National Aeronautics and Space Administration

Using 3D Printing for SmallSats & other Low(er) Cost Missions

Or, how to stop worrying, and love NASA-STD-6030

National Aeronautics and Space Administration Small Satellite Learning from Experience, Achievements and Resolution Navigation Forum

LEARN

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www.nasa.gov

Summary

- Additive Manufacturing at NASA
- *When* to Use Additive Manufacturing
- *How* to Use Additive Manufacturing
- Basic Principles of NASA-STD-6030 & 6033
- How NASA-STD-6030 & 6033 Can Help *You* (SmallSats)
- Examples

The Future is Now

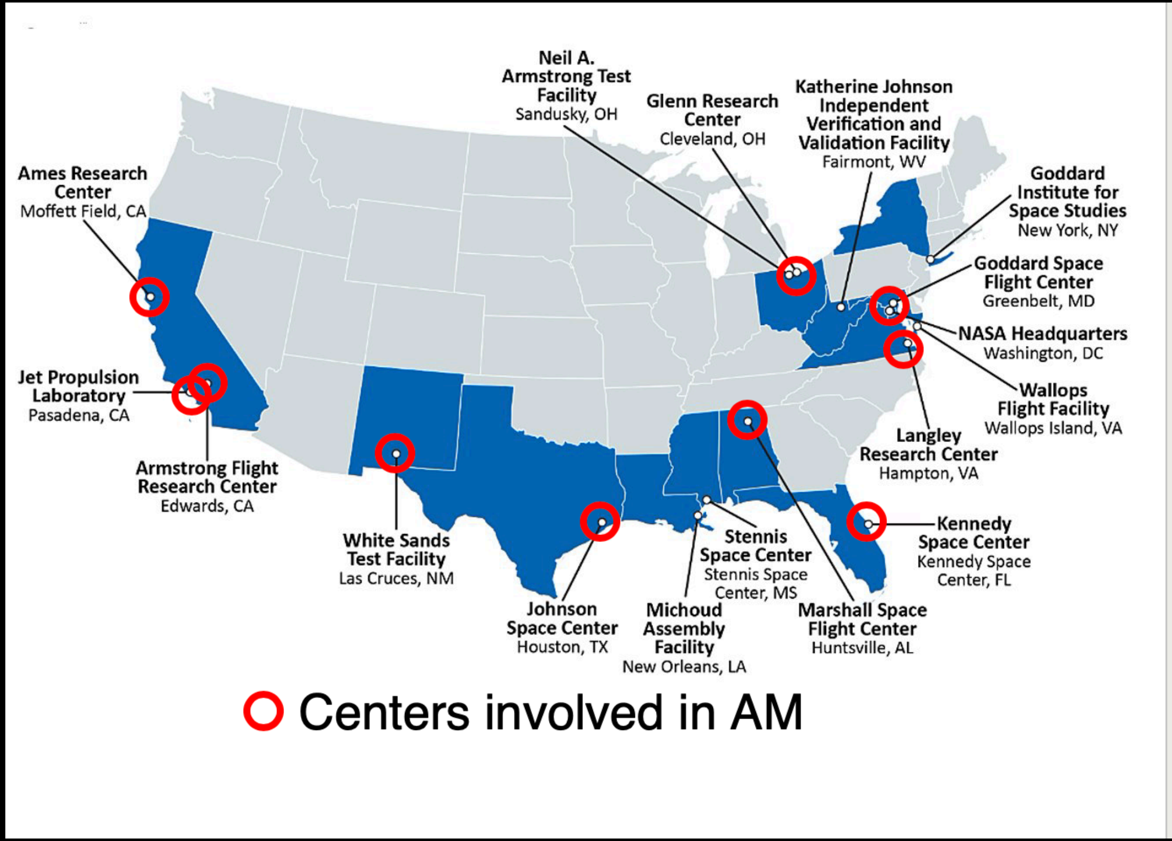
The implementation of additive manufacturing techniques to produce critical spaceflight systems is well underway. These technologies will be a key contributor to developing both launch vehicles and spacecraft that will play a crucial role in delivering the first woman and first person of color to the surface of the moon in 2025. To assist in the assurance of flight readiness, NASA has created comprehensive certification-based standards for mature technologies for both metallic and non-metallic materials.

-Alison Park, NASA Associate Tech Fellow for M&P

NASA and Additive Manufacturing

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**
  - **LaRC, GRC, ARC**



NASA's Roles in AM

- Drive AM technology innovations – more affordable access to space and advanced aeronautics applications
- Provide a framework for Spaceflight AM hardware certification
  - Enable NASA's tech authority to conduct meaningful and efficient evaluations of AM implementation
  - Advise NASA flight programs on potential risks – meeting objectives according to levied (and agreed upon) requirements and approved exceptions

When do I use Additive Manufacturing?

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When to Use Additive Manufacturing

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

When to Use Additive Manufacturing

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- ~~You need it to be cheap~~
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Recipe for Disappointment

- 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

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It doesn't need to be an exciting part!

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How do I use Additive Manufacturing?

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Do ***Not*** Buy an Additive Machine

Unless you really need to

How to Use Additive Manufacturing

- Buying, qualifying, operating and maintaining an AM machine is extraordinarily expensive.
- The purchase price of a machine is a small fraction of the setup costs alone.
- If you're not running the machine *most* of the time, it's not going to be a good investment.
- There are a fairly large number of build-to-print fabricators right now who can reliably print "good enough" parts.
- There are a few exceptions…

O.K…so you already bought the machine…

- Additive Manufacturing technologies can give you a mind-boggling amount of flexibility in how you print a part
- This is both a feature and a bug
- Some designers aren't *allowed* to use outside fabricators by their customers
  - (this doesn't apply to anyone in the room)
- There are circumstances where in addition to optimizing your geometry, you need to optimize your AM parameter sets
  - For small production volume facilities, this is the only compelling reason to buy a machine I've seen to date

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  - For small production volume facilities, this is the only compelling reason to buy a machine I've seen to date
- But for the most part, pick a parameter set (or three) **AND DON'T CHANGE IT.**

Basic Principles of NASA-STD-6030 & 6033

Or, how to stop worrying, and love NASA-STD-6030 & 6033 *as a tool* (not a requirement)

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NASA-STD-6030 & 6033 – Basic Principles

- *Understanding* and *Appreciation* of the AM process
- *Integration* across disciplines and throughout the process
- *Definition and Characterization of the process(es)*
- *Discipline to monitor and follow the plan*

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Understanding and Appreciation of AM

- Technologies: Laser, E-Beam, Direct Energy, Binder Jet, friction stir, etc.
- Feedstock: powder, wire, filament, plate, liquid, etc.
- Alloys: titanium, aluminum, stainless steel, copper, etc.
- Parameters: Beam size, speed, power, raster, hatching, etc.

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Secondary

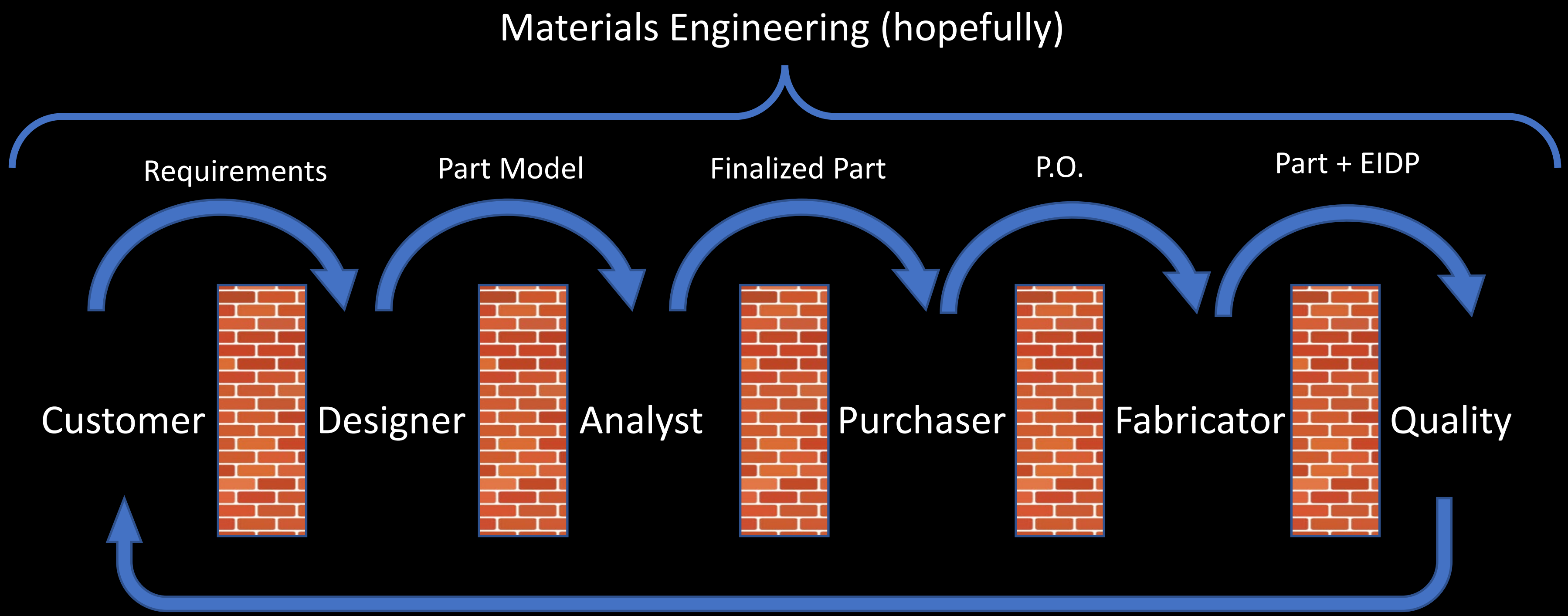
Understanding and Appreciation of AM

Everyone gets a seat at the table

And it's a BIG table

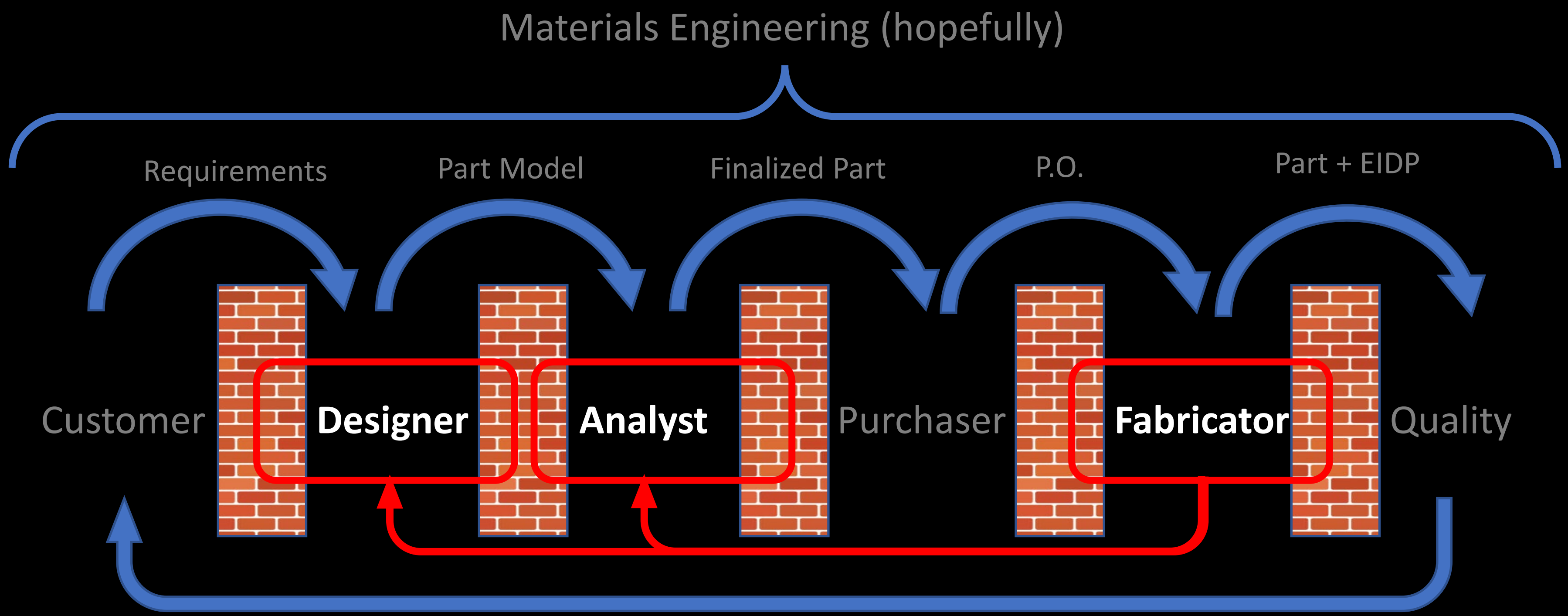
Multidisciplinary Integration

- You can <u>not</u> throw an AM design "over the wall"
- All stakeholders in the product value chain need a seat at the table *concurrently*



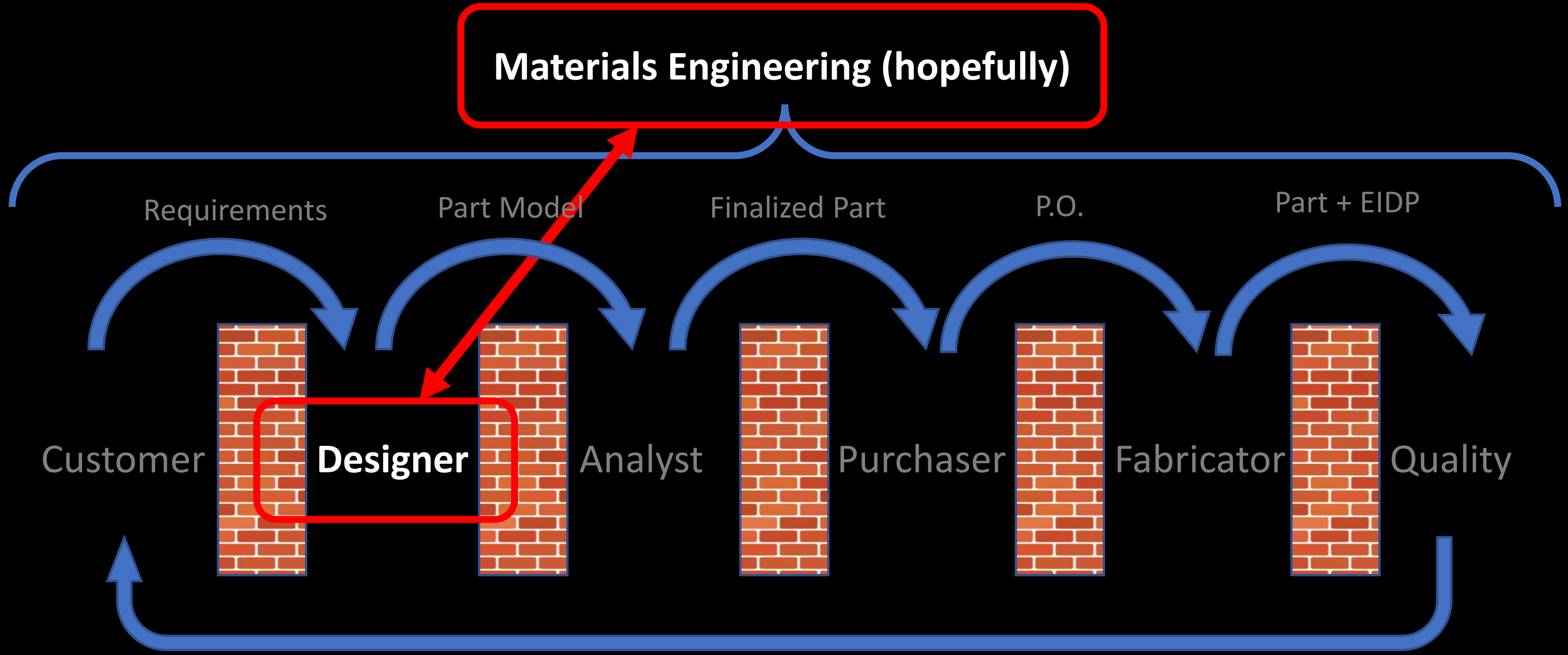
Multidisciplinary Integration

- The designer can't design a part without knowing what the design allowables are
- Analysist can't analyze the part unless they know what the design allowables are
- The fabricator needs to define and characterize their process before they can communicate this necessary information



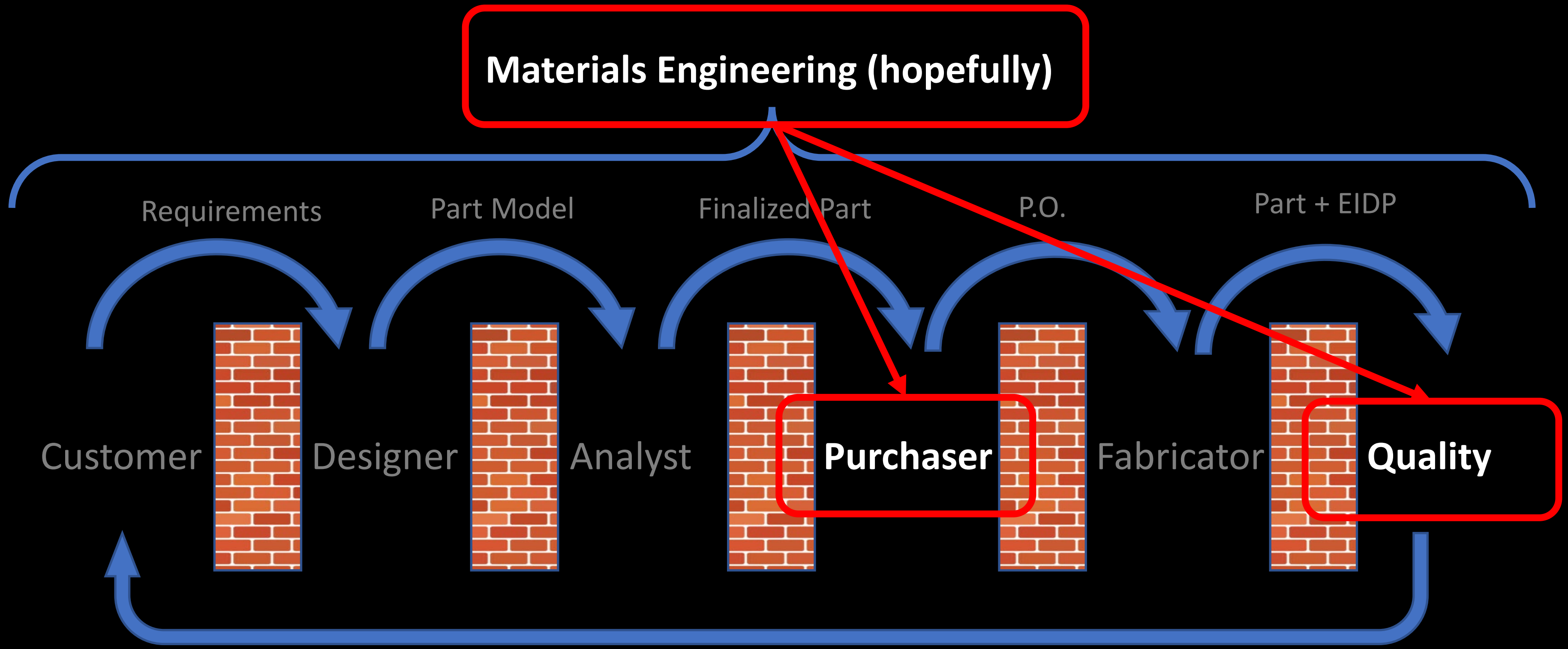
Multidisciplinary Integration

- Materials Engineers and Designers need to work together to ensure appropriate design allowables are being used



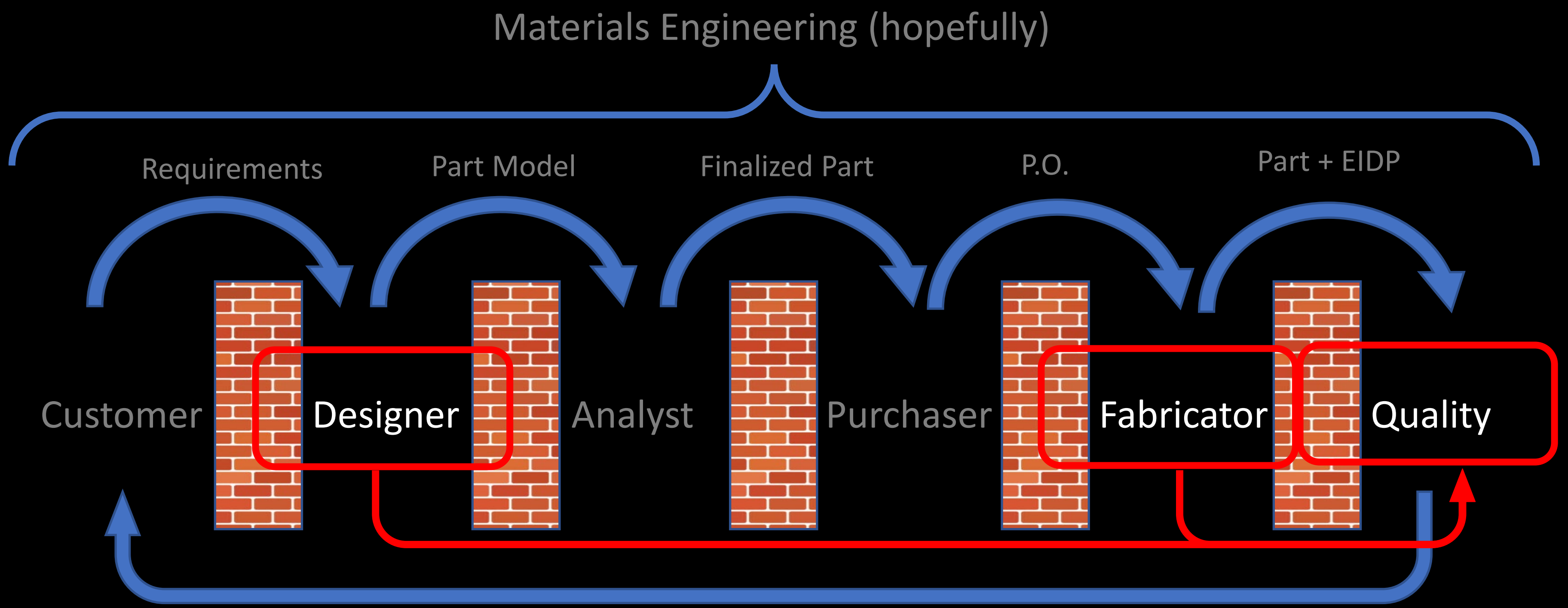
Multidisciplinary Integration

- M&P Engineers need to communicate with Purchasers & Quality Engineers to ensure the fabricator capabilities correspond to the part requirements



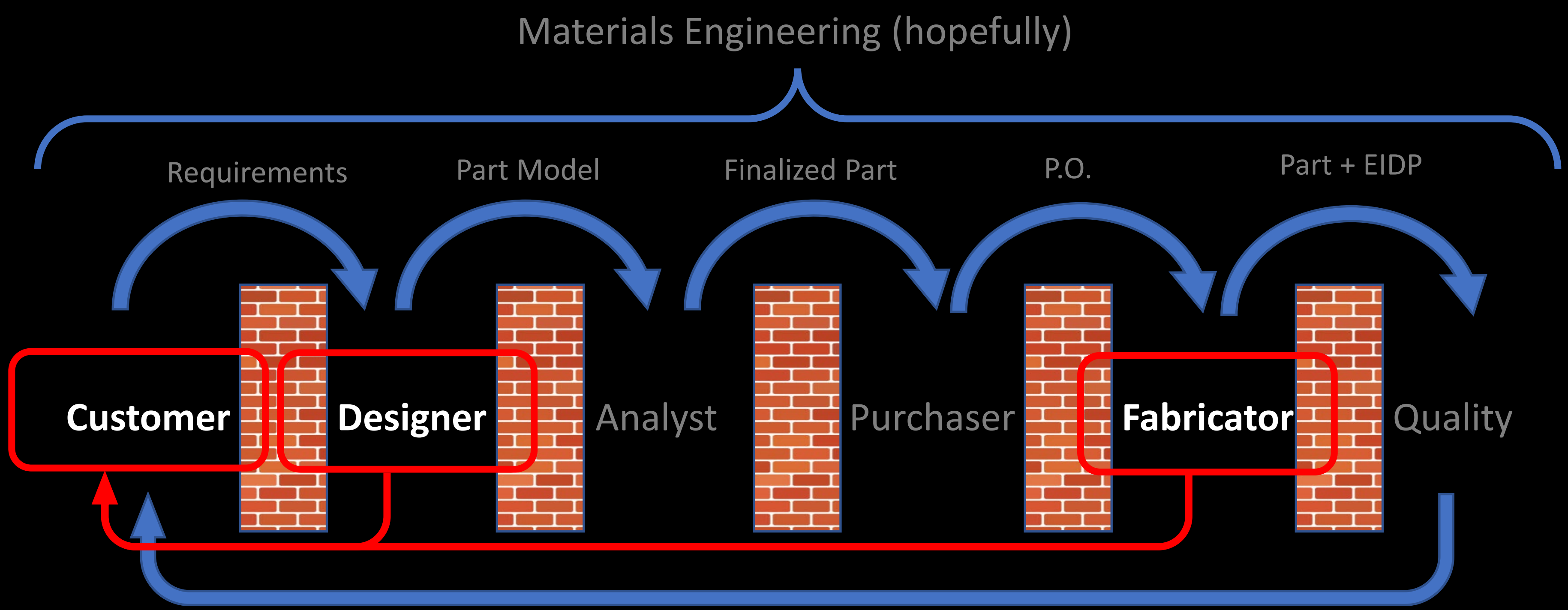
Multidisciplinary Integration

- Designers need to design a part that can be inspected by Quality
- Quality Engineers need to understand the Fabricator’s process control and ensure it meets the designer's intent (and drawing requirements)

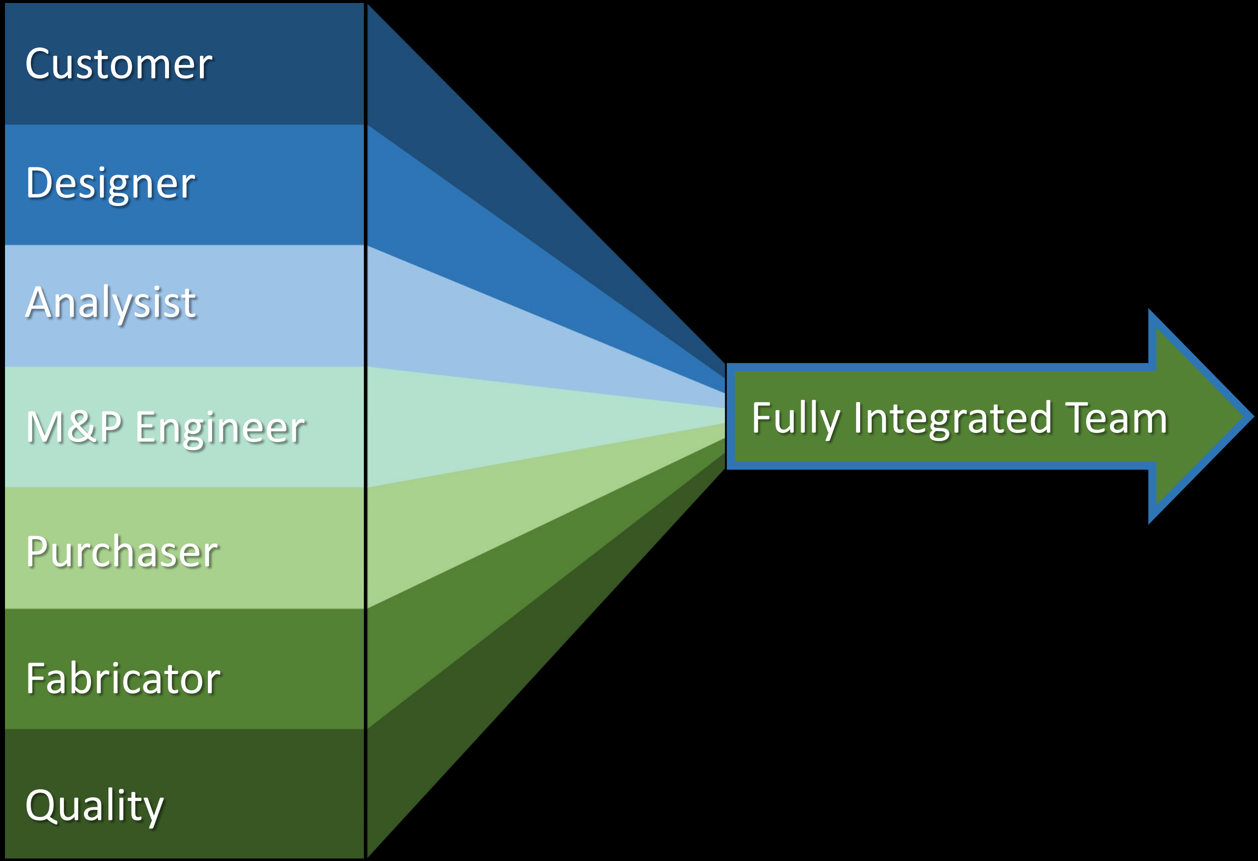


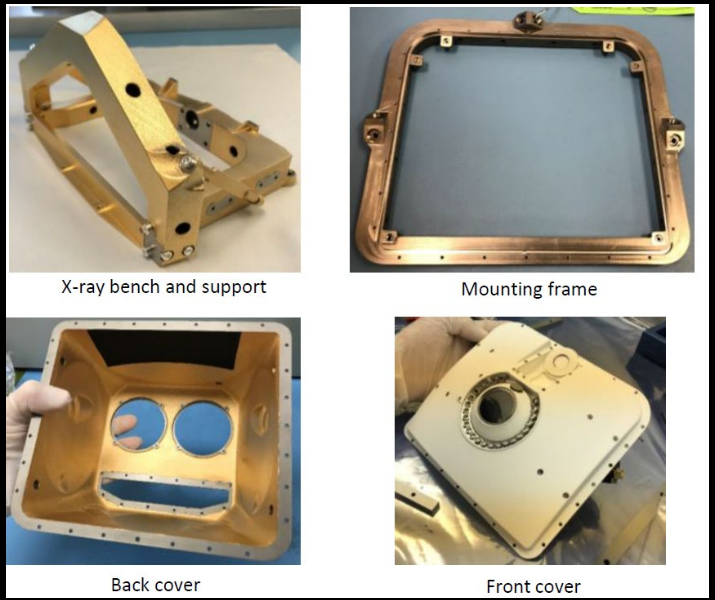
Multidisciplinary Integration

- Customers need to understand the design methodology
- Customers need to understand the fabricators process control

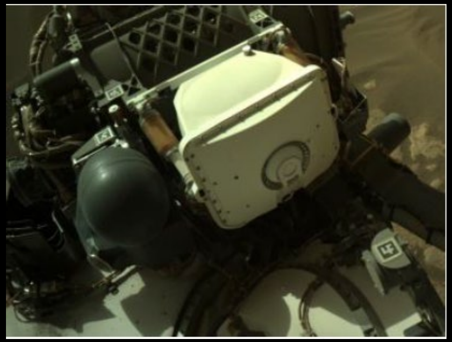


Multidisciplinary Integration





Images courtesy NASA/JPL Caltech



Successful AM Part

NASA-STD-6030 & 6033 – Basic Principles

- *Understanding* and *Appreciation* of the AM process
- *Integration* across disciplines and throughout the process
- ***Definition and Characterization of the process(es)***
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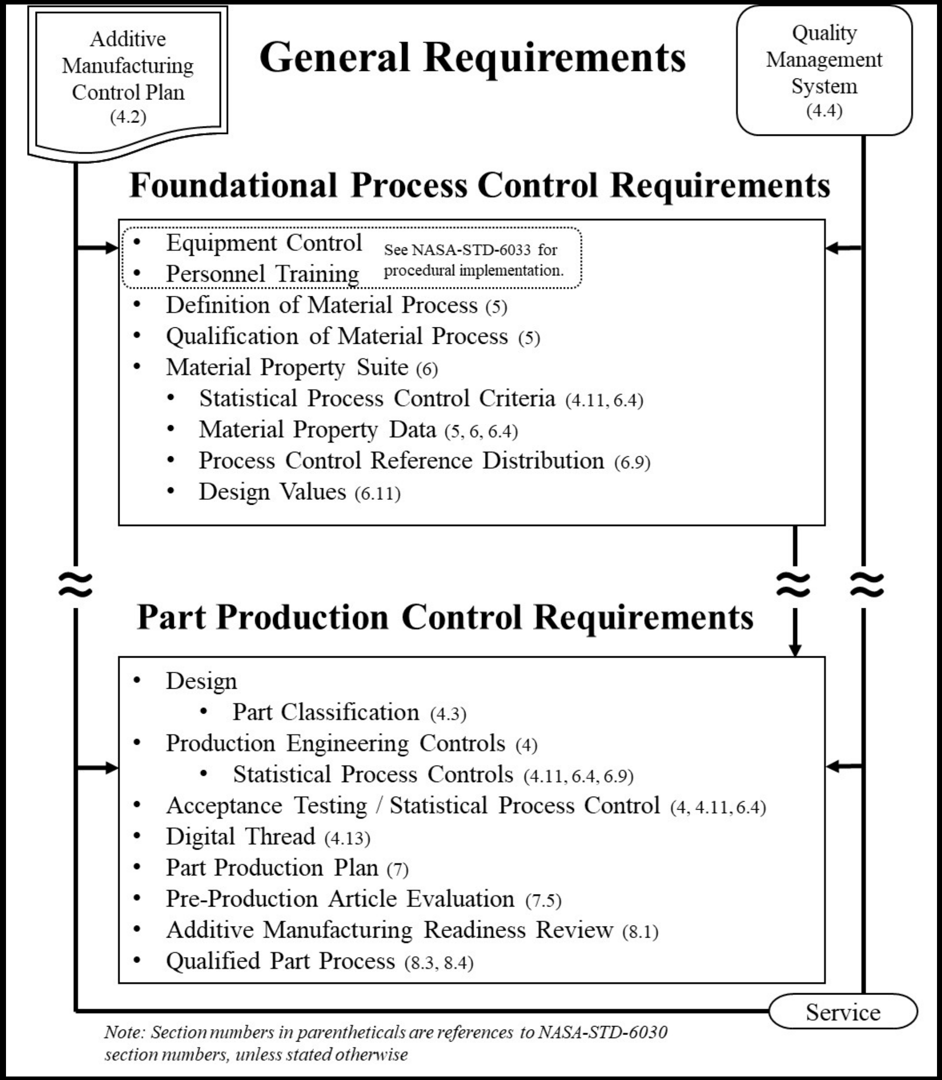
NASA Additive Manufacturing Framework

- NASA-STD-6030
  - 138 pages
  - 115 unique “shall statements”
- NASA-STD-6033
  - 31 pages
  - 31 unique “shall statements”



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- NASA-STD-6030
  - 138 pages
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- NASA-STD-6033
  - 31 pages
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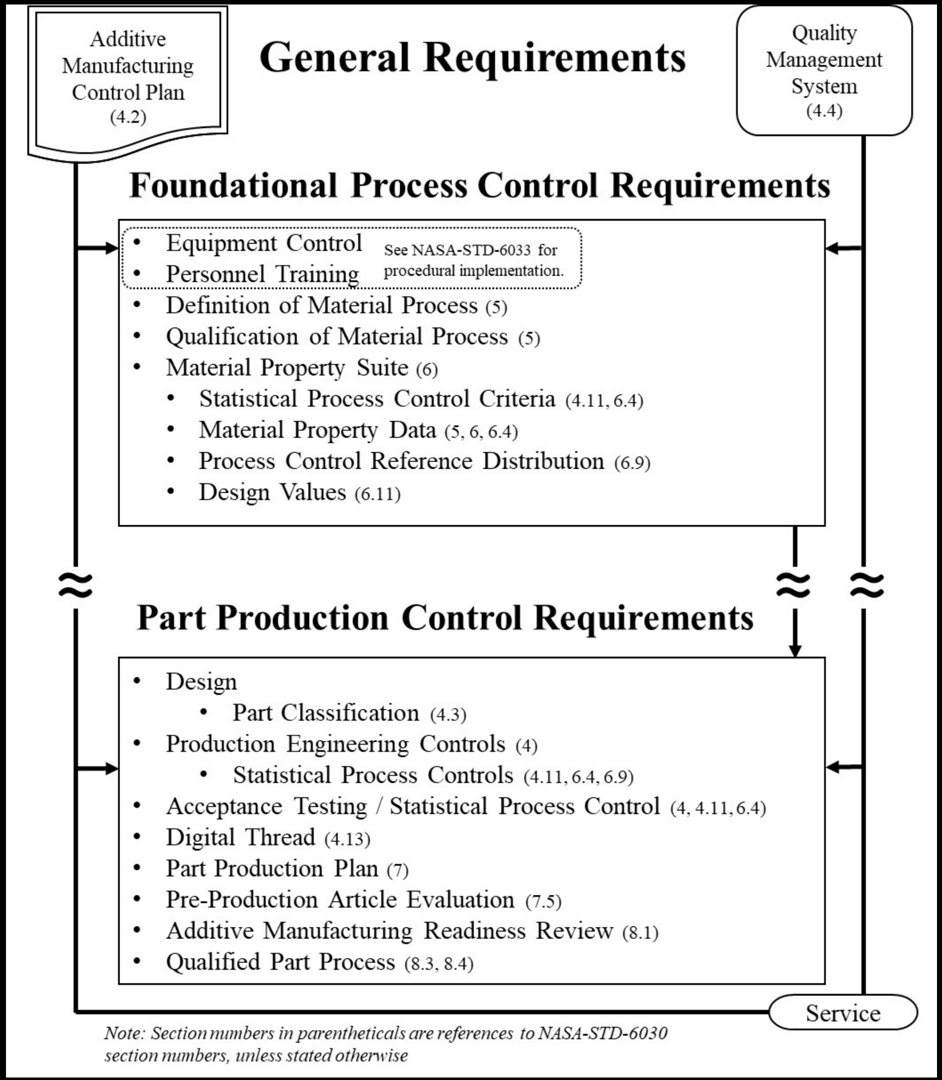
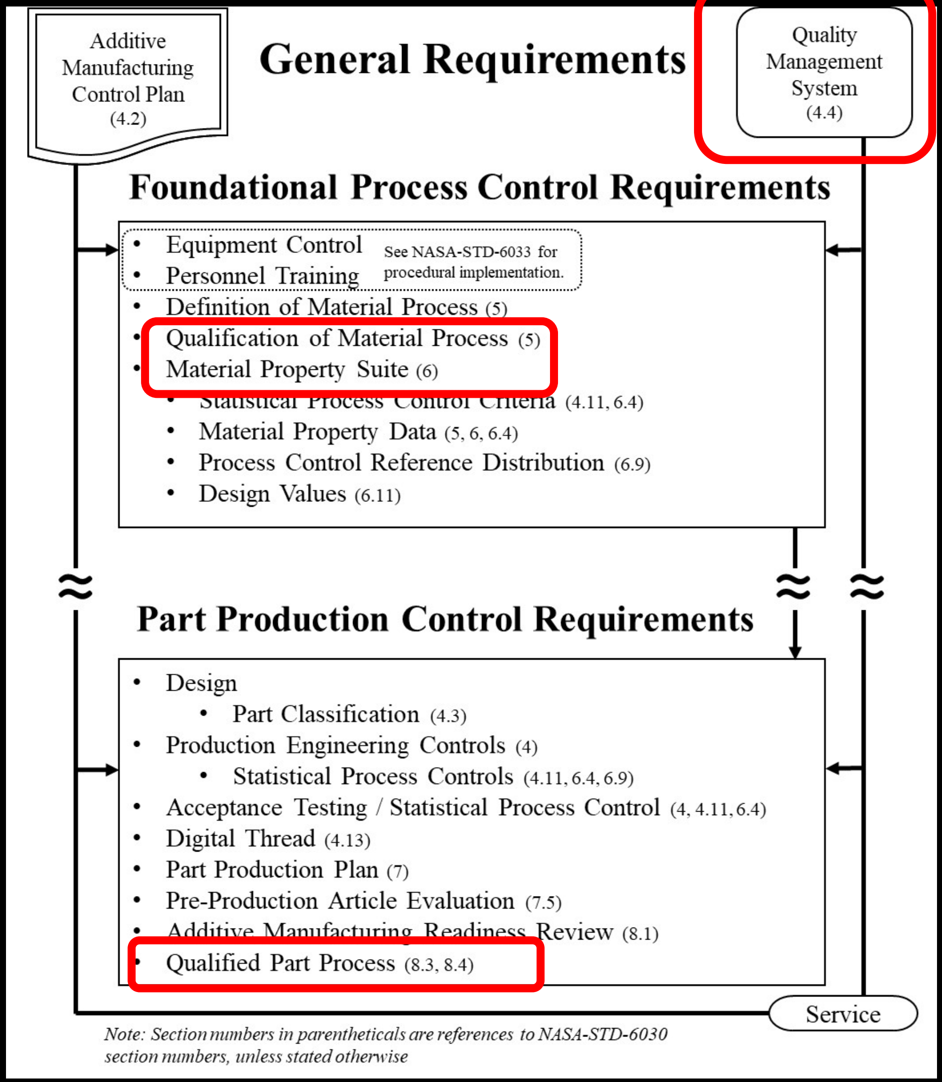
- **SmallSat and other low cost, high risk-tolerant missions, shouldn't use *most of them* (on contract)**



NASA Additive Manufacturing Framework

- But that doesn't mean they can't be *really* useful tools.



NASA Additive Manufacturing Framework

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4.4 Quality Assurance

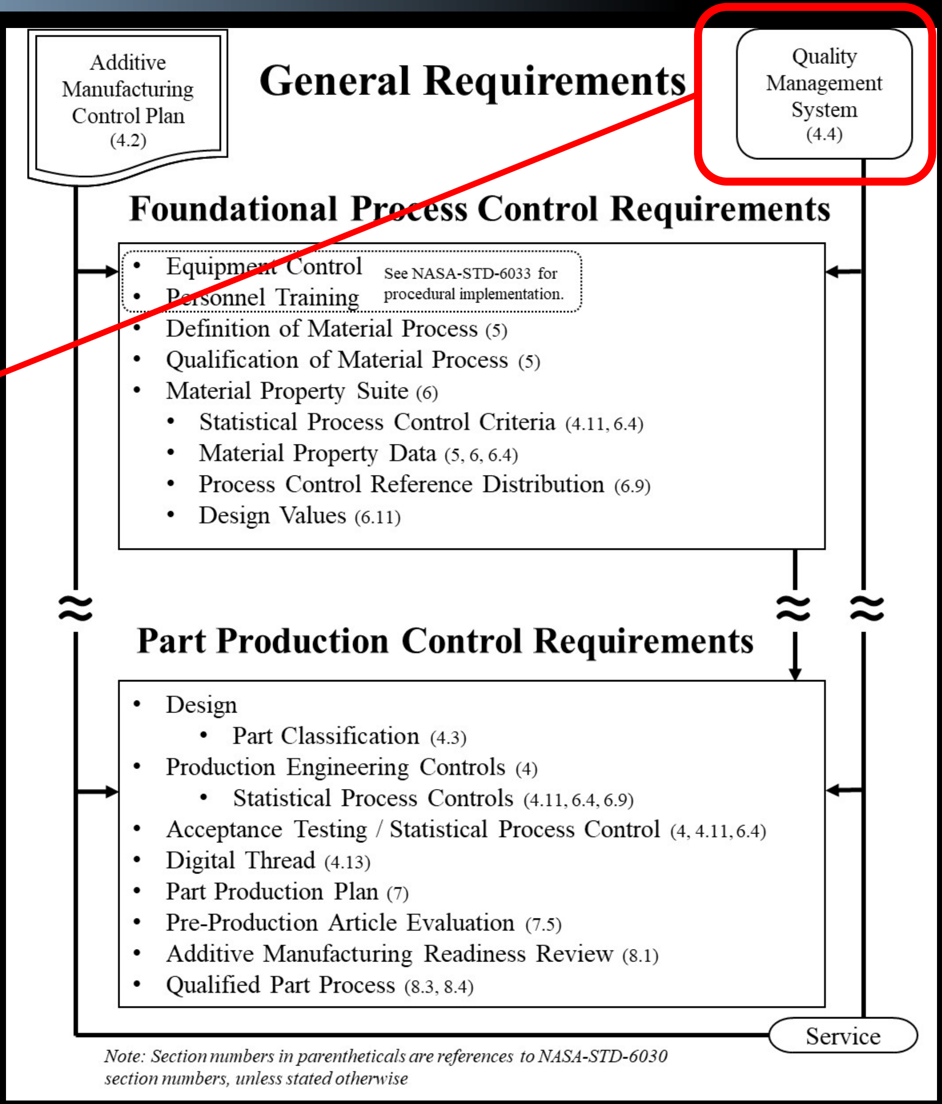
4.4.1 Quality Management Systems

[AMR-13] 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.

[Rationale: A QMS is required to ensure necessary process controls and mitigate risks associated with noncompliance. The AS9100 QMS requirement applies because an AM process is considered "complex" per NPD 8730.5, NASA Quality Assurance Program Policy, due to significant reliance on process controls for the reliability of the product. AM parts in Class A are also considered "critical" per NPD 8730.5.

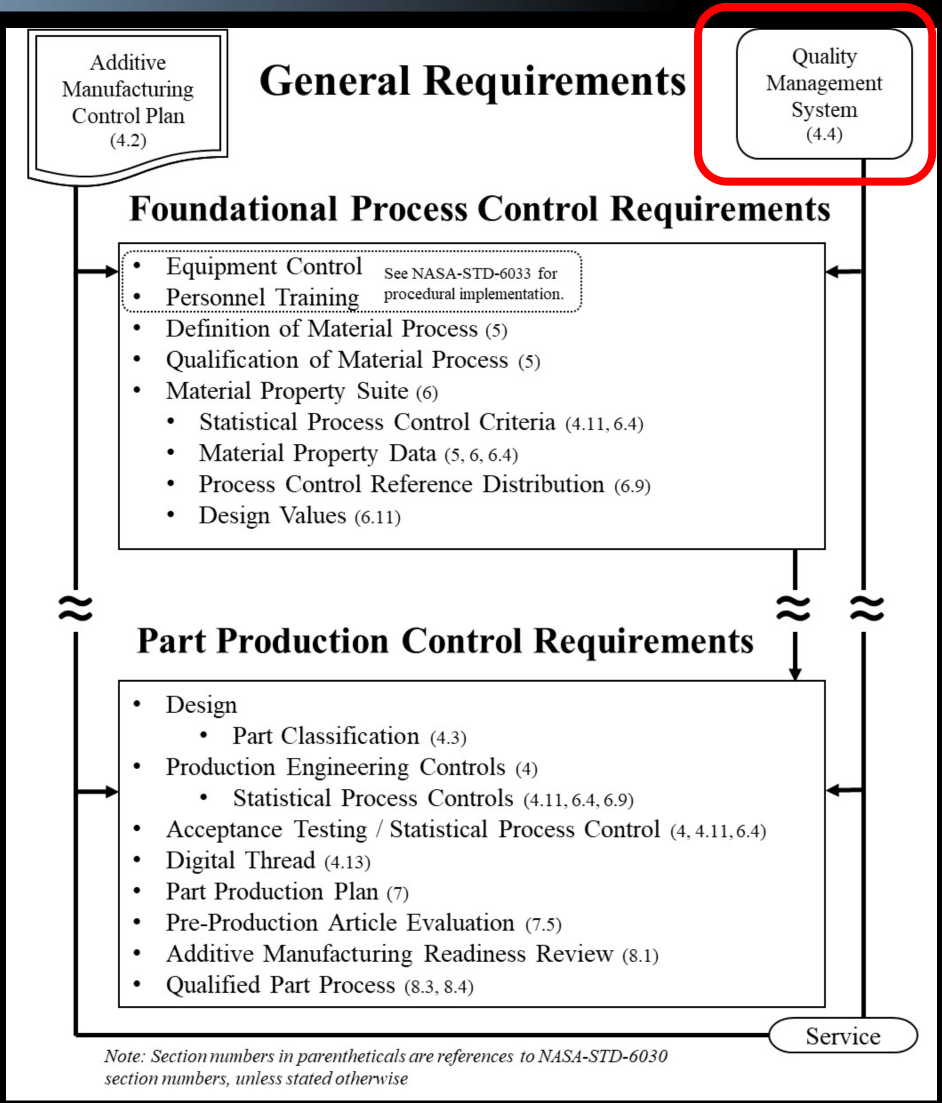
Note: Alternate QMS standards or supplier accreditation systems are more likely to be relevant at the subtier supplier levels (e.g., raw materials, post-processing, etc.) and should be considered by the CEO and NASA whenever reasonable.

Nadcap™ accreditation for L-PBF is recommended but not required.



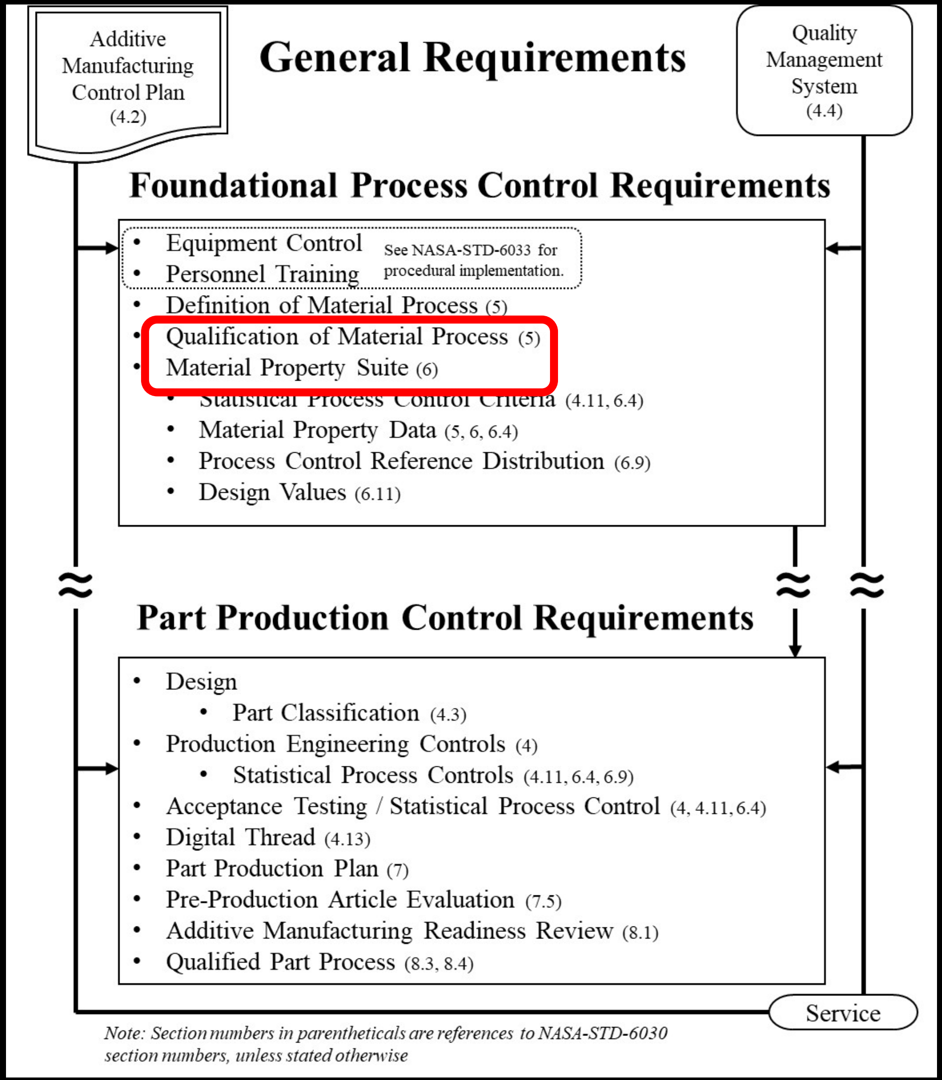
NASA Additive Manufacturing Framework

- "…QMS *compliant* to AS9100…"
- A formal accreditation from a third party is *really nice*, but not required.
- But, **<u>for SmallSat Programs</u>**, a *recent* accreditation from a *reputable* source gets you to "good enough" on *most* non-QMP/MPS requirements



NASA Additive Manufacturing Framework

- Qualified Material Process
  - Section 5
  - 26 pages
  - 24 “Shall Statements”
- Material Property Suite
  - Section 6
  - 26 Pages
  - 36 “Shall Statements”



NASA Additive Manufacturing Framework

- Qualified Material Process

5.2 Unique QMPs, Minimum Control Categories

[AMR-36] Each AM machine used to fabricate hardware **shall** have at least one QMP for each unique combination of the following control categories that affect the material condition:

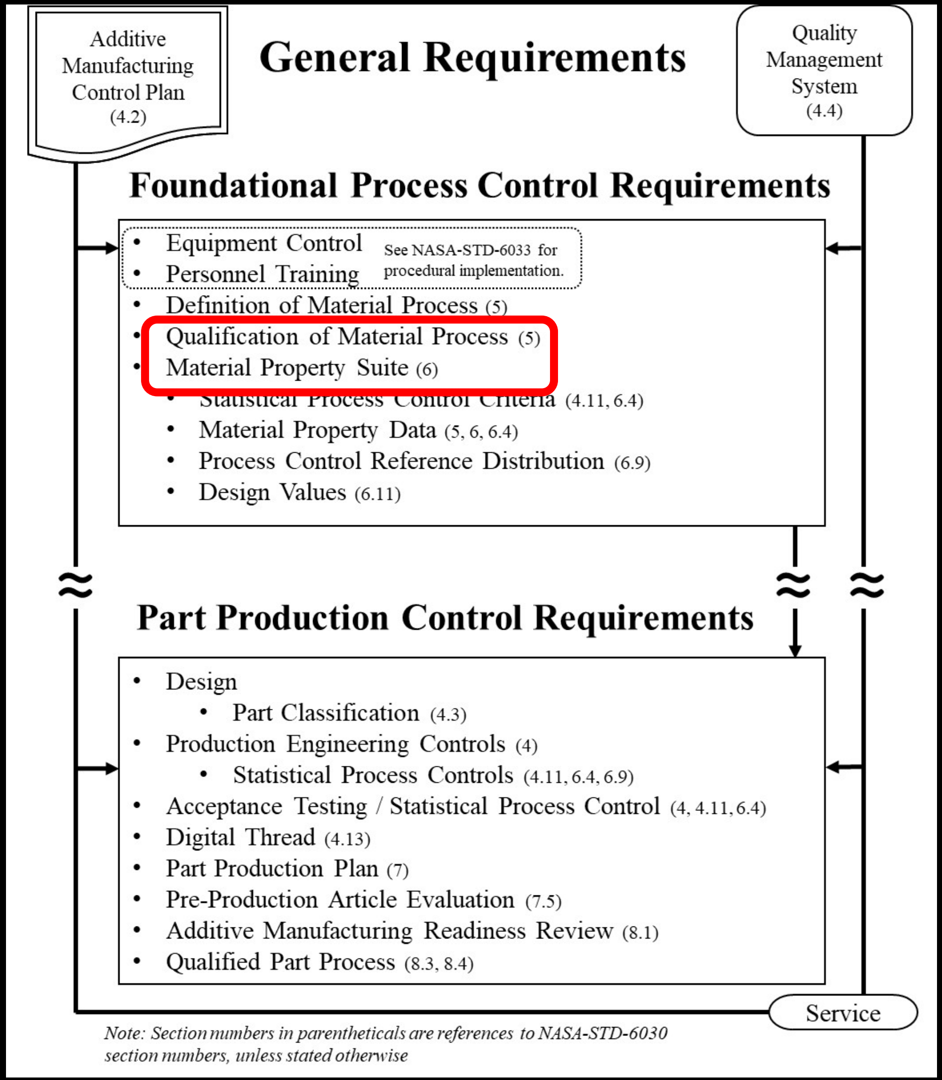
a. Feedstock specification and associated controls per section 5.4.1 of this NASA Technical Standard.

b. Associated machine, build process controls, and restart procedures per section 5.4.2 of this NASA Technical Standard.

c. Post-processing requirements per section 5.4.3 of this NASA Technical Standard.

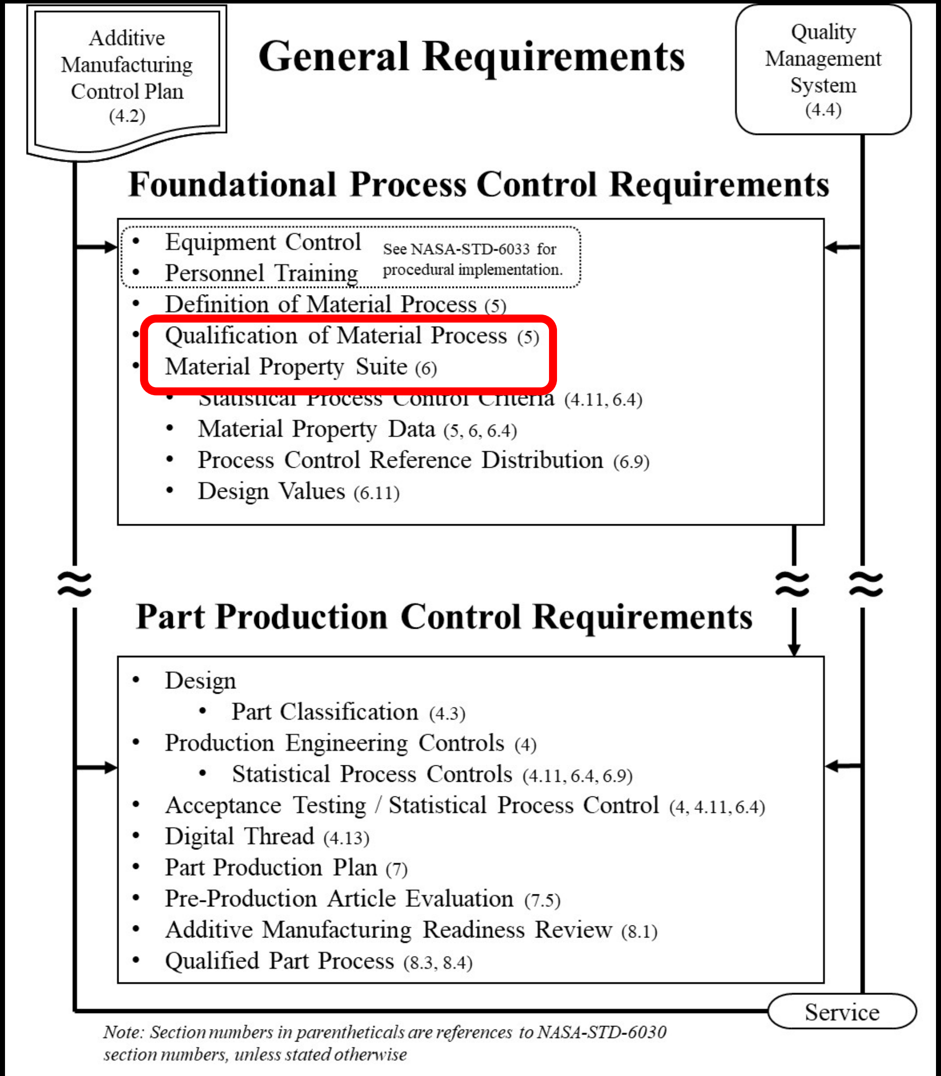
[Rationale: The QMP provides definition and control for foundational AM processes, enabling parts to be built with a process of verified material quality. These three parameter categories are fundamental to ensuring process repeatability.]

Note: AM machines may operate under the auspices of multiple unique QMPs if variations in controls or material post-processing exist.



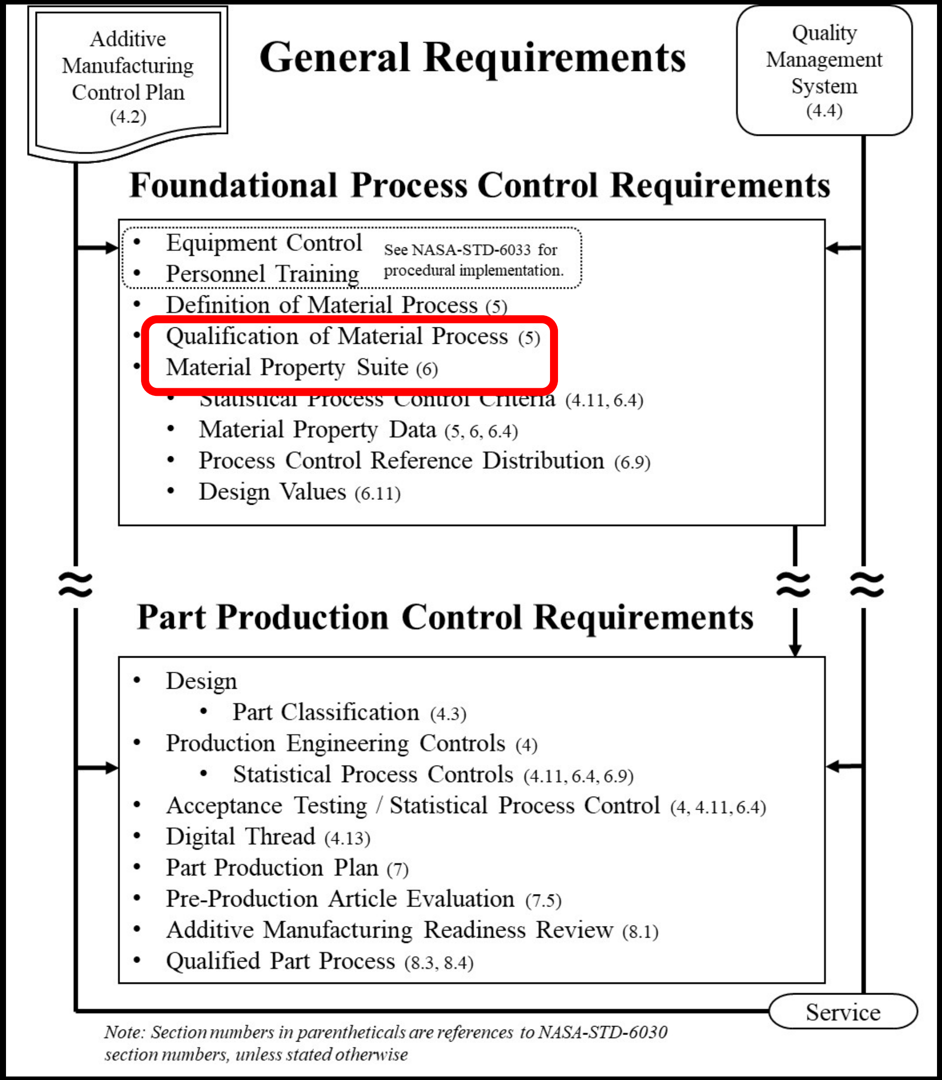
NASA Additive Manufacturing Framework

- Qualified Material Process
  - Feedstock Spec (ASTM/SAE could work)
  - Machine+Process Parameters
  - Post Processing Spec
- Pick a small number of permutations (≤3)
- That matches a LARGE dataset
  - 3+ feedstock lots
  - 10+ builds
  - 300+ tensile tests



NASA Additive Manufacturing Framework

- But 300+ tensile Samples is EXPENSIVE!
- Yeah, it is…you shouldn't pay for that
- Go to someone else who has already generated the data
- If they don't already have the data, you probably don't want to work them.



NASA Additive Manufacturing Framework

- Material Property Suite

6.2 Material Properties for Class C Parts

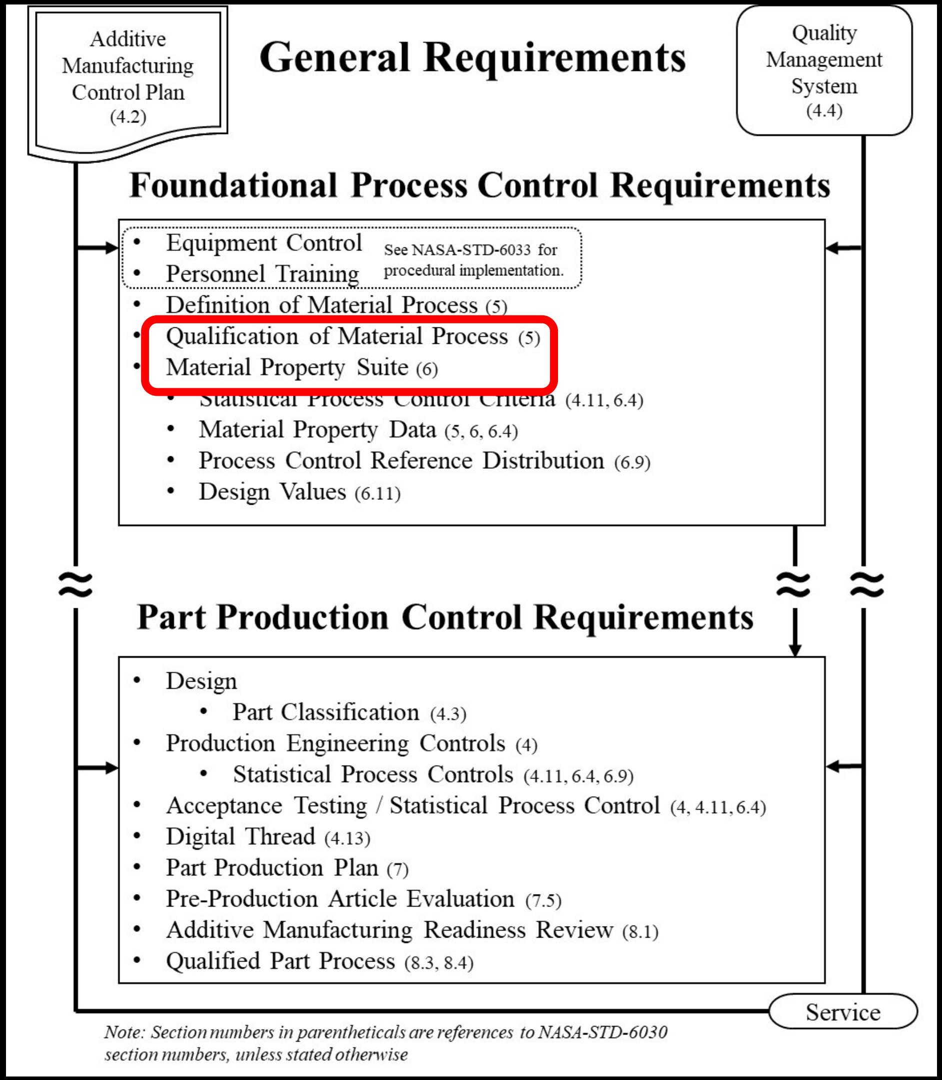
[AMR-62] For Class C parts, all required material properties needed to substantiate the manufacturability of the design and classification of the part **shall** be documented through the MUA process or the PPP, but may be of typical basis.

[Rationale: Understanding of material behavior is required for Class C components to ensure they are properly placed in Class C and perform their intended purpose.]

Material properties for Class C parts may be at a design basis (i.e., bounded statistically or by engineering judgment) or of typical basis (i.e., average values).

An MPS meeting the requirements for Class A and B parts is also acceptable for Class C parts.

i.e., don't do stupid &^%$



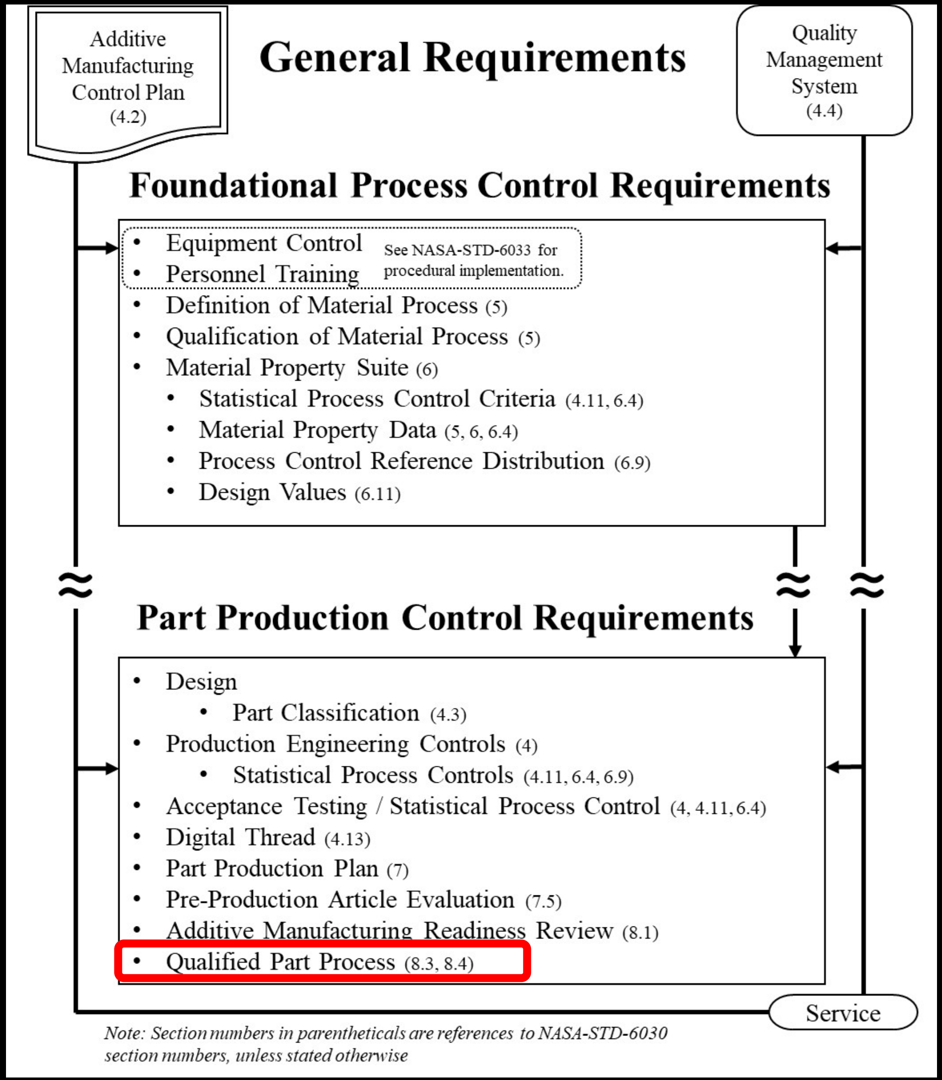
Qualified Part Process

- Once you've decided on a design
- Once you've decided on a vendor
- Once you've decided on a process
- Once you've "qualified the design"

- Do. Not. Change. *ANYTHING.*

- Once you've proved that something will work, you need to ensure that the Flight Part will be built *exactly the same way.*

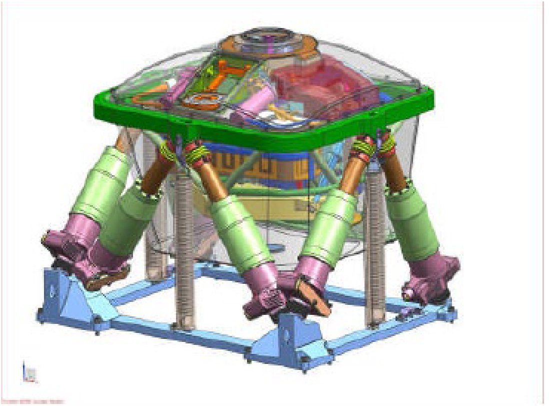
- This is especially important for Universities who own and operate their own AM machines

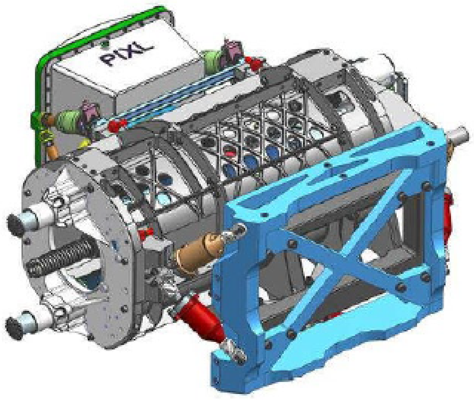


Example: PIXL (JPL)

Planetary Instrument for X-Ray Lithochemistry (PIXL)

- Combination of structural and non-structural parts
- Mission class D instrument, located on a high-value region of a Class A spacecraft
  - Cost sensitive mission, so savings from AM would reduce development time and costs for a braze joint
  - Parts are 100% inspectable with non-destructive evaluation
- Hardware developed prior to NASA-STD-6030 release
  - Used similar methodologies (i.e. process control)
  - Required 100% proof testing of all flight components

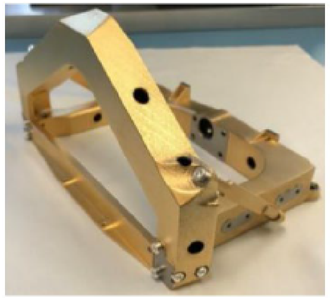




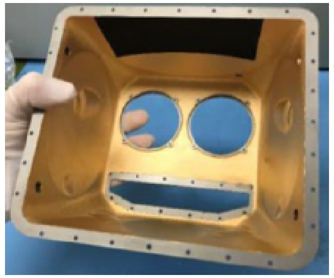
CAD images courtesy NASA/JPL-Caltech

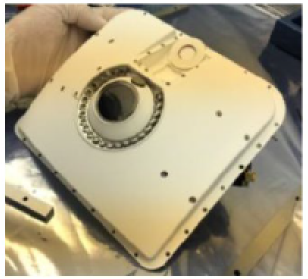
PIXL (cont.)

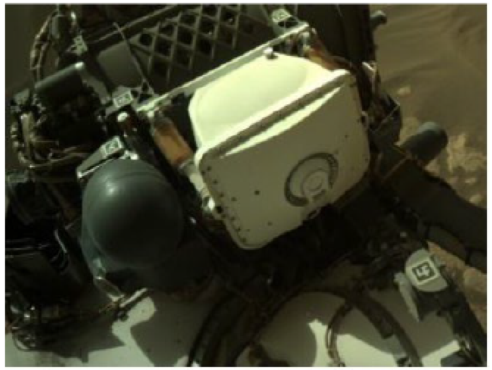
- Structural Ti-6Al-4V (top row) components
  - Leveraged America Makes B-Basis allowables for EB-PBF
  - Locked machine parameters and powder suppliers to America Makes-qualified suppliers
  - Mounting frame took serious effort for powder removal, given thin walls and hollow box-beam construction
- Non-structural AlSi10Mg (middle row)
  - No commercial database existed
    - Levied significant JPL investment into process control via post-build heat treatment to attain repeatable properties
    - Worked with a trusted vendor
  - Risks to mission were minimal, limited requirements levied on parts (dust shields)
- Reasons for success
  - Process control was implemented
  - Development plans were clearly communicated
  - JPL-led investments provided hard data to engineering review community
    - NDE inspectability and proof testing requirements helped with the narrative
  - Design was mass-constrained; AM provided cost, schedule, and mass relief (i.e. internal driving force)


X-ray bench and support


Mounting frame


Back cover


Front cover



Images courtesy NASA/JPL-Caltech

Example: GPX-2 (LaRC)

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National Aeronautics and Space Administration

Windform® XT 2.0 Use as 3U CubeSat Primary Structure

August 6, 2023

Amanda Stark

Andrew Paddock

Thuan Nguyen

Kurt Woodham

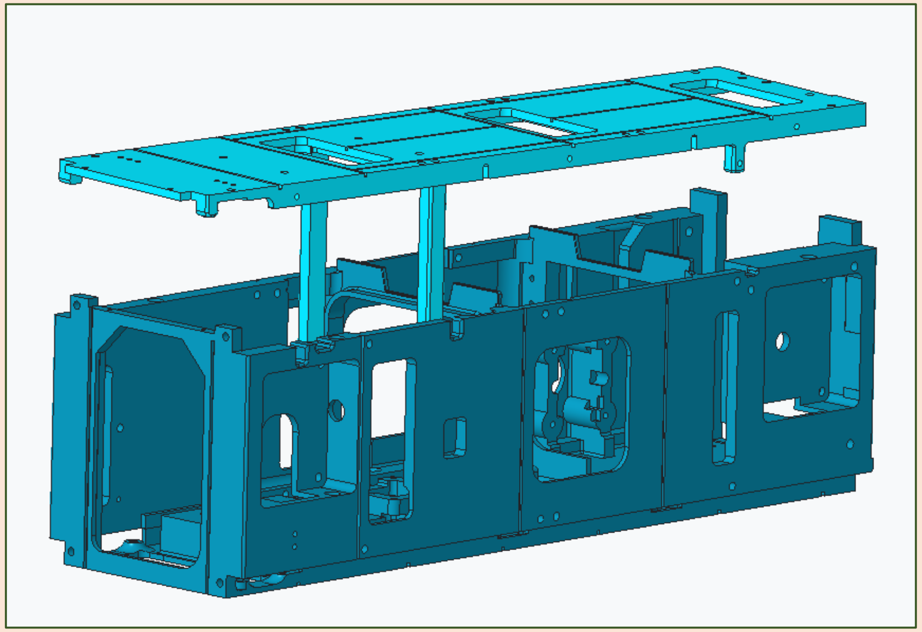
LINK: [Windform® XT 2.0 Use as 3U CubeSat Primary Structure (Paper)]

LINK: [Windform® XT 2.0 Use as 3U CubeSat Primary Structure (Presentation)]

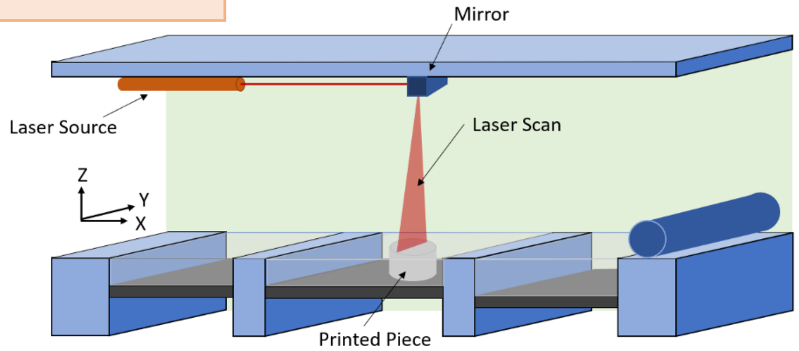
http://engineering.larc.nasa.gov/

Structural Design

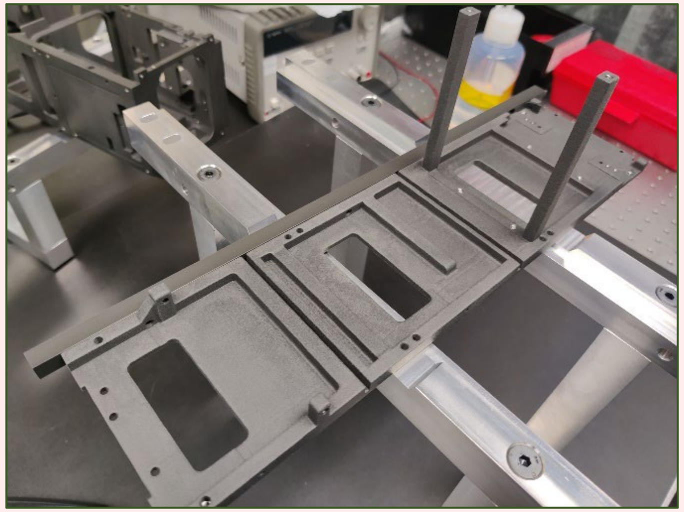
Creo CAD

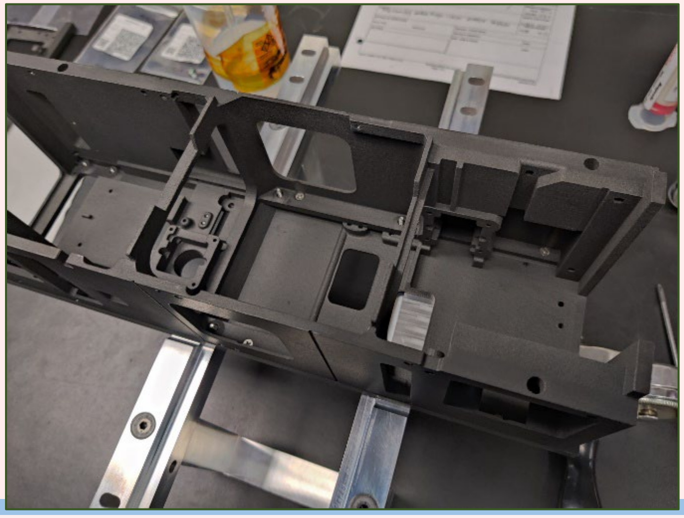


SLS with Windform® XT 2.0



Final Components





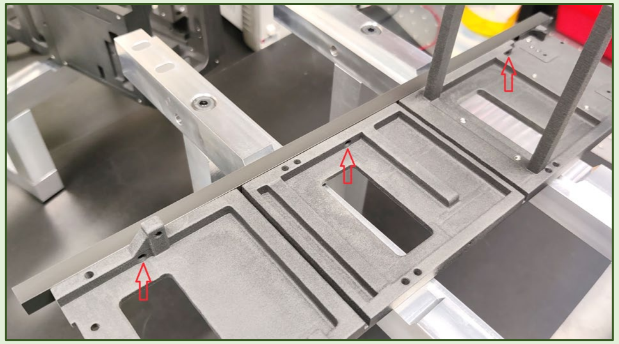
Lessons Learned Highlights

Joints for CTE Mismatch

- Aluminum rails fastened to Windform®

Lesson:

- Consider single fixed fastener with sliding attachment. Would need sub-assembly thermal testing



Polymer Loaded Joints

- Preloaded fasteners with plastic components experienced a loss of torque

Lesson:

- Work with materials to identify a torque/retorque schedule

Running Torque Measurement

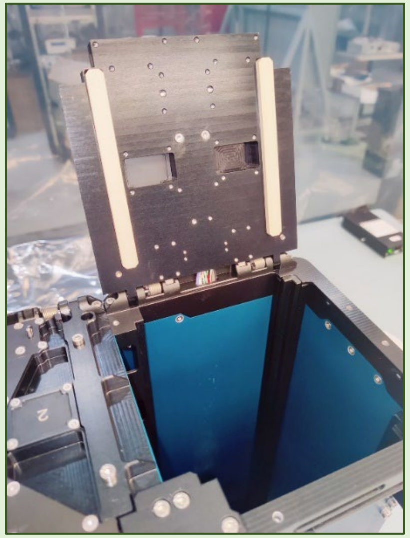
- Running torque generally not measured for tapped holes, but did uncover some anomalies

Lesson:

- Measure running torque for small, tapped holes

Fit Check

- Space craft fit test deployer but not flight deployer



Lesson:

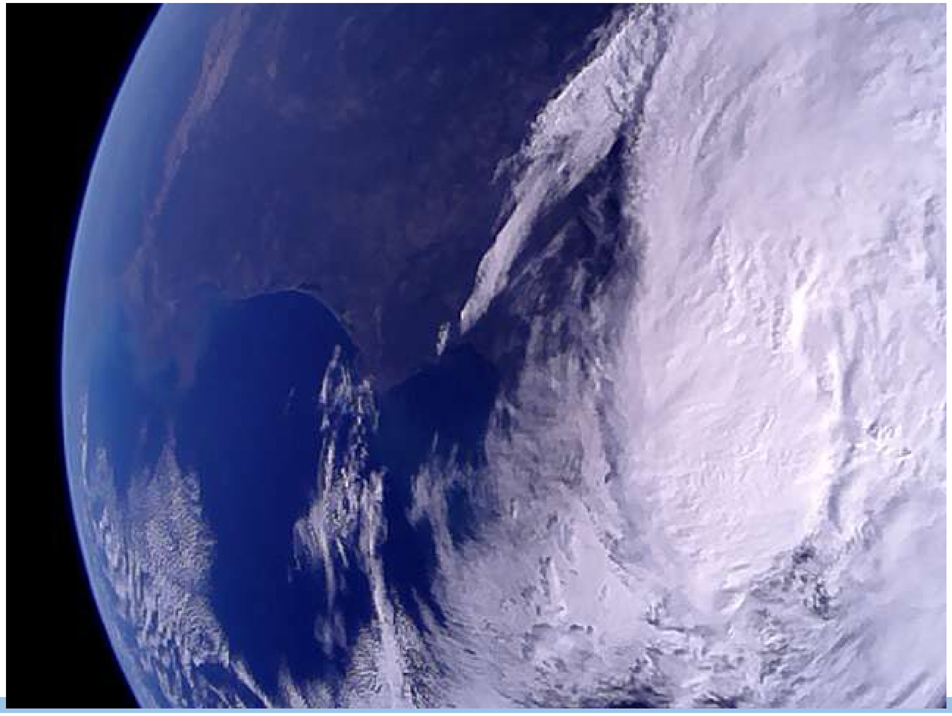
- Fit-check/measure all critical components/dimensions as soon as possible

Conclusion

GPX2 was the first to validate and launch a 3D printed material for the primary 3U structure.

- Allowed for freedom to design features that could not be realized through subtractive manufacturing
- Potential reduction in mass
- Lessons learned to streamline applications to future missions
- Collected temperatures on-orbit were within expected range

2022-09-28 14:24:54 UTC Gulf of Mexico, uCAM III Photo



2022-09-29 13:57:59 UTC Landfall over FL, uCAM III Photo

Recommendations

- Don’t buy a machine (unless you need to)

Recommendations

- Don't buy a machine
- Have an Integrated Design and Fabrication Team

Recommendations

- Don’t buy a machine
- Have an Integrated Design and Fabrication Team
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Recommendations

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