National Aeronautics and Space Administration

Lattices & Additive Manufacturing

How NASA-STD-6030 Can Help Make Your Designs a Reality

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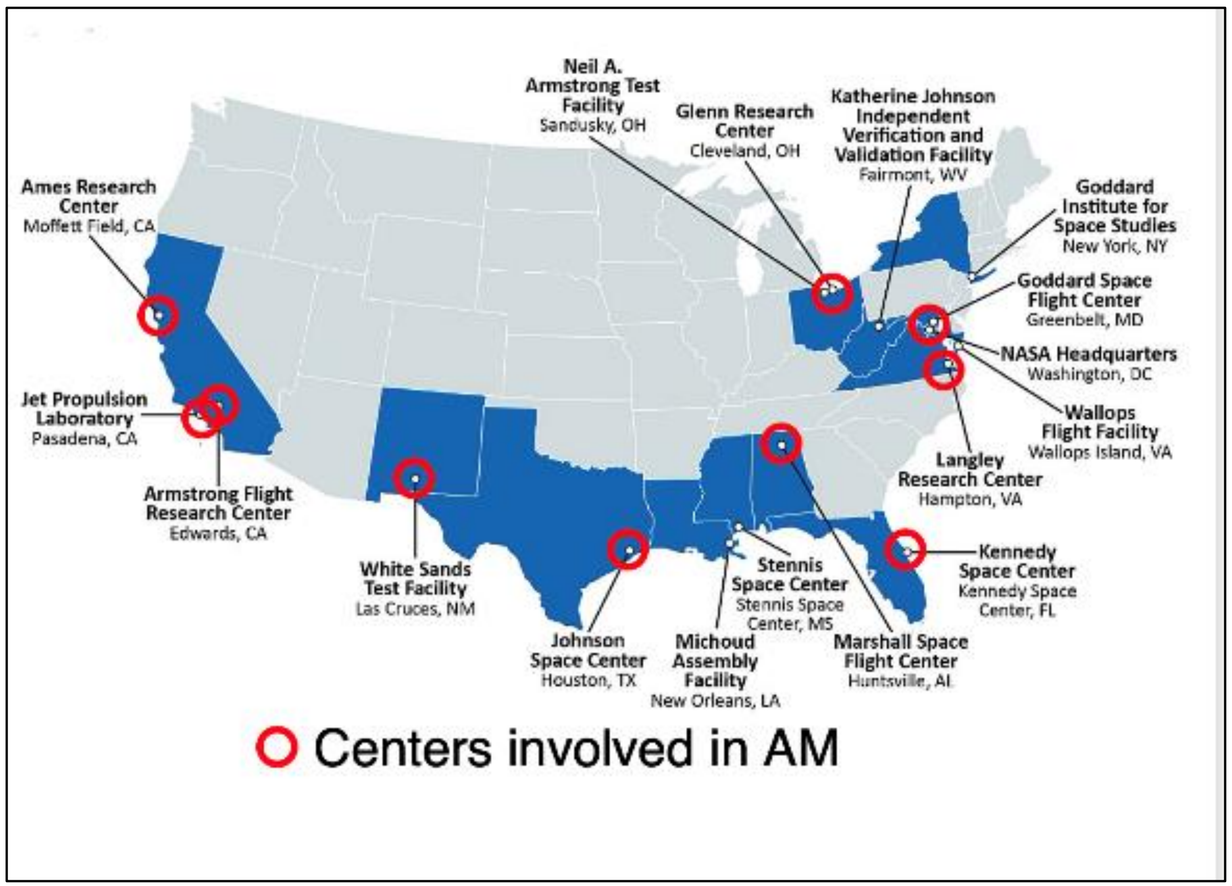
Questions

- Where does NASA use Additive Manufacturing?
- What are the Basic Principles of NASA-STD-6030?
- Why should I care about NASA-STD-6030 (and how should I use it)?
- What are the major stumbling blocks for AM implementation?
- I design lattices, why do I care about NASA-STD-6030?

Where does NASA use AM?

NASA is not homogeneous

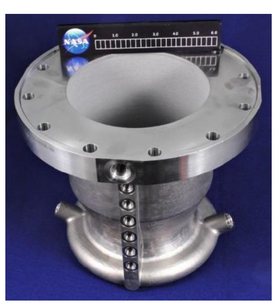
- –Technical and risk cultures vary by facility and mission, as shaped by its history
- –Human-rated spaceflight
  - •JSC, KSC, MSFC
- –Space Science
  - •GSFC, JPL
- –Aeronautics
  - •LaRC, GRC, ARC



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.



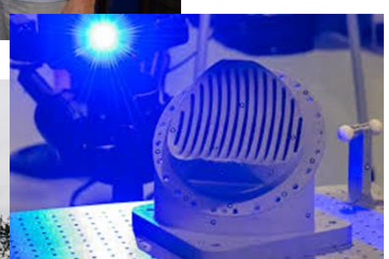
https://arc.aiaa.org/doi/abs/10.2514/6.2018-4625

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)

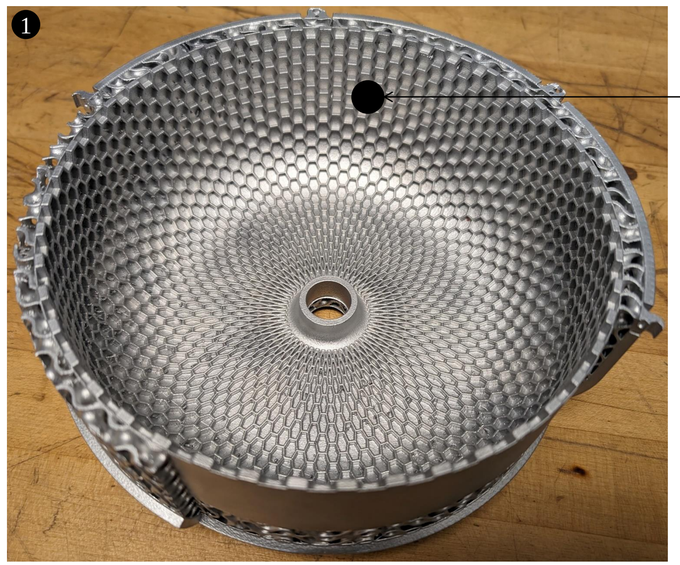
- Over 100 Weld Eliminated
- Nearly 35% Cost Reduction

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

Generative Design & Lattices (GSFC)

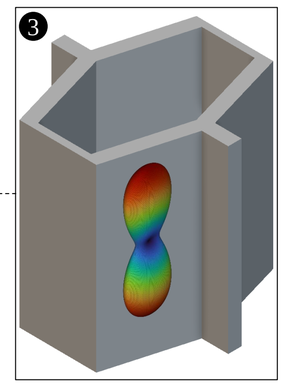
https://www.nasa.gov/science-research/nasa-turns-to-ai-to-design-mission-hardware/

Lattice Structure (Variable Lattice Network)
Metal Additively Manufactured Component

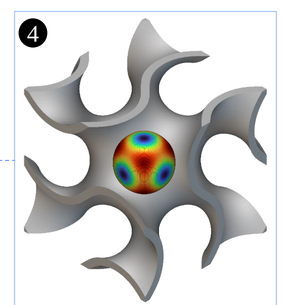


Lattice 1

Hexagonal
Honeycomb (Internal Stiffness)



TPMS Gyroid (Thermal Efficiency)

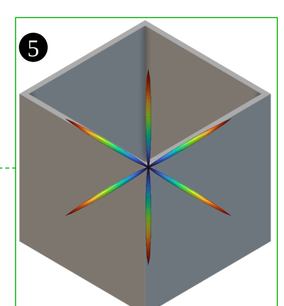


Lattice Structure Network (Close-Up)

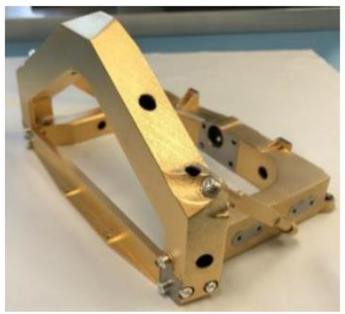
Lattice 2

Lattice 3

Square
Honeycomb (Shock Absorption)

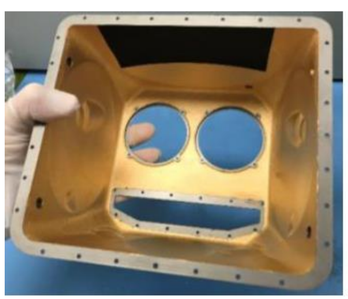


To Mars and Beyond (JPL)



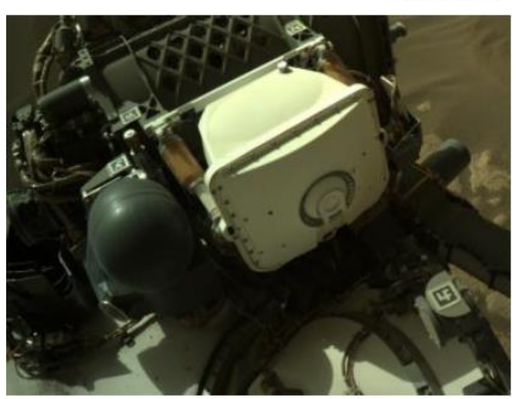
X-ray bench and support

Mounting frame

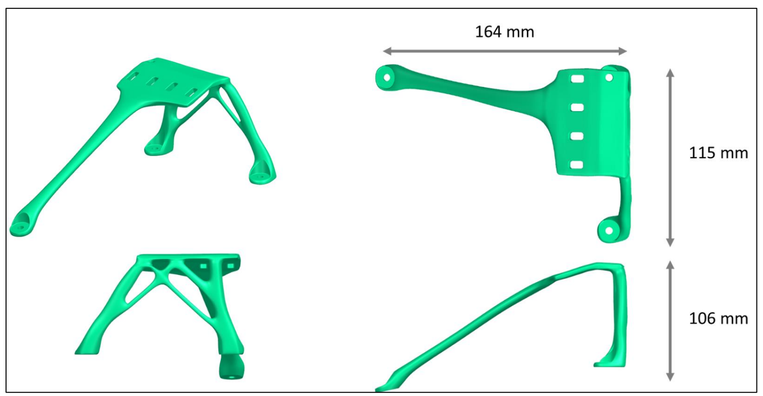


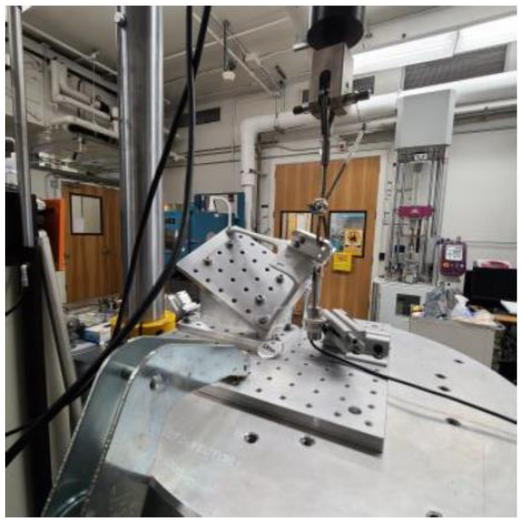
Back cover

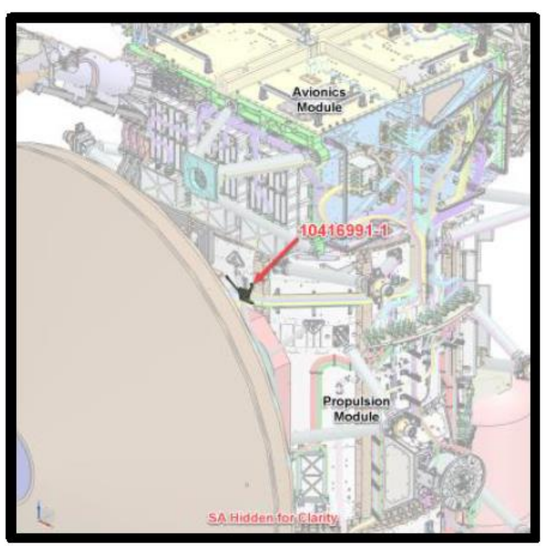
Front cover

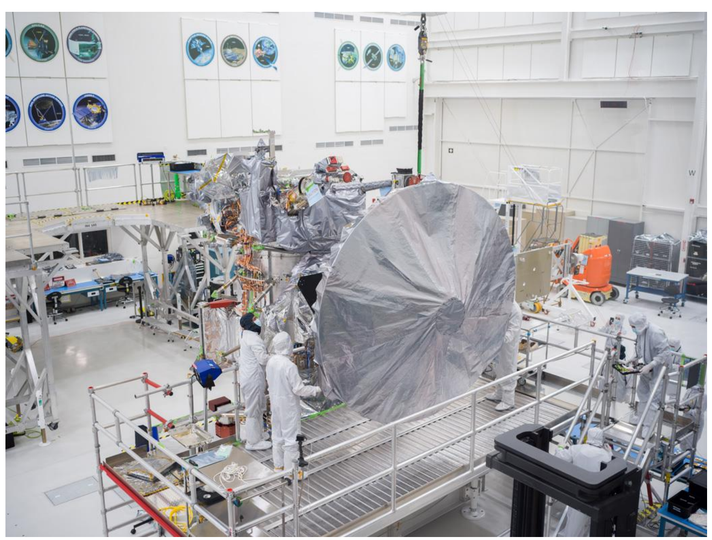


Images courtesy NASA/JPL-Caltech









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Nature **617**, 513–518 (2023) | Cite this article

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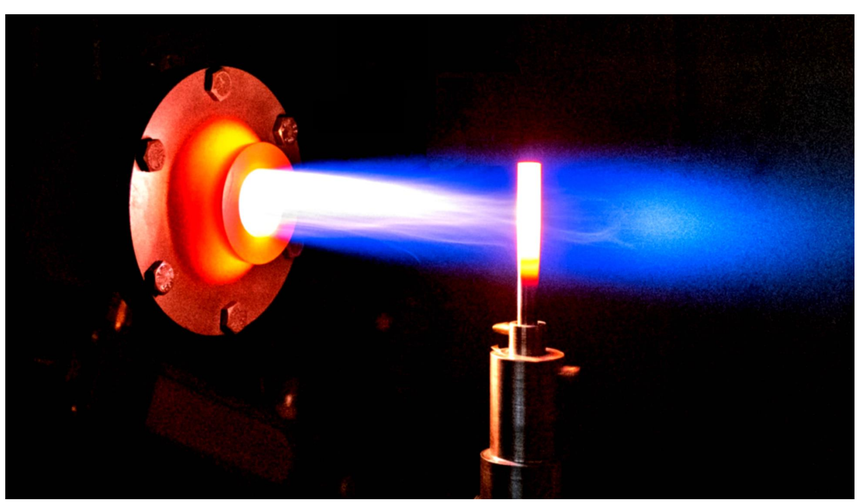
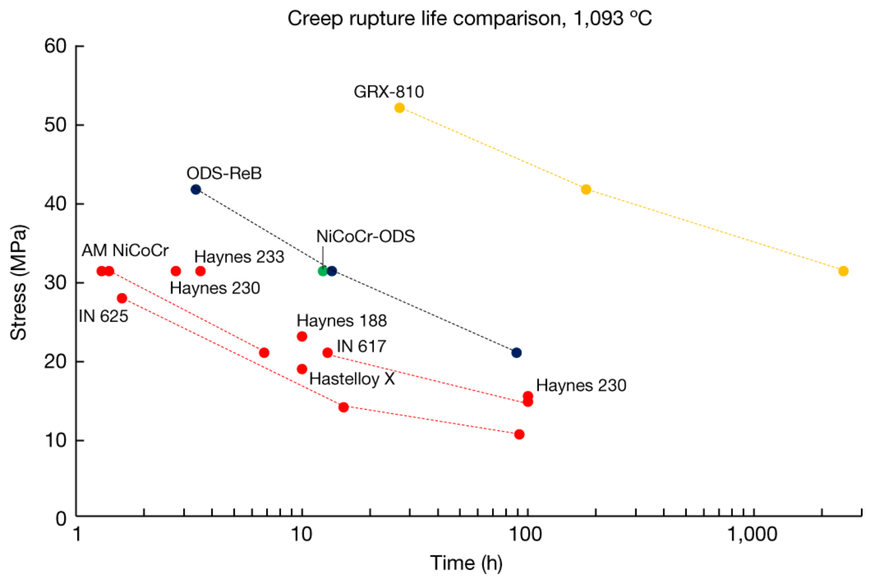
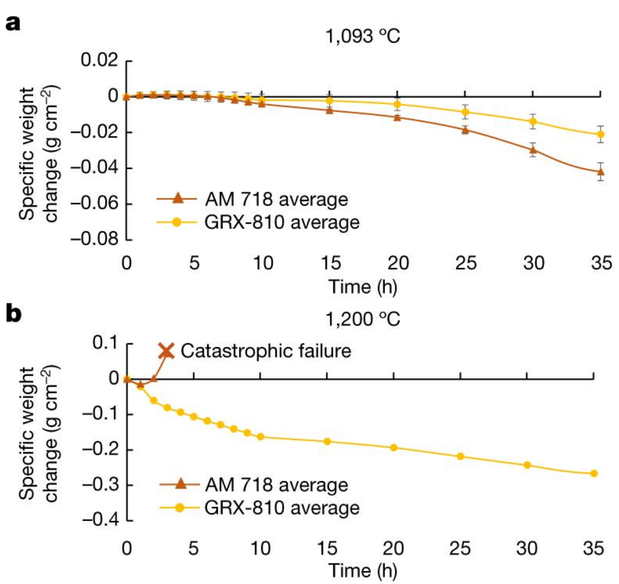
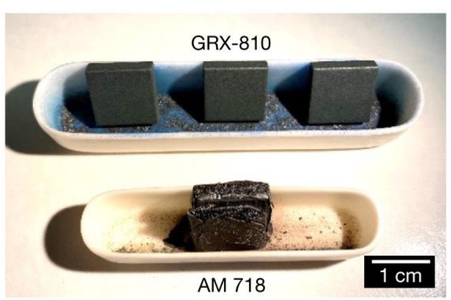
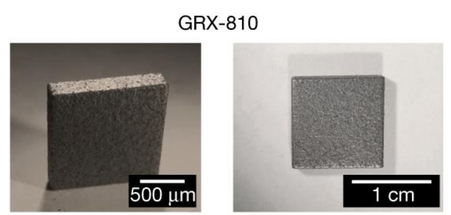










Why should I care about NASA-STD-6030?

- **It's a Requirement (you *have* to use it)**
  - –NASA set out to be first (because someone had to)
  - –NASA did not set out to be the only one (but here we are)
  - –In addition to NASA programs, NASA-STD-6030 is turning up in DoD Standards and DoD contracts

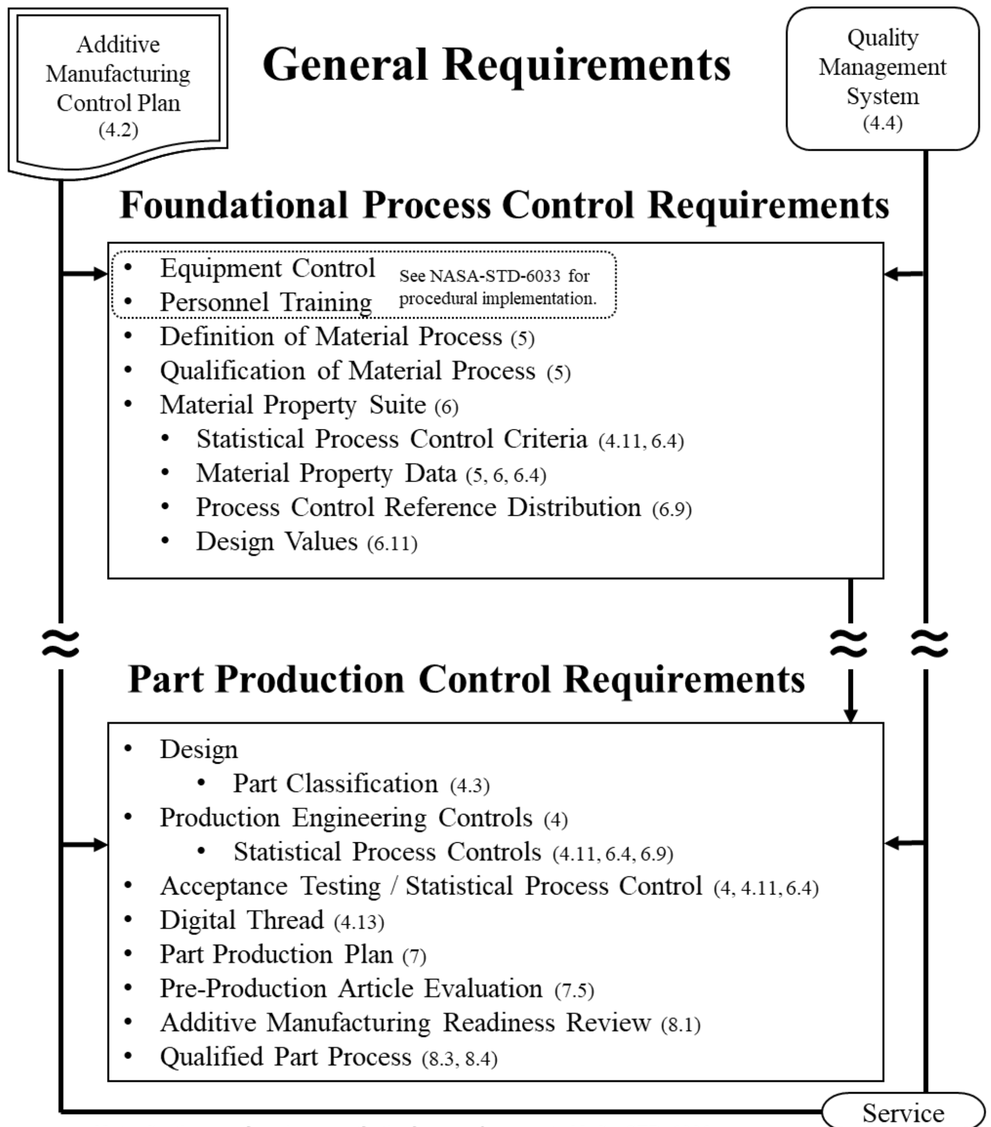
- **You want to make extremely reliable parts (you *should* use it)**
  - –More than anything else, NASA-STD-6030 makes you systematically *think* about how you use Additive Manufacturing
  - –AM Technologies and AM Manufacturing was born out of the "move fast and break things" mentality
  - –Moving Fast and Breaking Things is how you spark revolutionary change…
  - –It's *not* how you design, build, and field a part that could get someone killed

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

- **The Principles of "The NASA Way"**

- **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

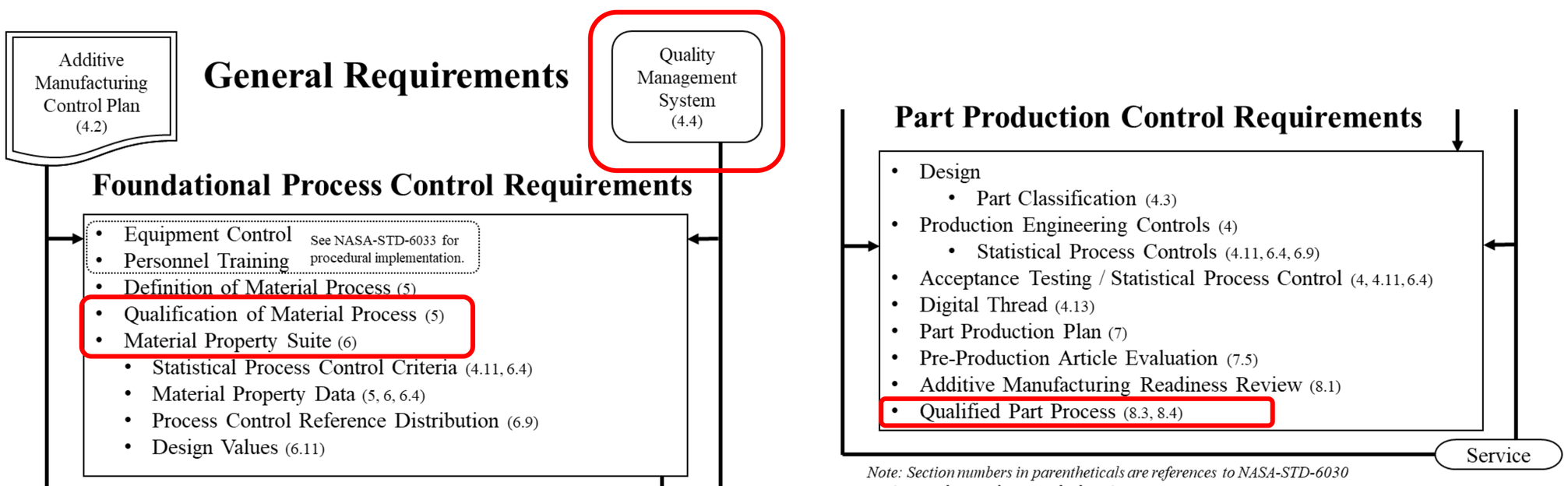


Note: Section numbers in parentheticals are references to NASA-STD-6030 section numbers, unless stated otherwise

How should I use NASA-STD-6030 (& 6033)?

- I *have* to use NASA-STD-6030
  - –Use it Early, Use it Often
  - –Talk to NASA (or your customer), do *not* struggle in silence!
  - –Write an AMCP sooner rather than later…everything follows from that

- I *don't have to* use NASA-STD-6030
  - –It's still an extremely useful tool



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What are the major stumbling blocks?

- NASA-STD-6030 is *Looooooooong*
- Lack of an Integrated Design, Procurement, & Manufacturing Team
- Intellectual Property & Prior Contracts

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 you 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*.

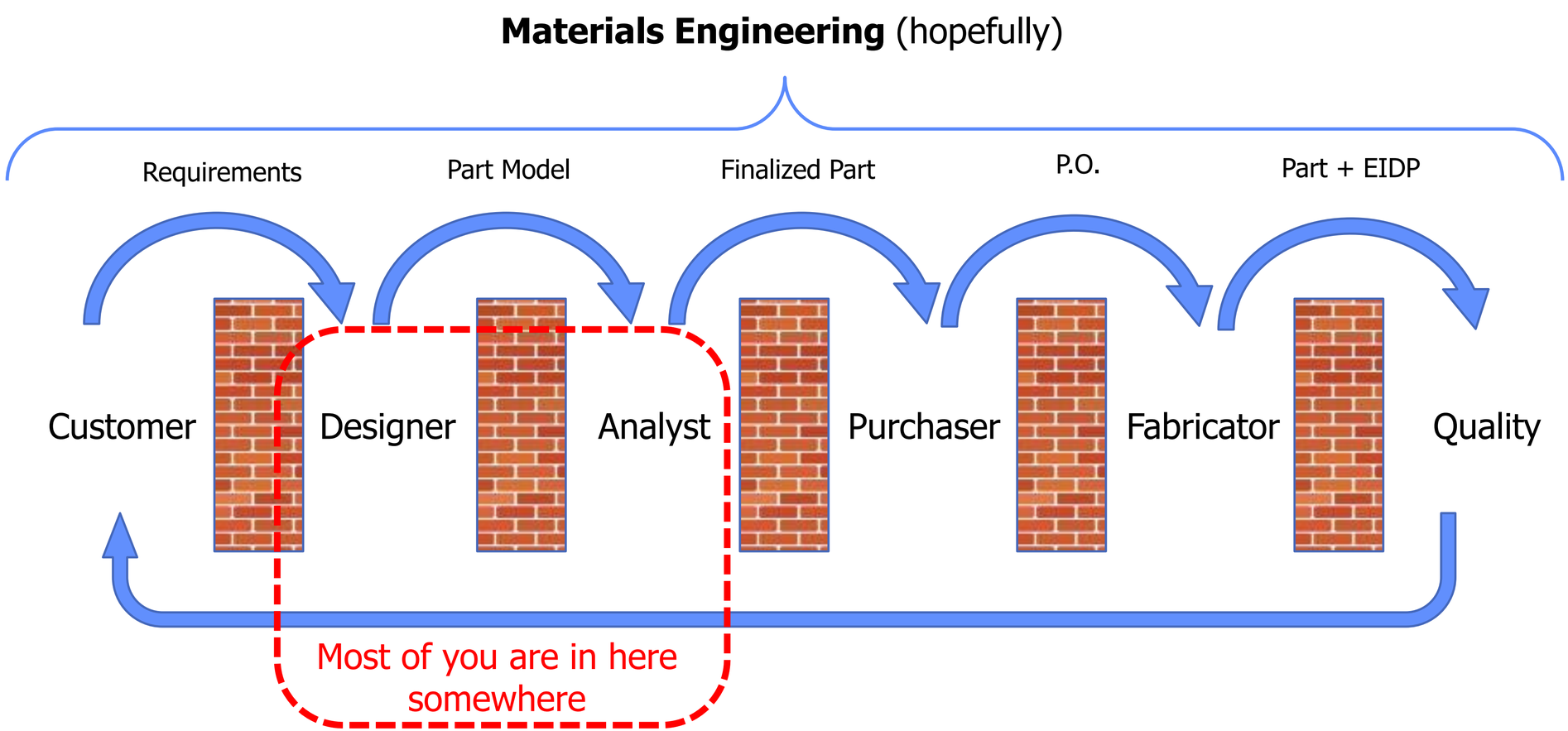
- An Additive Manufacturing Control Plan is how you document how you do AM *for yourself* and <u>*communicates it to your customers*</u>.

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

-Adam Savage (Mythbusters)

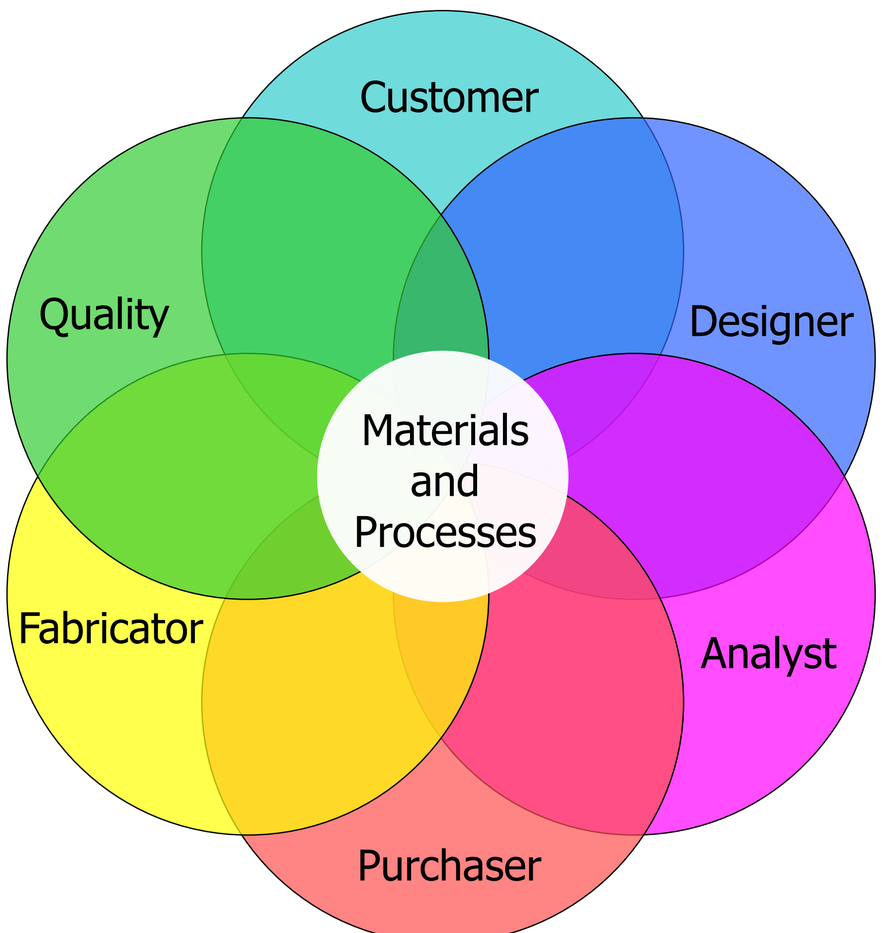
An Integrated Multidisciplinary TEAM

- 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., *you*…probably…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.

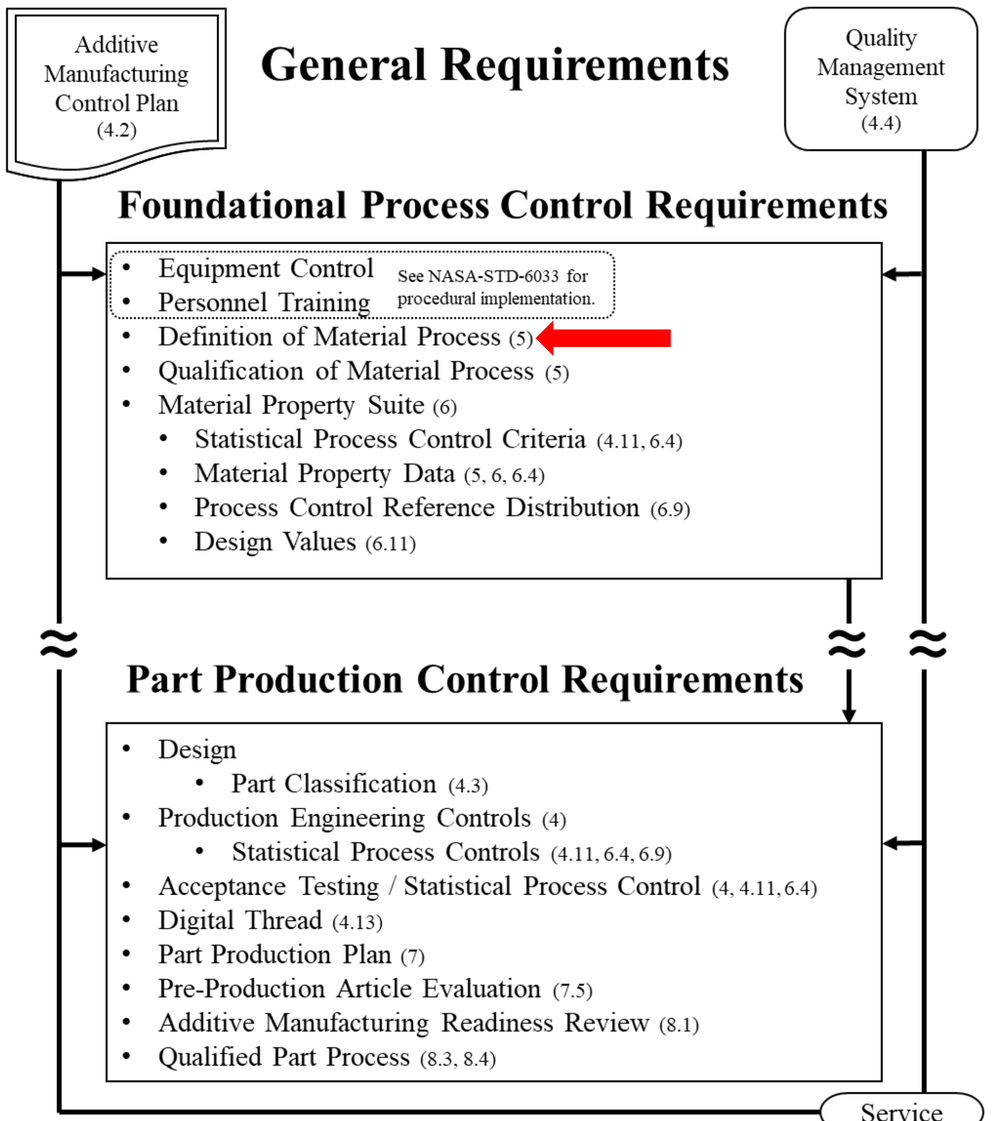
- Please Remember: For most Aerospace/Advanced Manufacturing applications, you still need to make most things "available upon request" to your customers
  - In most situations, you can require the customer to come to *you* to do it

Hoarding Knowledge Helps No One

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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What does this have to do with You*?*

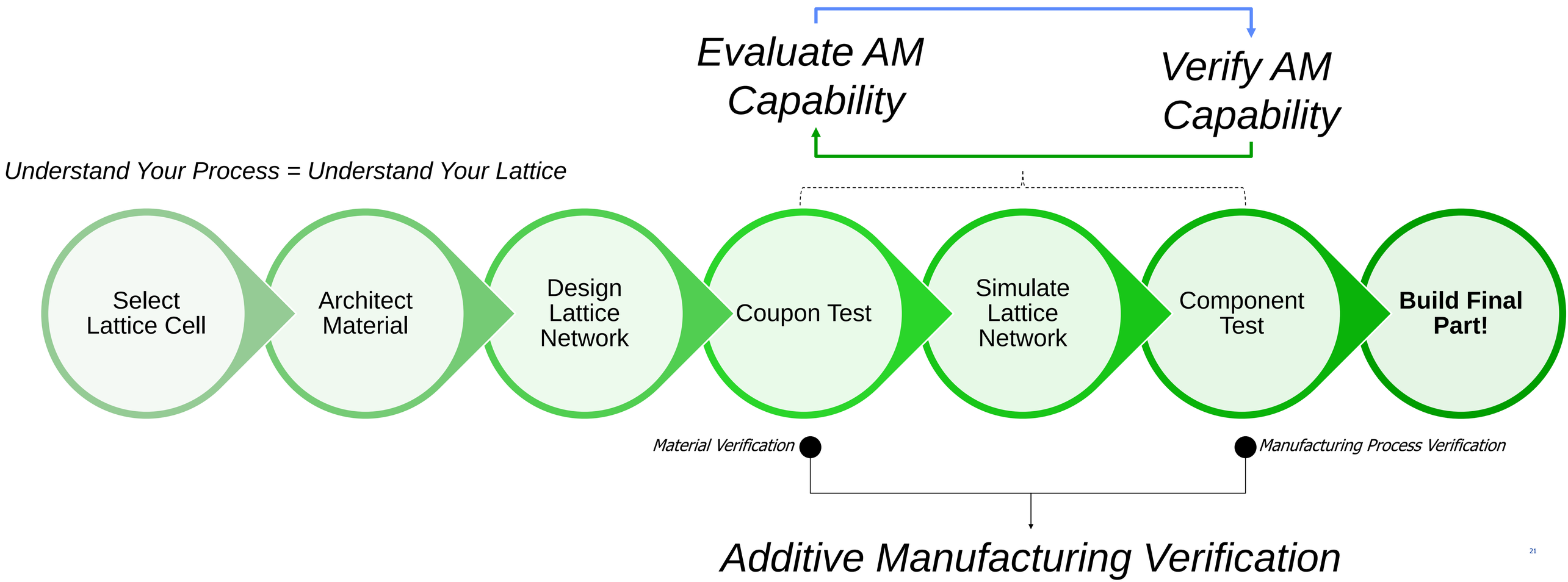
- Please let your vendors use the process parameters to print other people's parts

- The more the vendor uses the process, the more they understand it, the more they monitor it, the more reliable *your parts will be*.

- The more your Customers use AM, the more willing they are going to be to use *your parts*.

The Reality of Manufacturing Lattices

- Constant “Feedback Loop” in the Lattice Design Cycle w/ AM
  - –AM process becomes essential in verifying Lattice Integrity

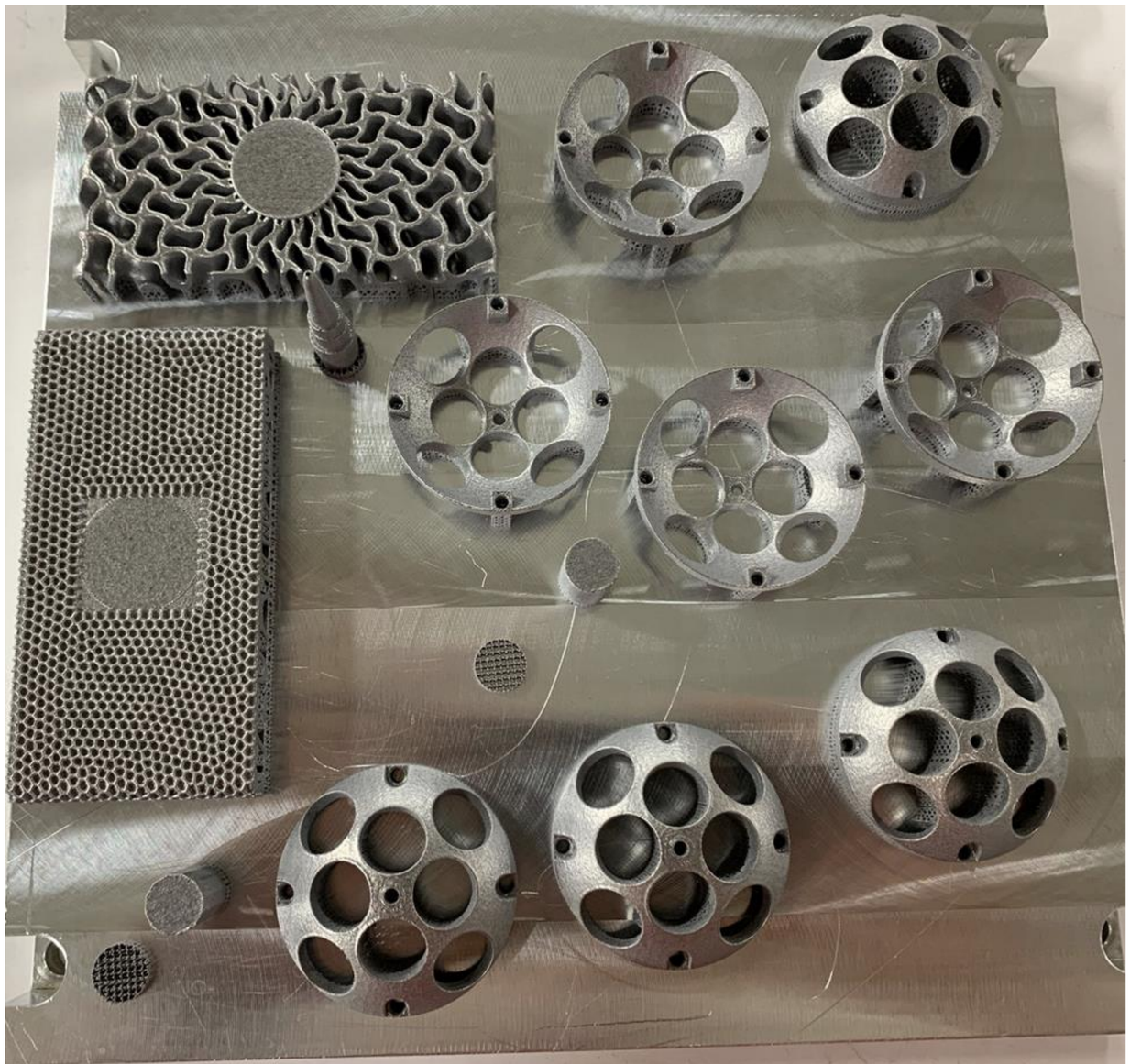


The Reality of Manufacturing Lattices

- Understanding the Manufacturing Process & Constraints is vital for success-

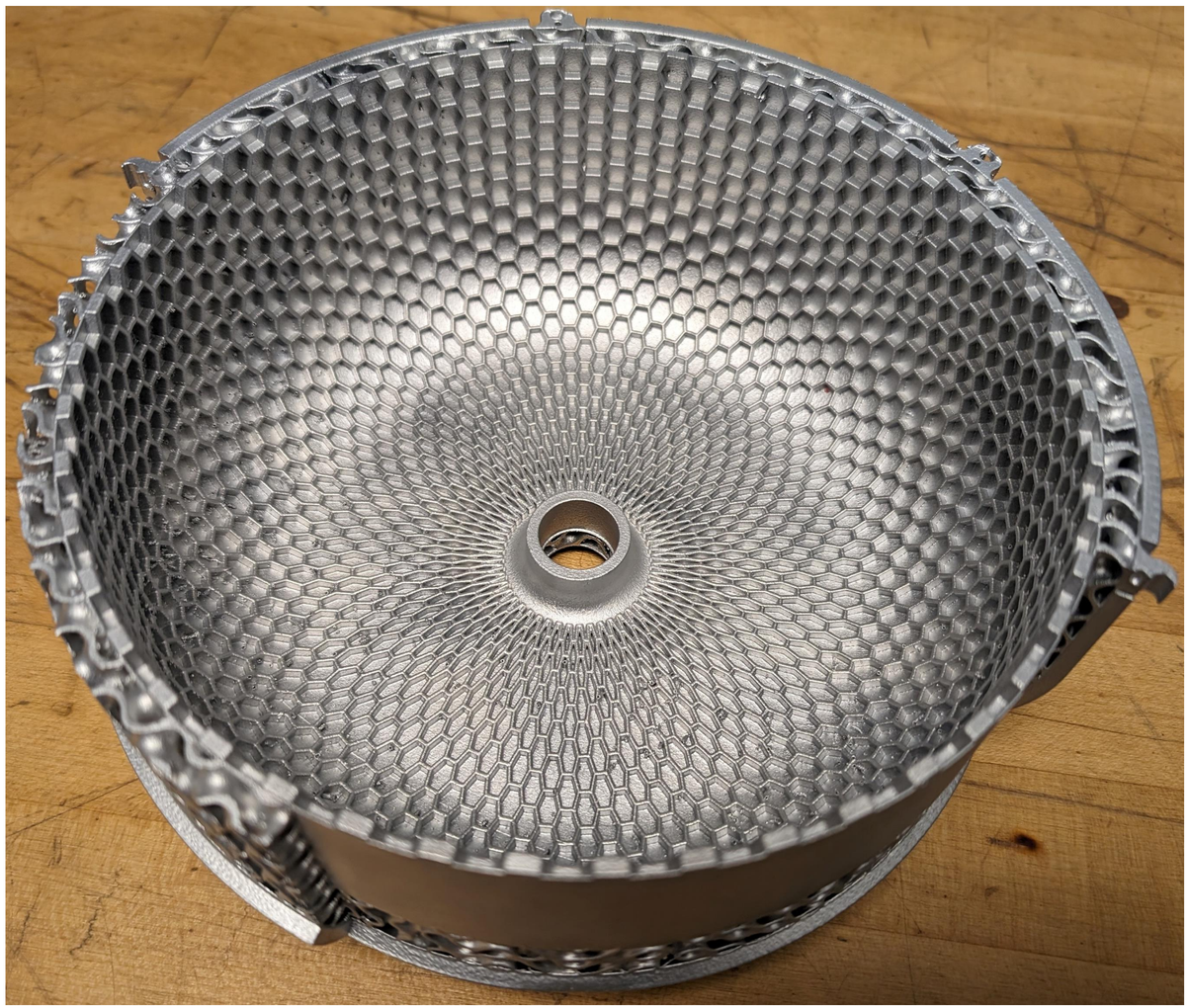
Understand AM process for..

- The selection of the correct material for the correct application domain
- The optimization of “Manufacturing Parameters” to improve efficiency & cost-effectiveness
- **To improve Quality Assurance!**
  - –Understanding of the AM process is vital in repeatability of the Lattice Network
  - –Printing 1 “Good” Lattice followed by 30 “I don’t know” isn’t helpful to anyone.



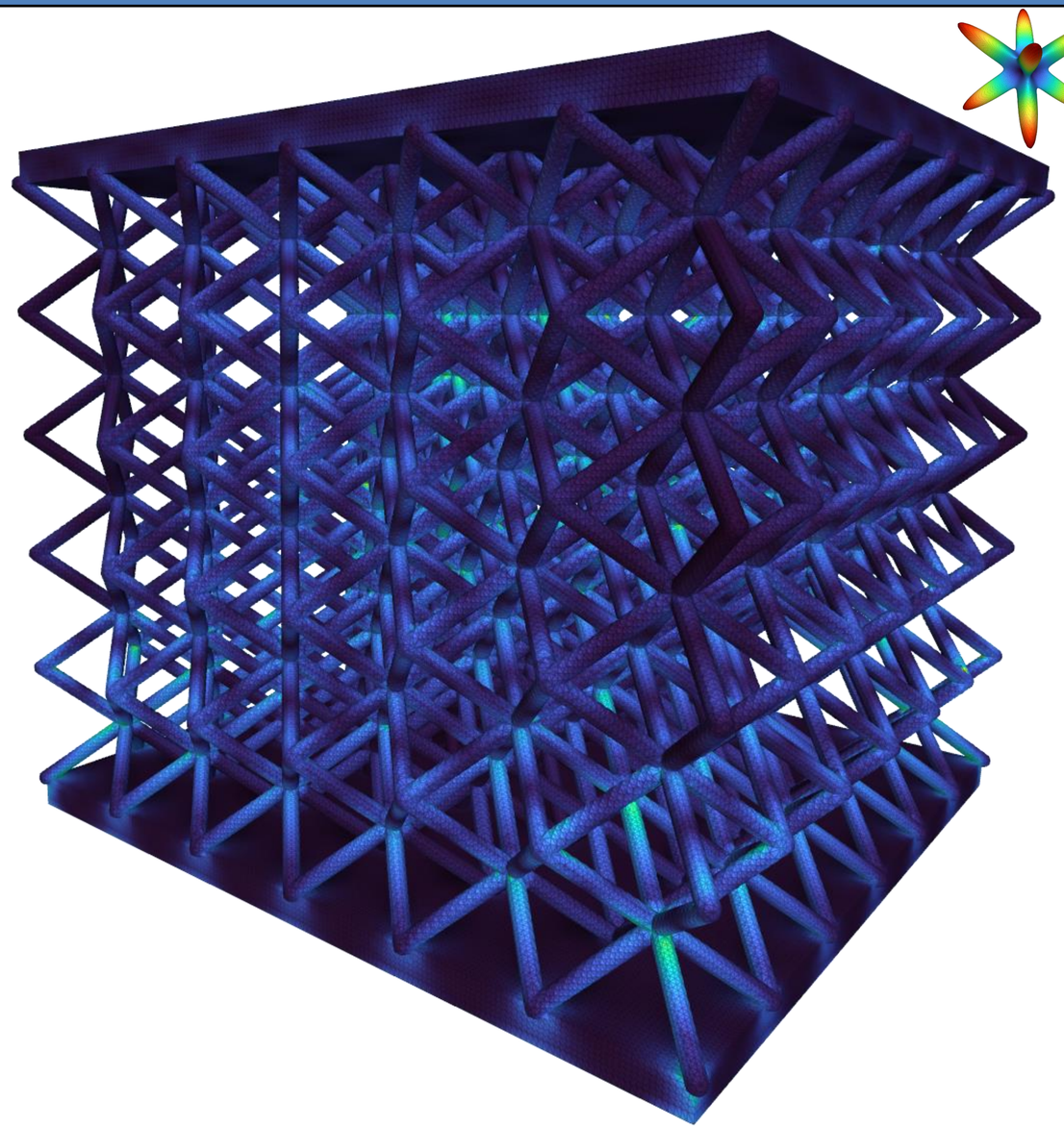
The Reality of Manufacturing Lattices

- Lattice Networks are difficult to simulate, therefore, difficult to predict (virtually)
- Testing becomes vital to verify lattice performance against design intent
- Without an understanding of the manufacturing process, the virtual predictability of a Lattice Network becomes impossible
- NASA-STD-6030 helps Lattice engineers spend more time “Architecting Materials” vs. “Fixing Weird Problems”
- Do it right the first time (instead of doing it over)

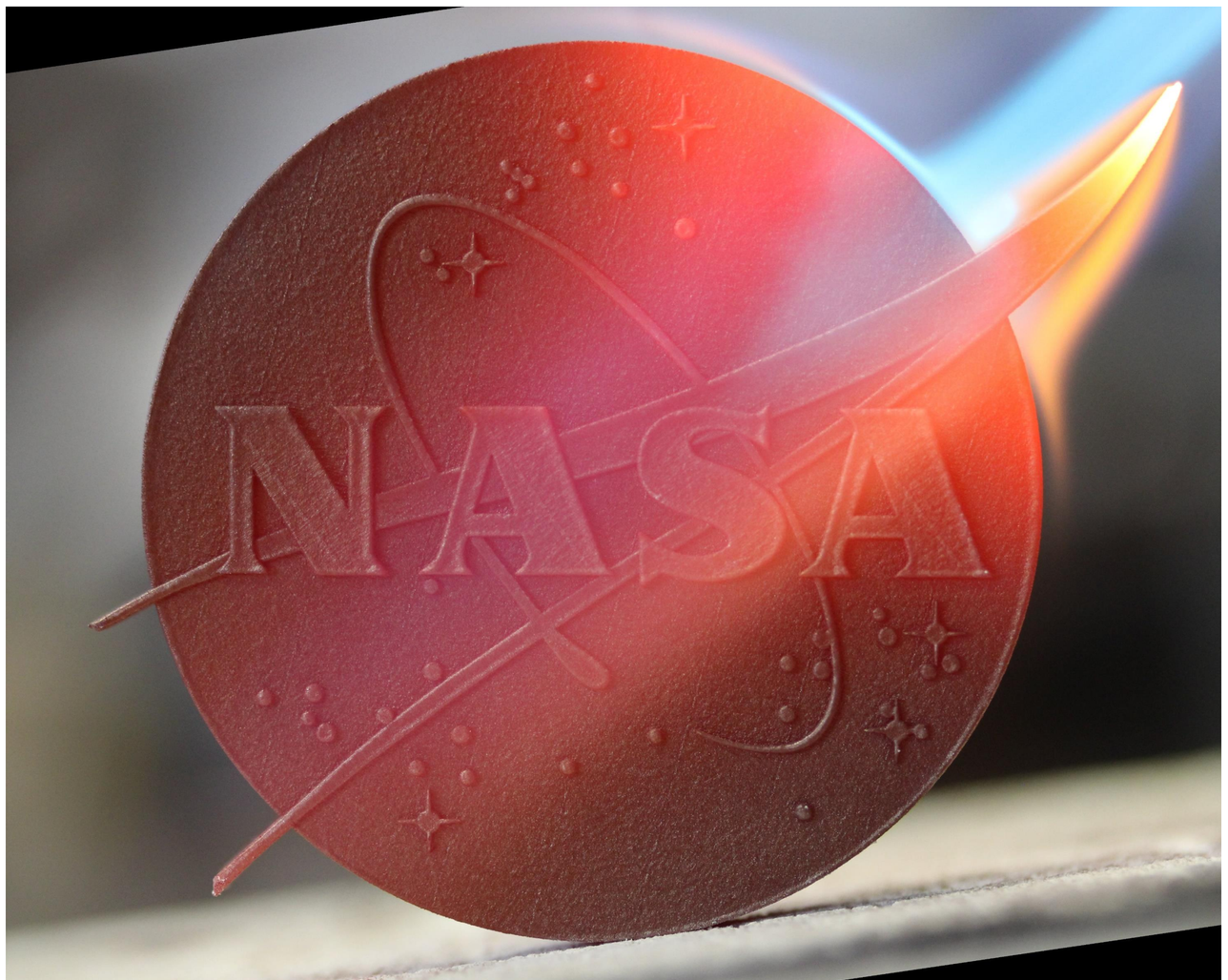


The Reality of Manufacturing Lattices

- Is there a better way…
  - Yes!
- NASA-STD-6030 helps Lattice engineers think about the manufacturing process to predict Lattice behavior
- Understanding the manufacturing process allows the Lattice engineers to determine the limits of the Lattice Network!
- Understanding in things like…
  - *What is the minimal manufacturable strut thickness?*
  - *What is the blend radius between in the lattice network?*
  - *What is the minimal wall thickness that can blend multi-Lattice networks?*
  - *Are there discrepancies between simulation and dog-bone test? –Material Qualification Verification*
  - *Are there discrepancies between simulation and component level testing? –Manufacturing Process Verification*



Thank you for your time!



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