a risk-based acceptance – may not be able to meet current Fracture Control requirements.




Definitions

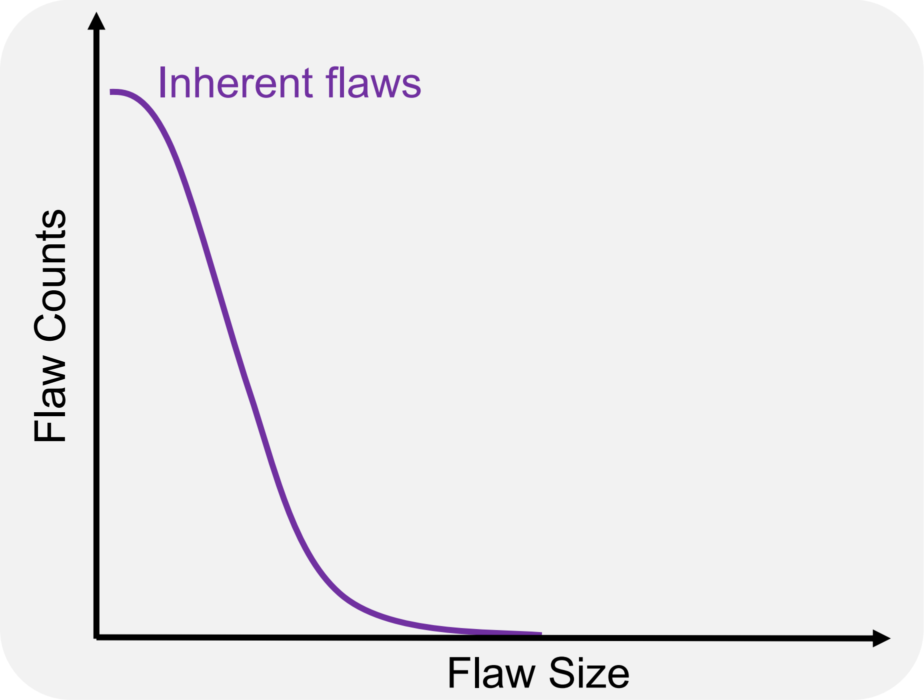
- Definitions from ASTM E1316: Standard Terminology for Nondestructive Examinations
  - **Flaw:** an imperfection or discontinuity that may be detectable by non-destructive test and is not necessarily rejectable.
  - **Defect:** one or more flaws whose aggregate size, shape, orientation, location, or properties do not meet specified acceptance criteria and are rejectable.





Definitions

- **<u>Inherent flaws:</u>** Flaws that are representative of the characterized nominal operation of a qualified AM process.
  - Inherent flaws are expected to be common enough that direct characterization is feasible. “Characterized” implies that most inherent flaws have been observed as part of AM process development and are included in the metallurgical and mechanical qualification data set.
  - Inherent flaws are not defined by size (e.g., small ≠ inherent), but are expected to be small in a well-controlled AM process.



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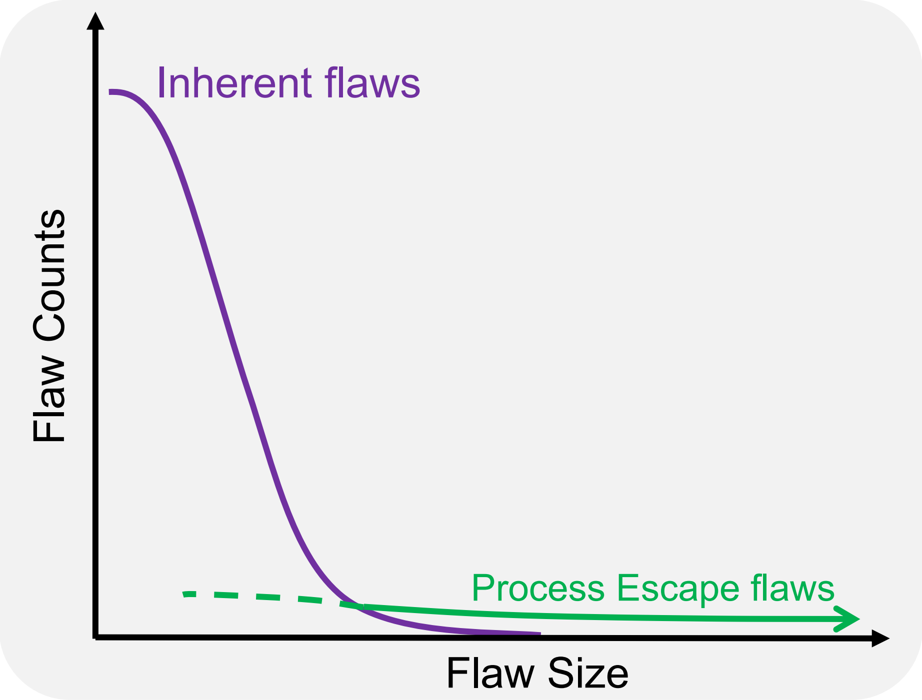
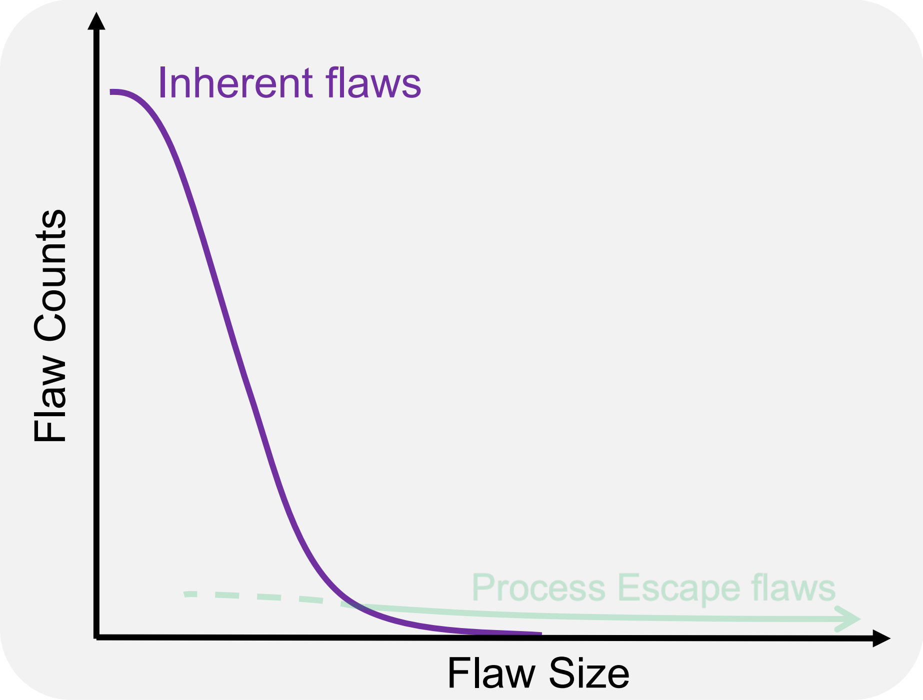
  - Inherent flaws are not defined by size (e.g., small ≠ inherent), but are expected to be small in a well-controlled AM process.
- **<u>Process escape flaws:</u>** Flaws that are not representative of the characterized nominal operation of a qualified AM process.
  - Process escape flaws are associated with some sort of process failure.
  - Process escape flaws may or may not be larger than inherent flaws, though generally are expected to be larger.
  - Process escape flaws have lower occurrence rates than inherent flaws.
  - Process escape flaws may or may not be detectable.



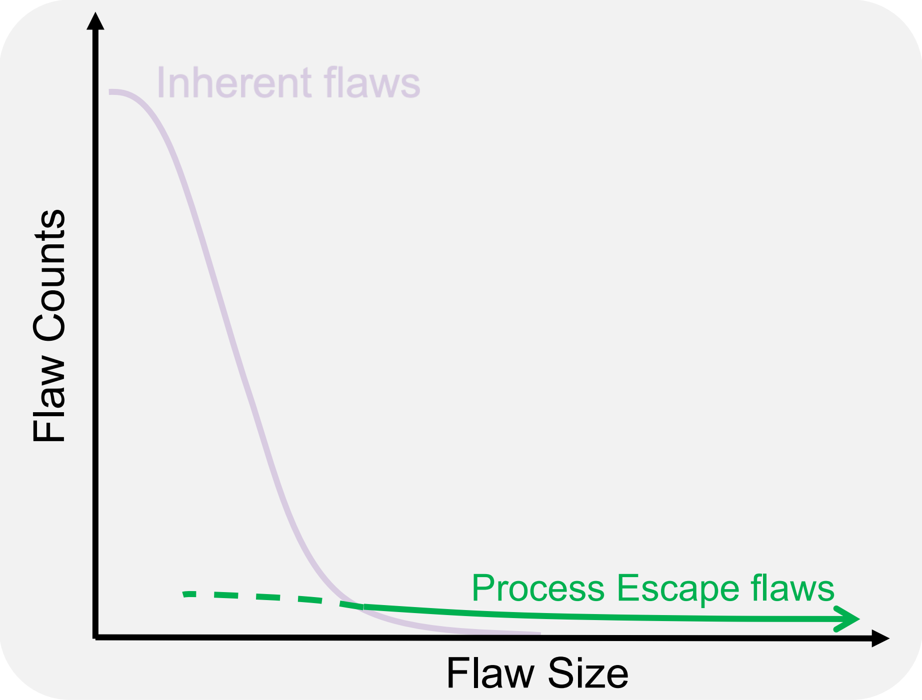
Inherent Flaws

- Baseline assumption: AM process is qualified to an appropriate AM standard (NASA-STD-6030) to the degree necessary for critical (“Class A”) AM components (QMP-A).
- The inherent flaw category allows for small, common flaws to be treated as a population, rather than individually:
  - Flaw state characterization builds upon metallurgical evaluations for material quality required by NASA-STD-6030. AM material qualifications already require assessments of material throughout the build area, encompassing the extremes of the process window, and at key AM influence regions (restarts, stitch-lines, overhangs, etc.)
  - Inherent flaw state characterization should appropriately account for AM influence factors that might vary the distribution of inherent flaws:
    - Component geometry
    - Thermal history
    - Variation within the process box
    - Machine parameter transitions
  - Process definition/qualification specimens include the inherent flaw state, which allows for continuity in material properties; the effects of inherent flaws are “baked in” to the material property definition.



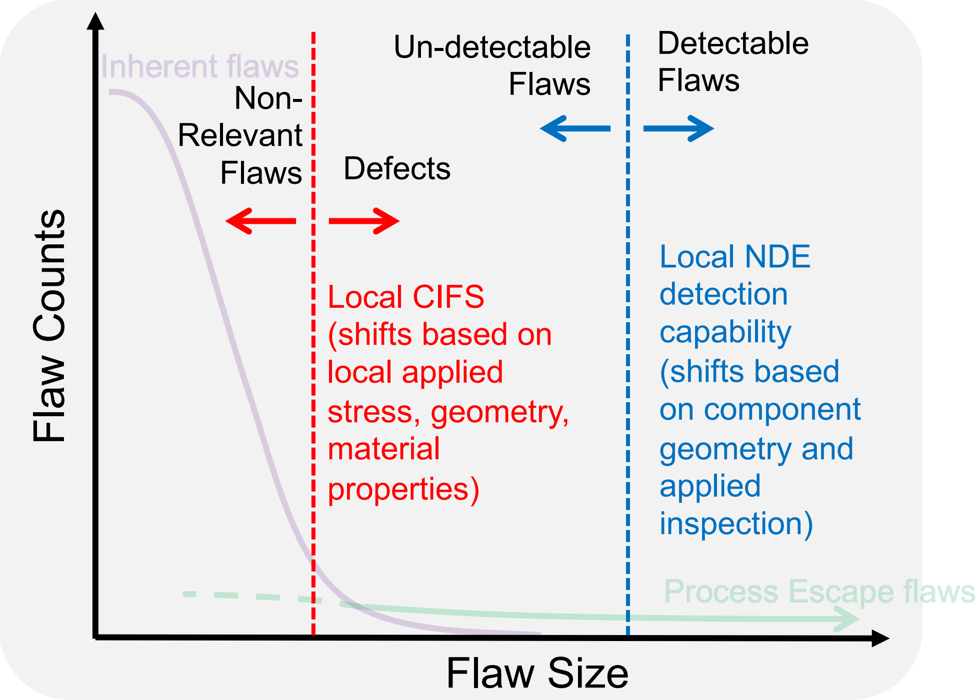
Process Escape Flaws

- Baseline assumption: AM process is qualified to an appropriate AM standard (NASA-STD-6030) to the degree necessary for critical ("Class A") AM components (QMP-A).
- Process escape flaw risk are identified through a rigorous assessment of the AM process:
  - Process Failure Modes & Effects Analysis (PFMEA): Potential process escape flaws are identified using systematic evaluations of the AM process
    - What is possible?
  - Triage process failure modes based on severity, occurrence, and detectability. Identify process failure modes that are unlikely to result in a process escape flaw. Focus is on detecting the process failure.
    - What can be screened?
  - Employ conservative estimates, physics-based limits, and experience to define appropriate process escape flaw populations.
    - What's left over?
  - PFMEA is not required by NASA-STD-6030; performed in support of meeting other requirements (NASA-STD-5019) or risk assessments.



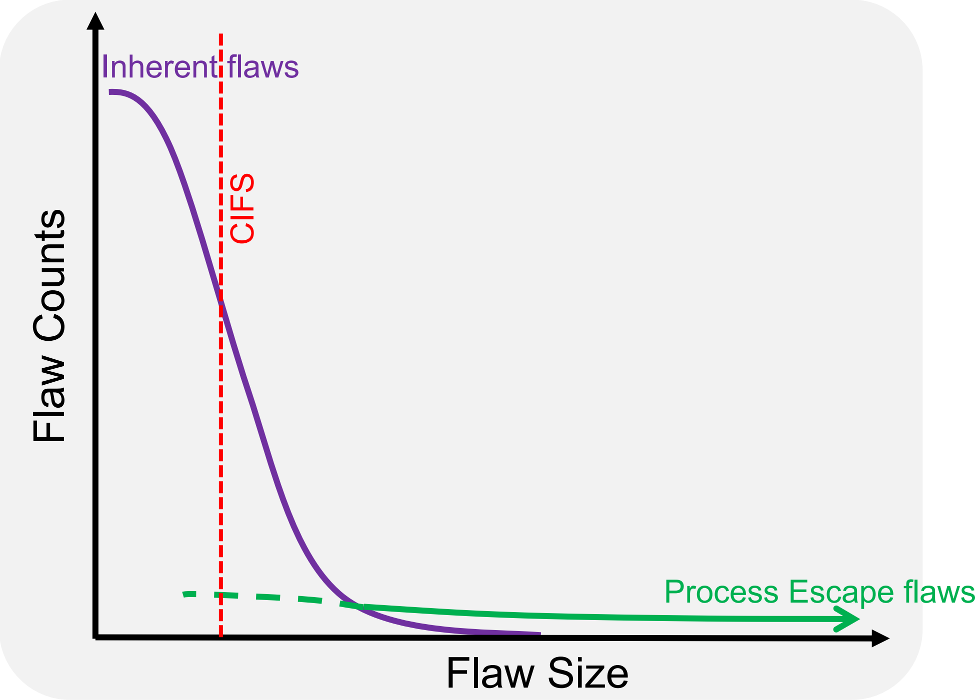
FC for Un-inspectable AM Components

- Process-level assessments to characterize AM flaws by the flaw size and rate of flaw occurrence. Two distributions are defined:
  - Inherent flaw distribution – expected to be relatively common and relatively small
  - Process escape flaw distribution – expected to be relatively rare and span the range of possible flaw sizes
- Component-level assessments define relevant flaw sizes:
  - Critical initial flaw size (CIFS): the largest flaw that will survive the mission life, with an appropriate factor of safety.
  - Minimum detectable flaw size: the flaw size above which the flaw is detectable with the chosen NDE technique.
- CIFS and detectability limit will shift locally and independently based on the component and application.
  - "Zone-based" analysis approach
- The relationship between the CIFS and the minimum detectable flaw size defines the risk scenario.
- Assumption: QMP-A per NASA-STD-6030 (or equivalent).



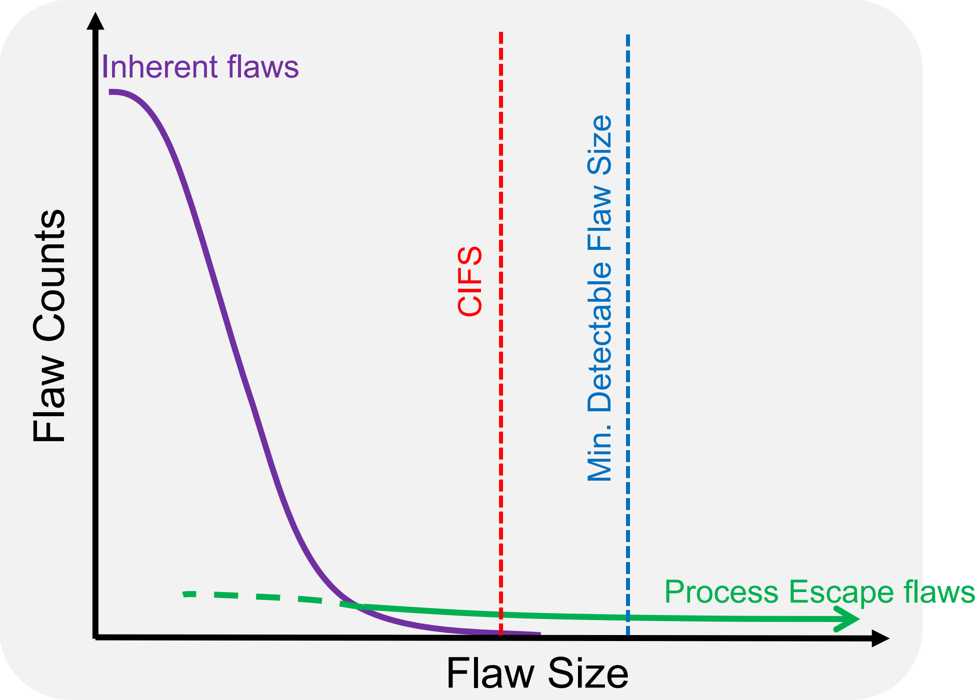
FC for Un-inspectable AM Components

- **Scenario 1:** CIFS within inherent flaw distribution
  - The probability of a critical flaw in a critical location is high – inherent flaws are common
  - CIFS should ideally be much larger than the sizes encompassed in the inherent flaw distribution.
  - Unacceptable risk: component redesign or AM process refinement is necessary.



FC for Un-inspectable AM Components

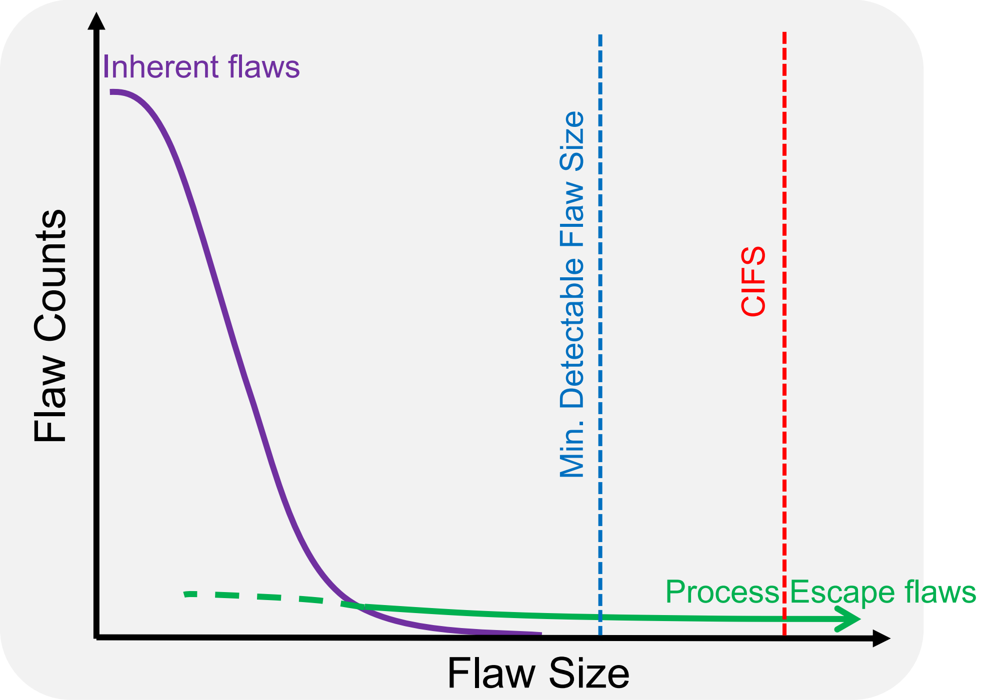
- **Scenario 2:** CIFS larger than inherent flaw distribution but smaller than NDE capability
  - Apply mitigations to limit the risk of process escape flaws
    - Identify (using PFMEA) potential process failures.
    - Assess the risk of each process failure:
      - Process controls
      - Physics-based limits to size or occurrence
      - Apply monitoring – In situ, machine health
    - Focus on controlling/detecting the process failure, not the process escape flaw.
  - Probabilistic damage tolerance
    - Acceptable probability of failure ➔ risk-base acceptance
    - Unacceptable probability of failure ➔ component redesign or AM process refinement.
  - Alternative approach per NASA-STD-5019 (if baseline risk) or risk-based acceptance (waiver).



FC for Un-inspectable AM Components

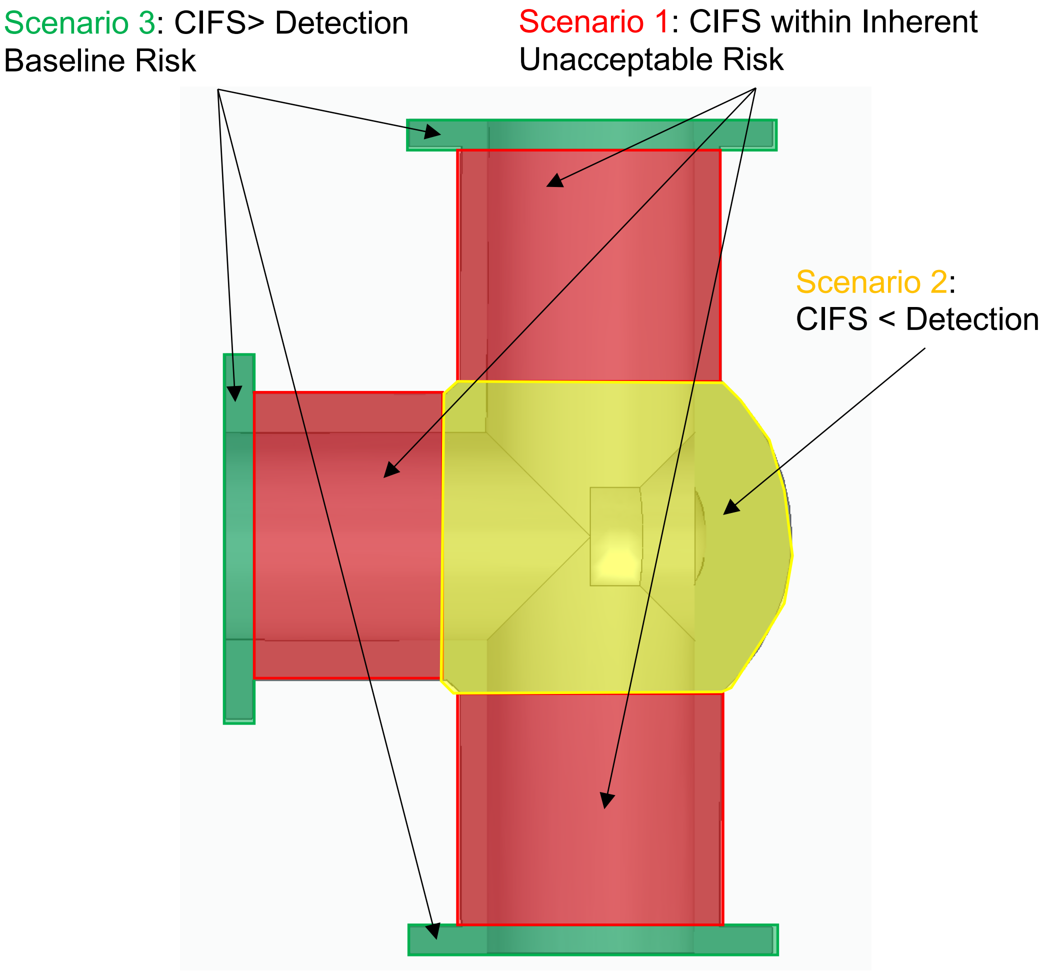
- **Scenario 3:** CIFS larger than NDE capability
  - Show by test or analysis that the component (or zone) is damage tolerance using traditional approaches
  - Compliant with NASA-STD-5019 – Baseline Risk

  - May not be possible for some AM components
  - May be possible for some “zones” within an otherwise un-inspectable component
    - Flaw detection “preempts” probabilistic assessment.



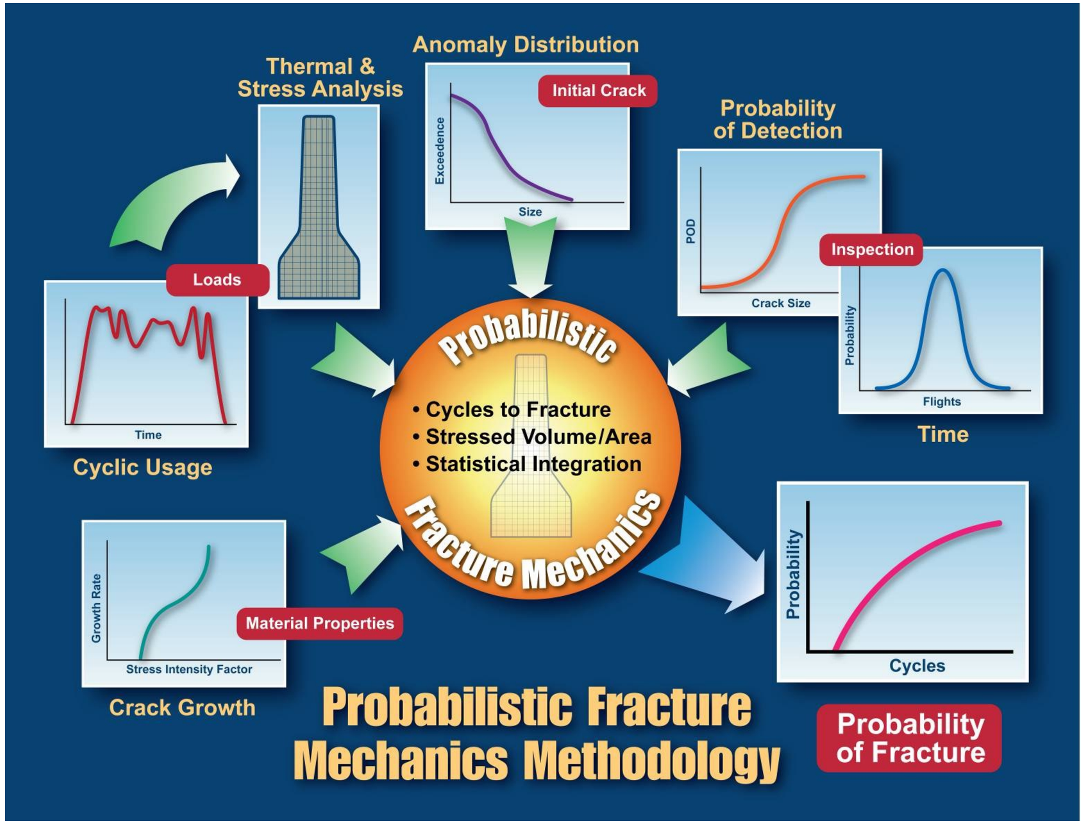
Zone-based Assessment

- A part may contain regions representative of each Scenario. Zone-based assessments support the approach:
  - Scenario 1: CIFS within Inherent
    - *Example*: High stress region with thin walls
  - Scenario 2: CIFS larger than Inherent & CIFS < NDE capability
    - *Example*: Low stress thick section with incomplete NDE coverage
  - Scenario 3: CIFS > NDE capability
    - *Example*: Low stress flange with a machined surface; full surface and volumetric NDE coverage
- Fracture control rationale based on the combined zone risk:
  - All green zones: Baseline
  - One red zone: Unacceptable
  - Mixed green and yellow zones: Risk-based rationales



Probabilistic Analysis

- Probabilistic damage tolerance analysis provides a means of assessing part risk in the absence of a bounding initial flaw size.
  - Similar to traditional deterministic damage tolerance, except that one or more analysis inputs takes the form of a statistical distribution. Common probabilistic inputs are anomaly distributions and probability of detection.
  - Analysis result is a “probability of fracture”, rather than a ”service life”.
- Potential advantages:
  - Automated tools allow for “component-scale” assessments of risk
  - Potential to reduce conservatism relative to the “worst-on-worst” deterministic approaches
  - Does not require extensive fatigue testing
  - Consistent with conventional NASA damage tolerance approaches, including supporting automated assessments of critical initial flaw sizes
- Disadvantages:
  - Requires characterization of flaw distributions
  - Different paradigm – risk vs. life
- DARWIN is an established probabilistic analysis tool and is used by industry for FAA hardware certification.



Residual Risks

- Residual risks include:
  - Un-identified process escape flaws
    - The process escape flaw logic relies on a comprehensive accounting of potential process failure modes: the assessment is only as good as the level of rigor in the PFMEA
    - Unknown or unidentified process escapes represent a risk.
  - Extreme values in the inherent flaw distribution
    - There is a potential for “rogue” flaws in the inherent distribution; that is, inherent flaws that are extremely rare and severely impact structural integrity
    - Rarity of such flaws precludes direct assessment; not in the material property definition.
    - Risk may be addressable using probabilistic damage tolerance methodology with extreme value approaches.
  - Implementation
    - How are flaw states appropriately characterized? What is a sufficient description of the inherent flaw state? How to appropriately account for AM influence factors?
    - How to integrate with NDE? How to leverage In-situ monitoring and computational NDE?
    - Can a comprehensive accounting of process escapes be generated? How do we appropriately characterize process escape flaw distributions?
    - How do we perform a robust probabilistic assessment? What inputs are critical? What probabilities of failure are acceptable?

Summary

- Fracture Critical AM components have the potential to challenge existing fracture control approaches, primarily through inspectability challenges. A philosophy is needed for assessing un-inspectable Fracture Critical AM components for NASA applications.
- Inherent flaws are representative of the characterized nominal operation of a qualified AM process.
  - Inherent flaws are expected to be small and common. The inherent flaw state can be characterized, and the effect of inherent flaws is included in the AM process and material property definition.
- Process escape flaws are not representative of the characterized nominal operation of a qualified AM process.
  - Process escape flaws are associated with some sort of process failure. They are expected to be relatively rare but may be of any size. Process escape flaws are evaluated through rigorous assessment and control of the AM process.
- Component level assessments of the critical initial flaw size (CIFS) and the non-destructive evaluation (NDE) flaw detection capability inform the risk associated with an AM component or zone:
  - Scenario 1: CIFS is within the inherent flaw distribution – Unacceptable risk
  - Scenario 2: CIFS is smaller than the NDE detection capability, but larger than the inherent flaw distribution – Risk-based assessment
  - Scenario 3: CIFS is larger than the NDE detection capability – Baseline risk
- Residual risks remain, and implementation details must be resolved.

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Thank you.

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