Overview of Flight Certification Methodology for Additive Manufacturing

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Frontiers in Additive Manufacturing Evolution
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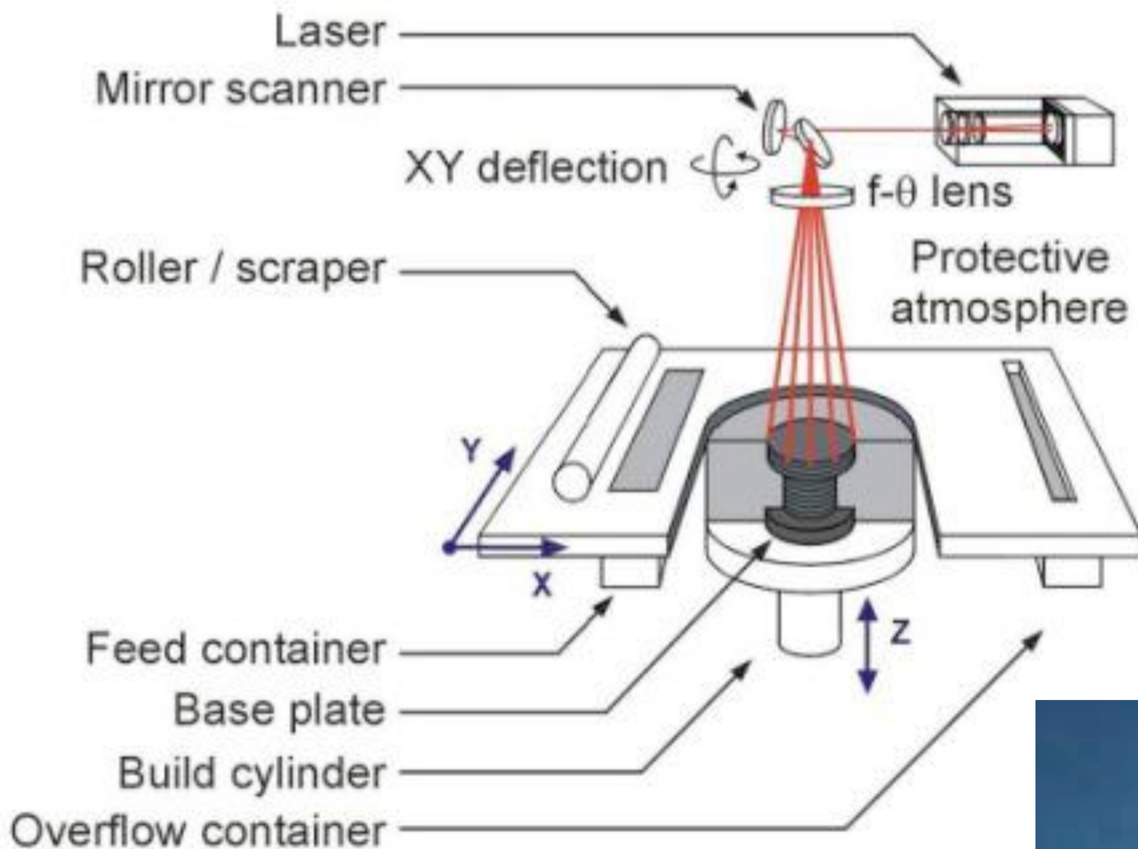
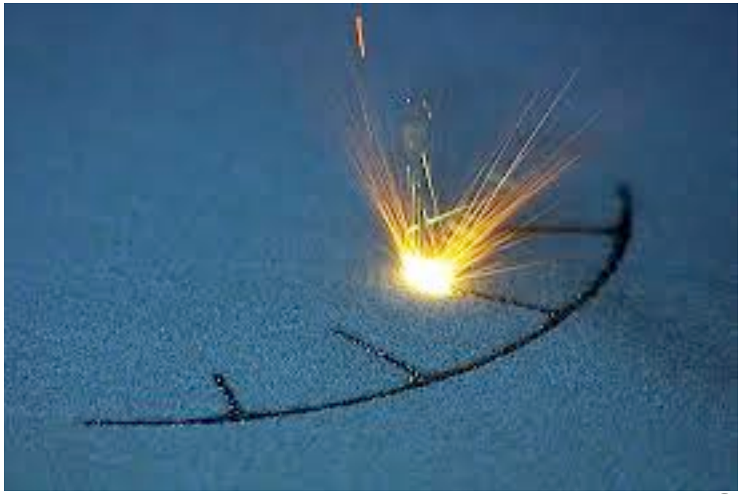
AM Certification

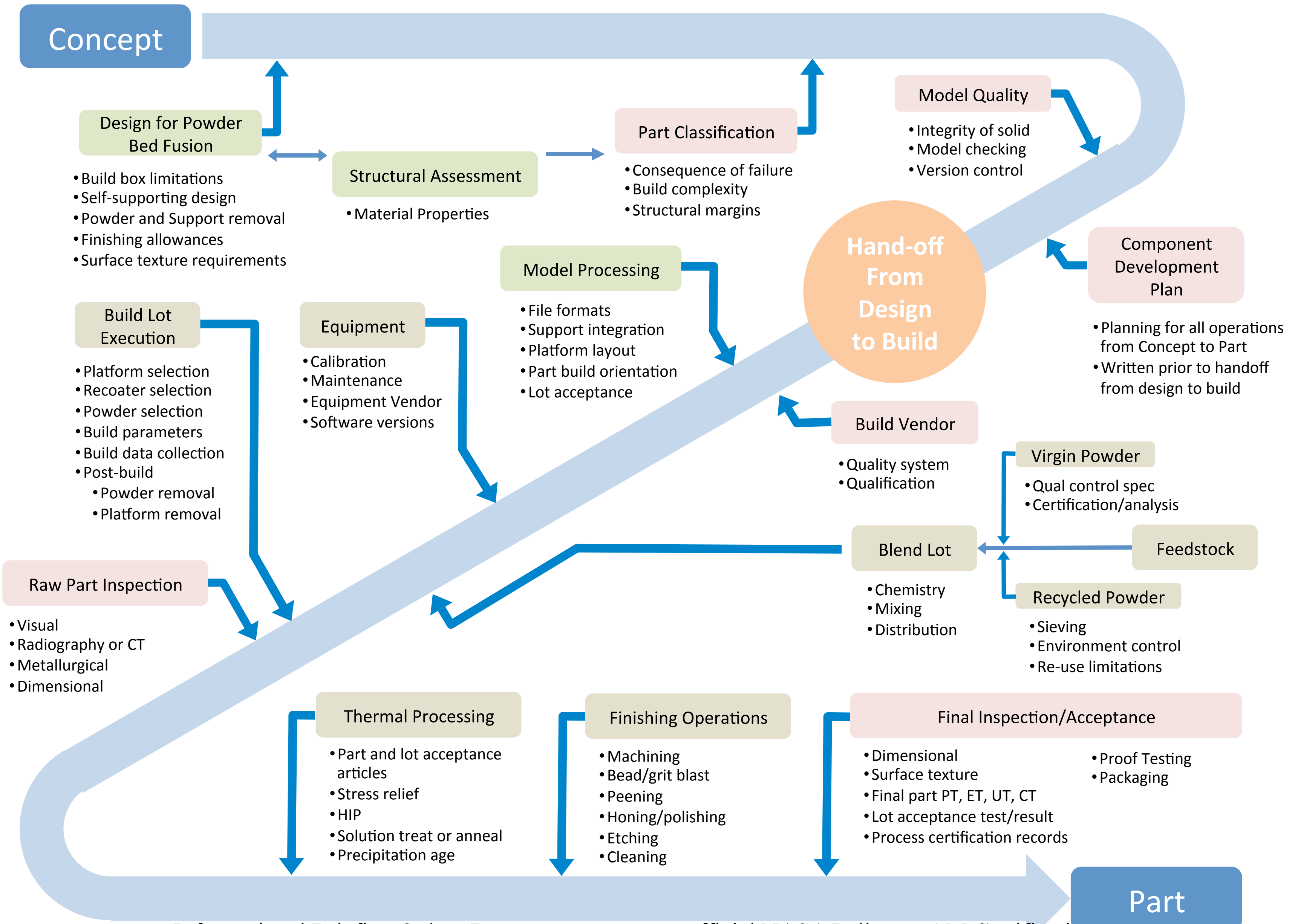
- Opportunity
  - Additive manufacturing offers revolutionary opportunities in mechanical design innovation, system performance, cost savings, and schedule reduction
- Risk
  - Process sensitivity :: unknown failure modes
  - Lack of governing requirements
  - Rapidly evolving technology
  - Too easy, too cheap = ubiquitous, lack of rigor
  - AM related failure tarnishes the technology
- Requirement choices dictate how we embrace, foster, and protect the technology and its opportunities wisely

The Powder Bed Fusion Process





The AM Path: Concept to Part



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Requirements Approach

- Typical scenario used to control critical processes
  - Broad Agency-level standards provide requirements
    - NASA-STD-6016 Materials
    - NASA-STD-5012 Propulsion Structures
    - NASA-STD-5019 Fracture Control
  - *Which call* process or quality standard controls product, for example:
    - AWS D17.1 Fusion Welding for Aerospace Applications
    - SAE AMS 2175 Classification and Inspection of Castings
    - SAE AMS 4985 Ti-6-4 Investment Castings
  - *Which call* considerable collections of "Applicable Documents"
- Additive manufacturing standards currently very limited
  - Lacking standardization is a universal, industry-wide issue, not just NASA
  - Mainly ASTM, Committee F42 on Additive Manufacturing
    - F3055 Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718)with Powder Bed Fusion
    - F2924 for Ti-6-4, F3001 for Ti-6-4ELI, F3056 for In625
  - Other Standards organizations in planning
    - SAE AMS, AWS
- NASA required to develop government requirements to balance AM opportunities and risks.

NASA Approach to AM Requirements

- Develop a Center-level (MSFC) requirement
  - Allows for more timely release (now targeting May 2015)
  - Review circle much wider than common
    - Centers
    - NESC (materials, structures, NDE, Reliability)
    - Partners (Aerojet-Rocketdyne, Lockheed Martin)
    - Industry (GE, Honeywell)
    - Certifying Agencies (FAA, USAF)
- Revise as needed / Levy as required
- Watch progress of standards organizations and other certifying Agencies
- Incorporate AM requirements at an appropriate level in Agency specifications
  - Incorporate necessary detail, or
  - Point to Center document or industry standard

AM Certification

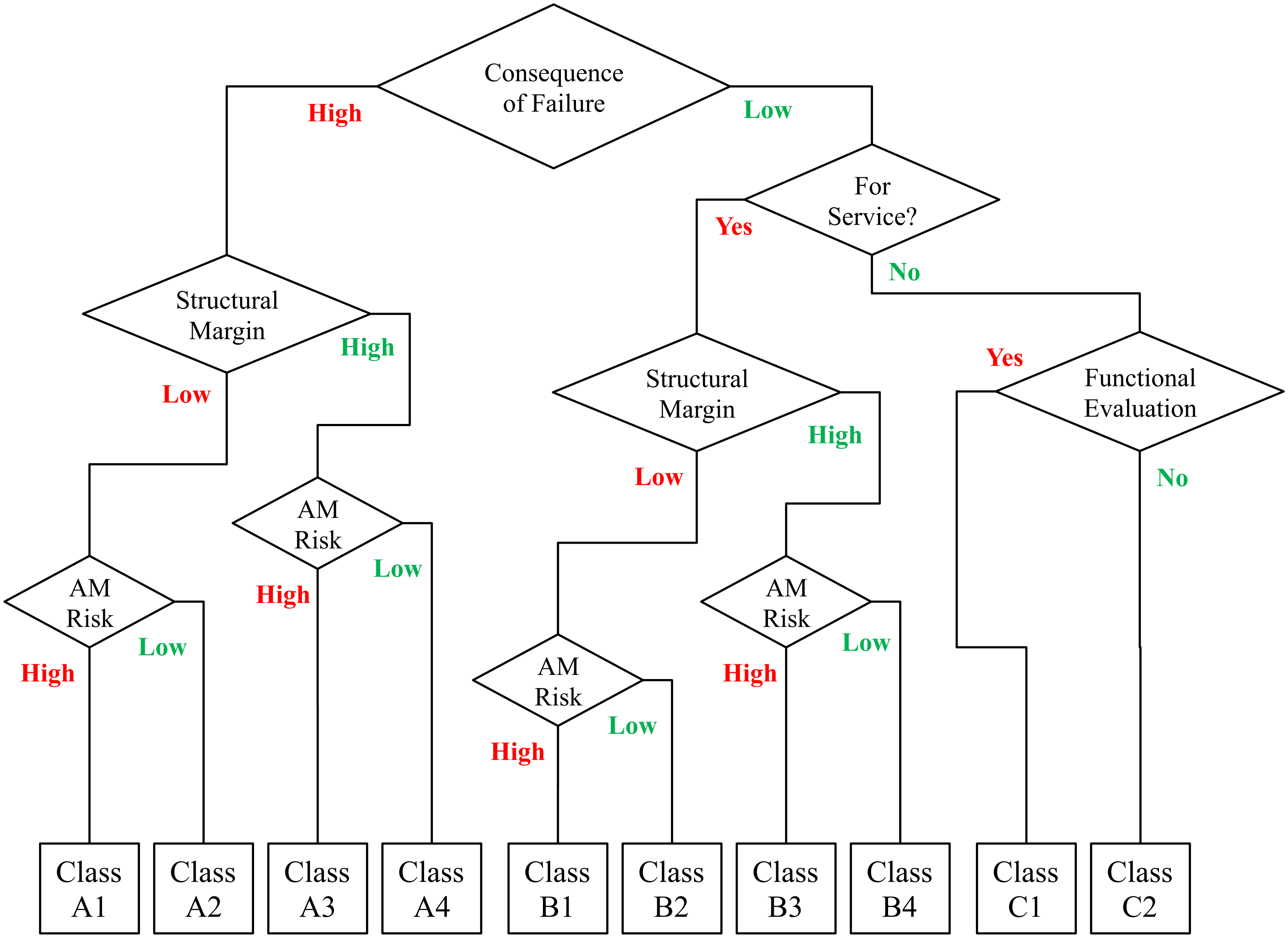
Key topics in the draft AM requirements

- ***Tailoring***
- Governing standards
- AM Design
- ***Part Classification***
- Structural Assessment
- Fracture Control
- Qualification Testing
- ***Part Development Plans***
- ***Process Controls***
- ***Material Properties***
- Finishing, Cleaning, Repair Allowances
- Part Inspection and Acceptance

Tailoring and Part Classification

- Tailoring and Part Classification provide flexibility within the requirements
- Tailoring
  - Document targets succinct, high-level requirement statements
  - Avoids inflexible detailed requirements
  - Considerable commentary on intent
  - Allows for user tailoring to intent
- Classification
  - All AM parts are placed into a simple risk-based classification system to help customize requirements according to risk
  - Three decision levels
    - Consequence of failure (High/Low) {Catastrophic or not}
    - Structural Margin (High/Low) {strength, HCF, LCF, fracture}
    - AM Risk (High/Low) {build complexity, access, inspectability}
  - Part classification highly informative relative to part risk.

AM Certification



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Part Development Plans

- Part Development Plans (PDPs) document the implementation and interpretation of the requirements for each AM part
- Companion to drawing
  - Intended as a configuration controlled document, enforced by the drawing to convey process controls and requirements
  - Must capture all requirements not within drawing notes
- Content varies with extent of approved internal specifications available for drawing call-out
- Content varies with part classification
- Example Content:
  - Part classification and rationale
  - Witness sampling requirements and acceptance criteria
  - First article evaluations and re-sampling periods
  - Build orientation, platform material, and layout
  - Special cleaning requirements
  - Repair allowance, Inspection requirements, critical dimensions

Process Controls

- Four types of process control are levied
  - Metallurgical Process
  - Part Process
  - Equipment Process
  - Vendor Process
- Each process requires qualifications or certifications

Metallurgical Process Control

- Metallurgical Process Constituents
  - Feedstock controls
    - Chemistry
    - Powder morphology (PSD, shape, atomization methods)
  - Fusion process controls
    - Machine type
    - Parameters: laser power, speed, layer thickness, hatch width, etc.
    - Chamber atmosphere
  - Thermal processing controls
    - Governs microstructural evolution
    - As-built through recrystalization
    - Final densification
- When finalized and locked as a process, a *Qualified Metallurgical Process* (QMP) is established and referenced for use in part processes

Part Process Control

- Part Process governs all operations needed to produce a given part to defined part process
- Largely documented via drawing and PDP
- Includes every step in part production
  - QMP
  - Build layout
  - Witness specimens and testing
  - Powder removal
  - Platform removal
  - Thermal processing
  - Final machining operations
  - Surface improvement
  - Inspections
  - Part acceptance requirements
- Part Process Control is typically documented through a traveller system. Once established, locked, and approved, the sequence is considered a *Qualified Part Process* (QPP)

Equipment Process Control

- Equipment Process
- Like all process-sensitive equipment, all AM-related equipment requires proper calibration and maintenance
- The scope of such equipment calibration and certification remains to be determined
  - Mechanical
  - Electronic
  - Optical
  - Software
- Control of machines is critical
- How to allow for updates to improve machine performance?
  - Not common for any flight process-sensitive system

Vendor Process Control

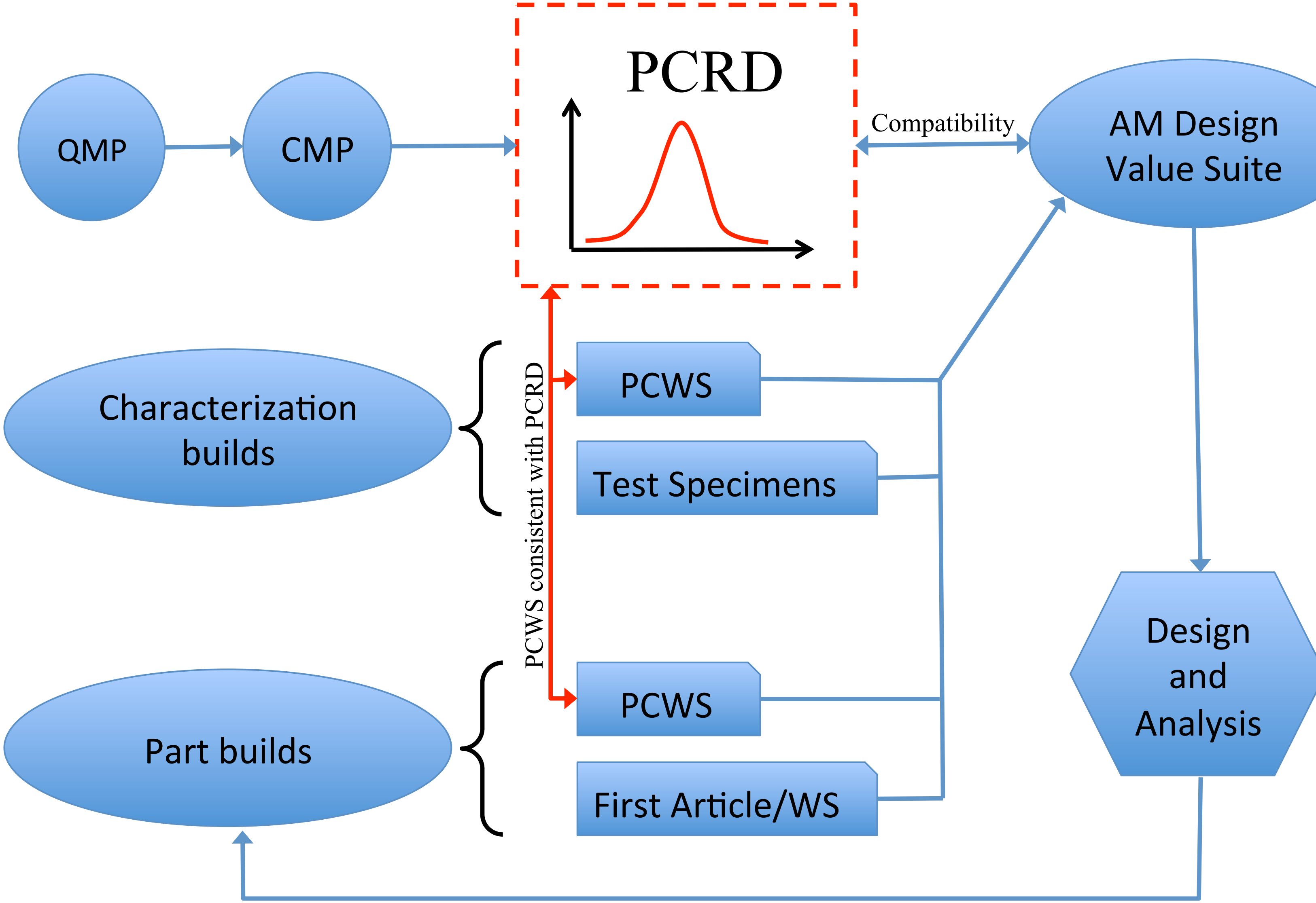
- Design vendor
  - Provides the part design and associated CAD
    - CAD model file controls
    - CAD model checking
    - STL file generation

- Build Vendor
  - Developing criteria for approved build vendor list
  - Requires S&MA audit and approval
  - Quality systems in place, e.g. AS9100
  - Manages machine quality control program
  - Electronic file control, part interaction (support structures)
  - Feedstock handling, part handling, nonconformance system
  - Management of aerospace flight quality hardware and process
  - User training and skill requirements
  - Safety protocols

Material Properties

- Material properties often confused with certification
  - Certification >> material properties
- Highly "localized user" process requires different thinking
- Shift emphasis away from exhaustive, up-front material allowables intended to account for all process variability
- Move toward ongoing process monitoring with thorough, intelligent witness sampling of each build
- Hybrid of Statistical Process Control and CMH-17 approach for process-sensitive composite material equivalency
- Utilize a QMP to develop a *Process Control Reference Distribution* (PCRD) of material properties that reflects not the design values, but the actual mean and variability associated with the controlled AM process
- Enforce suite of design values compatible with PCRDs
- Accept parts based on comparison to PCRD, not design values
- PCRDs are continuously updated, design suite must be monitored and determined judiciously early on
- Allows for adoption of new processes without invalidating large allowables investments

AM Certification – Material Properties



Key Knowledge Gaps and Risks

- Available requirements will not mitigate AM part risk to an equivalent level as other processes for some time to come!
- Known Unknowns needing investment:
  - Unknown failure modes :: limited process history
  - Open loop process, needs closure or meaningful feedback
  - Feedstock specifications and controls
  - Thermal processing
  - Process parameter sensitivity
  - Mechanical properties
  - Part Cleaning
  - Welding of AM materials
  - AM Surface improvement strategies
  - NDE of complex AM parts
  - Electronic model data controls
  - Equipment faults, modes of failure
  - Machine calibration / maintenance
  - Vendor quality approvals

Summary

- Must balance AM opportunities and risks
- Set requirements to allow innovation while managing risk
- Center-level AM requirements currently in draft
  - Will have wide-ranging review
  - Defines the expectations for engineering and quality control in developing critical AM parts
- Orion pace is challenging the requirements development
  - Will need to serve as a pathfinder for requirements methodology
- Need Agency level cooperative effort to help close knowledge gaps in certification requirements to better manage AM risk

Take-Away Concepts

- Design Certification
  - Design value suite, compatible with AM-unique issues

- Process control areas
  - Qualified Metallurgical Process
    - Feedstock, fusion process, thermal process
  - Part Process Control
    - Part development plan
      - Companion to drawing
    - Process control witness
      - Methodology which evaluates in SPC sense
      - Use of process mean and variability to show control
  - Equipment Process Control
    - Calibration, maintenance
    - Fitness for service declaration
  - Vendor Controls
    - Quality processes
    - Operator training