NASA'S CERTIFICATION AND QUALIFICATION CHALLENGES FOR ADDITIVELY MANUFACTURED HARDWARE: WHAT IS NEXT?

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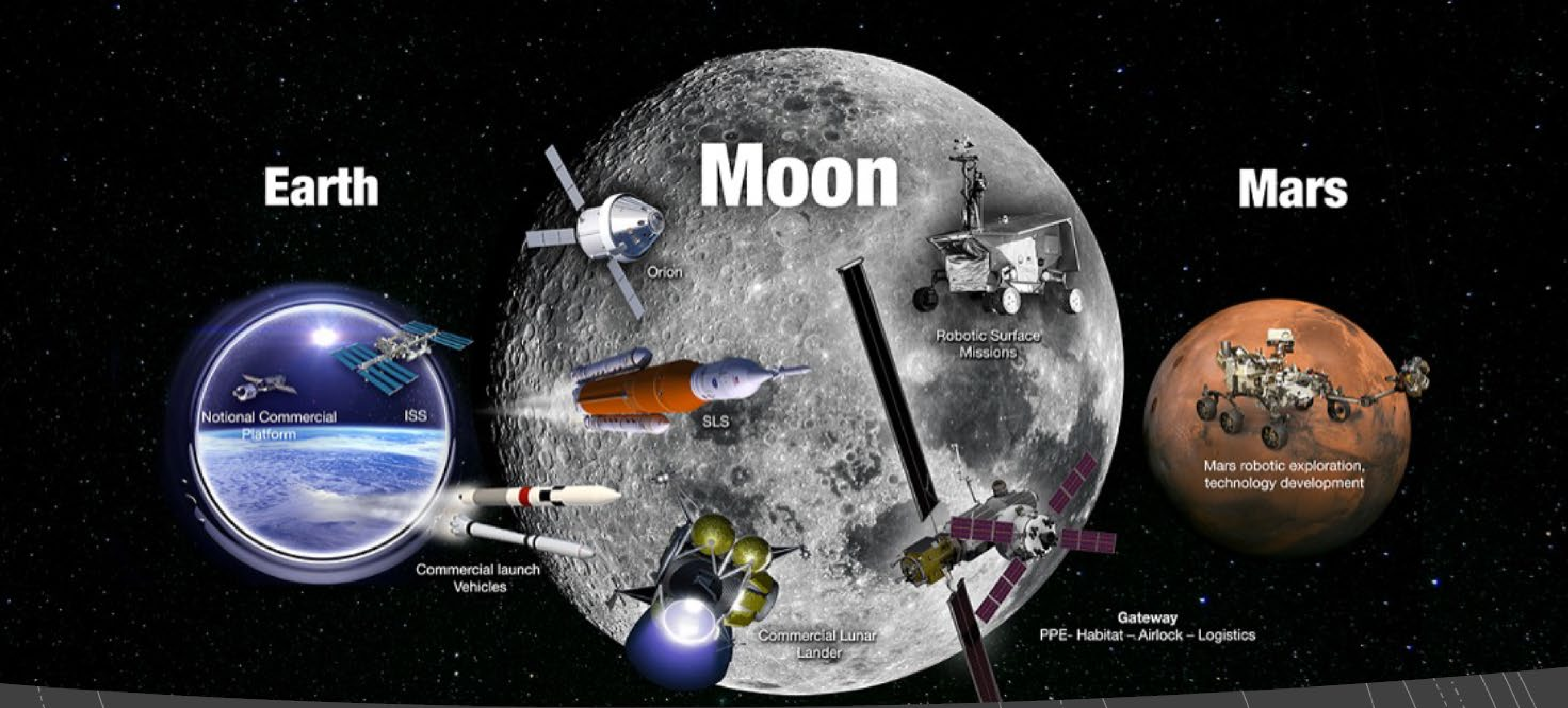
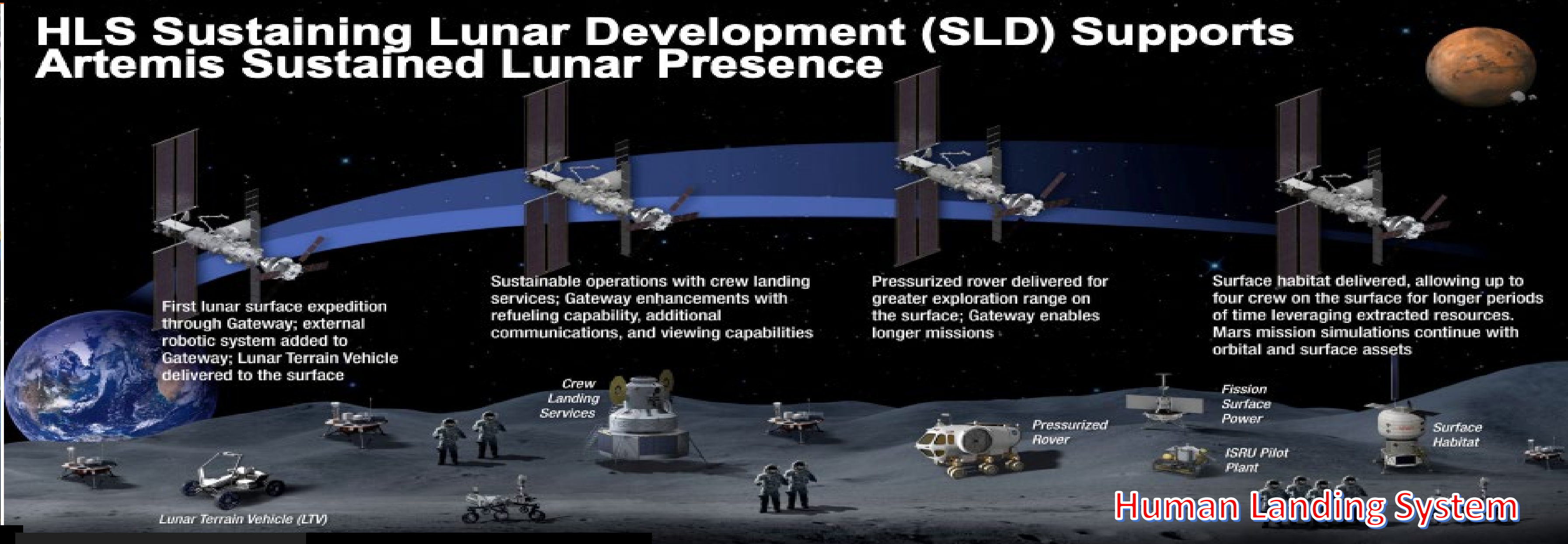
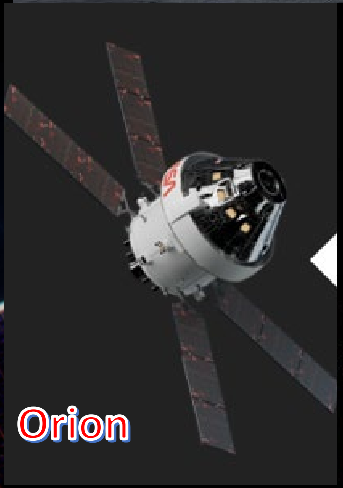


Exciting time at NASA with a lot of activities around Earth Orbit, getting ready to go to the Moon with eyes on Mars

AM Insertion into NASA Spaceflight Systems





NASA Goes Nowhere Without its Partners!

Great appreciation to the ESA/Airbus contributions to the Artemis missions!

Orion's European Service Module on Artemis 1.

Overview of Presentation

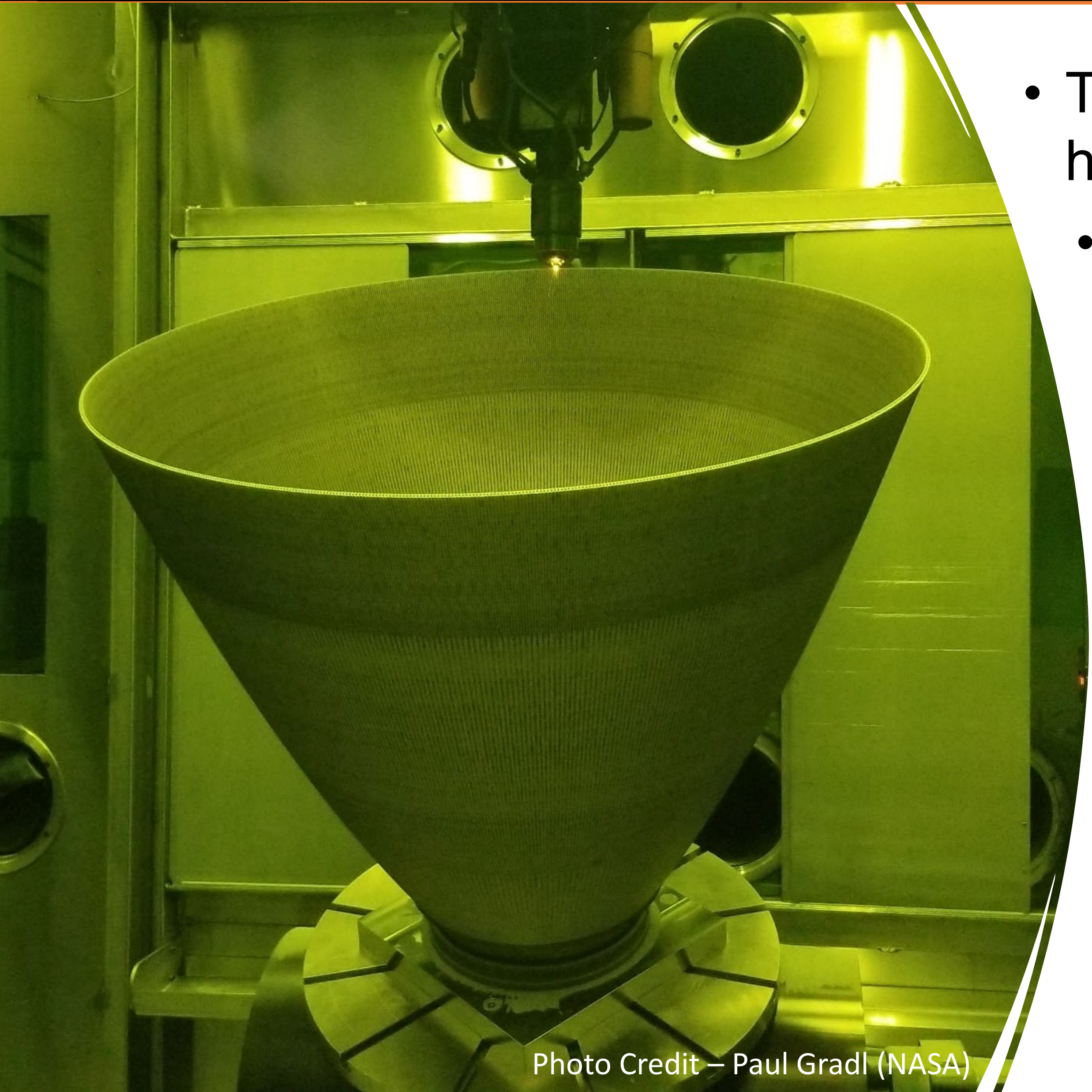


Photo Credit – Paul Gradl (NASA)

- The structural integrity challenge of highly complex AM hardware
  - Systematic framework to address AM flaw state
    - The Inherent Flaw
    - The Process Escape Flaw
  - Critical Initial Flaw Sizes and detectability limits
  - Risk scenarios within the framework
  - The accounting challenge and mitigations for open questions and risks

Challenges with Highly Complex AM Components

Reality:

- AM brings new design freedom leading to larger parts with complex geometries that are not easily inspected in final form
- Such parts will be used in fracture critical applications
- AM is not a perfect process, flaws must be expected
- Fracture control requires a feasible rationale for precluding failure due to flaws

Challenge:

- How do we develop fracture control rationale for un-inspectable AM components?
- How do we communicate risk associated with un-inspectable AM components?

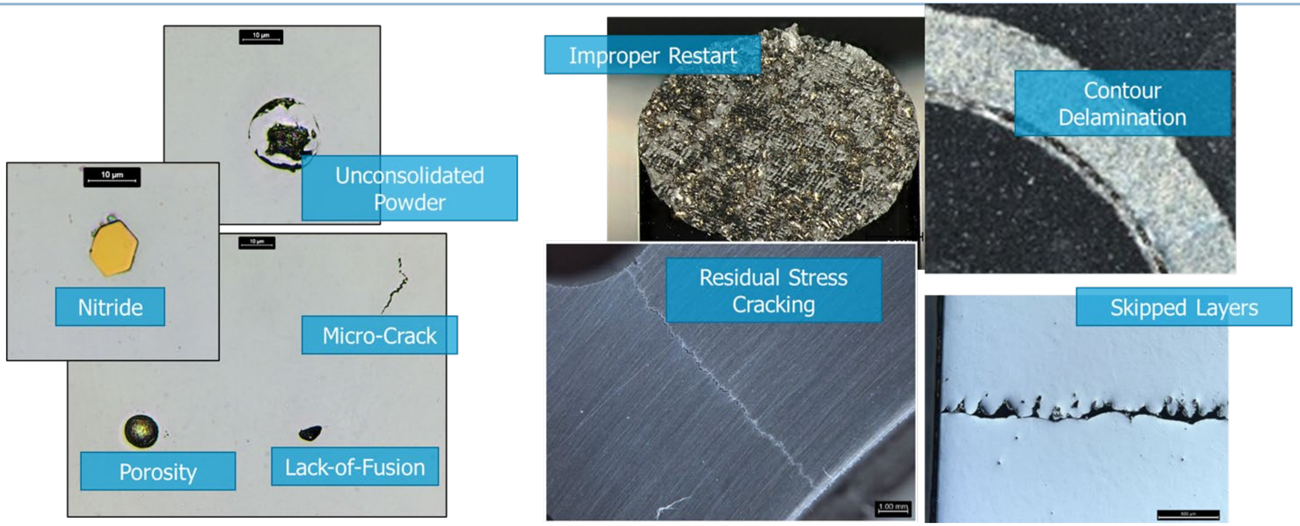
Approach:

- Develop a consistent philosophy for assessing un-inspectable Fracture Critical AM components ***through a systematic framework to address flaw states***
  - Complex problem – expect incremental developments, potential redirection, future adaptations
  - Likely a risk-based acceptance – may not be able to meet current fracture control requirements at the baseline risk level.



AM Fracture Critical Components – why so special?

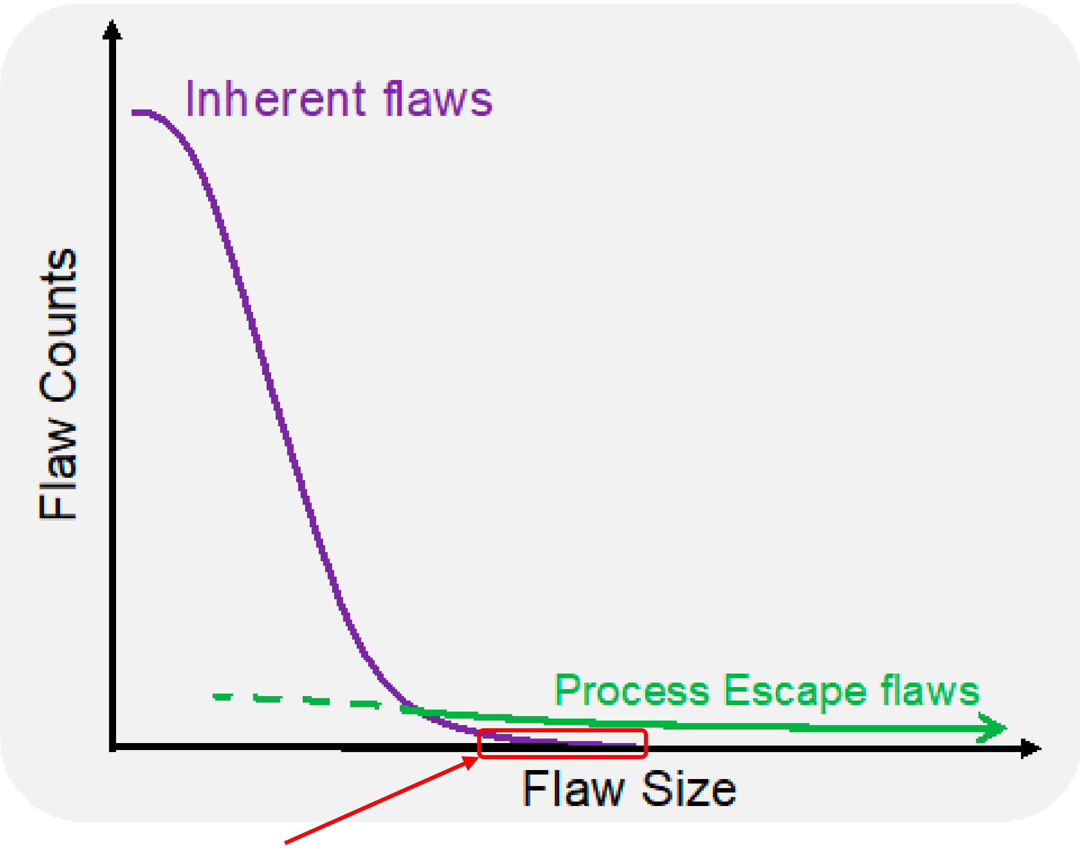
	AM Materials	Wrought Materials
Material Quality	Material quality is highly process-dependent; variation from machine to machine.	More consistent quality due to small number of dedicated production mills with extensive experience.
Flaws	Flaws are intrinsic to the process	Flaws are typically rare
Inspectability	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



Systematic Framework to Address Flaw State

- **Inherent Flaws -** Flaws that are representative of the characterized nominal operation of a <u>qualified</u> AM process
  - 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
  - Not defined by size (e.g., small ≠ inherent), but are expected to be small in a well-controlled AM process
  - The inherent flaw category allows for small, common flaws to be treated as a population, rather than individually
  - Process definition/qualification specimens include the inherent flaw state, which allows for continuity in material properties; the effects of most inherent flaws are “baked in” to the material property definition.
  - *Systematically defining, characterizing, and controlling the inherent flaw state of the AM process can be used as one part of the foundation for developing fracture control rationale for un-inspectable parts*

Distributions of flaw density and size

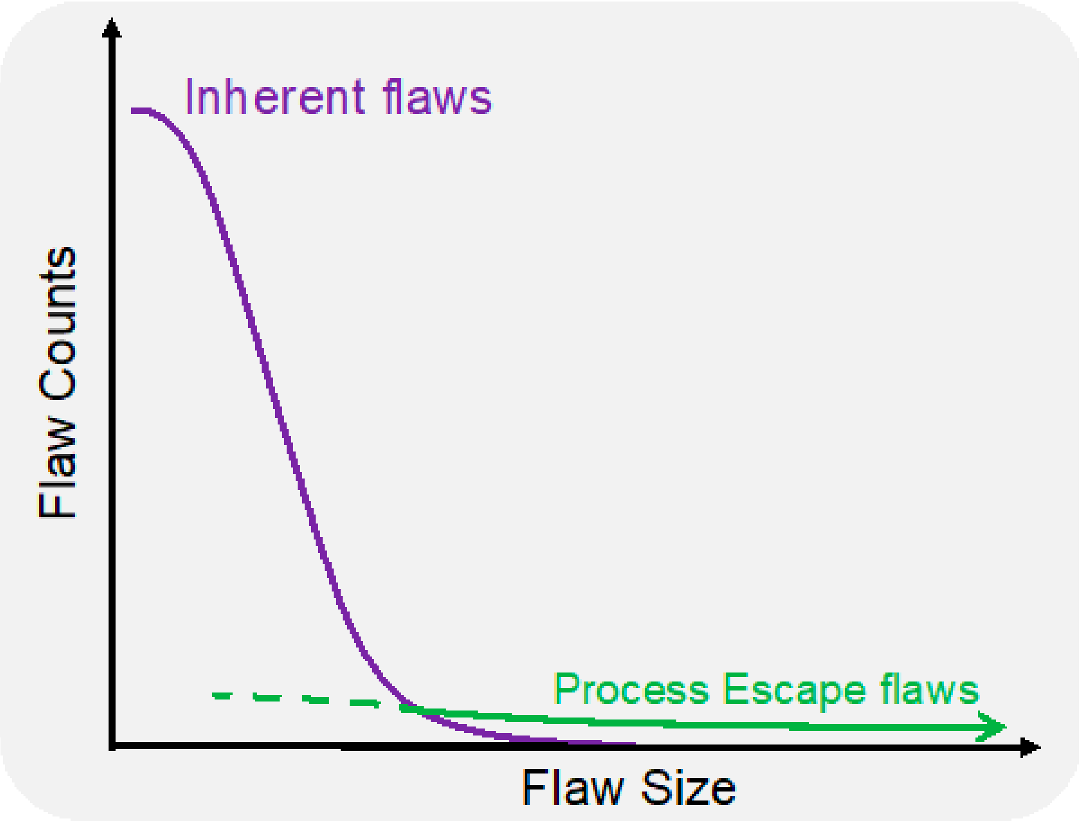


CHALLENGE: large, rare (rogue) flaws of the inherent distribution are likely not accounted for in material characterization and therefore must be accounted for in the damage tolerance framework.

Systematic Framework to Address Flaw State

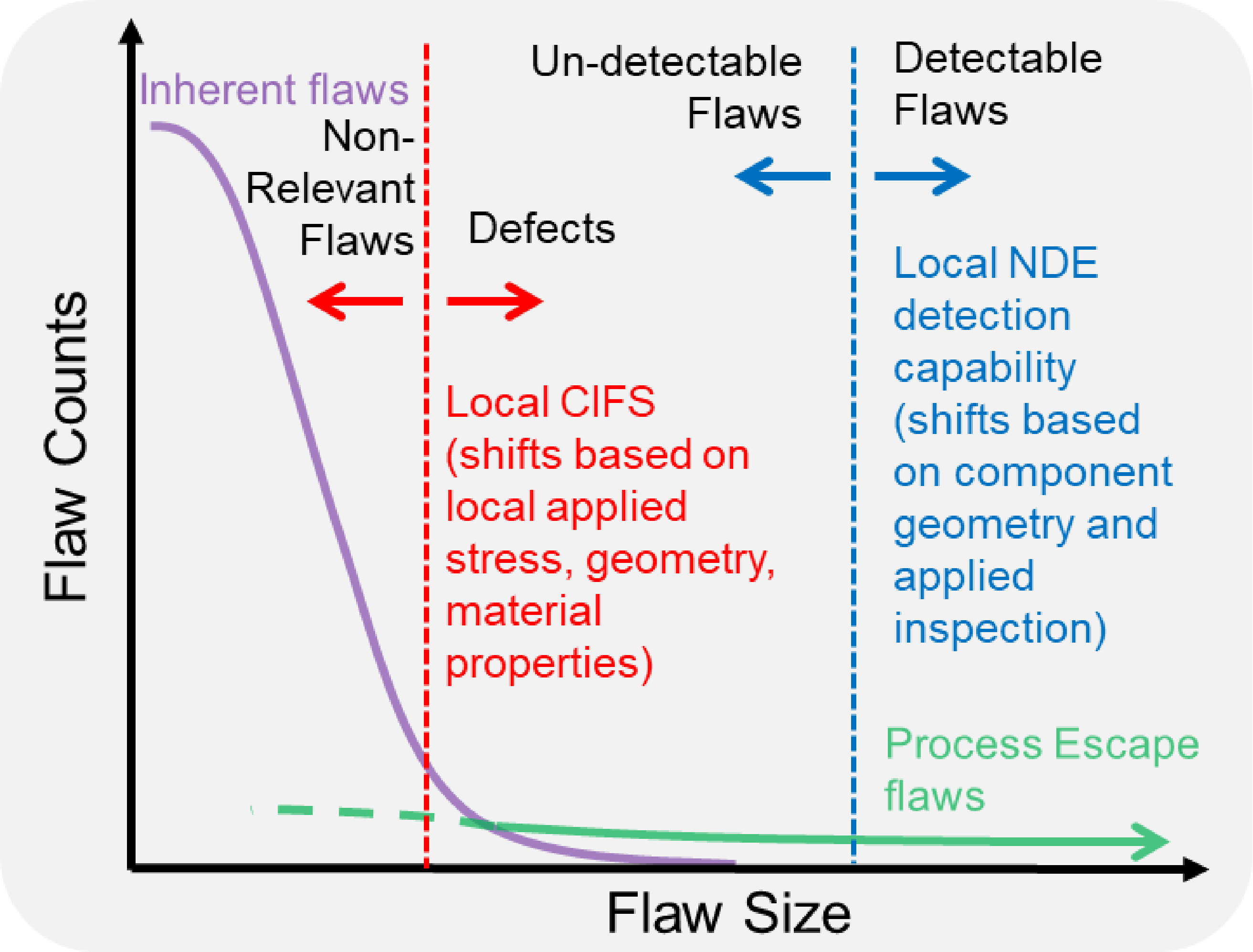
- **Process-escape Flaws** - Flaws that are not representative of the characterized nominal operation of a qualified AM process
  - Associated with some sort of process failure
  - May or may not be larger than inherent flaws, though generally are expected to be larger
  - Have lower occurrence rates than inherent flaws
  - May or may not be detectable
  - Process escape flaw risks 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
    - Triage all process failure modes based on severity, occurrence, and detectability.
    - **Focus is on detecting the process failure**.
    - Employ conservative estimates, physics-based limits, and experience to define appropriate process escape flaw populations.

Distributions of flaw density and size



Critical Initial Flaw Sizes and Detection Limits

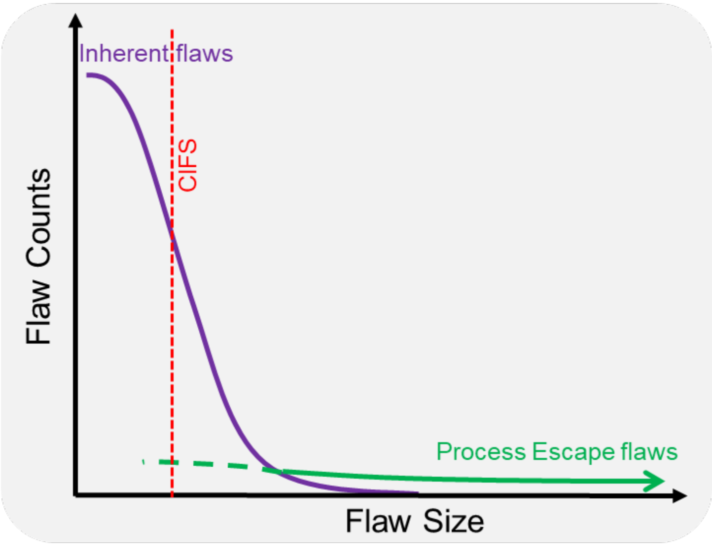
- Evaluate how AM component materials and stress state interact with the defined Inherent and Process Escape flaw distributions based on size:
- Component-level assessments define relevant flaw sizes:
  - <u>Critical initial flaw size (CIFS):</u> the largest flaw that will survive the mission life, with an appropriate factor of safety.
  - <u>Minimum detectable flaw size:</u> the size above which the flaw is reliably detectable with the chosen NDE technique.
- CIFS and detectability limit will shift locally and independently based on the component and application.
  - Infers a "Zone-based" analysis approach
- The relationship between the CIFS and the minimum detectable flaw size defines the risk scenario.



Risk Scenarios to Consider

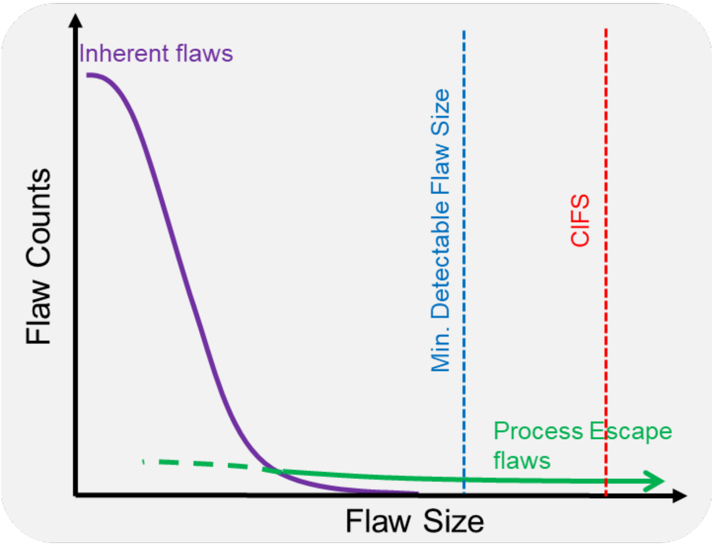
Scenario A: CIFS within inherent flaw distribution

- 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.



Scenario B: 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.

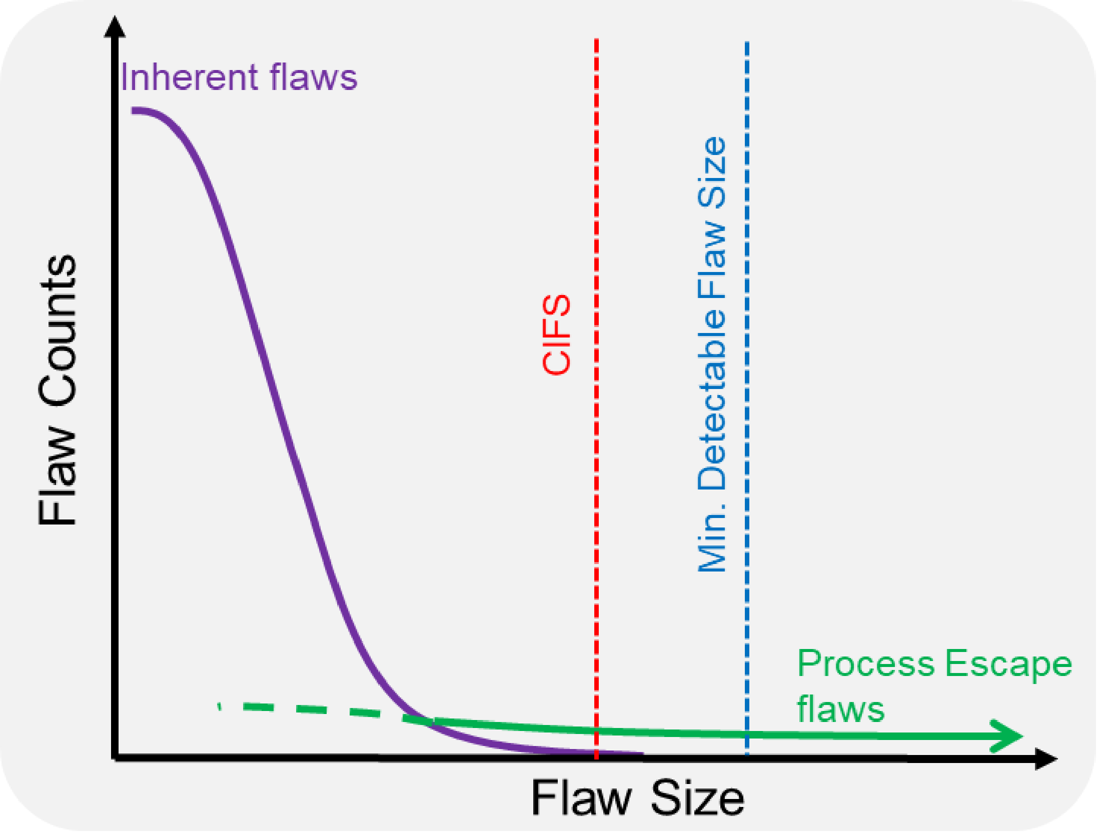


Risk Scenario of Significant Challenge

Scenario C (un-inspectable AM hardware)

- CIFS is larger than most of inherent flaw distribution
- CIFS is smaller than NDE capability

- Possible Approach
  - Inherent flaws are generally below the CIFS, EXCEPT the very rare, large flaw in the tail of the distribution
  - Focus is on process-escape flaws
  - Think about mitigations to limit the risk of process-escape flaws
    - Rigorous PFMEA to identify potential process failures
  - Assess the risk of each process failure
    - Classic Process Controls, in-situ monitoring, machine health monitoring
    - Goal is to control process failures, not process-escape flaws
  - Probabilistic Damage Tolerance
    - Probability of fracture rather than a defined service life
    - Acceptable probability of failure → risk based acceptance
    - Unacceptable probability of failure → redesign or use a different manufacturing process



The Accounting Challenge and Mitigations

- **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 through physics-based bounding rationale and the use probabilistic damage tolerance methodology with extreme value approaches
- **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
- **Open questions and residual risks remain regarding implementation and available mitigations**
  - How are flaw states appropriately characterized? What is a sufficient description of the inherent flaw state?
  - How to leverage In-situ monitoring for either process control or a form of 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 component-level probabilities of failure are acceptable?

All these questions, and more, await us. Join us as we search for the answers!

NASA