NASA’s Approach on the Evaluations of “Materials Engineering Equivalence” Methodologies in Achieving and Sustaining Efficient Qualification and Certification of AM Materials and Parts

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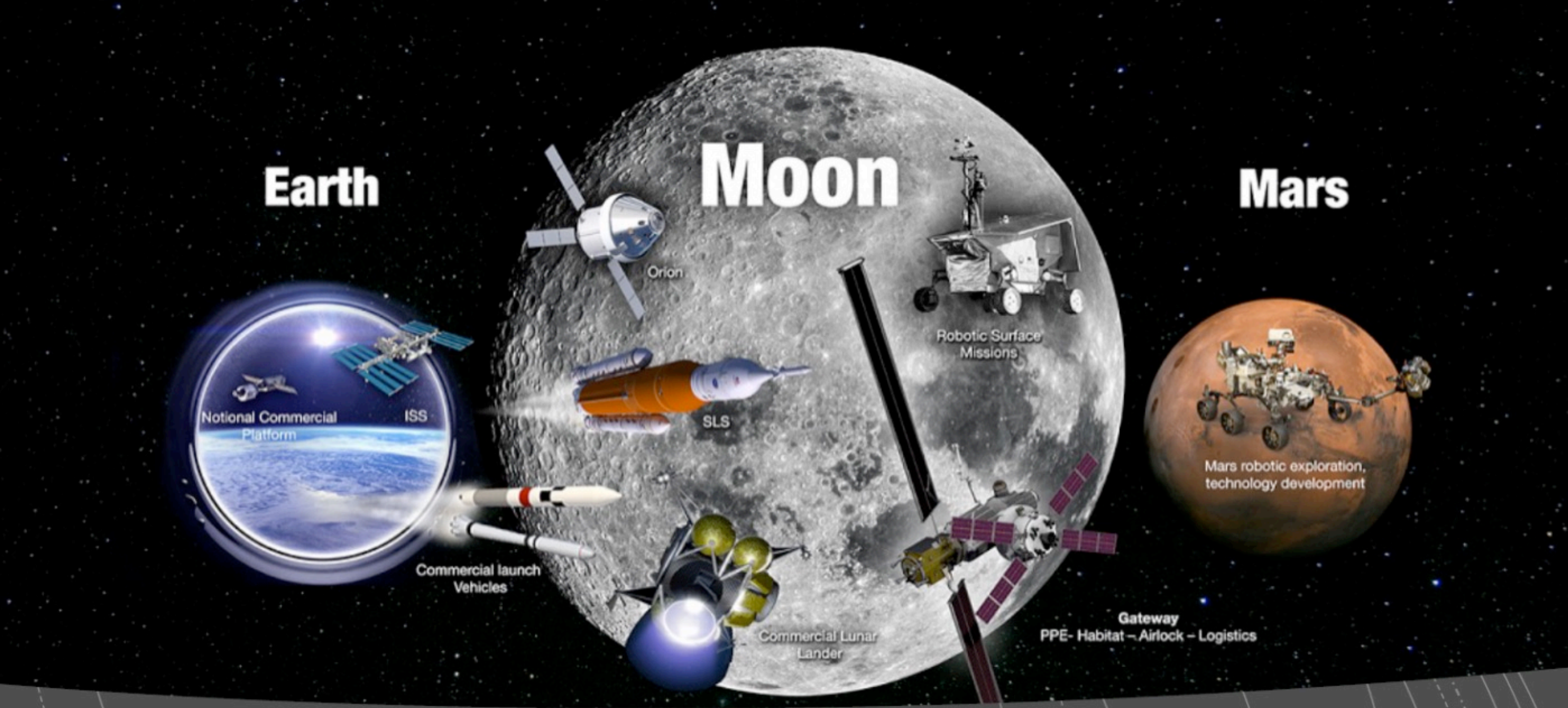
22 March 2023
TMS 2023 San Diego, CA



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

Overview of Presentation


Photo Credit – Paul Gradl (NASA)

- NASA's Agency-wide Certification Perspectives on AM
- NASA Qualification and Certification (Q&C) Strategy – basis, methodology and implementation approach
- Importance of AM Materials Engineering Equivalency Methods
  - Prerequisite, Baseline, Toolbox
  - Examples of applications

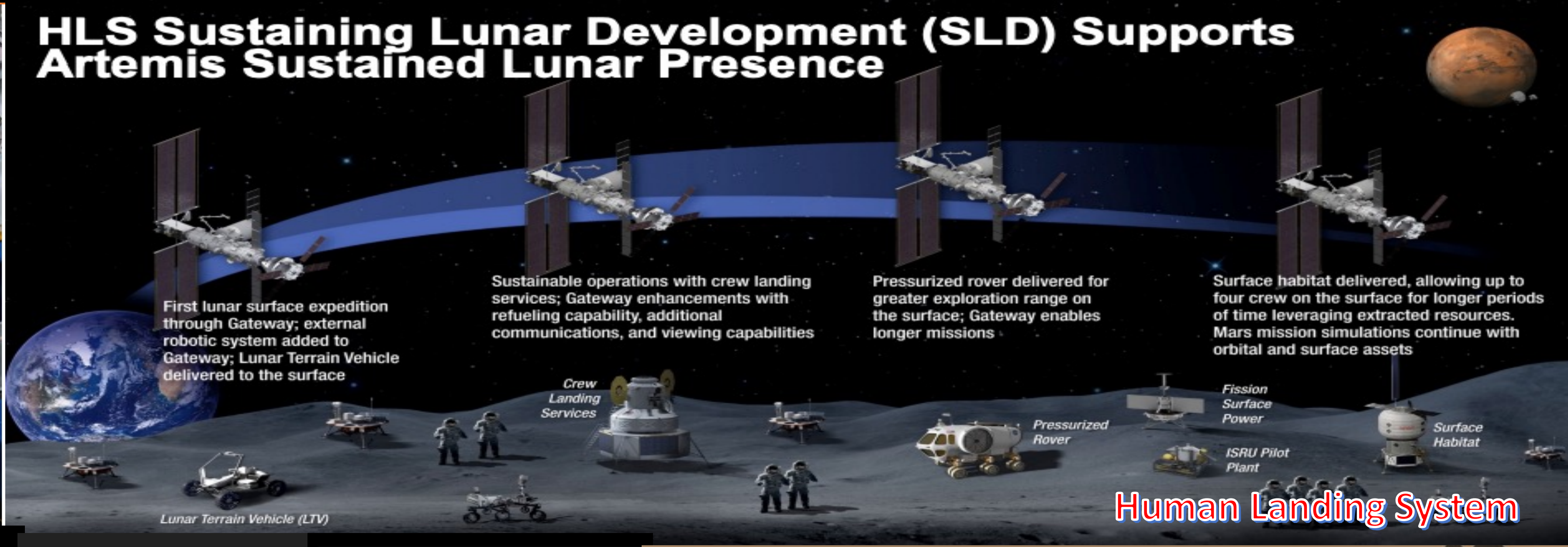
Notes from a Certification Agency Perspective

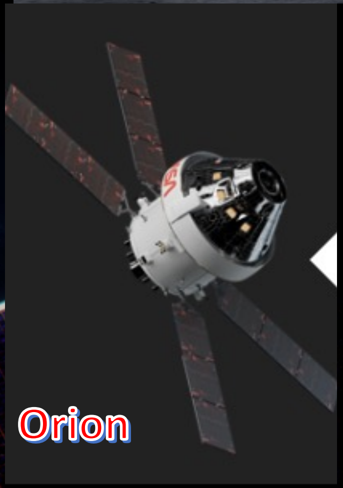
- AM is likely one of the biggest opportunities for enabling the mission, and conserving cost and schedule
- AM technology will continue to be a moving target.
  - It is on a pace similar to Moore's Law.
  - Adds to hype surrounding the technology

- AM in *fracture critical* applications is likely one of the biggest risks in hardware reliability
- AM implementation is local: each AM machine is like a self-contained foundry, with independent failure modes

- As of now, there is no accepted common engineering practice for AM, as exists for other material and manufacturing processes
- A project without AM requirements holds a largely unchecked risk in hardware implementation
- AM implementations and associated risk postures vary widely based on culture and personalities involved
- AM has yet to reach a stage of proper "institutionalization" at many places (over-reliance on individuals)
- NASA's Internal Technical Standard (NASA-STD-6030and 6033) is intended as a basis to understand AM risk and to provide a common standard by which to judge AM implementations --an aid for programs to control risk, with tailoring for efficiency

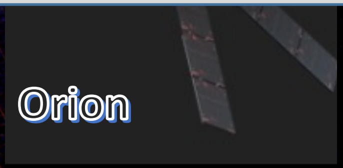
AM Insertion into NASA Spaceflight Systems

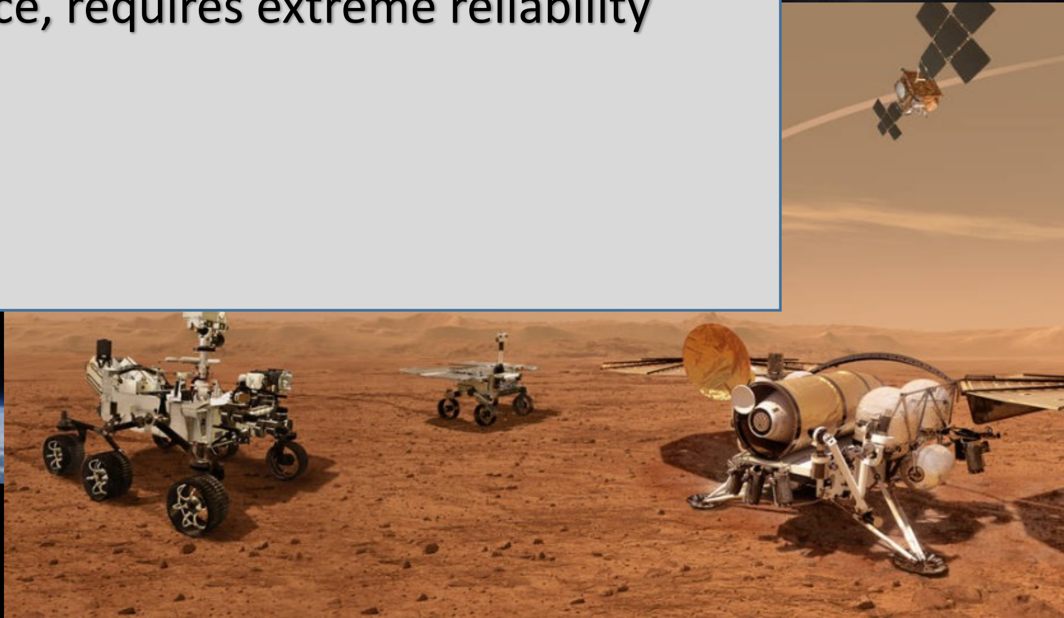




AM Insertion into NASA Spaceflight Systems

NASA moving from Low Earth Paradigm to Deep Space Paradigm
AM Parts being used in critical Spaceflight systems
Human exploration of space, especially deep space, requires extreme reliability





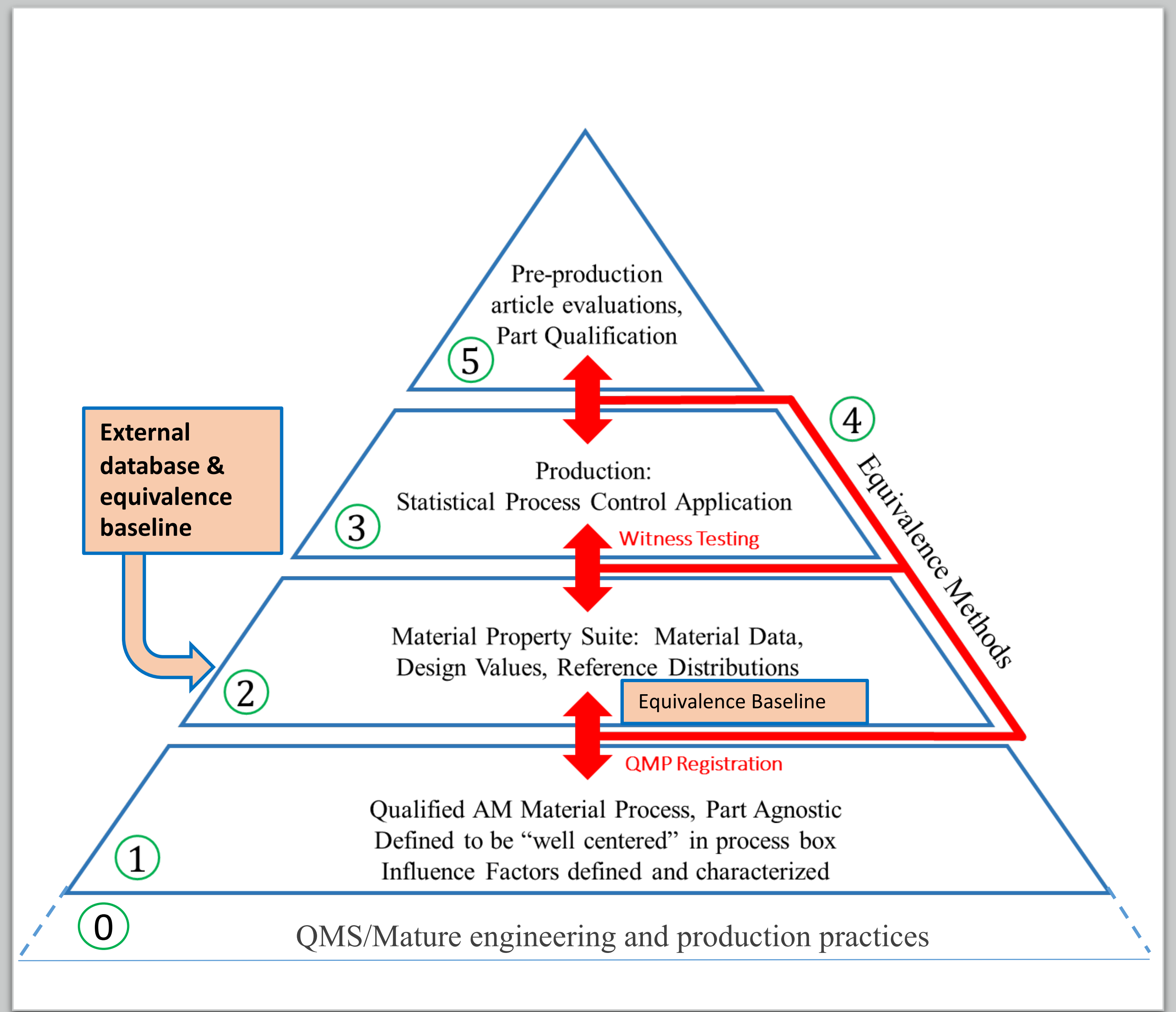
Qualification and Certification – NASA Definition

- Answer varies by industry and even by culture within industries
- The following interpretations are common within NASA:
  - **Qualification** applies to
    - Parts and components
    - Processes
  - **Certification** applies to
    - Design (e.g., status following Design Certification Review)
    - Subsystems (e.g., engine level certification test series)
    - Integrated system (e.g., collective certification for flight for launch vehicle)

- **Good Analogy** (*credit to K. Slattery*)
  - Qualification = Final Exams, varies by subjects, teacher set the requirements, students get graded for their performance
  - Certification = Earning your diploma, need to meet minimum number of credits
  - Bottom line = developing and characterizing a stable, robust, and repeatable process is the equivalent of all the coursework and homework

NASA Q&C of AM Hardware – Backbone Philosophy

- **"Are you mature for production"** (0)
  - Quality Management System (QMS)
  - Prerequisite – matured engineering and production practices
- **"Do you know how to define your process and how to control"** (1) (2) (3)
  - Qualified Material Process (QMP) - Equipment/Feedstock/Fusion and Thermal process
  - Material data/Design Values/Statistical Process Control
- **"Do you understand Part Production Control Requirements"** (5)
  - Part design, assessment and analysis, preproduction articles, and AM production controls
- **Finally, "Do you know how to establish the equivalency holistically between blocks using interrelated and causal material characteristics" – *the Glue*** (4)



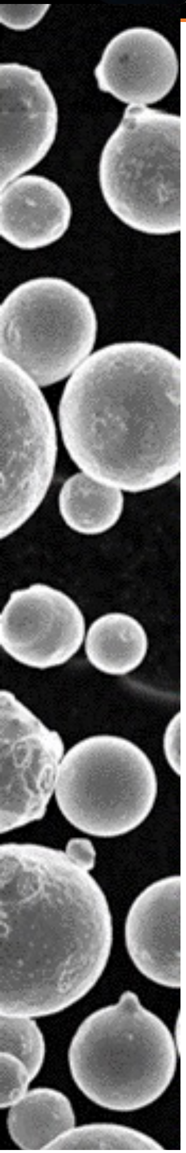
Engineering Equivalency Methodologies

- ***When can I use it*** – To answer typical questions like these…
  - What should I do to qualify my new machine/process regarding material performance to verify that my material allowables are applicable?
  - What evaluations should I do for part acceptance?
  - What should I do to confirm that my AM builds are consistent over time?
  - What do I need to do to confirm that the material in my AM part is representative of the material in my AM specimens used for characterization?
  - How do I enable the use of external AM material property databases for my in-house processes?

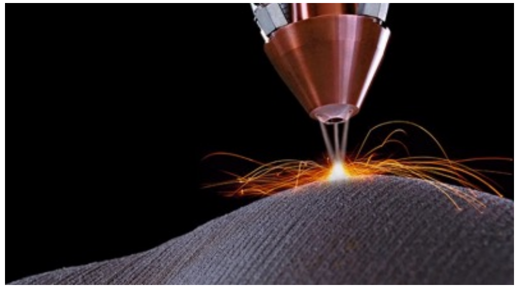
- ***Why should I use it***
  - To make a well-informed decision regarding the consistency of AM materials by leveraging all available information across a variety of metrics of engineering significance
  - To enable the *continuous* substantiation of material allowable and design value concepts in AM
  - To leverage the concept that material performance is derived from the **Process → Structure → Property → Performance** relationship

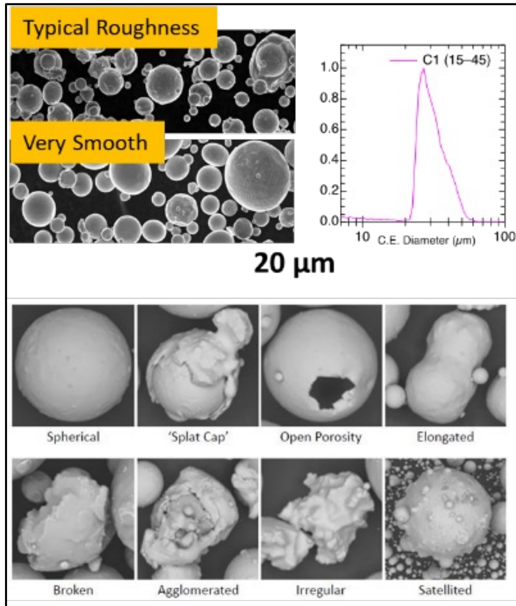
- **Steps to take**
  - Satisfy the prerequisite → set the baseline → use various tools in the toolbox → establish the equivalency with (notional) confidence

Prerequisite to Engineering Equivalency

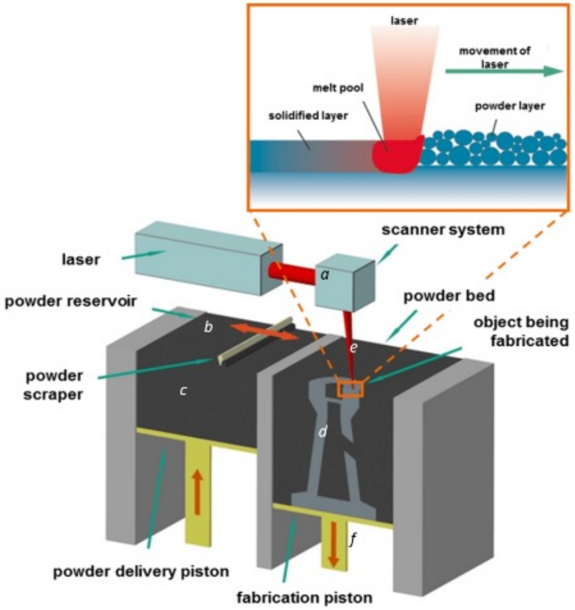


- The starting point for equivalence generally must be a reasonable match to the starting point that created the equivalence baseline
- Avoid expecting equivalence between apples and oranges
- Look for similitude in the following
  - Feedstock specification
    - Alloy chemistry
    - Feedstock production controls
    - Physical characteristics
    - Identical specification is best for similitude
  - Basic process definition and ***qualified processes***
    - LB-PBF under compatible conditions
    - DED under similar build conditions and scope
- Engineering equivalence may be possible across broader differences in starting points, but expect the depth of equivalence evaluation to be more exhaustive.

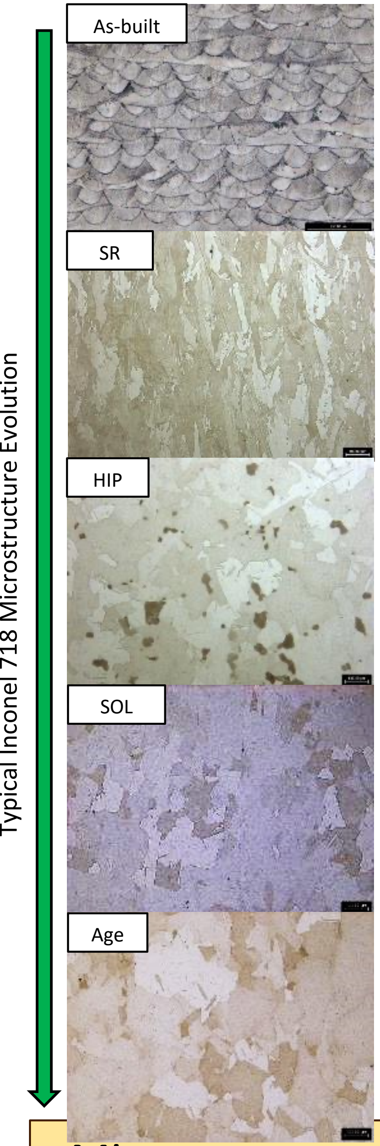




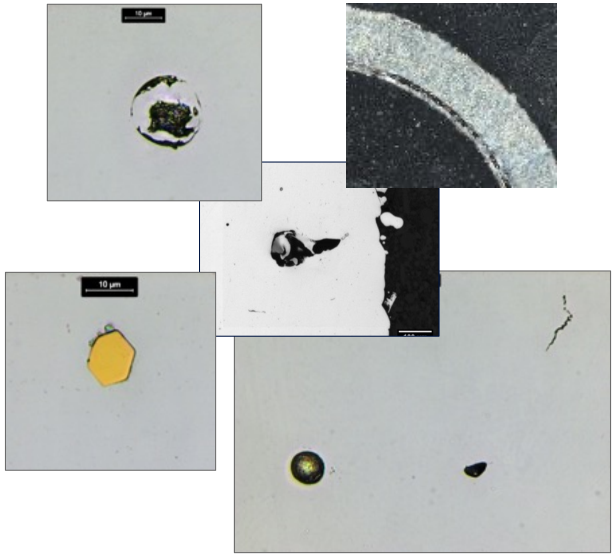
Powder Morphology. Courtesy Metal AM, Winter 2017.

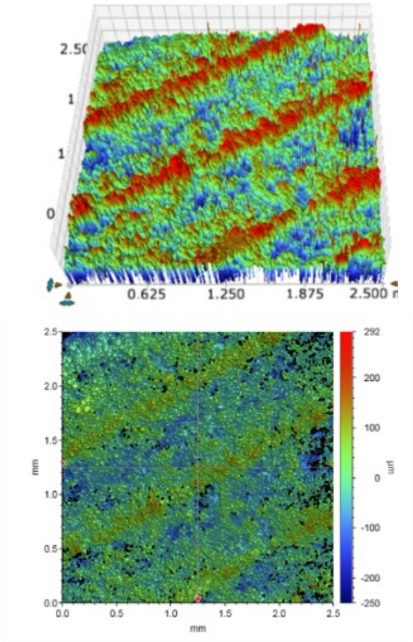


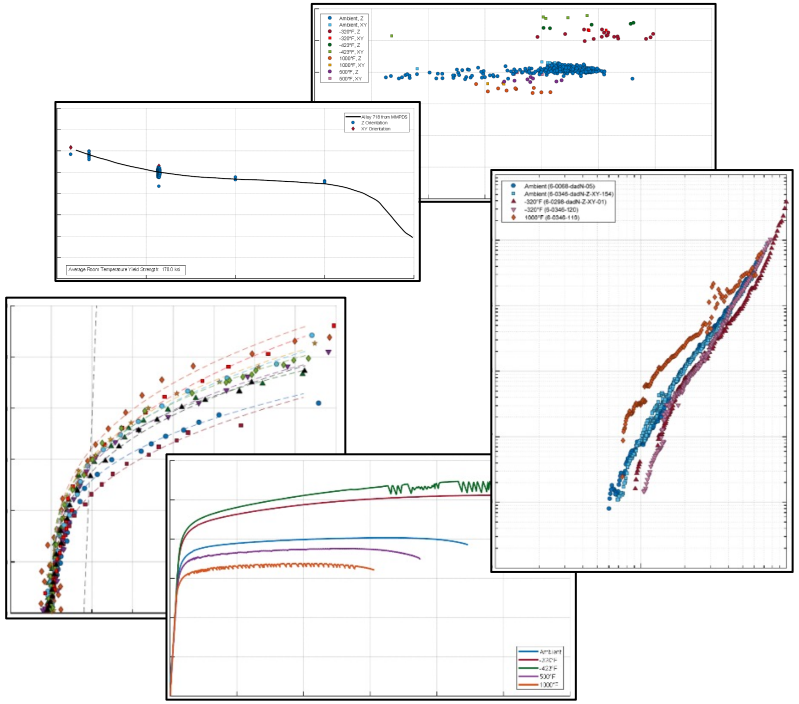
Baseline for Material Engineering Equivalence



- The QMP process yields (or typically utilizes) a core set of data that allows first-principal evaluations of material quality that derive from the ***Process → Structure → Properties → Performance*** relationship.
- Advocating for a single data package called a Material Engineering Equivalence Baseline
  - Includes nominal states and ***allowable variation*** for *microstructure, flaw state, surface quality, and mechanical properties*.
- The baseline data set can be used to keep the AM ecosystem self-consistent and healthy from first principals of material quality and performance







Microstructure

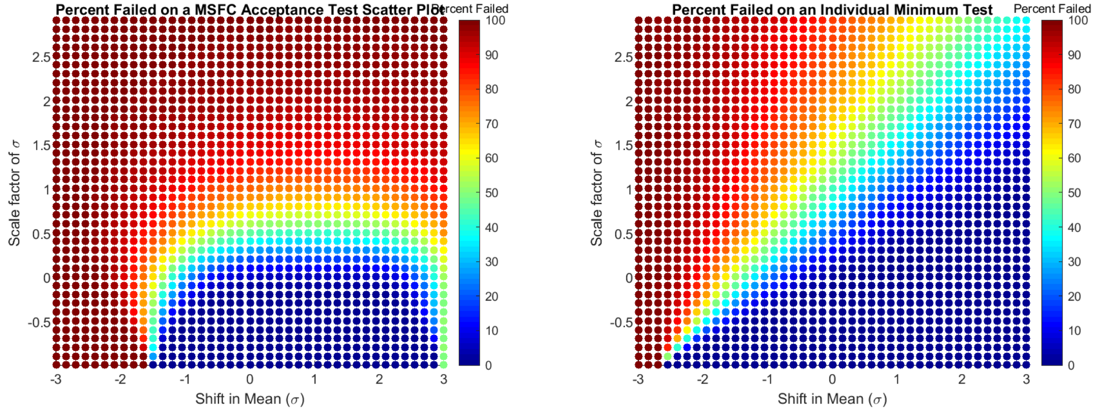
Flaw State

Surface Quality

Mechanical Properties

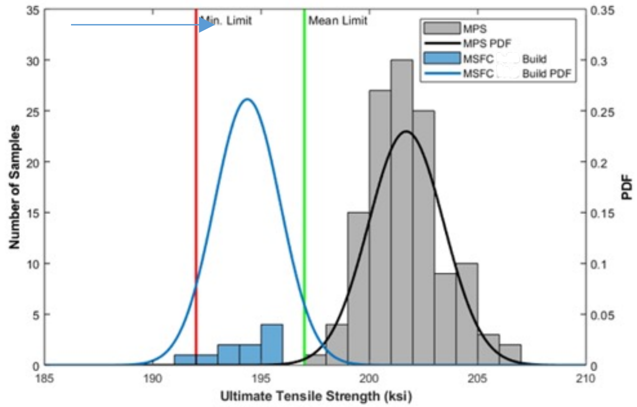
A Tool Box to Engineering Equivalency - Statistics

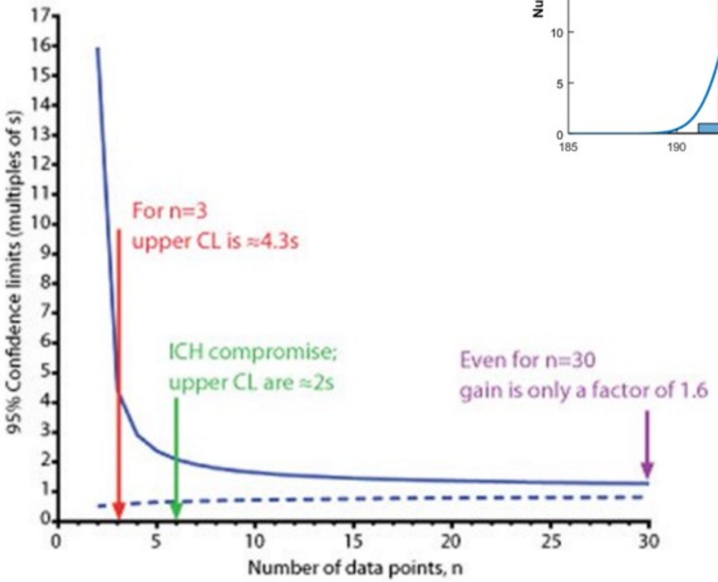
- Statistics - Core part of the equivalence toolbox
- Most situations in AM needing equivalence evaluation do not have the luxury of sufficient data quantities for statistical determinations, *at a desired level of confidence*
  - Despite this, statistics as a tool is ***indispensable in equivalence***
- Leverage stats for definitive determinations whenever feasible
- Use for insight and decision making in engineering equivalence
- Design of acceptance tests, control charts, “in-family” evaluations



Monte Carlo simulations of acceptance test methodologies

In-family / out of family “engineering assessments”





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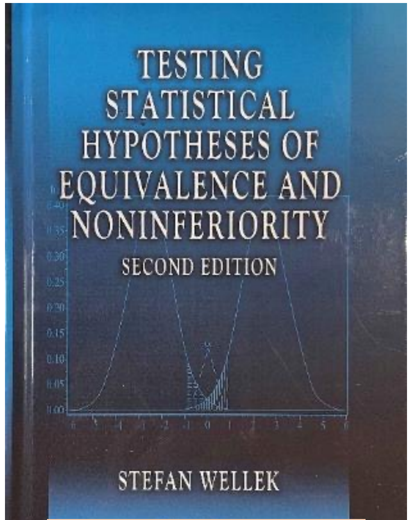
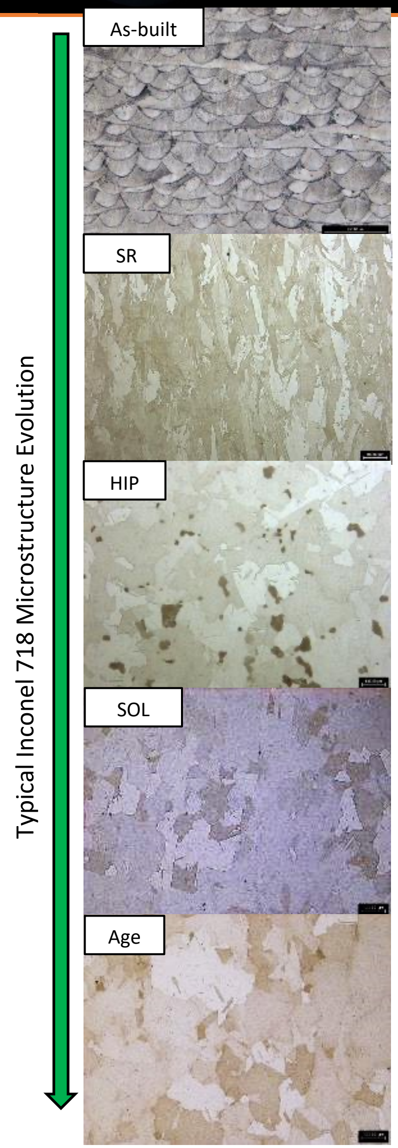
By Chris Burgess, PhD

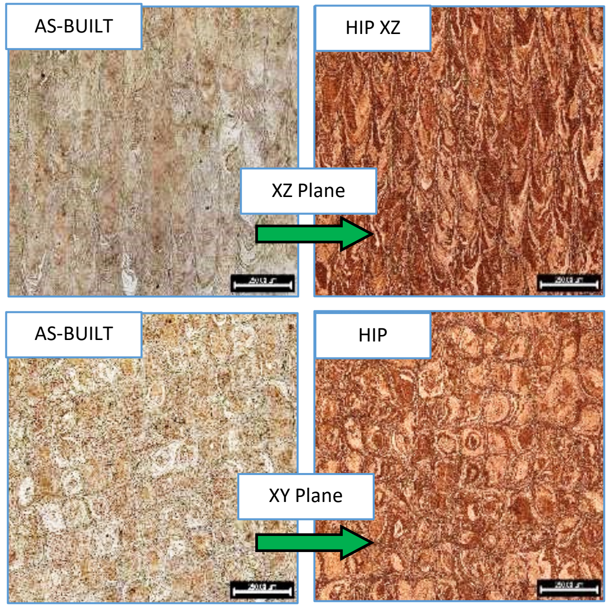


The Deep End…

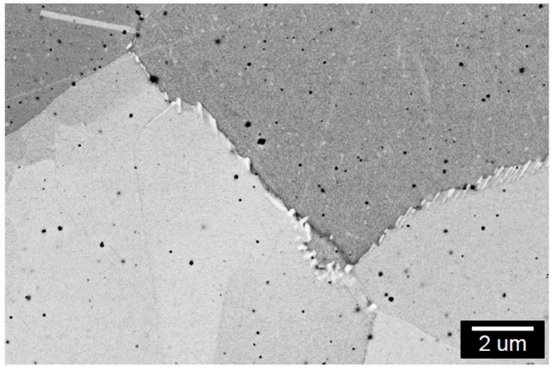
A Tool Box to Engineering Equivalency - Microstructure



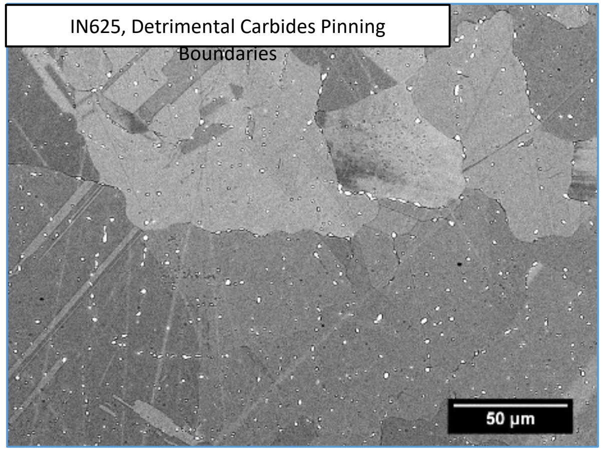
- Long term success in AM means understanding microstructure
- Material performance derives from microstructure, *particularly the details of performance*
  - E.g., corrosion or fatigue crack initiation are performance details not always well correlated to other properties
- Equivalence in microstructure can be difficult to quantify
  - Requires engineering judgement
- Understand the desired, or expected, microstructure
  - Define its core characteristics in the as-built and final forms
  - Phases, precipitates, recrystallization, grain size, grain shape, twinning, etc.
- Understand potential undesirable microstructures
  - Describe what the microstructure should NOT be



GR-COP42, Typical limited recrystallization



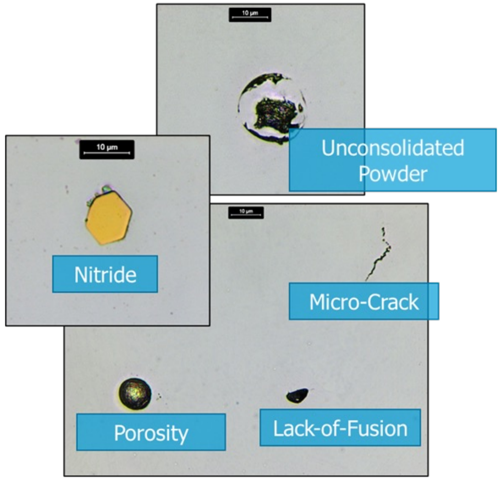
IN718 δ-phase at boundaries

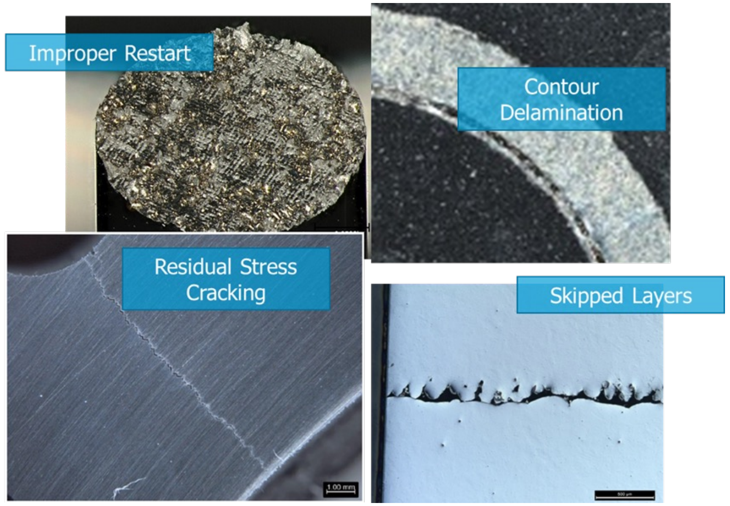


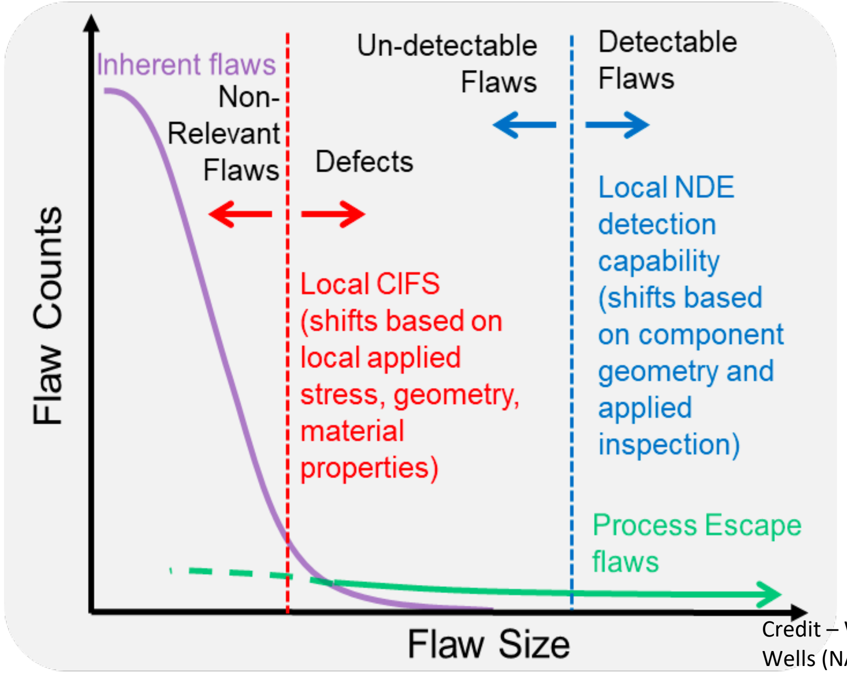
Undesired lack of recrystallization in IN718

A Tool Box to Engineering Equivalency – Flaw Population

- In AM, the flaw population is a primary governor of material performance
- Quantifiable metrics are feasible to aid equivalency judgements for common inherent flaws — generally the focus for equivalency
  - Causes, types, sizes, and frequencies of occurrence
- Equivalence in flaw population focuses on consistent material of intended quality — process escape flaws are not the focus here.

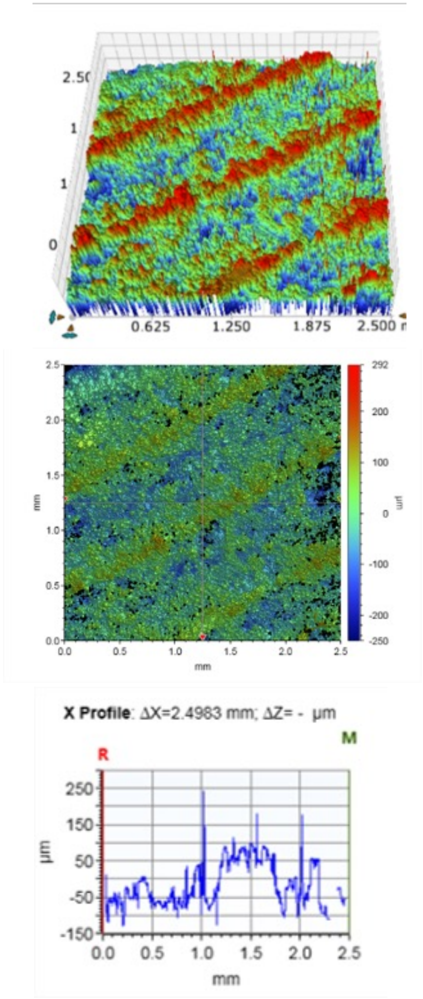




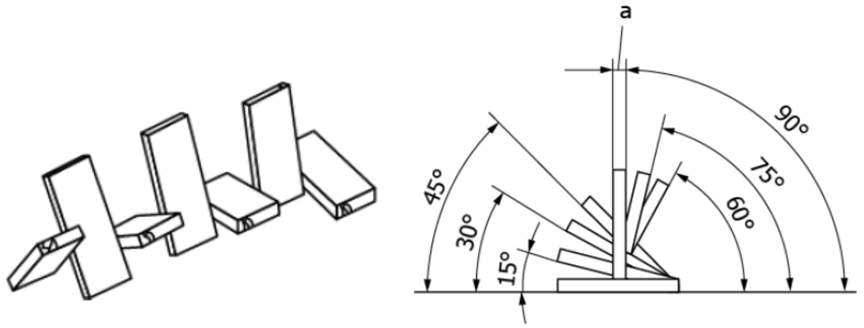


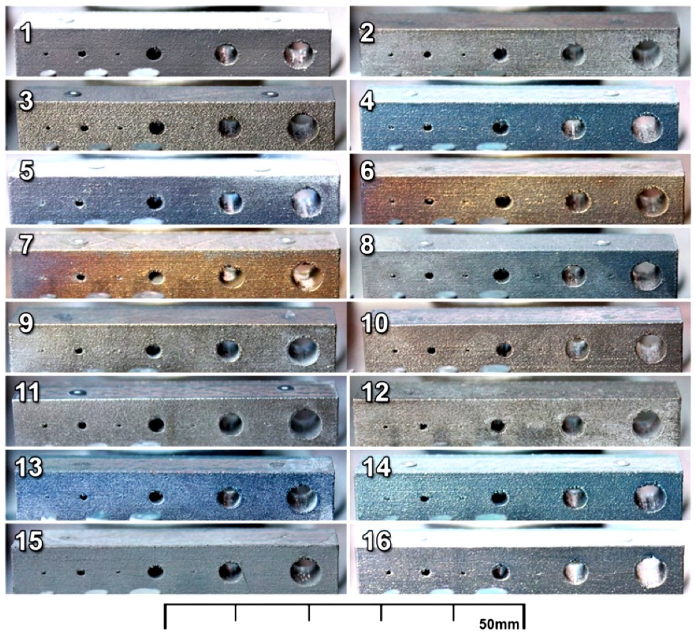
Credit – Wil Tilson and Doug Wells (NASA)

A Tool Box to Engineering Equivalency – Surface Quality



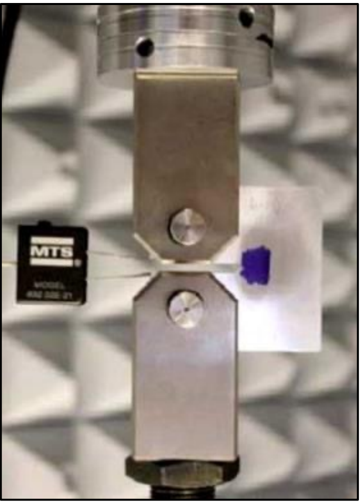
- Evaluation of the surface quality, resolution of detail, and accuracy in dimensions can be important metrics when evaluating equivalency
- Surface quality may have direct influence on mechanical performance of AM materials when as-built surfaces remain
  - Fatigue life
  - Ductility
- Surface quality has numerous existing metrics defined, though their applicability to AM surfaces remains a topic of research
- Evaluations of equivalency regarding detail resolution can be difficult and subjective, not unlike microstructure comparisons
  - Brings "engineering judgement" to bear in engineering equivalency assessments



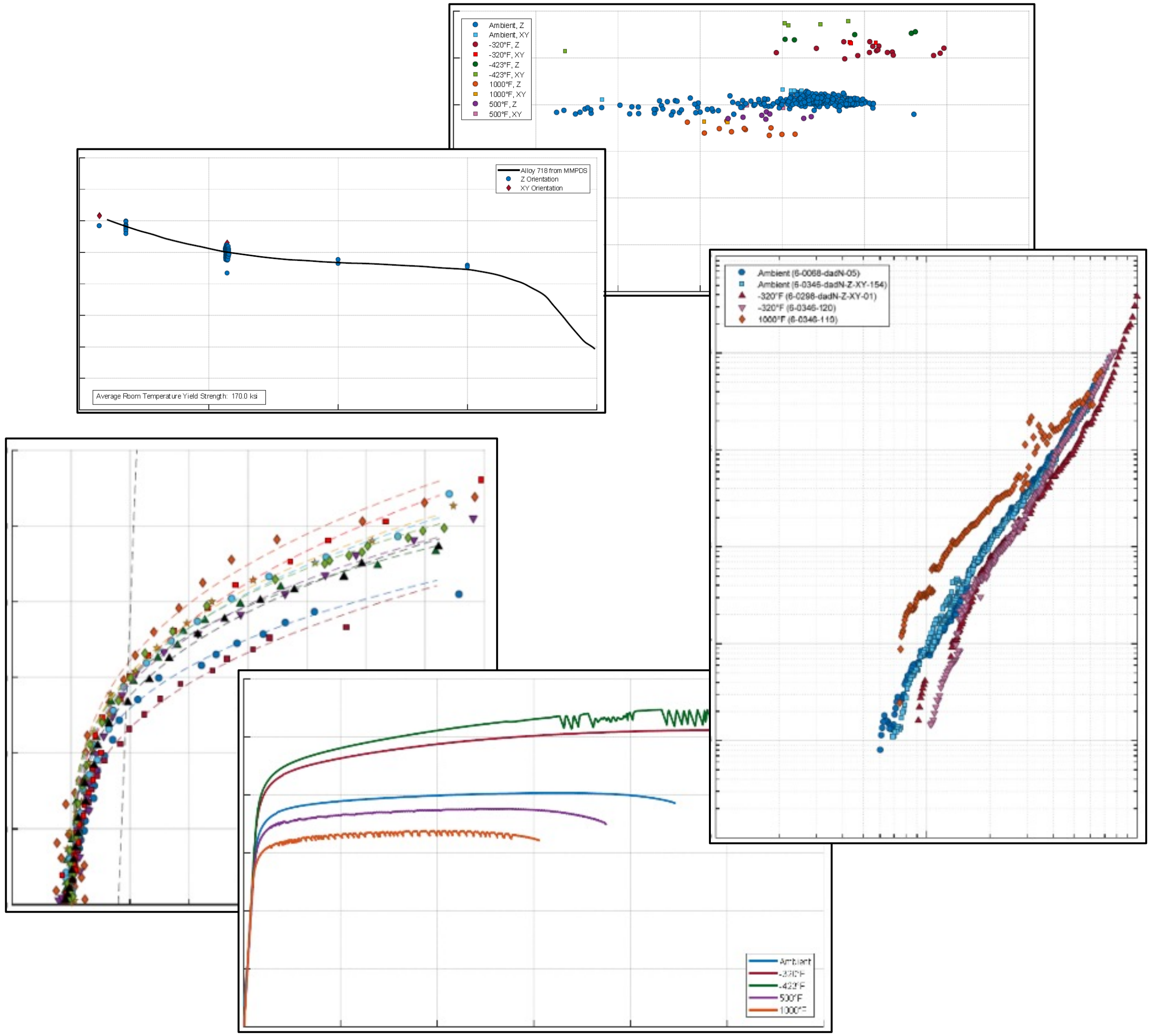


Gradl et al.,
Additive Manufacturing 47 (2021) 102305

A Tool Box to Engineering Equivalency – Mechanical Performance



- Tensile strength is the predominant indicator of performance
  - Ultimate and yield strength
  - *Ductility* (elongation and reduction in area)
- Consider other failure mechanisms in the material system
  - Various failure mechanisms may show some correlation to each other, but actual material capability in each will be independent
    - Fatigue crack initiation
    - Toughness and tearing resistance
    - Fatigue crack growth rate
    - Special interest properties
      - Stress rupture
      - Temperature dependence
      - Environmental (HEE, SCC, SLC…)



Examples of Applications of EQ

Machine/Process Qualification (IQ/OQ)

See Qualified Material Process, QMP, and QMP Registration in NASA-STD-6030

Objective:

Demonstrate material quality from a specific machine under defined conditions is equivalent to past material used to set design properties.

Why use Engineering Equivalence?

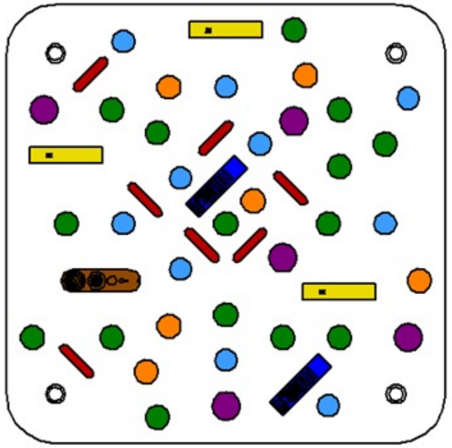
Re-occurring operation required of every AM machine. Testing quantities for high statistical confidence is generally impractical, or limited to a single attribute (e.g., tensile).

Tools: (use them all)

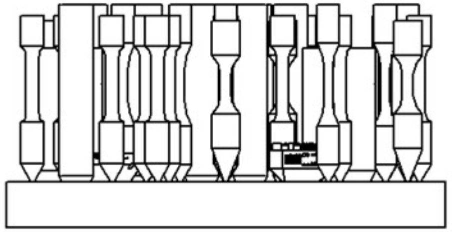
Feedstock similitude, microstructure, flaw population, surface quality, mechanical properties, statistical assessment

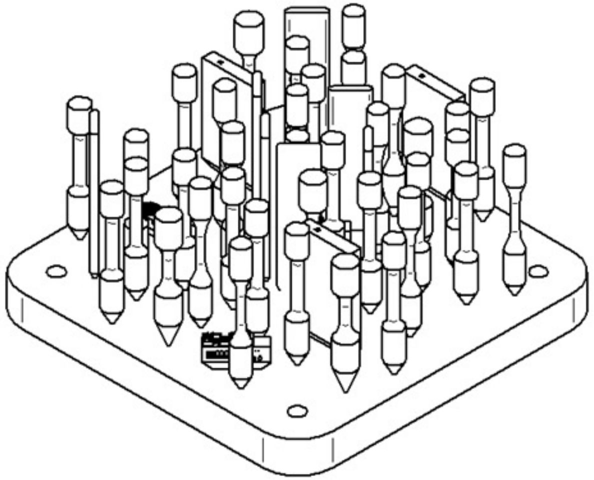
Equivalence Confidence:

Moderate to high, based on limited evaluations available across all tools.



Specimen Type	Qty	Name	Key
High Cycle Fatigue	10	HCF-1 thru HCF-10	
Low Cycle Fatigue	5	LCF-1 thru LCF-5	
Tensile (RT)	15	TN-1 thru TN-15	
Tensile (Cryo, ET)	6	TN-16 thru TN-21	
Fracture Toughness	3	FT-1 thru FT-3	
Metallographic Samples	7	MET-1 thru MET-7	
Dimensional Samples	2	D-1 thru D-2	
Contour Analysis Samples	1	C-1	





Examples of Applications of EQ

Material Allowable and Design Value Databases

Objective:

Leverage pre-existing AM material databases for material allowables and design values to reduce cost.

Why use Engineering Equivalence?

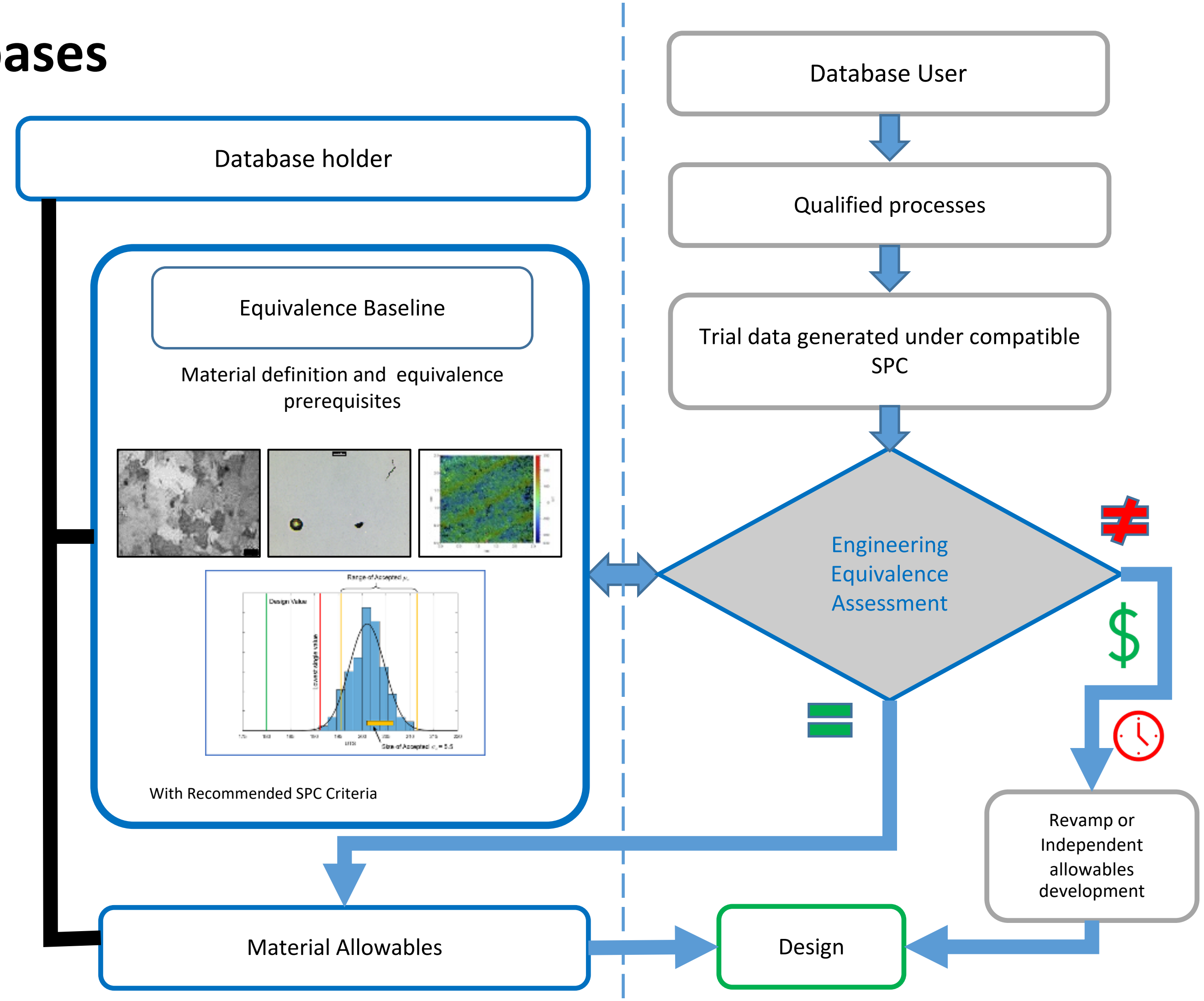
Equivalence evaluations will be less expensive than full characterization. Similitude across numerous metrics between baseline and trial data reduces the risk of unforeseen failure modes in the trial material and provides confidence trial material will meet expectations of the alloy.

Tools: (use all available)

Feedstock/process similitude, microstructure, flaw population, surface quality, mechanical properties, statistical assessment (usually moderately robust)

Equivalence Confidence:

High, based on evaluations available across all tools. Evaluations generally will have tangible statistical significance in sample quantity and lot variability.



Examples of Applications of EQ

Part Qualification (PQ)

Objective:

Substantiate within pragmatic limitations that the material quality throughout a new AM part is equivalent in the engineering sense to past material used to set design properties, i.e., substantiate specimen-to-part equivalence for applicability of allowables.

Why use Engineering Equivalence?

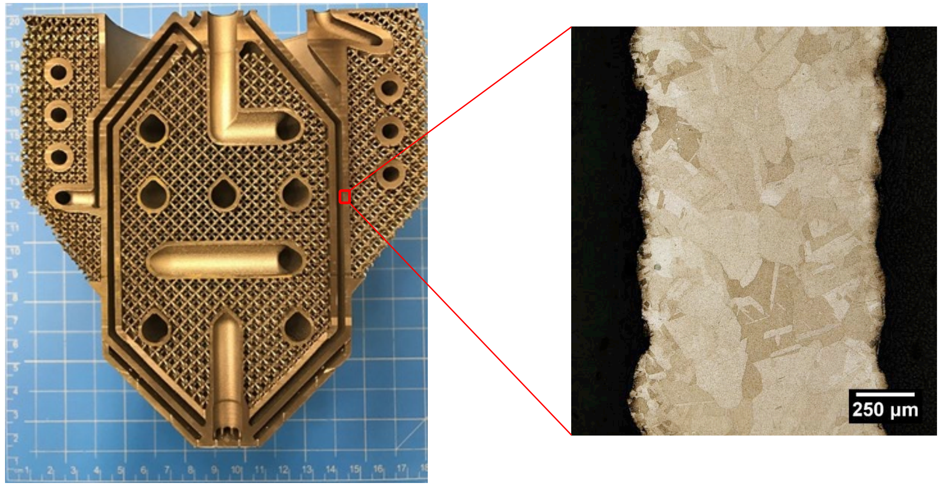
AM material quality within parts is likely to vary with geometry and build conditions. Evaluation of all properties directly is rarely feasible. Require internal quality and mechanical properties to be in family with the equivalence baseline. Engineering judgement is likely required.

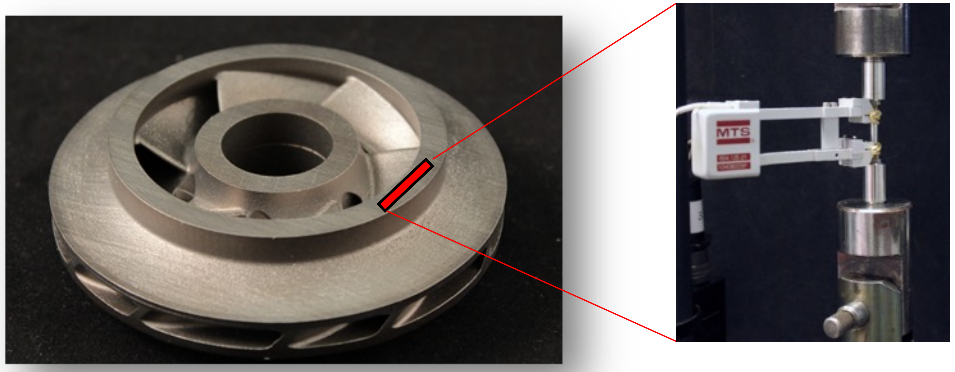
Tools: (use all available, may be limited)

Feedstock similitude, *microstructure & flaw population (always)*, surface quality, mechanical properties (as available), statistical assessment (usually limited)

Equivalence Confidence:

Moderate, based on limited evaluations available across tools.





Conclusions

- There is more to AM alloys than bulk chemistry and tensile strength.
- Most AM alloys are exceedingly complex and require precise metallurgical control to meet engineering expectations against a variety of failure mechanisms that are often assumed to follow a specific alloy or alloy class based on precedent from traditional product forms:
  - Strength, ductility, fatigue, heat resistance, cryogenic ductility, toughness, tearing resistance, fatigue crack growth, stress rupture, hydrogen embrittlement, intergranular cracking, general corrosion, stress corrosion cracking, etc.
- Engineering equivalence is a methodology for evaluating the quality of AM materials that acknowledges the broad range of characteristics that must be assured for an alloy to meet its expectations.
- Like all alloys, AM material performance is derived from the Process → Structure → Property relationship
- Equivalence means “in-family.” ***Not*** “better than or equal to.”
- Maintaining engineering equivalence in AM materials when qualifying processes, qualifying parts, applying SPC, and accepting builds is the cornerstone of enabling the reliable use of material allowables and design values.
- Engineering equivalence is the enabler that allows the AM material ecosystem to remain healthy and self-consistent in the face of sensitive processes with a multitude of known and unknown failure modes.
- The devil is in the details: engineering equivalence is not an easy task - it requires reliable and diverse datasets, depth of knowledge in materials, good engineering judgement, and collaboration between engineering and quality assurance organizations.
- Balance is needed in the application of engineering equivalence to maintain the objectives and advantages of material engineering equivalence without an undue burden on operations.

Giving Credits to Co-Authors

- Doug Wells (original presenter on this topic)
- Will Tilson
- Samuel Cordner
- Mallory James
- Brian West
- Andrew Glendening
- Richard Russell