Qualification Challenges for Additive Manufacturing Processes and Parts

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Outline

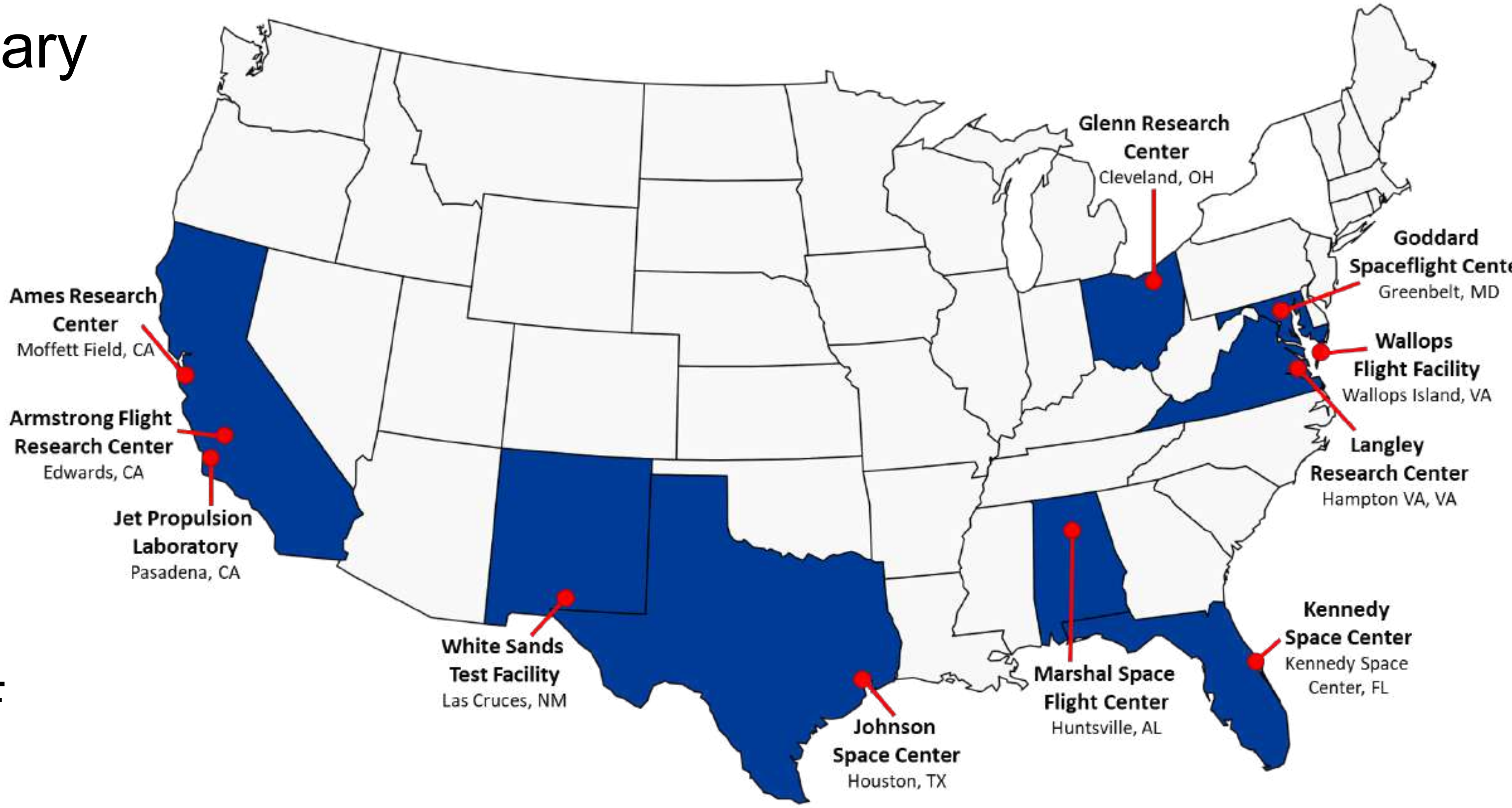
- Where NASA uses Additive Manufacturing
- The Basic Principles of NASA-STD-6030
- The Biggest Qualification Challenges for Additive Manufacturing Processes and Parts

Additive Manufacturing at NASA

Where does NASA use AM?

NASA is not homogeneous

- Technical and risk cultures vary by facility and mission, as shaped by its history
- Human-rated spaceflight
  - JSC, KSC, MSFC
- Space Science
  - GSFC, JPL
- Aeronautics
  - ARC, AFRC, GRC, LaRC, WFF



Engines (MSFC)

NASA MSFC has also built channel-cooled combustion chambers using L-PBF, but that use bi-metallic additive and hybrid techniques.

- The materials used vary from Inconel® 625 and 718, Monel® K-500, GRCop-84, and C18150 metal alloys.
- Designs tested ranged from 200 to 1,400 psia in a variety of propellants and mixture ratios, producing 1,000 to 35,000 lbf thrust.

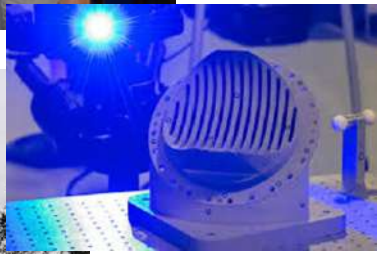
https://arc.aiaa.org/doi/abs/10.2514/6.2018-4625

NASA MSFC rocket injectors made by AM resulting in a 70% reduction in cost.

- Using traditional manufacturing methods: 1 Year, 163 parts
- With AM, 4 months. only 2 parts

28-element Inconel® 625 fuel injector built using a laser powder bed fusion (L-PBF) process

https://www.nasa.gov/press/2014/august/sparks-fly-as-nasa-pushes-the-limits-of-3-d-printing-technology/
https://arc.aiaa.org/doi/abs/10.2514/6.2018-4625



RS25 Prime Contractor, Aerojet Rocketdyne, technician exhibits the RS-25 pogo accumulator (top and middle), which was subsequently hot-fire tested (bottom)

- Over 100 Weld Eliminated
- Nearly 35% Cost Reduction

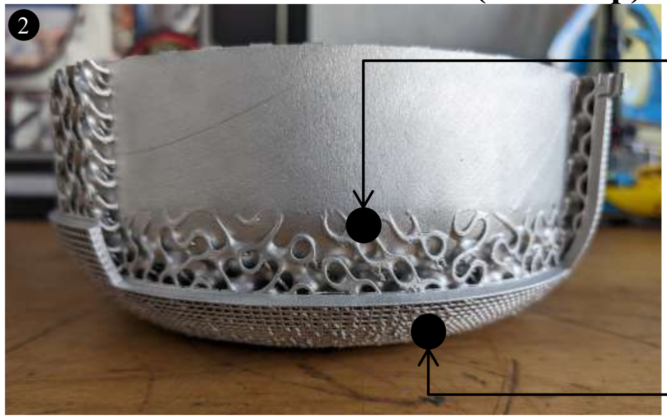
https://www.nasa.gov/exploration/systems/sls/nasa-tests-3-d-printed-rocket-part-to-reduce-future-sls-engine-costs

Generative Design & Lattices (GSFC)

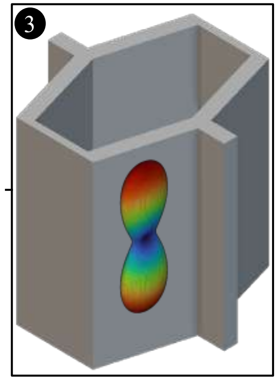
https://www.nasa.gov/science-research/nasa-turns-to-ai-to-design-mission-hardware/

Lattice Structure (Variable Lattice Network)
Metal Additively Manufactured Component

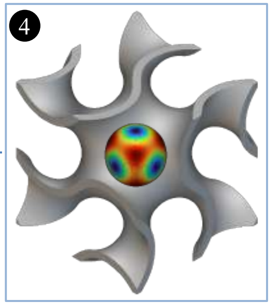
Lattice Structure Network (Close-Up)



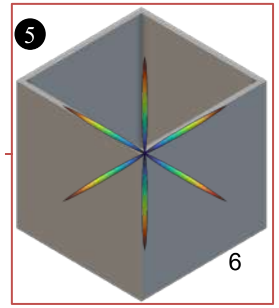
Hexagonal Honeycomb (Internal Stiffness)



TPMS Gyroid (Thermal Efficiency)



Square Honeycomb (Shock Absorption)



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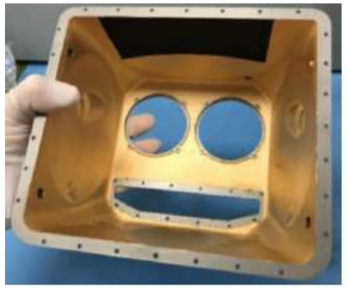
To Mars and Beyond (JPL)


X-ray bench and support


Mounting frame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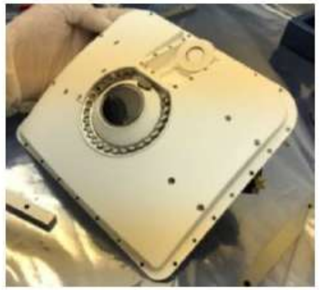
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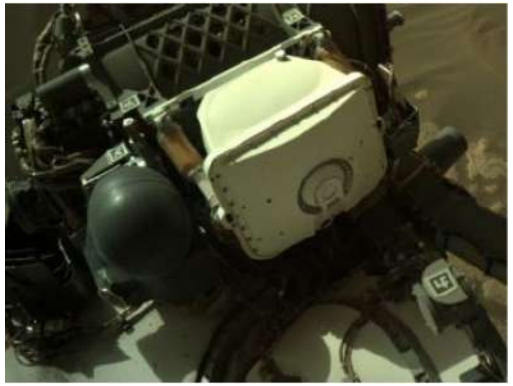

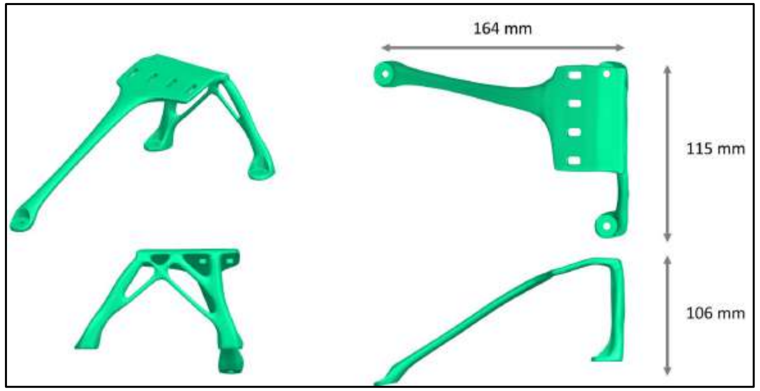

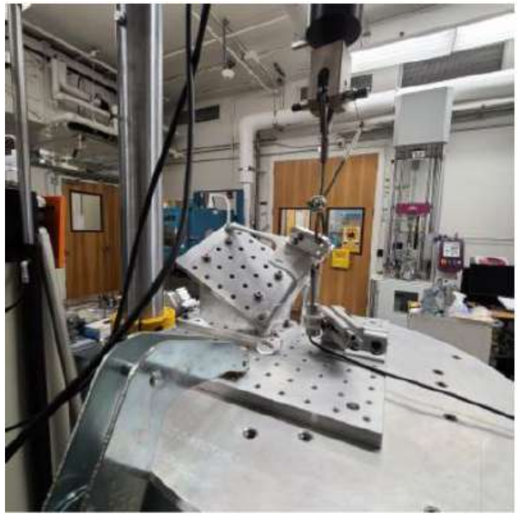

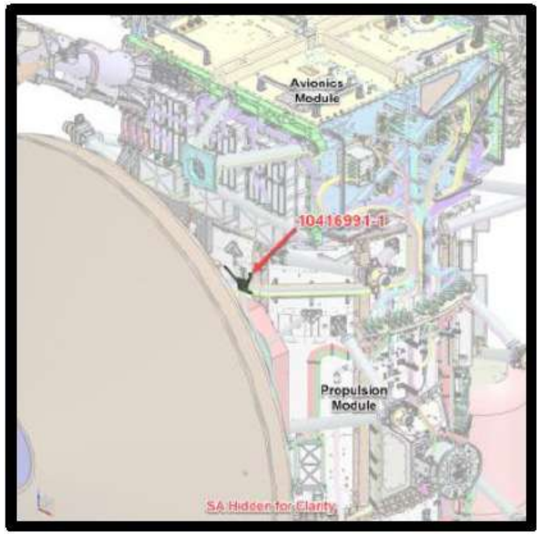

Images courtesy NASA/JPL-Caltech

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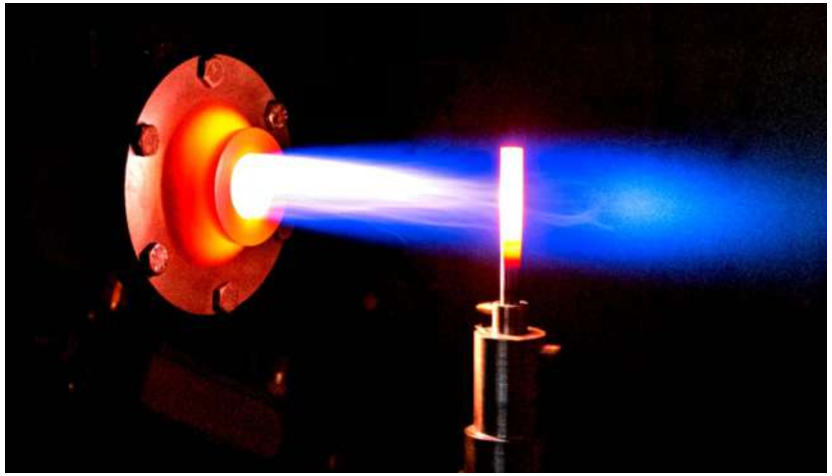

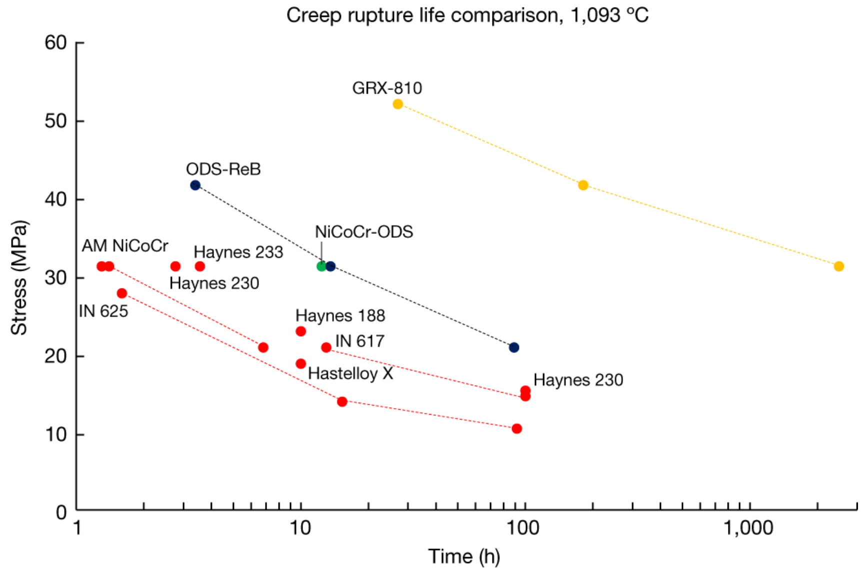

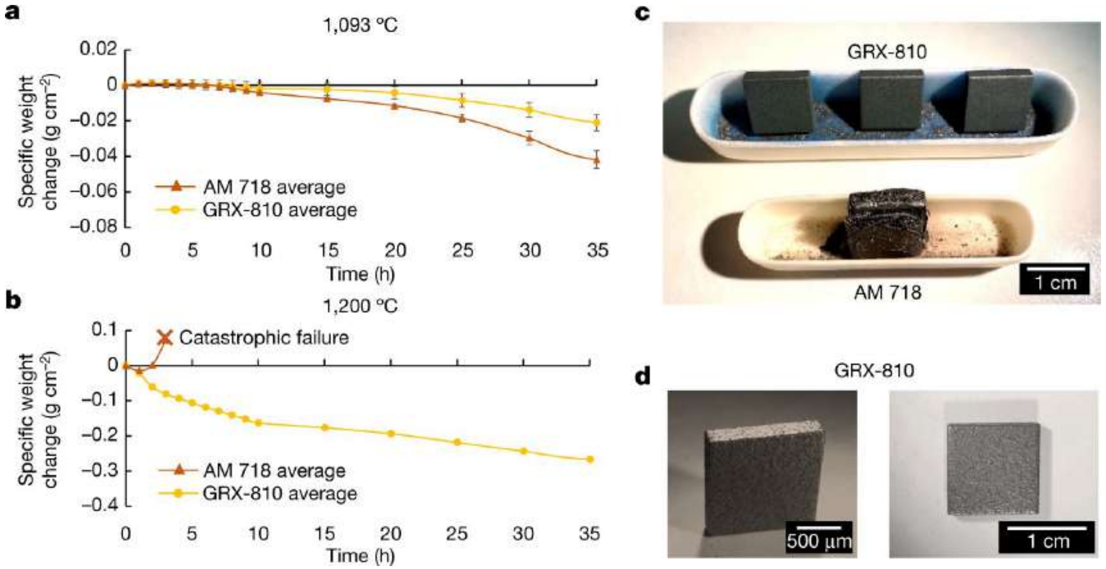

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The Basic Principles of NASA-STD-6030

The "NASA Way"

Disclaimer: “Certification” and “Qualification”

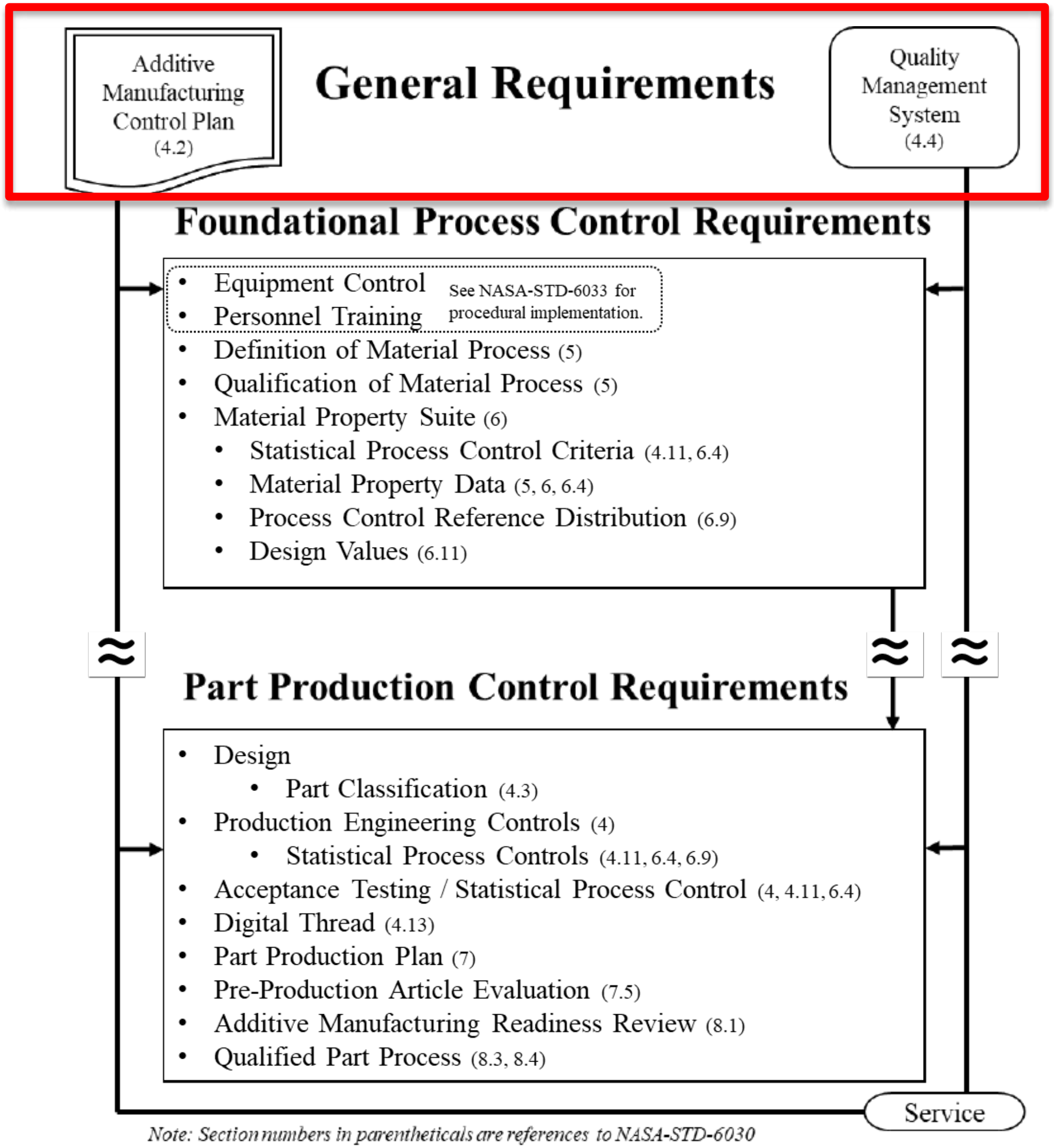
- There is NO centralized Certification or Qualification body at NASA.
- Each individual Program/Project is responsible for “Qualifying*” AM Processes and “Certifying” AM Flight Hardware.
  - *or accepting another projects “qualification”
- There is an informal group of Materials Engineers across the agency who routinely communicate to help ensure that AM requirements are being implemented across the agency as consistently as possible.
- The hope is that by maintaining a single “NASA AM Ecosystem”, the non-recurring engineering costs associated with each new using program or project will be dramatically reduced.

What are the Basic Principles of NASA-STD-6030?

- **Document what you do & follow the documentation**

  4.4.1 Quality Management Systems *– A QMS compliant to SAE AS9100, Quality Management Systems – Requirements for Aviation, Space, and Defense Organizations, or an alternate QMS approved by the CEO and NASA, documented or referenced in the AMCP,* ***shall*** *be in place for all entities involved in the design, production, and post-processing of AM hardware*

- Quality Management System/QMS is mentioned ~100 times in NASA-STD-6030
- Having a well defined and executed QMS is *critical* for the production of high reliability spaceflight hardware.
- Almost every work product mentioned in NASA-STD-6030 must be maintained under configuration/revision control

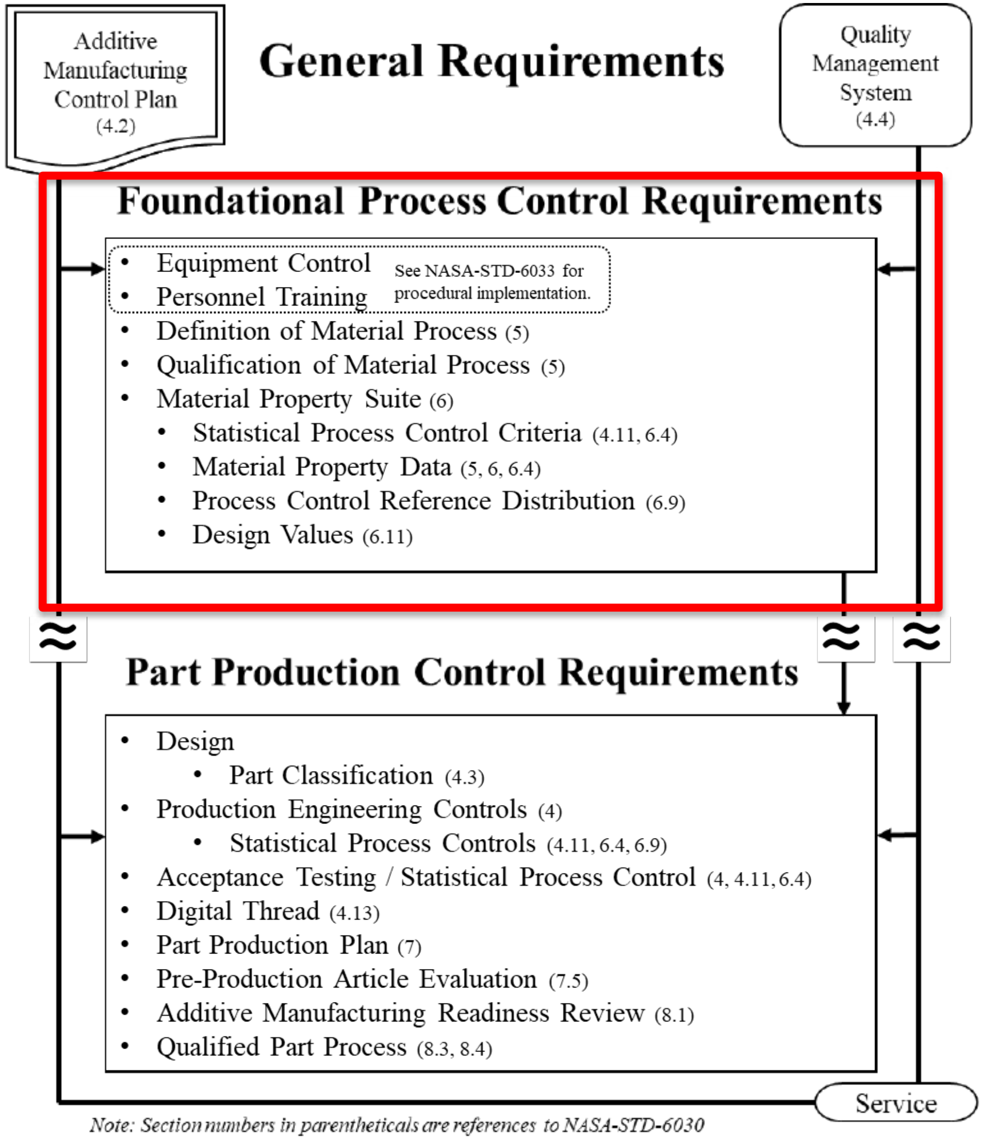


Note: Section numbers in parentheticals are references to NASA-STD-6030 section numbers, unless stated otherwise

What are the Basic Principles of NASA-STD-6030?

- **Document what you do & follow the Documentation**

- **Foundational Process Controls**
  - How to define your process
  - How to characterize your process
  - How to monitor your process
  - How to use your process in a design



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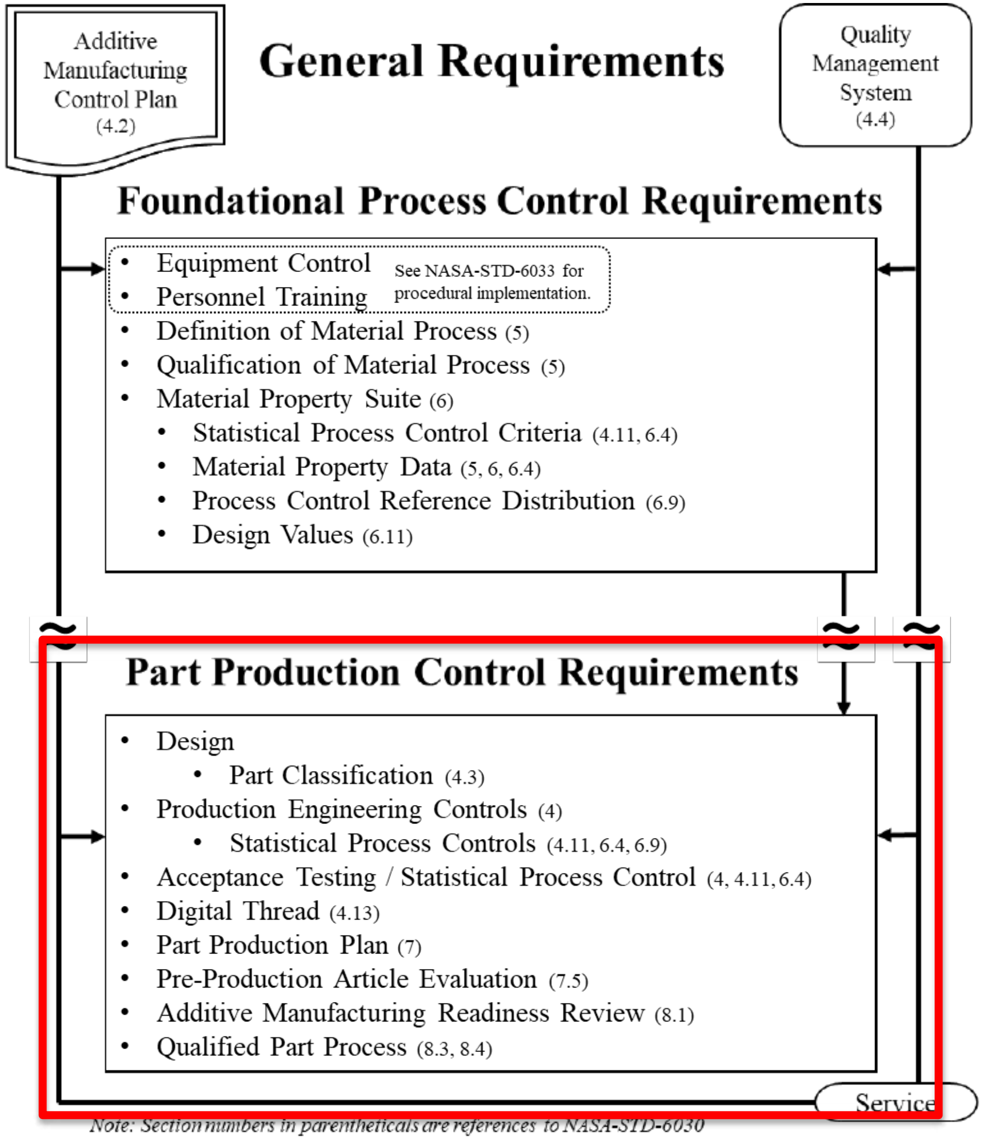
What are the Basic Principles of NASA-STD-6030?

- **Document what you do & follow the Documentation**
- **Foundational Process Controls**
  - How to define your process
  - How to characterize your process
  - How to monitor your process
  - How to use your process in a design
- **Part Production Controls**
  - How to document *why* AM works for your part
  - How to plan to make your part
  - How to qualify your part
  - How to make your part successful



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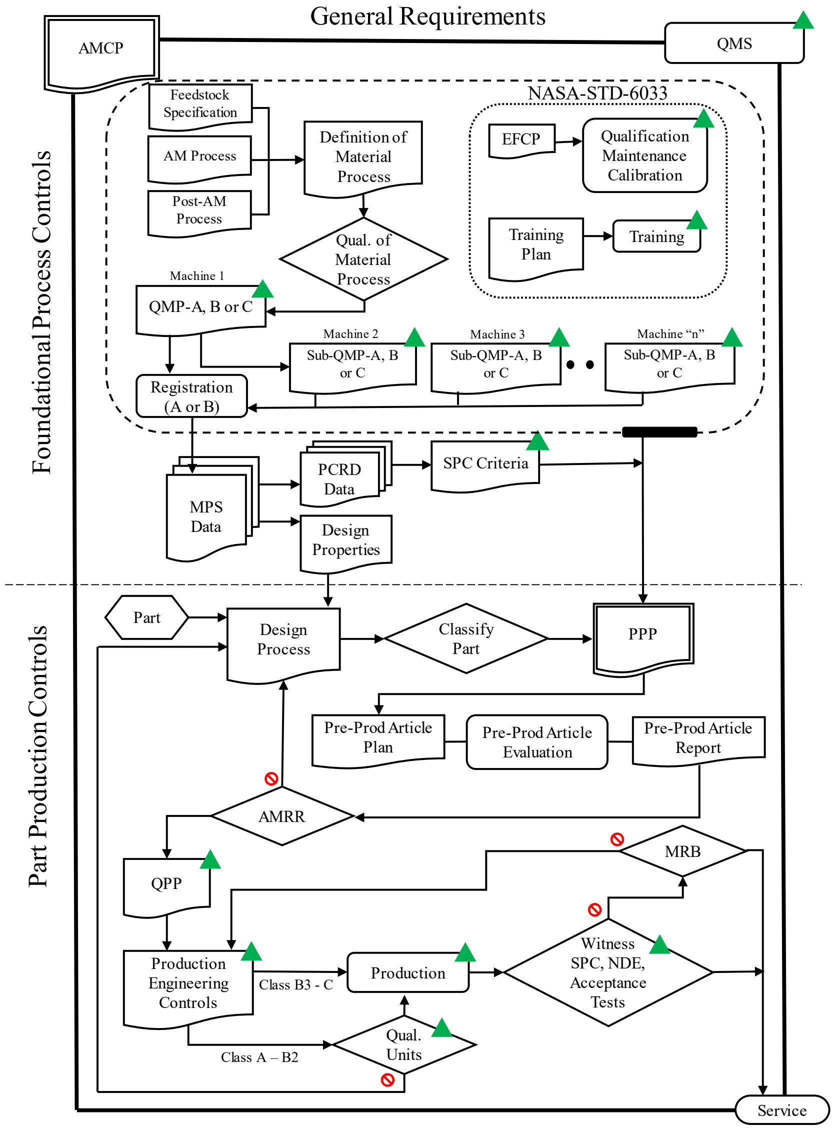
Where is the Quality in (AM) Qualification?



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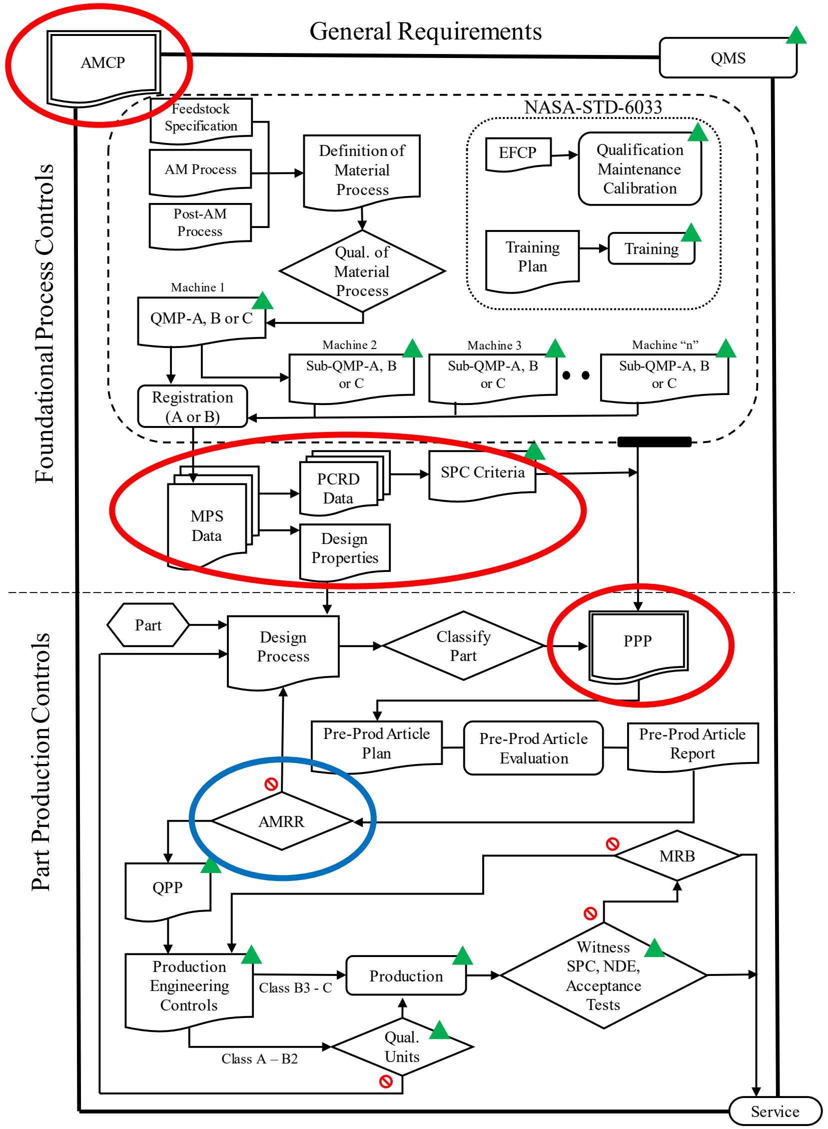
Where is the Quality in Qualification?

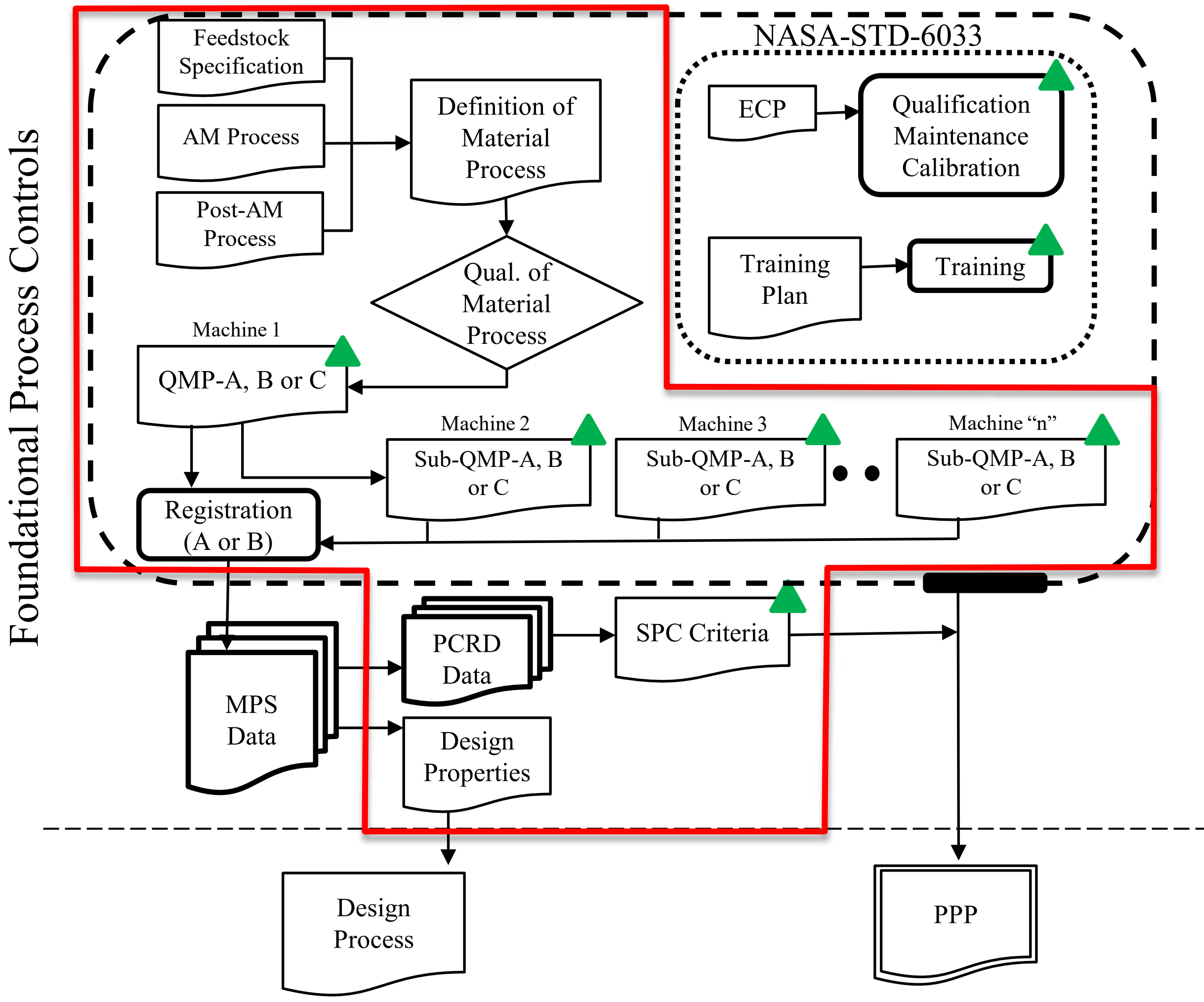
- There are only three deliverables:
  1. Additive Manufacturing Control Plan (AMCP)
  2. Material Property Suite (MPS) via an MUA
  3. Part Production Plan (PPP)

- In many/most cases NASA is expected to be invited to the Additive Manufacturing Readiness Review (AMRR)
  – NASA's attendance is only required for Class some Class A Parts
  – NASA Approval is NOT required



Where is the Quality in Qualification?

- A Qualified AM Process begins as a Candidate QMP
- Defines aspects of the basic, *part agnostic*, fixed AM process:
  - Feedstock
  - Fusion Process
  - Thermal Process
- Enabling Concept
  - Machine qualification and re-qualification, monitored by…
  - Process control metrics, SPC, all feeding into…
  - Design values
- Quality Engineering plays a vital part
  - Needs to ensure everything is documented and followed
  - However, NASA doesn't have direct oversight of this facet of an AM program in the vendor base

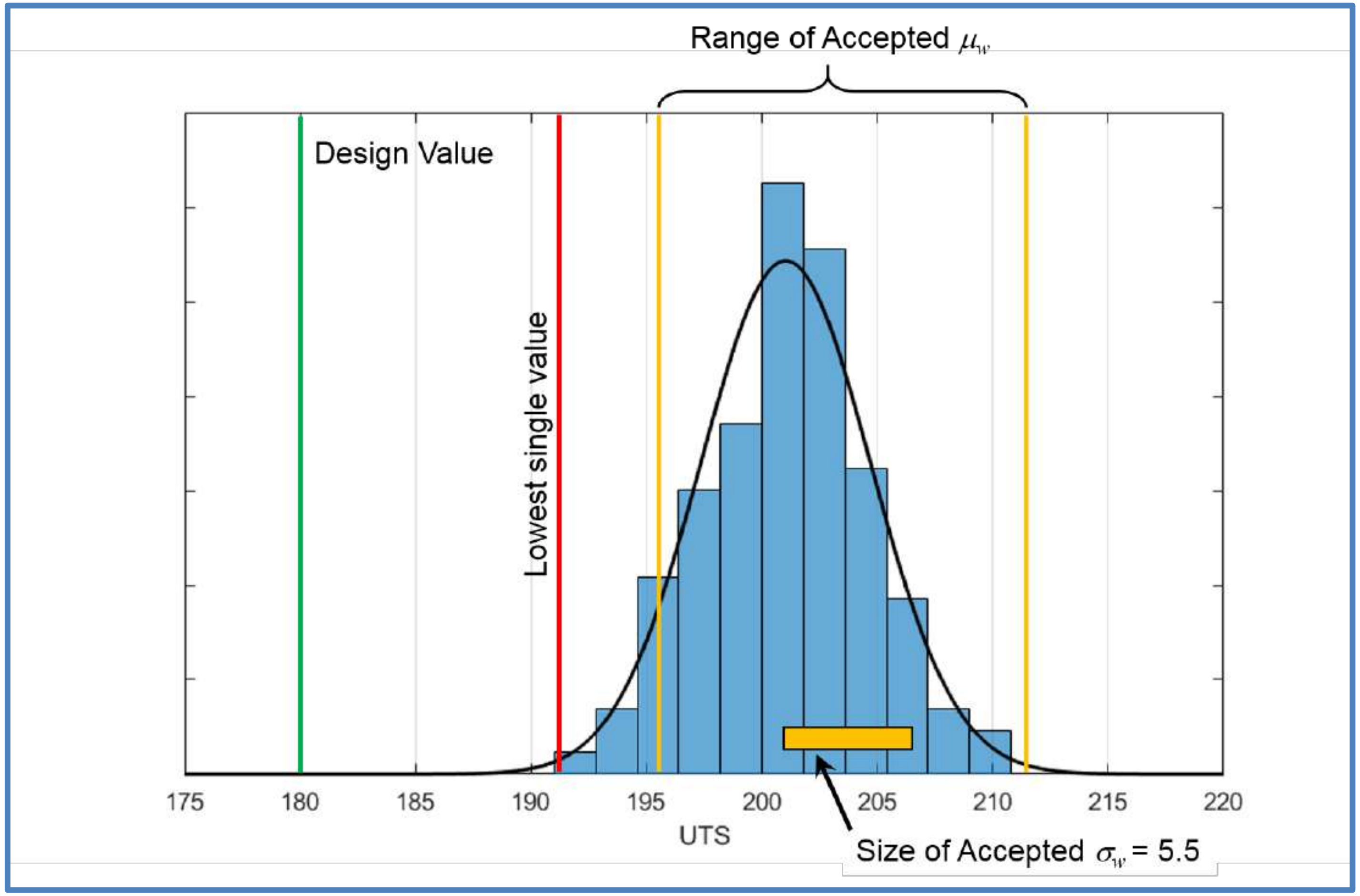


Where is the Quality in Qualification?

- Witness test acceptance is not intended to be based upon design values or "specification minimums"

- Acceptance is based on witness tests reflecting properties in the MPS used to develop design values

- Suggested approach
  - Acceptance range on mean value
  - Acceptance range on variability (e.g., standard deviation)
  - Limit on lowest single value



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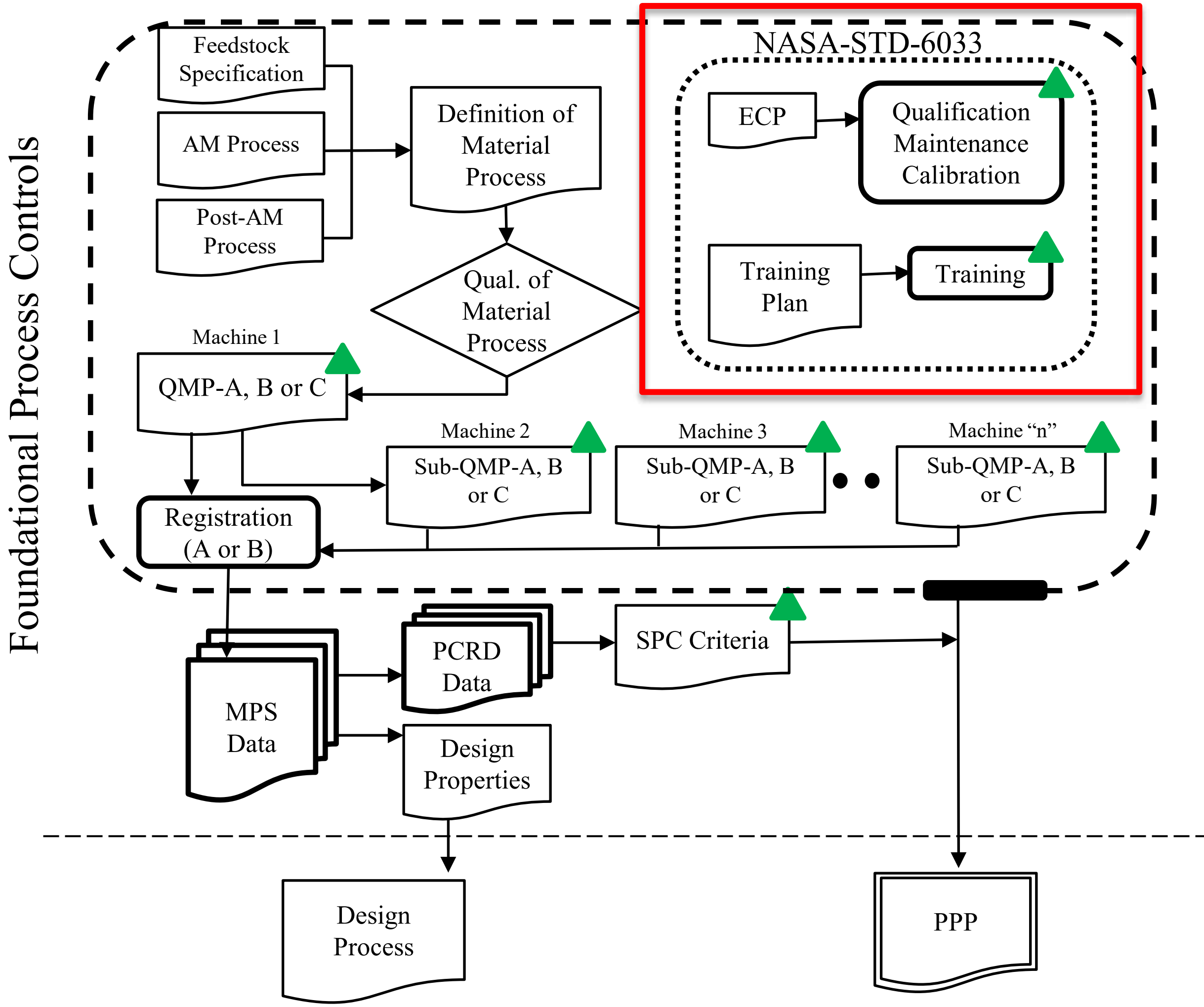
Where is the Quality in Qualification?

- NASA-STD-6033 deals with everything that has to do with the Additive Manufacturing *Facility.*
- Fundamentally, the requirements on an AM Factory are no different than any other
- Third-party AS9100 certification will get you 99% of the way there.



Qualification Challenges for Additive Manufacturing Processes and Parts

MATERIALS ENGINEERING
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What are the major stumbling blocks?

- Using additive manufacturing where it makes sense
- NASA-STD-6030 is *Looooooooong*
- Lack of an integrated design, procurement, & manufacturing team
- Intellectual property & prior contracts

Additive Manufacturing is Not Here to Save You

- You have a fully designed part
- You need it to be good
- You need it to be cheap
- You need it quickly

Additive Manufacturing is Not Here to Save You

- ~~You have a fully designed part~~
- ~~You need it to be good~~
- ~~You need it to be cheap~~
- ~~You need it quickly~~

} Recipe for Disappointment

Additive Manufacturing is Not Here to Save You

- ~~You have a fully designed part~~
- ~~You need it to be good~~
- ~~You need it to be cheap~~
- ~~You need it quickly~~
- You need to prototype and/or iterate a *lot*
- You need an *extremely* optimized part (i.e., topology optimization)
- You can't easily make the part using legacy "subtractive manufacturing"
- You need a part with a high "buy to fly" ratio

Additive Manufacturing is Not Here to Save You

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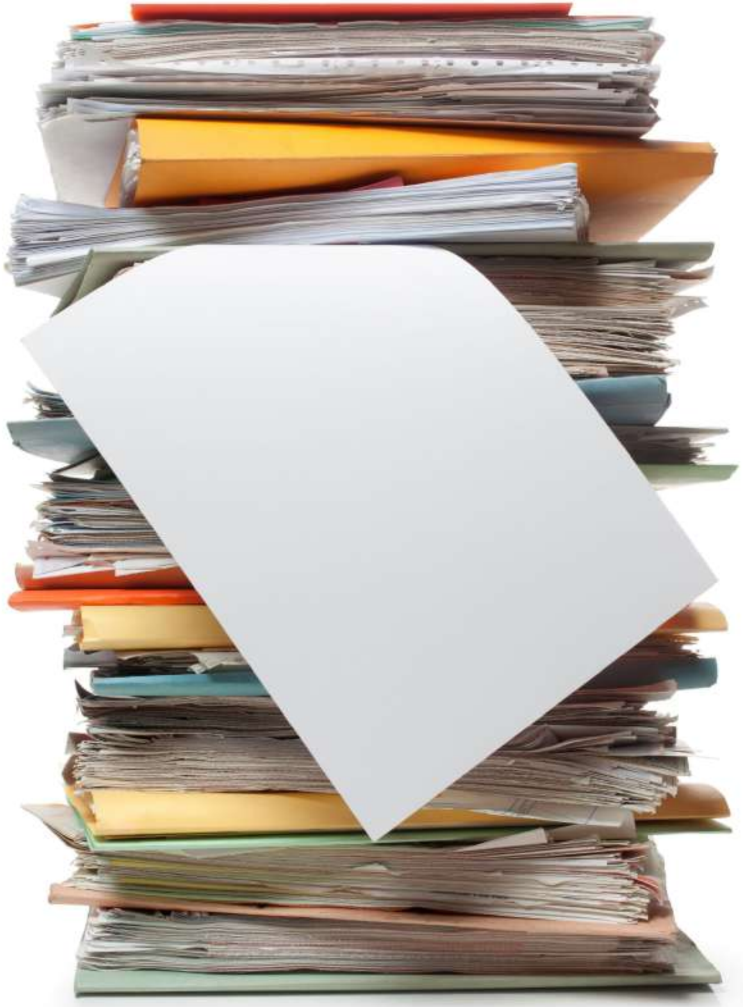
- You need to prototype and/or iterate a *lot*
- You need an *extremely* optimized part (i.e., topology optimization)
- You can't easily make the part using legacy "subtractive manufacturing"
- You need a part with a high "buy to fly" ratio
- **You literally *can't* make it any other way**
- **You want to decrease part count**

One Requirement at a Time

- NASA-STD-6030
  - 138 pages
  - 115 unique "shall statements"
  - Additive Manufacturing Control Plan

- NASA-STD-6033
  - 31 pages
  - 31 unique "shall statements"
  - Equipment and Facility Control Plan



Additive Manufacturing Control Plan

- NASA is NOT trying to tell fabricators exactly *how* to utilize AM (mostly)

- NASA *is* telling you all the things you have to:
  - **Think about** Sometimes the Stupid Questions are the most important
  - **Define** If you haven't defined something, you can't do it again
  - **Control** Without controls, how do you know you're doing it
  - **Monitor** Controlling something doesn't mean it can't go *wrong*

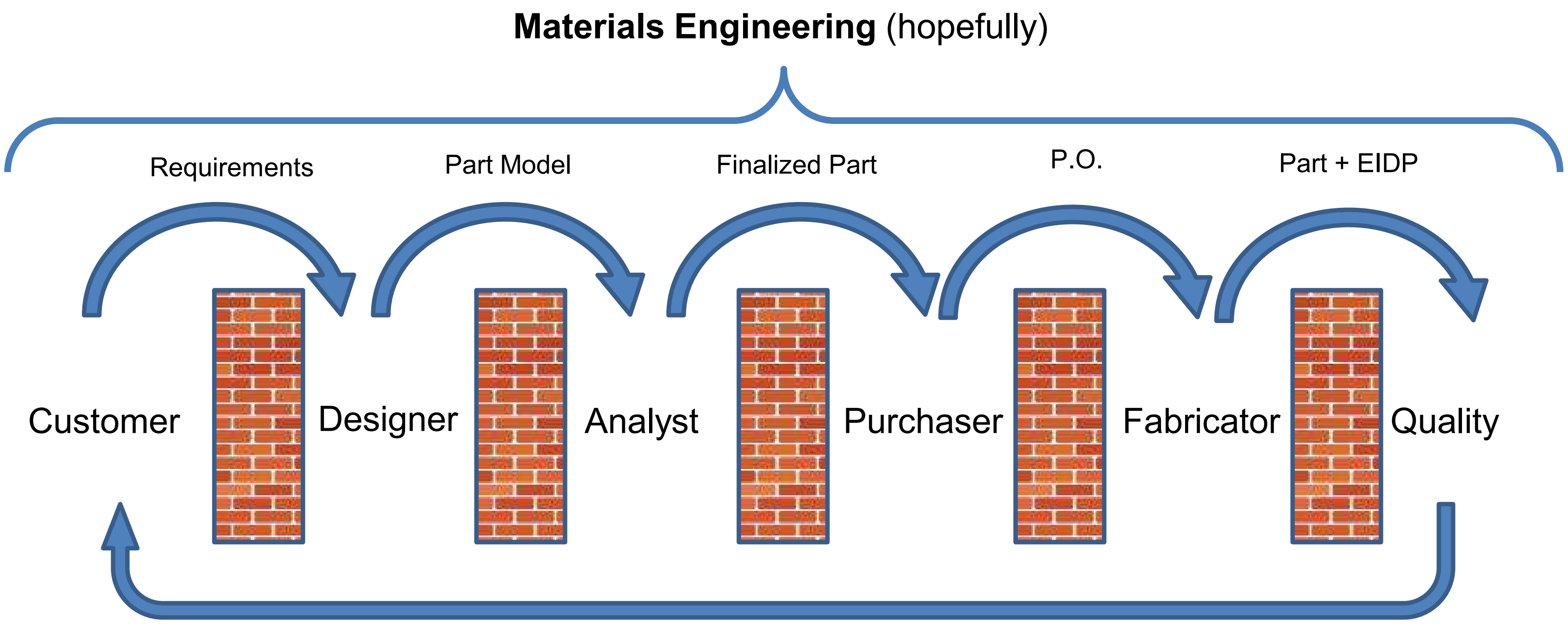
- An Additive Manufacturing Control Plan is how you document how you do AM *for yourself* and *communicates it to your customers*.

"Remember kids, the only difference between screwing around and science is writing it down"

-Adam Savage (Mythbusters)

An Integrated Multidisciplinary TEAM

- You can not throw an AM design "over the wall" (yet)



An Integrated Multidisciplinary TEAM

- You can not throw an AM design "over the wall" (yet)
- All stakeholders need a seat at the table *concurrently*

Intellectual Property & Prior Contracts

A lot of people have spent a lot of money figuring out AM…

1. Customer
   - e.g., NASA
2. Cognoscente Engineering Organization (CEO)
   - i.e., might be the same as the Customer
3. Fabricator
   - i.e., might be the *same* as the CEO…might be separate company

Hoarding Knowledge Helps No One

- Hoarding knowledge isn't really an issue for vertically integrated organizations

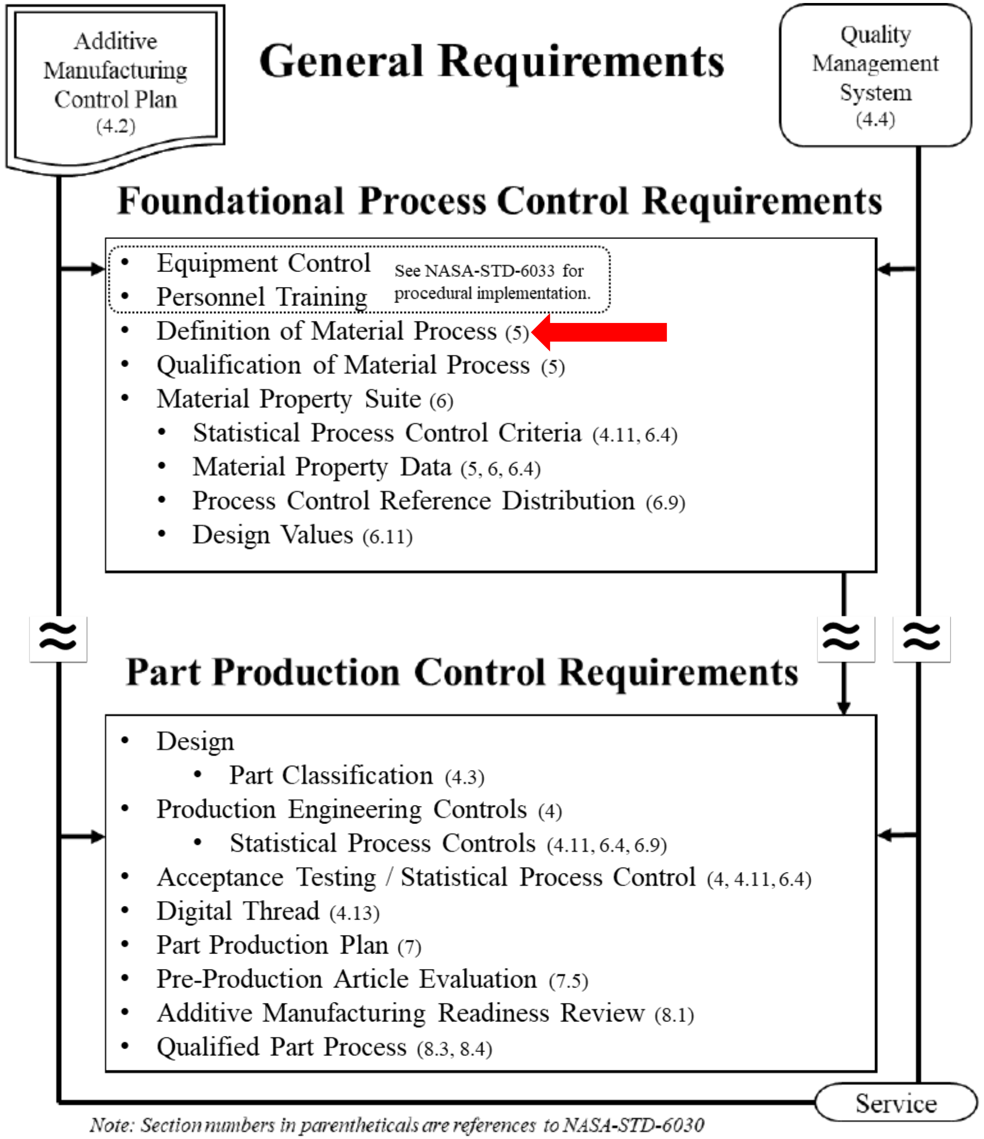
- If the Designer *is* the Fabricator, the inability to share information (usually) isn't a problem.

- Please Remember: For most Aerospace/Advanced Manufacturing applications, you still need to make most things "available upon request" to your customers
  - In most situations, you can require the customer to come to *you* to do it

But when the CEO *is NOT* the Fabricator

Hoarding Knowledge Helps No One

- By *far* the biggest roadblock for the author's organization are prior contracts in our potential vendor base
- Many if not most fabricators have entered into agreements where they don't actually own the Intellectual Property associated with the processes they use in their own facility. (or at least they've convinced themselves that's the case)
- Tensile Data alone, does not a competitive advantage make
- AM Process Parameters and Post Processing Specifications are a more understandable problem, but still make things difficult.
- Shackling your vendors will NOT help you or your partner fabricators in the long run
- The widespread utilization of successful AM processes is in EVERYONE'S best interest, even if its at a competitor
- **The more AM is used *generally*, the more *your* customers will be comfortable using *your* technologies**



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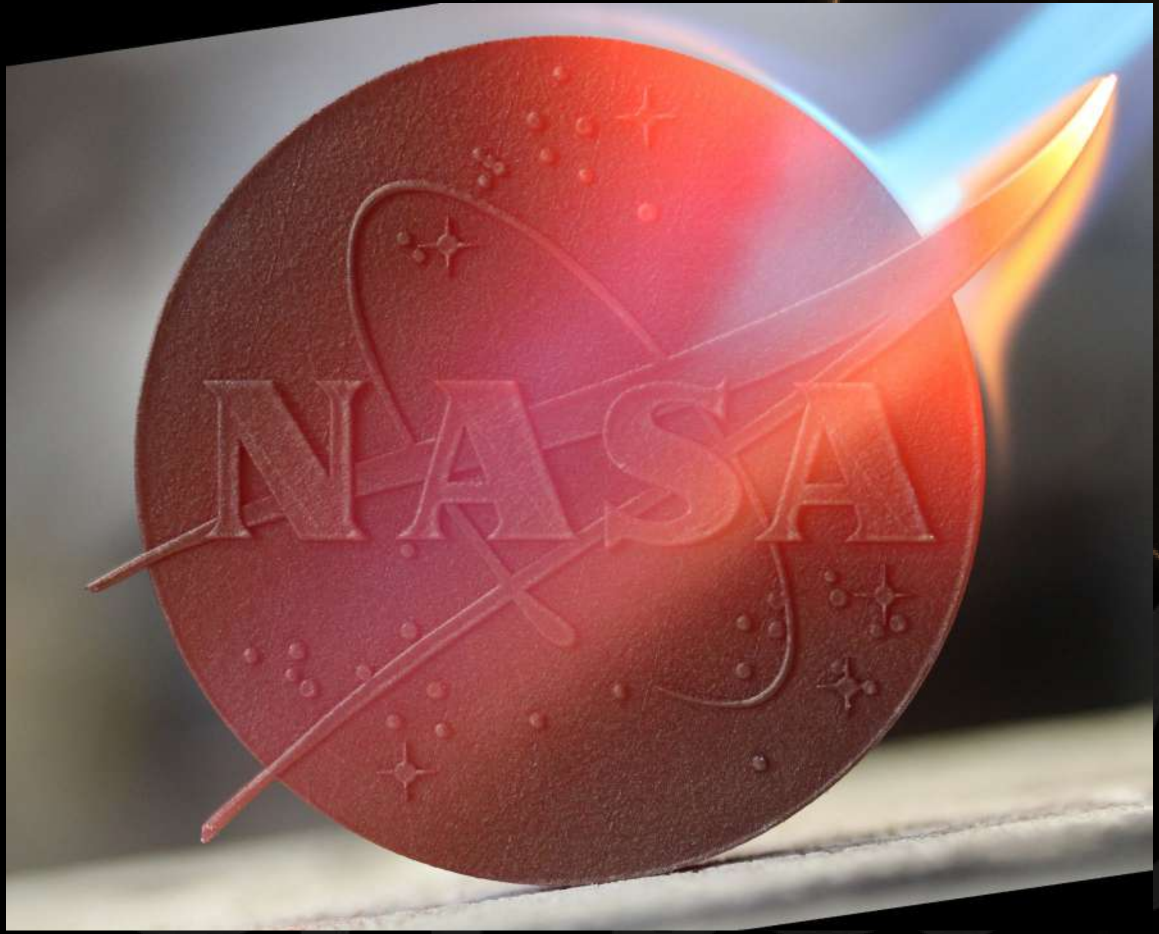

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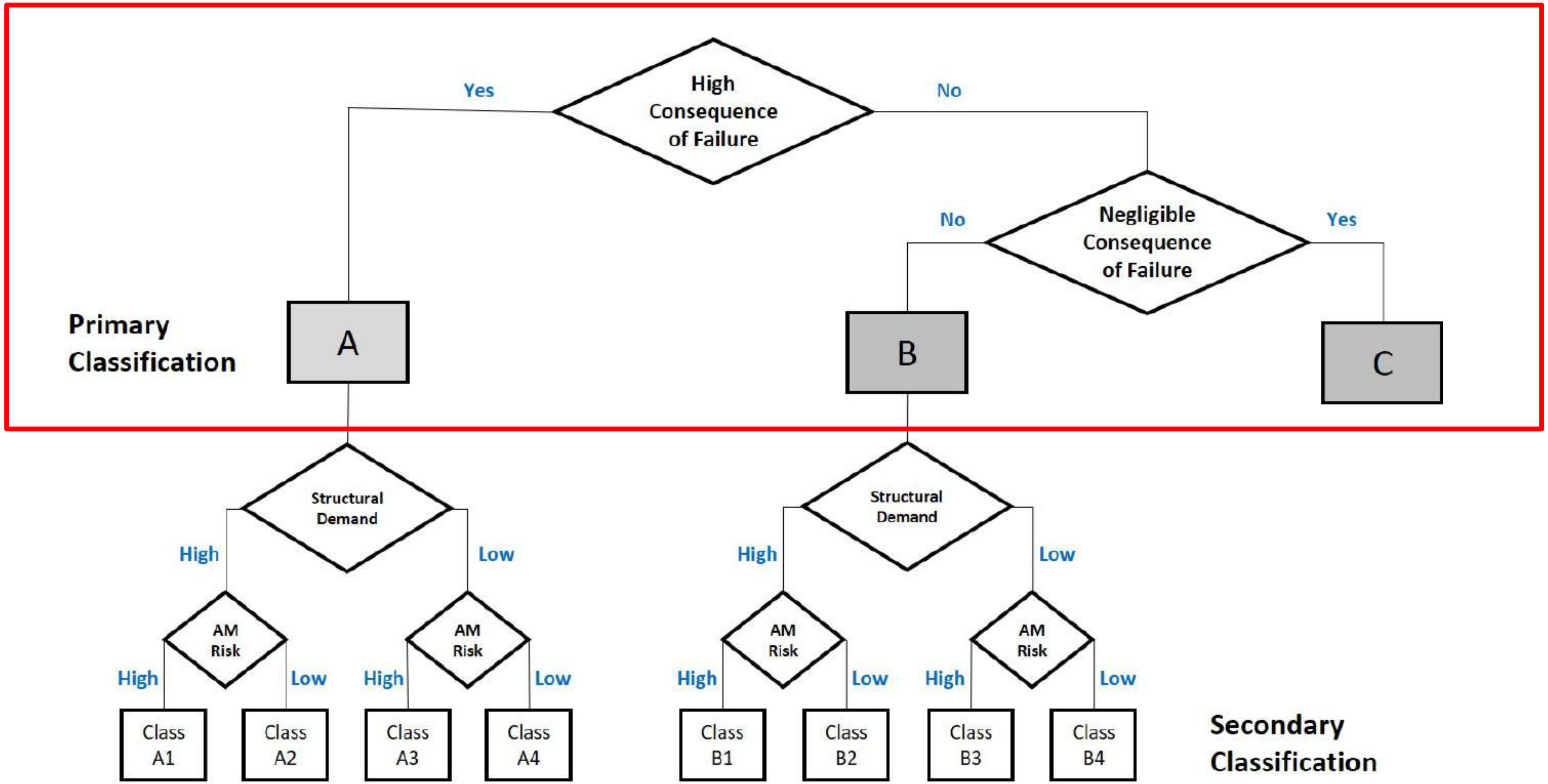
Backup

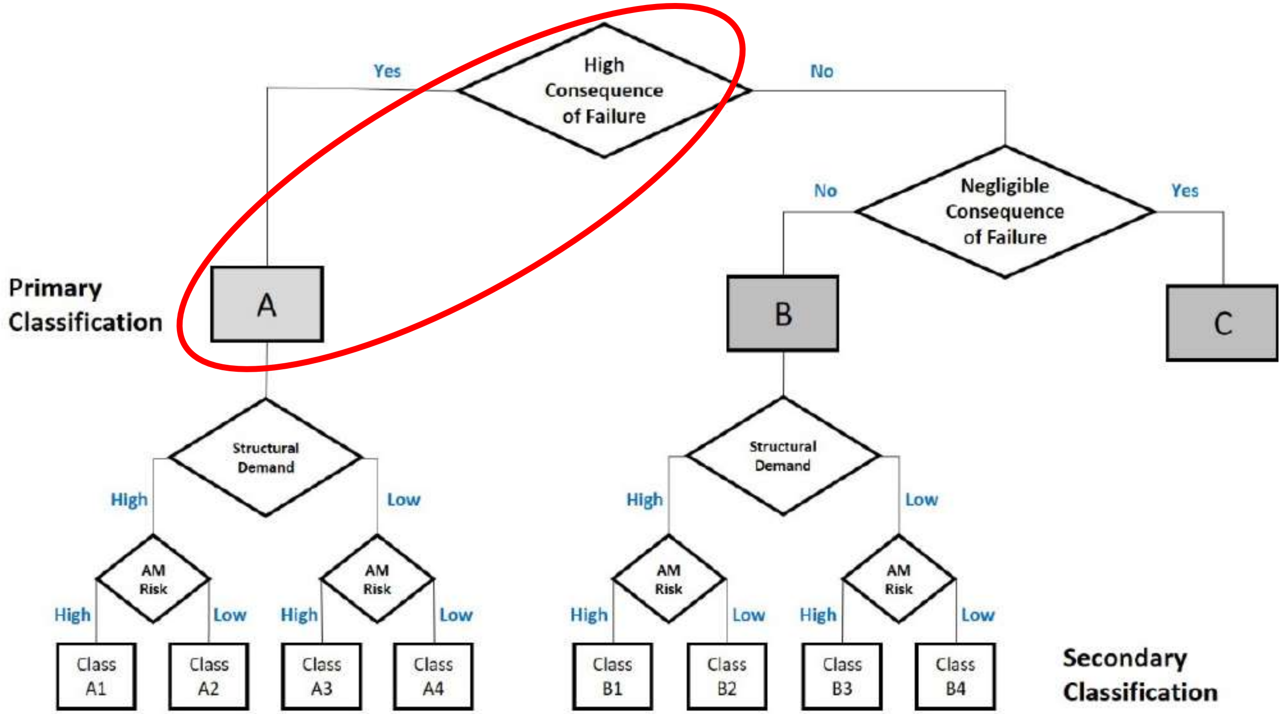
Classification



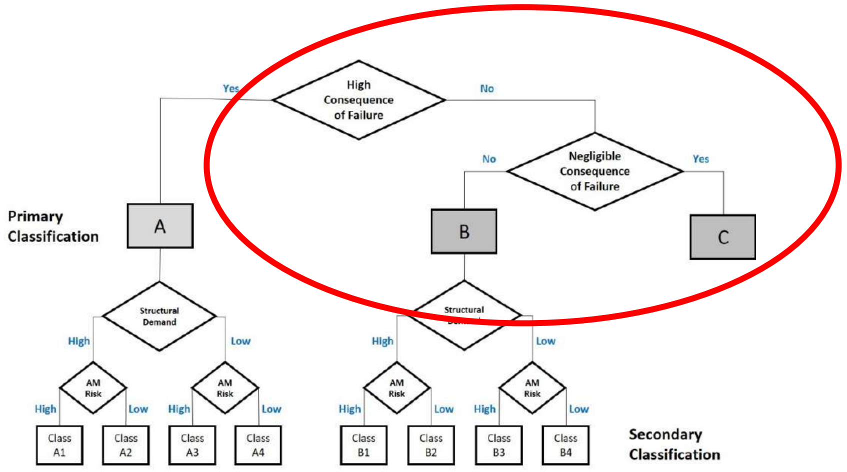
High Consequence of Failure

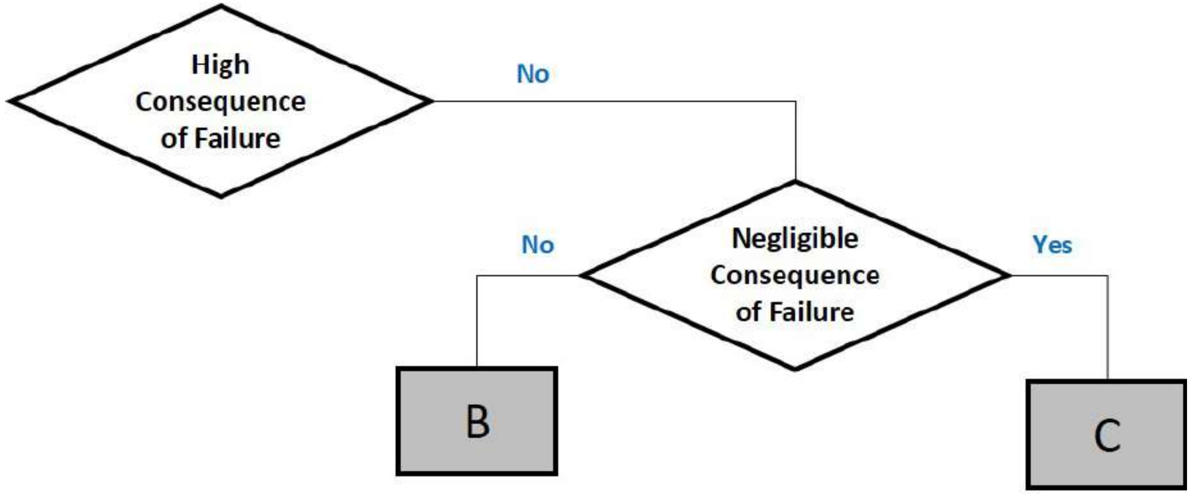
- A part **shall** be designated as Class A, High Consequence of Failure, if failure of the part leads to a **catastrophic**, **critical**, **or safety hazard** and/or the part is **defined as mission critical by the program or project**.

- Class A parts **shall not**:
  - Be made from polymeric materials
  - Be fasteners
  - Contain printed threads.



Negligible Consequence of Failure





- Parts not designated Class A or Class C **shall** be designated as Class B.
- Class B parts **shall** not:
  - Be fasteners
  - Contain printed threads.

Negligible Consequence of Failure

- A part **shall** be designated as Class C, Negligible Consequence of Failure, provided that ALL of the following criteria are satisfied:
  - Failure of part does not lead to any form of hazardous condition.
  - Failure of part does not eliminate a critical redundancy.
  - Part does not serve as primary or secondary containment.
  - Part does not serve as redundant structures for fail-safe criteria per NASA-STD-5019, Fracture Control Requirements for Spaceflight Hardware.
  - Part is not designated "Non-Hazardous Leak Before Burst" per NASA-STD-5019.
  - Failure of part does not cause debris or contamination concerns, as defined by the Non-Fracture Critical Low-Release Mass classification per NASA-STD-5019, NASA-STD-6016, and/or other project/program requirements.
  - Failure of part causes only minor inconvenience to crew or operations.
  - Failure of part does not alter structural margins or related evaluations on other hardware.
  - Failure of part does not adversely affect other systems or operations.
  - Failure of part does not affect minimum mission operations.