National Aeronautics and
Space Administration

Additive Manufacturing Overview: Propulsion Applications, Design for and Lessons Learned

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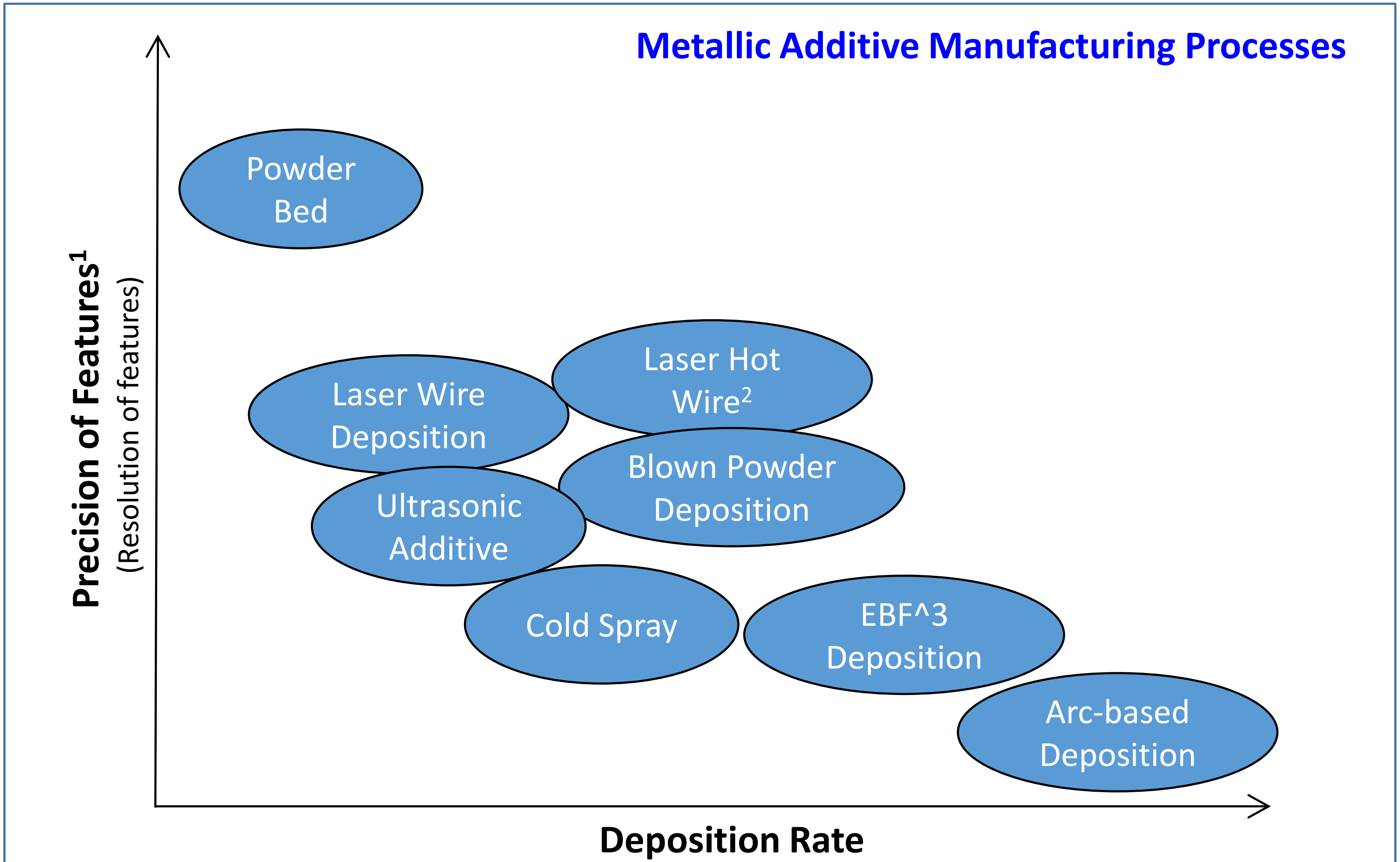
MARSHALL
SPACE FLIGHT CENTER

Overview of SLM Applications at NASA

- NASA is advancing additive manufacturing for propulsion applications on variety of flight and development programs
- Focus of additive manufacturing is powder-bed fusion techniques
  - Powder-bed = Selective Laser Melting (SLM) = Direct Metal Laser Sintering (DMLS)
  - SLM being used on RS25 Core Stage Boost Engines for Space Launch System (SLS)
- Larger scale deposition technologies also being evaluated
  - Blown powder deposition = Directed Energy Deposition (DED)
    - Hybrid additive/subtractive technology
  - Wire-Fed Deposition
    - Laser heat source
    - Pulsed-arc heat source
    - Electron beam heat source (Electron beam freeform fabrication)
  - Hot-wire hybrid technologies

Comparison of Metal AM Processes

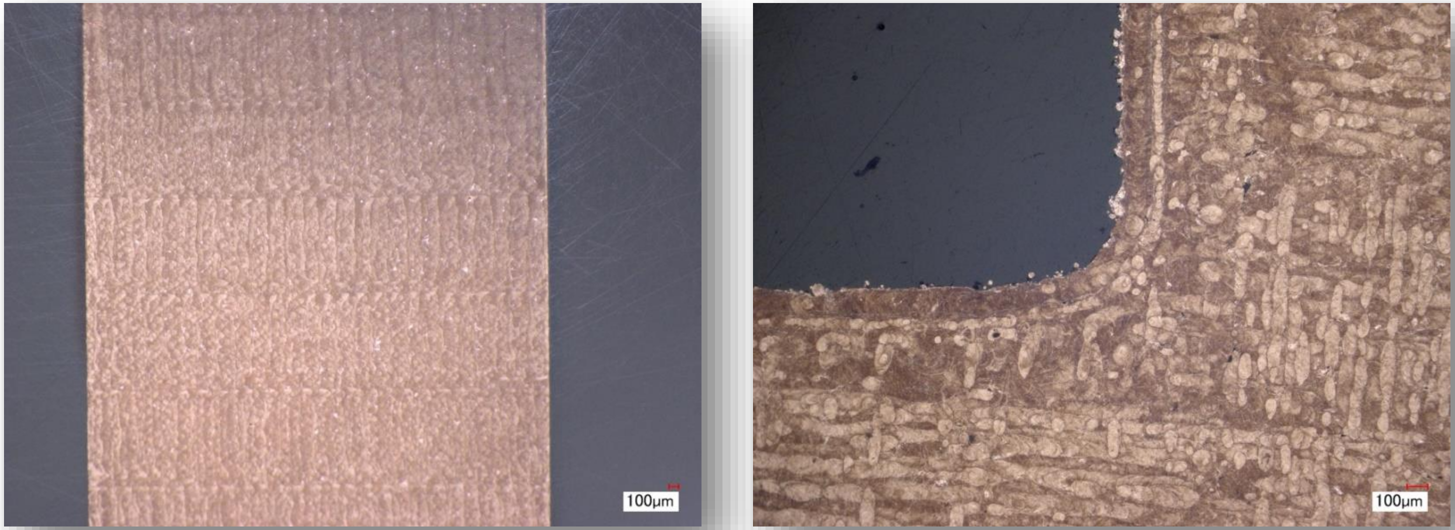


[1] Precision refers to the as-built state and does not encompass hybrid techniques and/or interim machining operations that would increase resolution. There are also a lot of other factors not considered in this chart including heat inputs to limit overall distortion.
[2] Technology still under full development

References:

- Honore, M. "Structural strengthening of Rocket Nozzle Extensions by Means of Laser Metal Depositioning". In Support of Volvo Channel Wall Nozzle. Force Technology. MTI Mtg Laserfusing Presentation. 1 February, 2013.
- O'Neill., W., Cockburn., A., et al. "Supersonic Laser Deposition of Ti and Ti64 Alloys". 5th International Symposium on High Power Fibre Laser and their Applications/14th International Conference on Laser Optics. July 1, 2010. St. Petersburg, Russia.
- Gradl, P.R. "Rapid Fabrication Techniques for Liquid Rocket Channel Wall Nozzles", 52nd AIAA/SAE/ASEE Joint Propulsion Conference, Propulsion and Energy Forum, (AIAA 2016-4771)

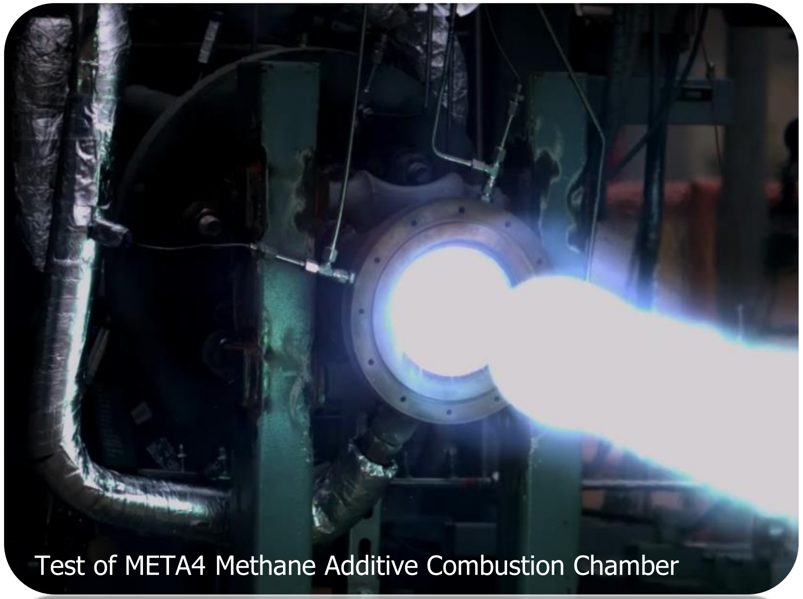
Additively Manufactured SLM Material is Unique



SLM GRCop-84 Copper-alloy Material in the As-built Condition (ASTS, Huntsville)

Video of SLM Parts Being Printed

Application Examples for Liquid Rocket Engines



Test of META4 Methane Additive Combustion Chamber

Additive Combustion Chambers Assembly

GRCop-84 3D printing process developed at NASA and infused into industry

LOX/Methane Testing of 3D-Printed Chamber
Methane Cooled, tested full power

Ox-Rich Staged Combustion Subscale Main Injector Testing of 3D-Printed Faceplate

Additively Manufactured GRCop-84 and C-18150 Combustion Chambers accumulated over **5700 sec hot fire time**

Reference:

Gradl, P.R., Protz, C., Greene, S.E., Ellis, D., Lerch, B., and Locci., I. "**Development and Hot-fire Testing of Additively Manufactured Copper Combustion Chambers for Liquid Rocket Engine Applications**", 53rd AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2017-4670)

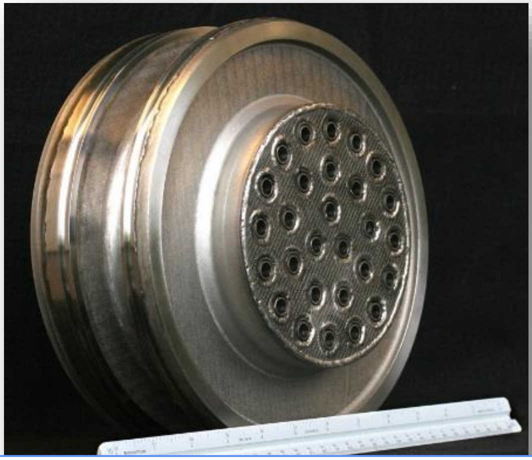
Gradl, P., Protz, C., Greene, S.E., Garcia, C., Brandsmeier, W., Medina. C., Goodman, D., Baker, K., Barnett, G. **Design, Development and Hotfire Testing of Monolithic Copper and Bimetallic Additively Manufactured (AM) Combustion Chambers for LOX/Methane and LOX/Hydrogen Applications** Paper presented at 63nd JANNAF Propulsion Meeting/9th Liquid Propulsion Subcommittee, December 5-9, 2016. Phoenix, AZ.

Video of AM GRCop-84 Chambers

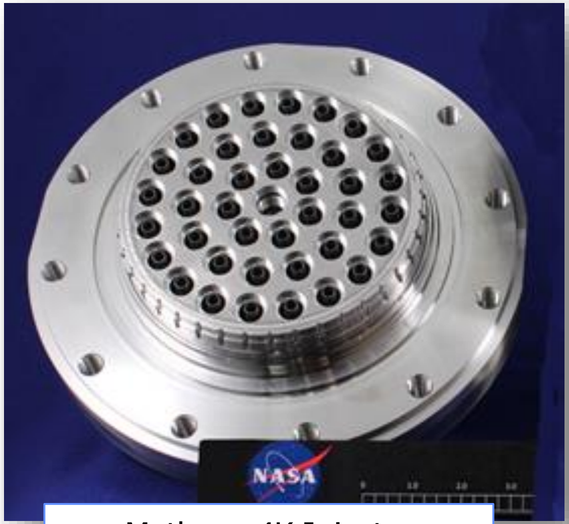
Additive Injector Development

100# LOX Propane
Injector Built 2012
Tested Nov 2013

1.2K LOX Hydrogen
First Tested June 2013
>3900 sec hotfire



20K LPS Subscale Tested Aug 2013
(3) Subscale Injectors Tested



Methane 4K Injector
Printed manifolds and
parametric feature
Tested Sept 2015

LPS 35K Injector
Welded Manifolds
Tested Nov 2015

CH4 Gas Generator Injector
Testing Summer 2017

Ref: Brad Bullard
Sandy Elam Greene

Injector Development Supporting 20-35k-lb$_f$ Test bed

Ref: Brad Bullard
Greg Barnett

Video of Additive Injector Testing

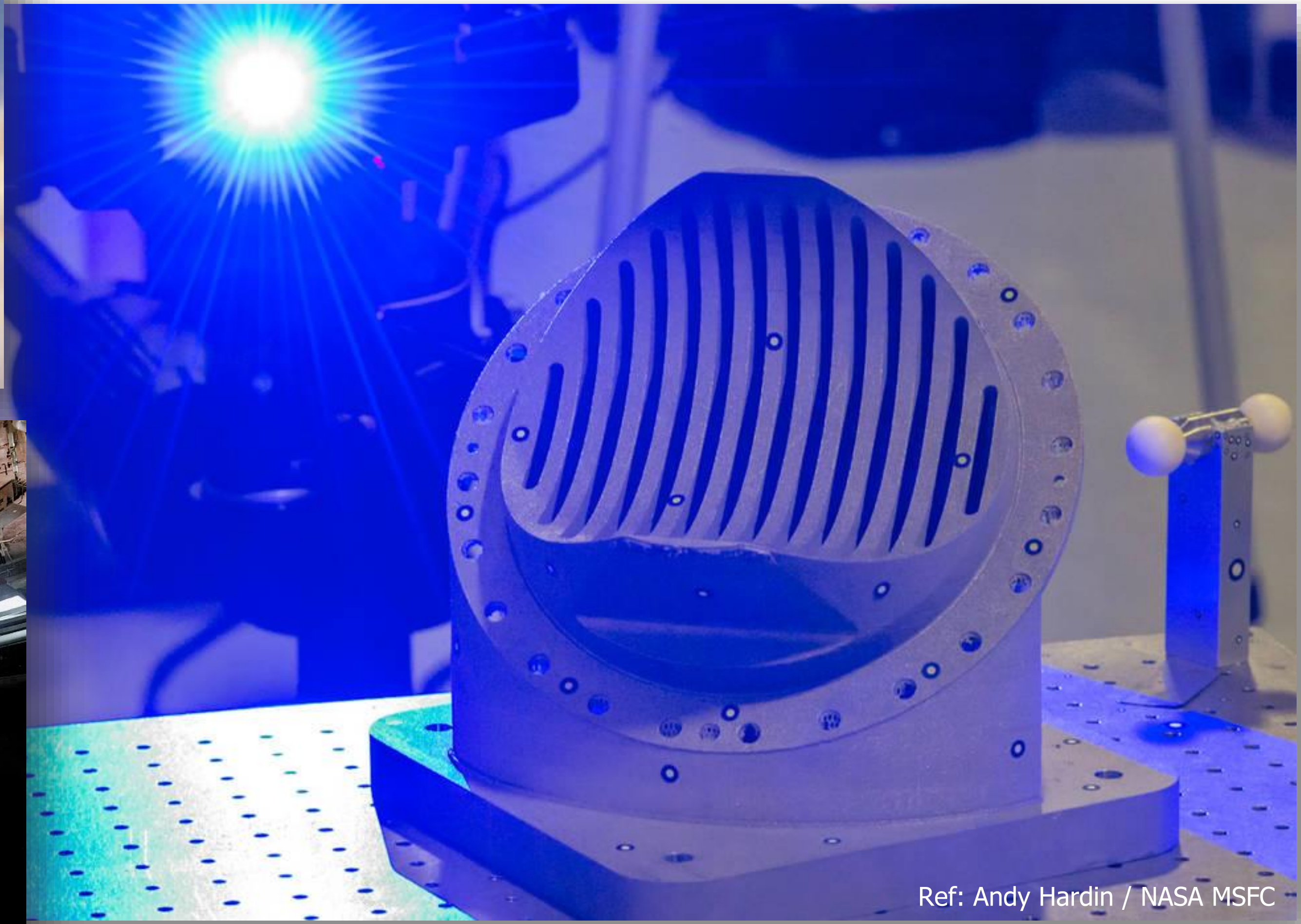
Additively Manufactured Injectors Hot-fire Tested at NASA range from 1,200 lb_f to 35,000 lb_f thrust

SLS Program / RS25 Pogo Z-Baffle

Inconel 718

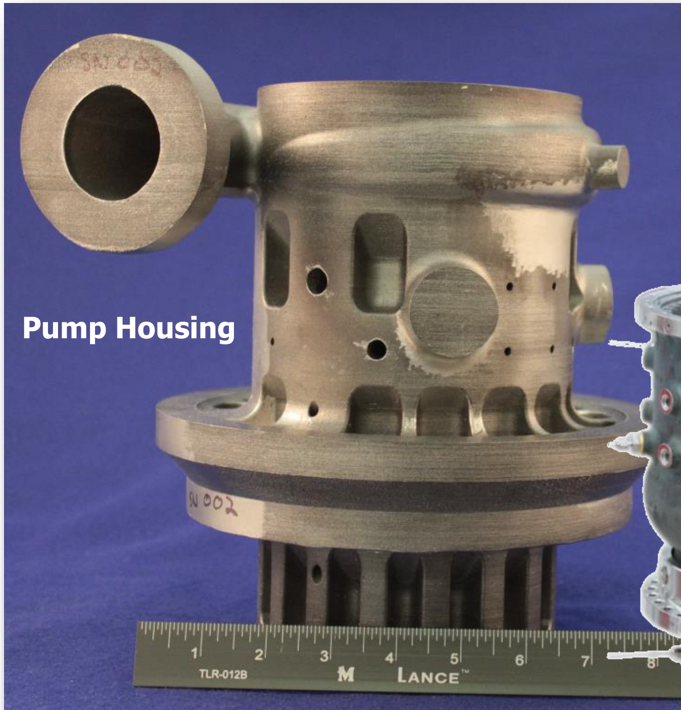
Used existing design with additive manufacturing to reduce complexity from 127 welds to 4 welds

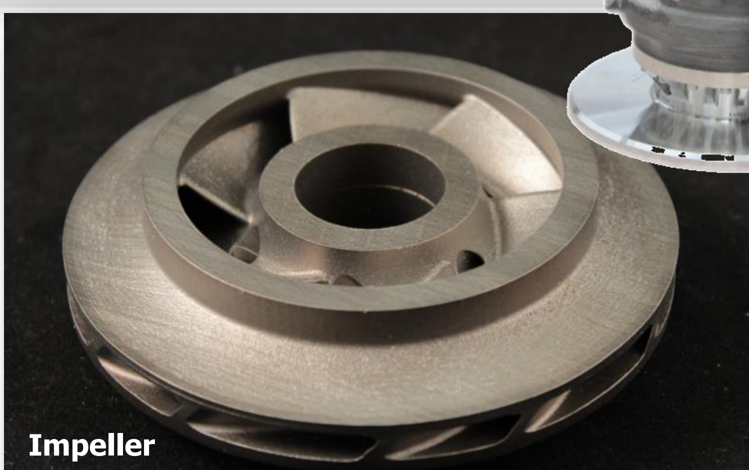
- 1 of 35 part opportunities being considered for RS25 engine

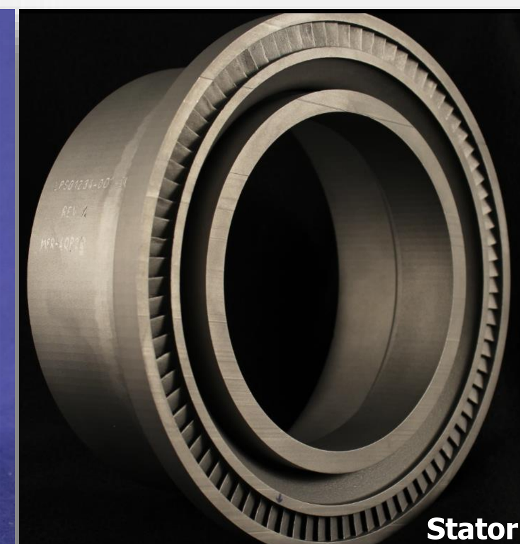


Ref: Andy Hardin / NASA MSFC

AM Turbomachinery – Liquid Oxygen Pump, 35k-lb$_f$ Test bed





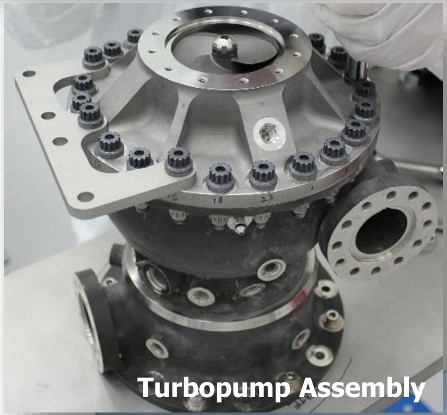


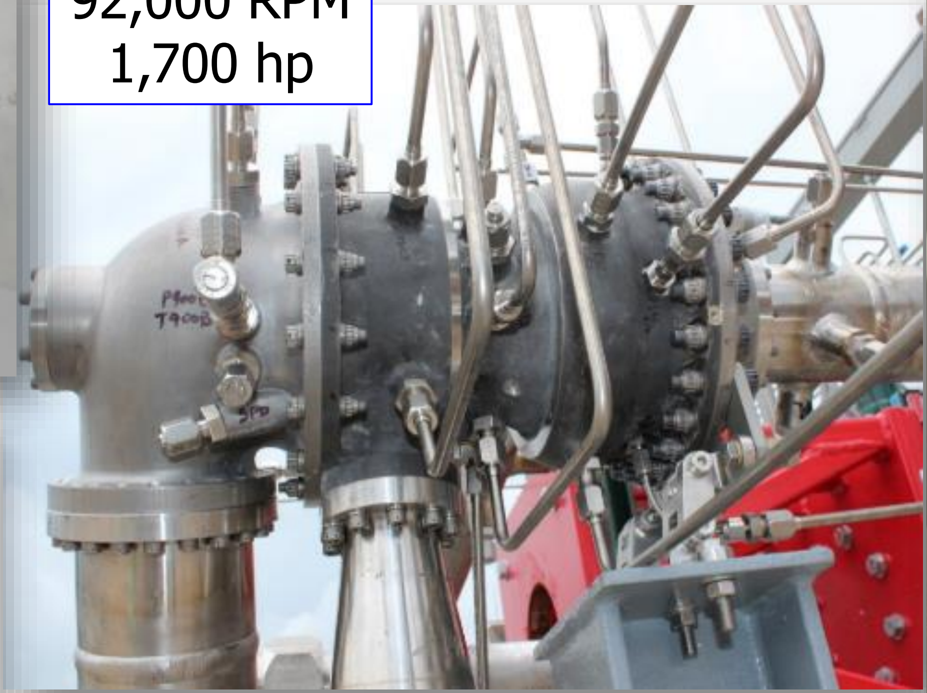
Ref: Derek O'Neal / NASA MSFC

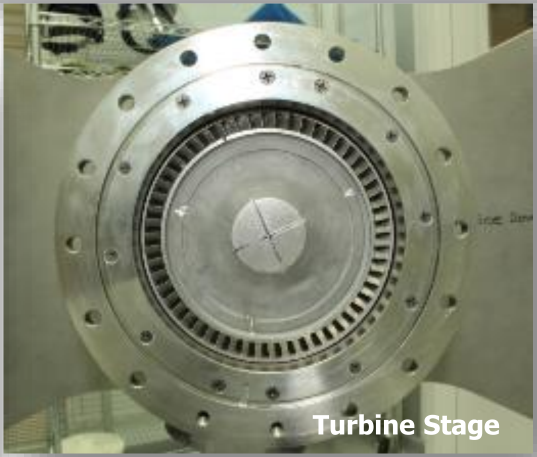
Turbomachinery – Fuel Turbopump

92,000 RPM
1,700 hp


Inducer Assembly


Turbopump Assembly

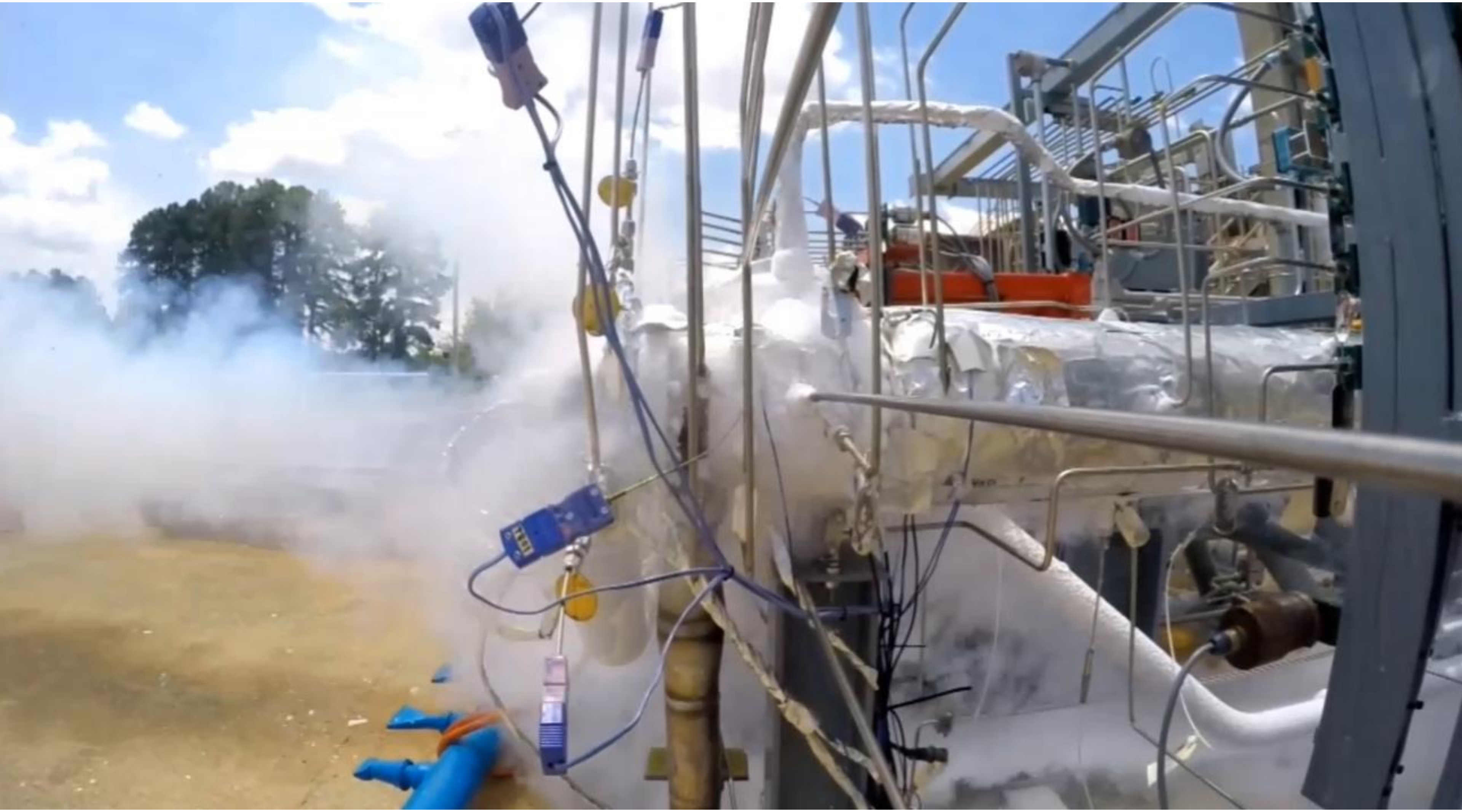



Turbine Stage


Rotating Assembly

Ref: Marty Calvert / NASA MSFC

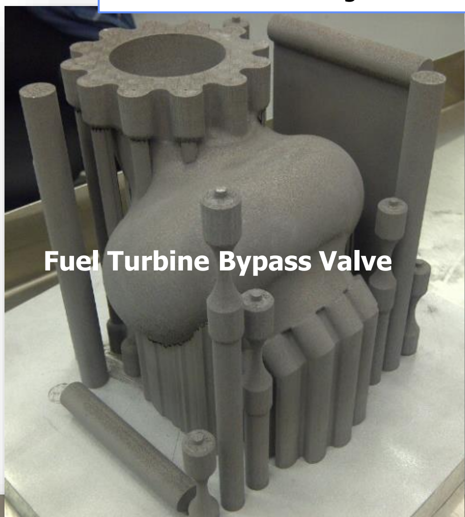
Video of AM Fuel Turbomachinery Hot-fire

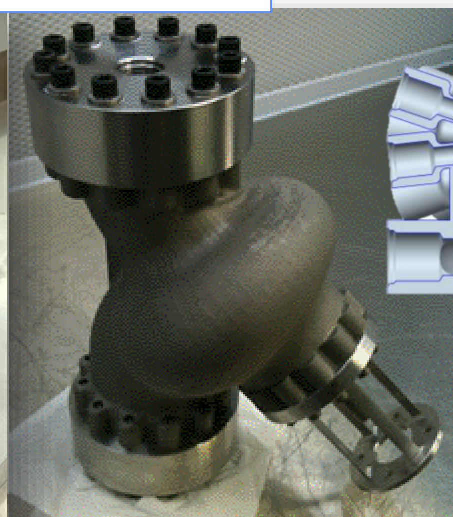


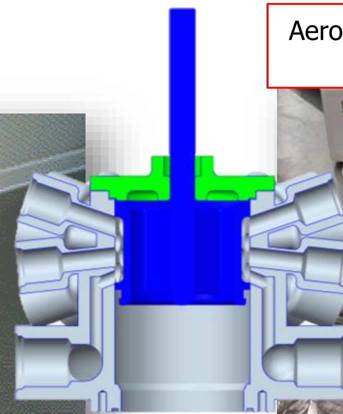
Ref: Marty Calvert / NASA MSFC

Additively Manufactured Valves

Hot Hydrogen Gas @350°F and up to 2000 psig
Versions in Aluminum, CoCr and Inco 718
Reduced weight from 60 lbs to 10 lbs





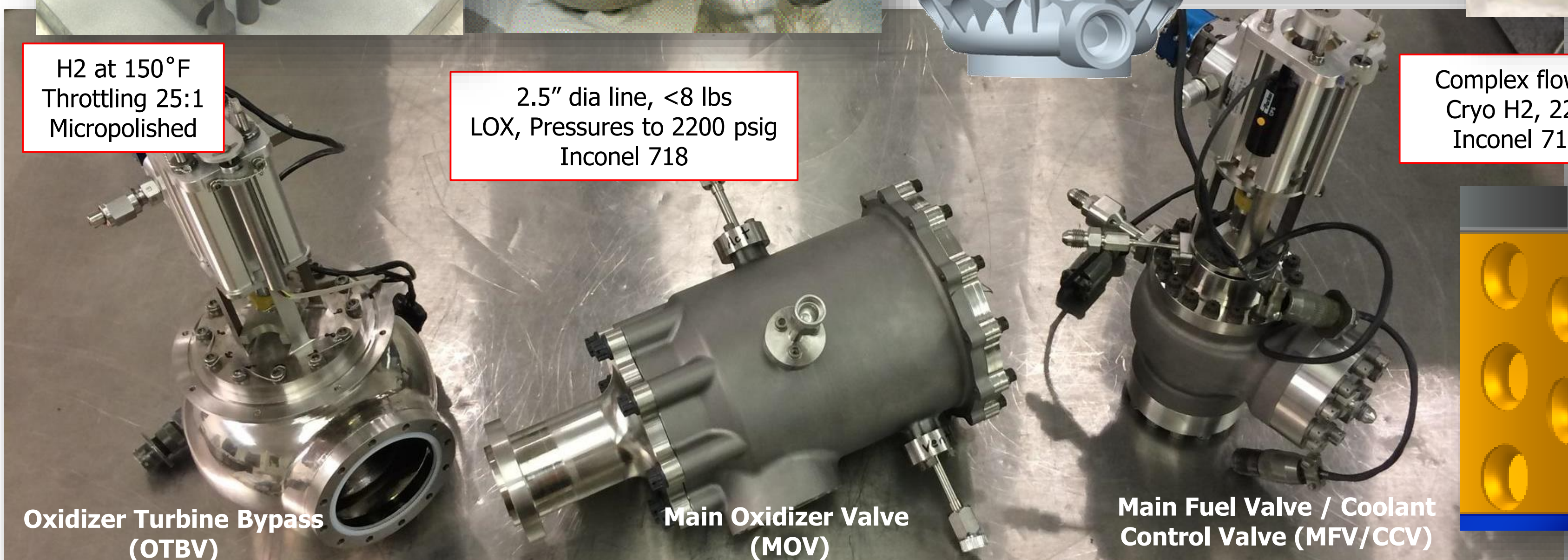


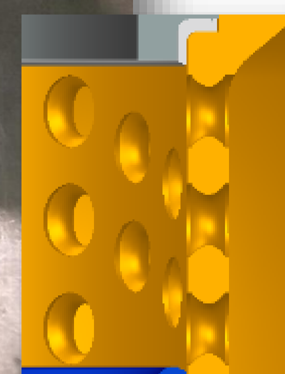
Aerospike Engine Multi-port Valve
280 GPM, 750 psig

H2 at 150°F
Throttling 25:1
Micropolished

2.5” dia line, <8 lbs
LOX, Pressures to 2200 psig
Inconel 718

Complex flow orifices
Cryo H2, 2200 psig
Inconel 718, 7 lbs





Ref: Jim Richard, Dave Eddlemen, Travis Davis / NASA MSFC

Video of Flow Testing MPV

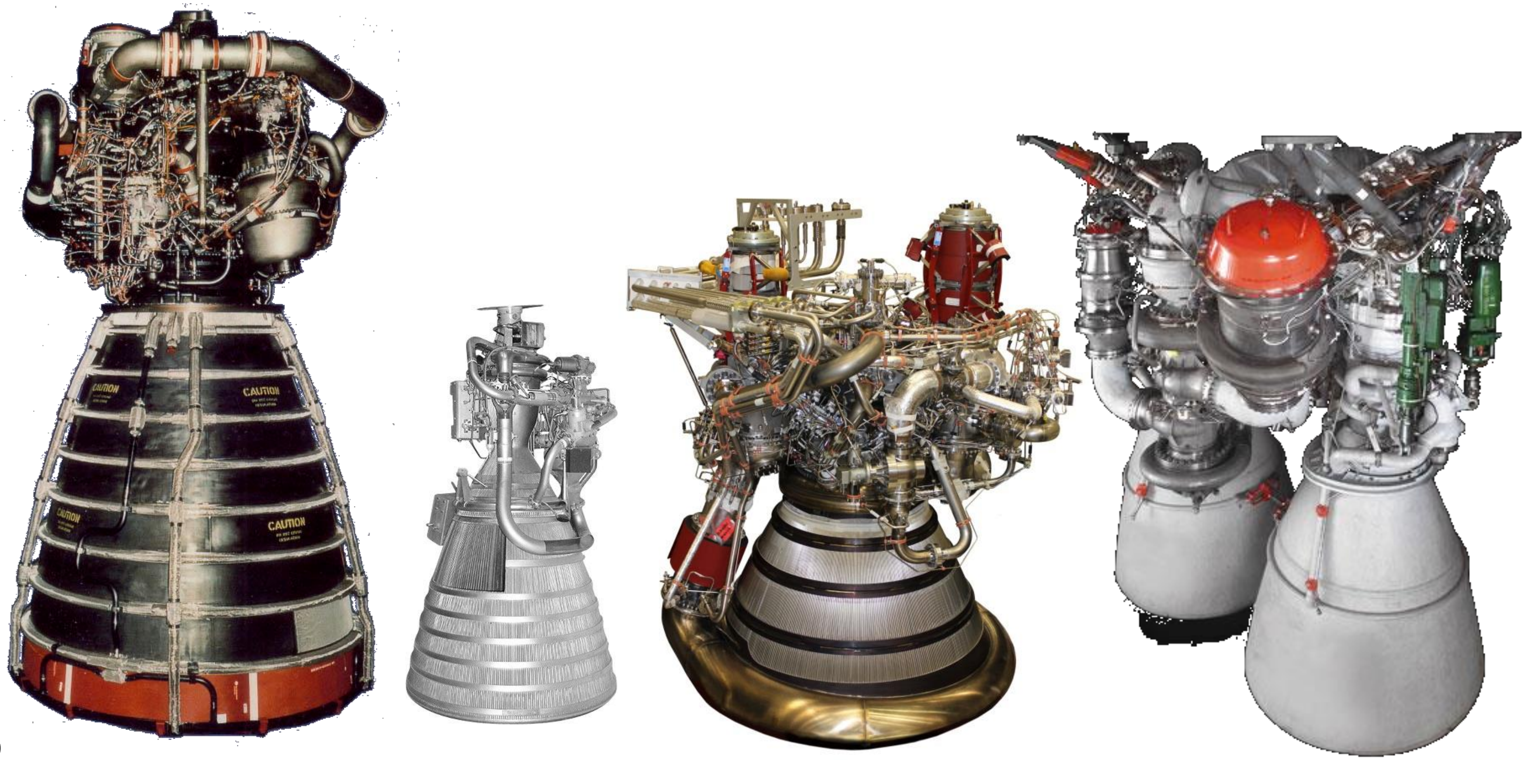
Multi Port Valve (MPV) Testing at 750 psig

What about the scale of SLM?

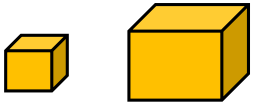
Although new machines are being introduced, current state of the art is limited in size…

Engine

SSME/RS-25 **RL-10A-4** **J-2X, Regen Only** **RD-180**



SLM Build Boxes



10x10x10 15.5x24x19
(inches)

90″ 46″ 70″ 56″

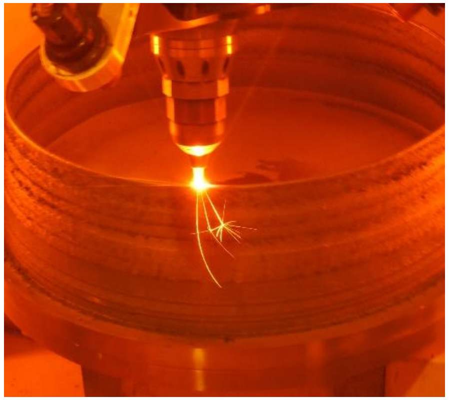
Nozzle Exit Dia.

Gradl, P.R., Brandsmeier, W. Alberts, D., Walker, B., Schneider, J.A. **Manufacturing Process Developments for Large Scale Regeneratively-cooled Channel Wall Rocket Nozzles**
Paper presented at 63nd JANNAF Propulsion Meeting/9th Liquid Propulsion Subcommittee, December 5-9, 2016. Phoenix, AZ.

Technologies Support Large Scale Additive Manufacturing

- NASA has researched a variety of large scale techniques for liquid rocket nozzles and considering for other applications. Techniques include:
  - Blown Powder Deposition *(LENS, LFMT, DED)*
  - Wire-based Freeform Deposition *(LMD, LDT)*
  - Arc-based wire deposition *(MDDM, Arc-DED)*
  - Electron Beam Freeform Deposition *(EBF^3)*
  - *Laser hot-wire and hybrid technologies*

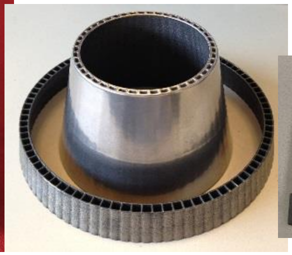

24″ Blown Powder Deposition, Inco 625




Arc-Deposition of MCC Liner, Inco 625


24″ Final Machined

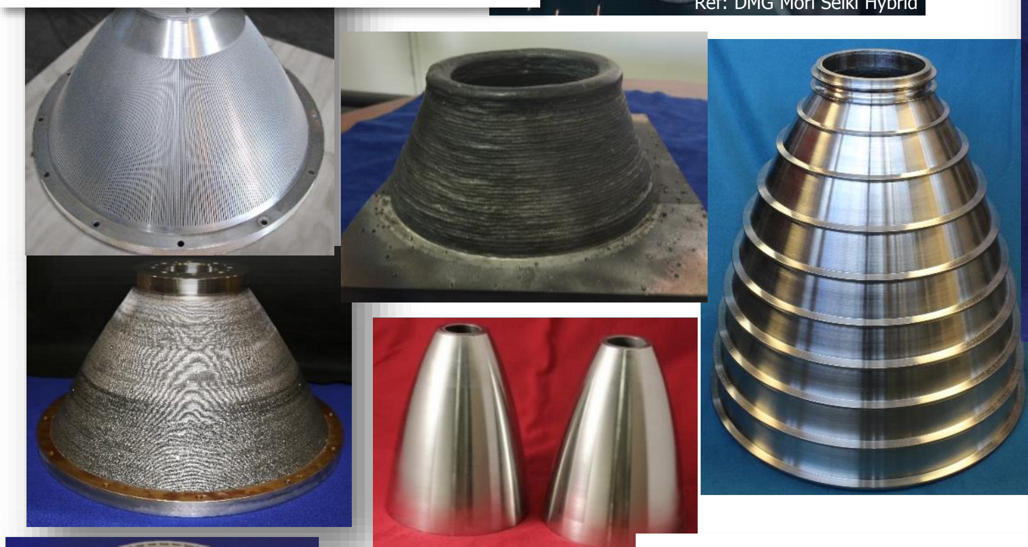

Blown Powder Deposition, Inco 625



Large Scale Additive Deposition Nozzle Technology

Large Scale Deposition: Blown Powder and Arc Deposition

Additive Wire-based Channel Closeout



Freeform AM Deposition with Integral Channels

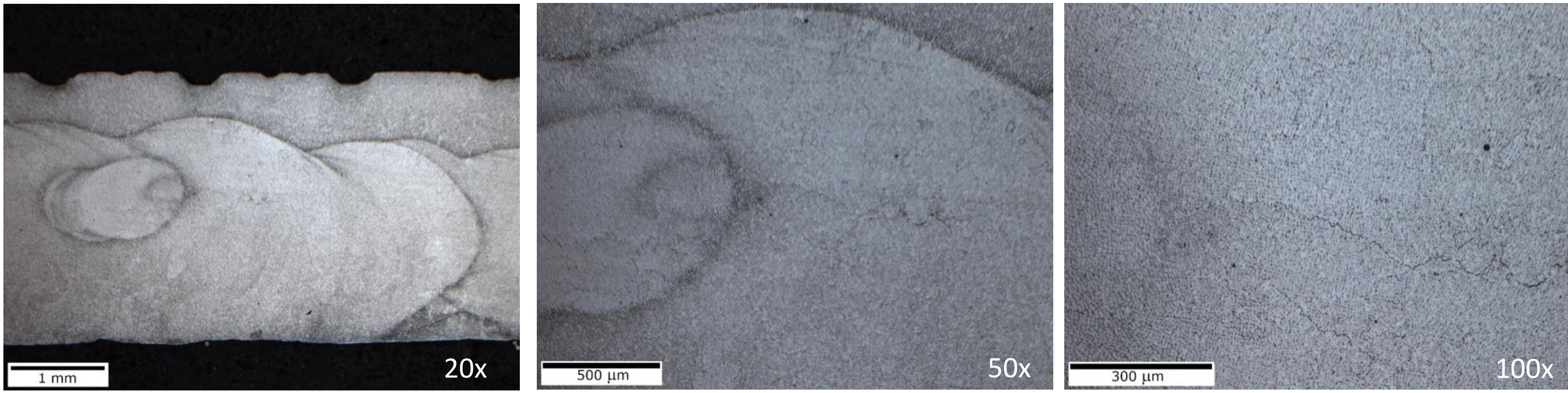
References:

Gradl, P. “Rapid Fabrication Techniques for Liquid Rocket Channel Wall Nozzles.” AIAA-2016-4771, Paper presented at 52nd AIAA/SAE/ASEE Joint Propulsion Conference, July 27, 2016. Salt Lake City, UT.

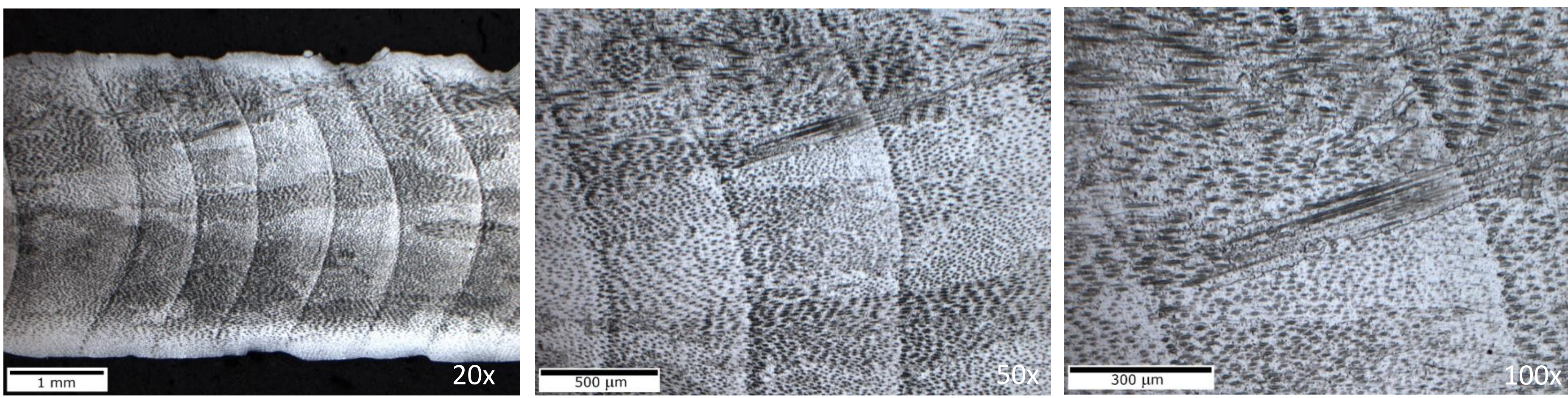
Gradl, P.R., Brandsmeier, W. Alberts, D., Walker, B., Schneider, J.A. Manufacturing Process Developments for Large Scale Regeneratively-cooled Channel Wall Rocket Nozzles. Paper presented at 63nd JANNAF Propulsion Meeting/9th Liquid Propulsion Subcommittee, December 5-9, 2016. Phoenix, AZ.

Micros of Build Orientation

Inco 625 As-Built - Hoop

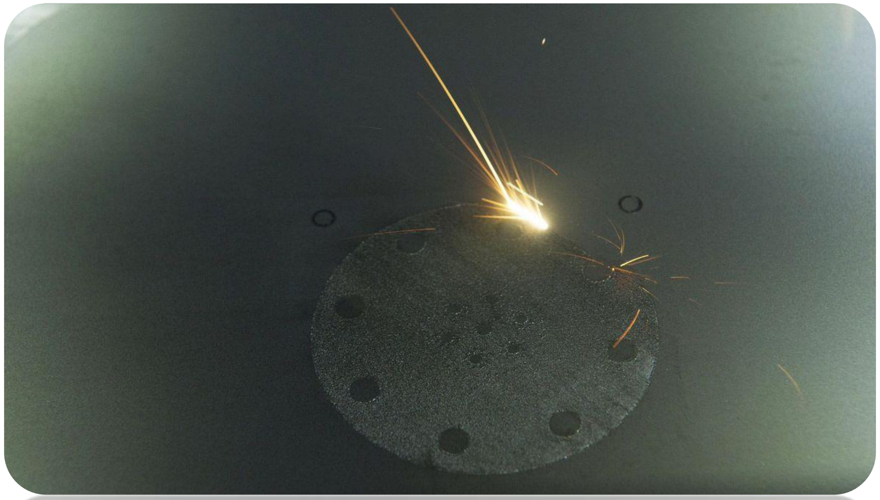


Inco 625 As-Built - Axial

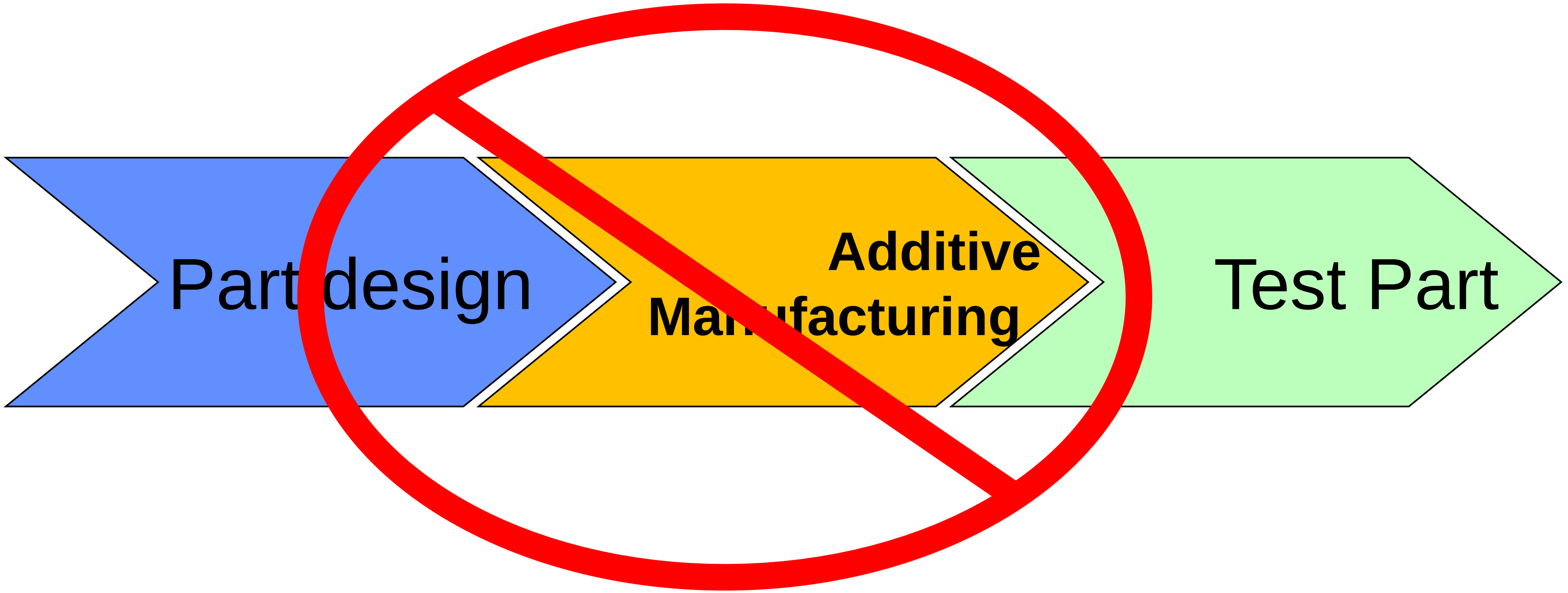


Basic Overview of Additive Manufacturing Process

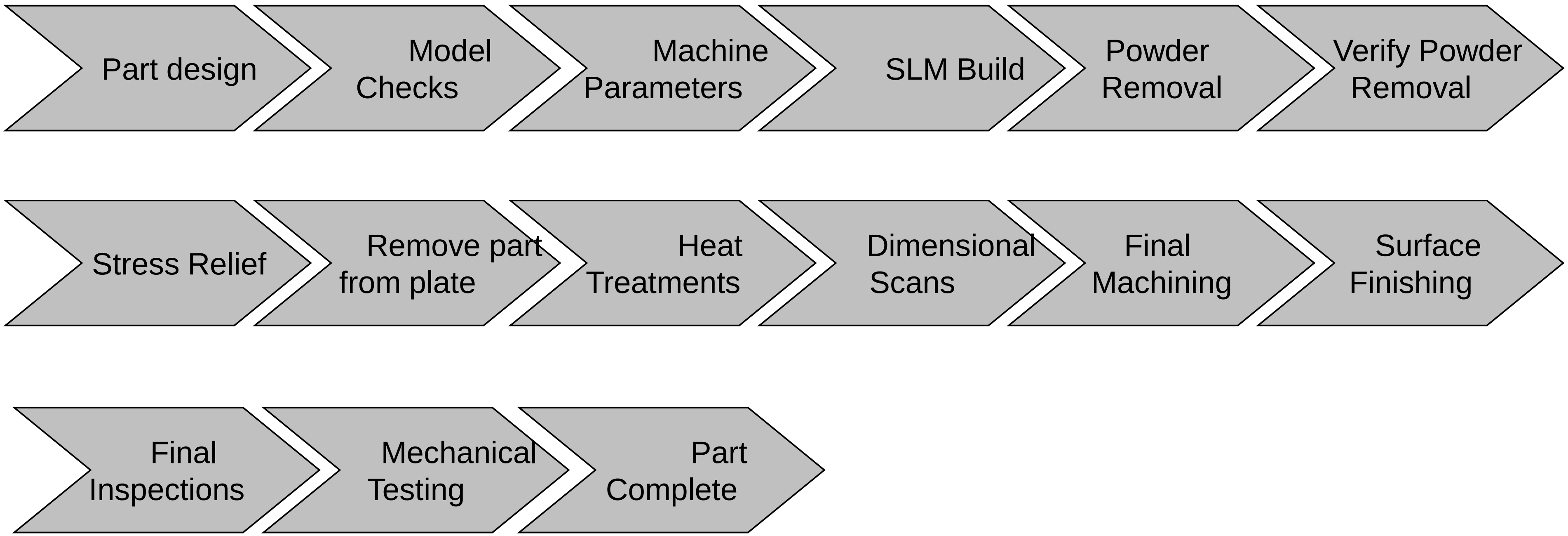
Design for Additive and Lessons Learned



Perceived Process Flow

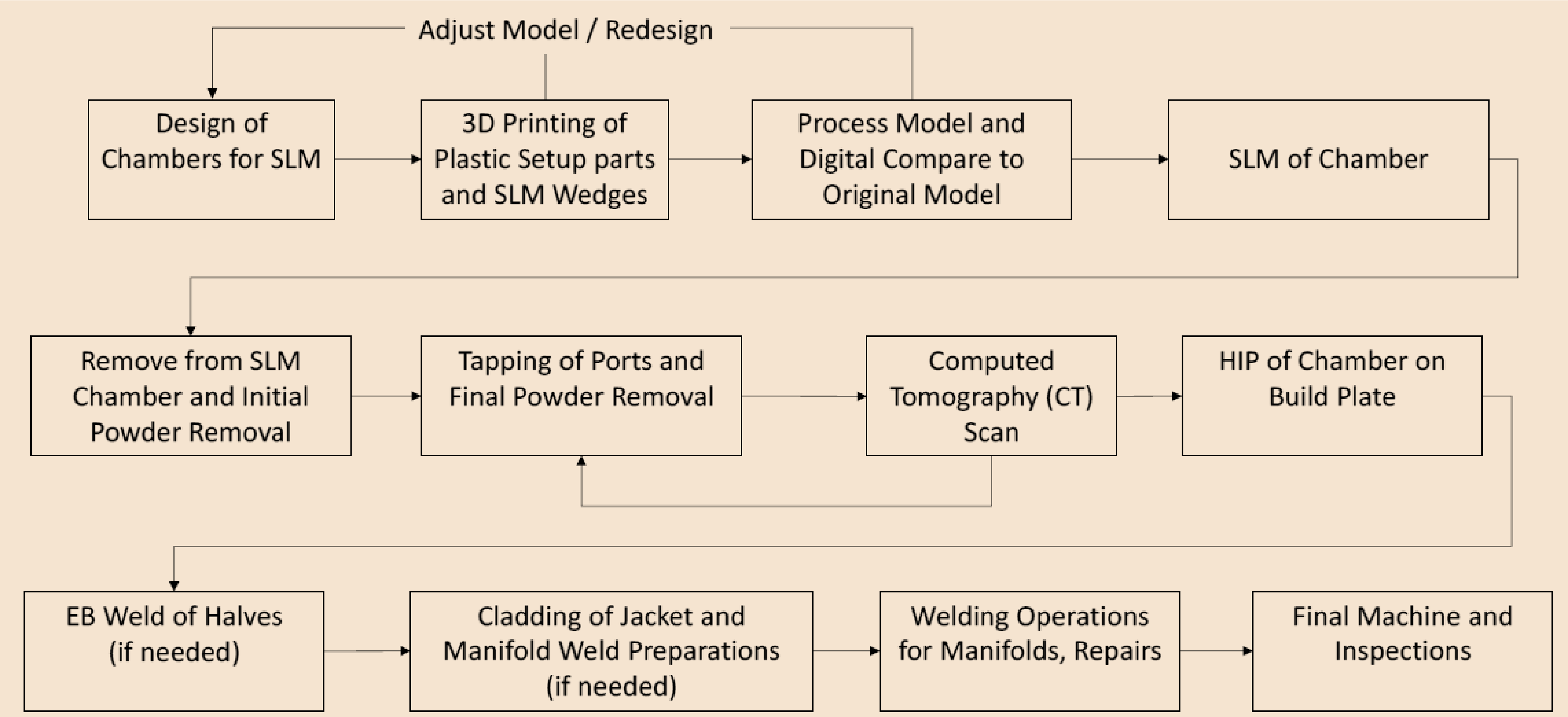


Actual Process Flow



Each process step also includes a series of additional tasks in order to properly design, build, or complete post-processing

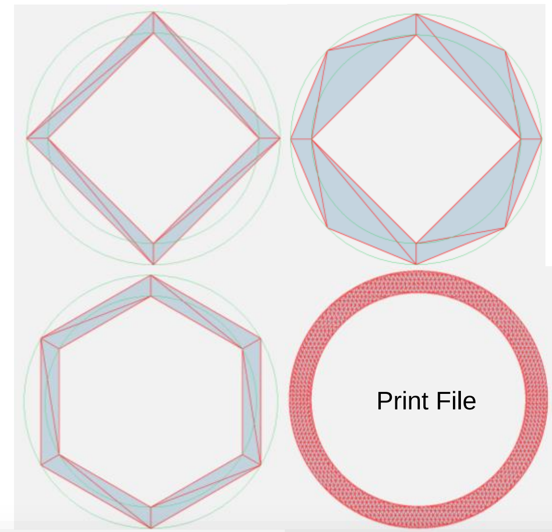
Generic Flow for Additive Combustion Chamber Fabrication Process

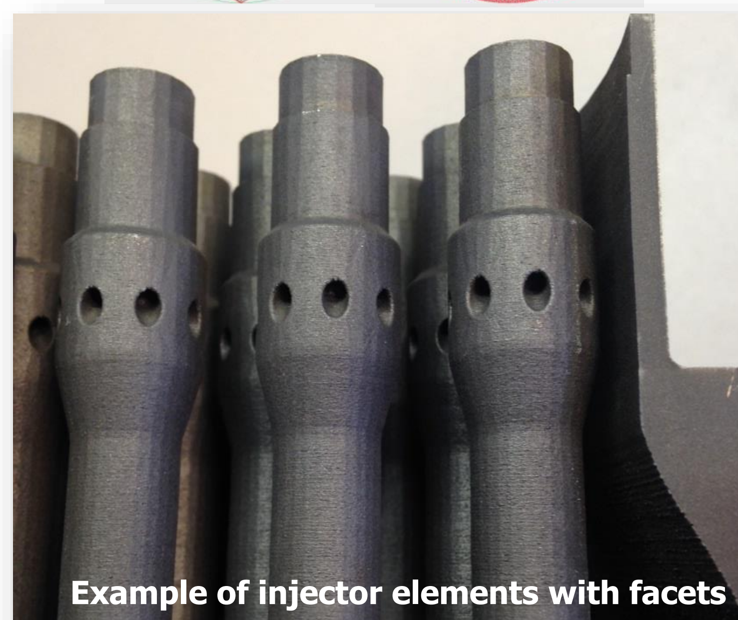


Considerations in Design and Printing

- The printer is going to (attempt to) print geometry based on the CAD model
- Most 3D printers use .stl files (stereolithography)
  - .stl files are flat triangles used to approximate CAD geometry
  - The .stl file is sliced into layers to generate the laser toolpath / code
- Have observed significant differences in surfaces, although based on geometric features
- Finer resolution files are significantly larger and machines can be limited on toolpath code

Same CAD file with different export parameters

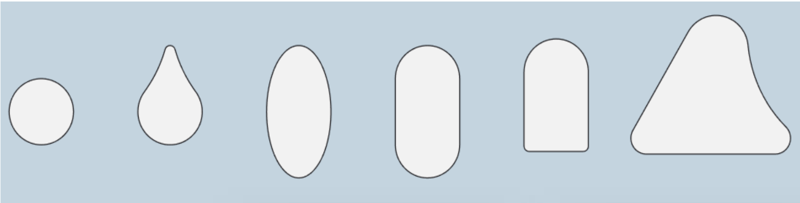


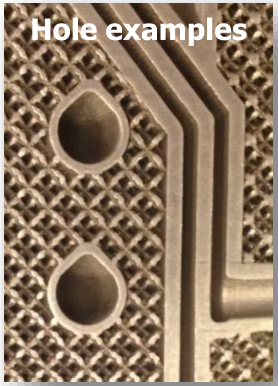

Example of injector elements with facets

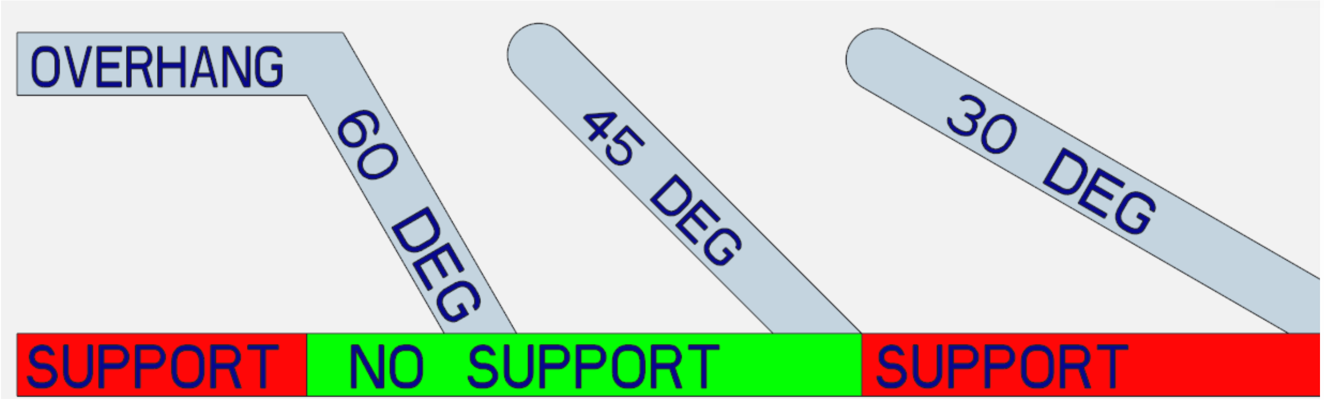
Considerations in Design and Printing

- Angled feature designs are limited (measured from horizontal)
  - Features <45º normally require support
  - Features >45º normally do not require support
  - Consider features in all dimensions
- Holes cannot be printed as true holes if larger diameter
  - Largest unsupported hole ~ .250”
  - Smallest hole/feature ~.030”
- Overhangs can be created, but require supports (and subsequent

Hole design examples



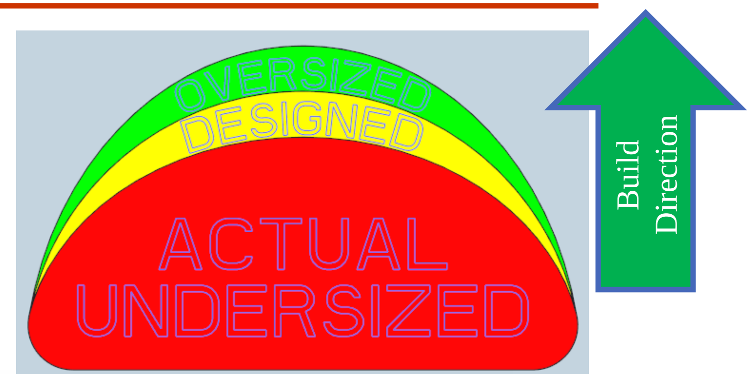


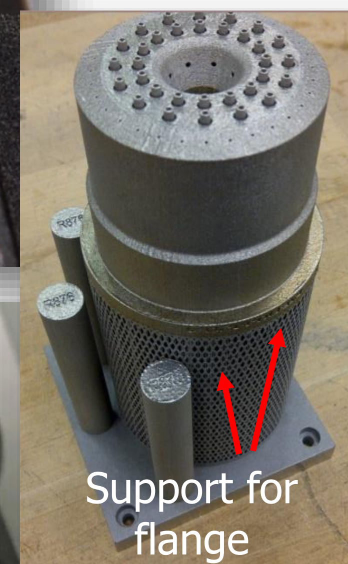


Angled wall design example

Considerations in Design and Printing

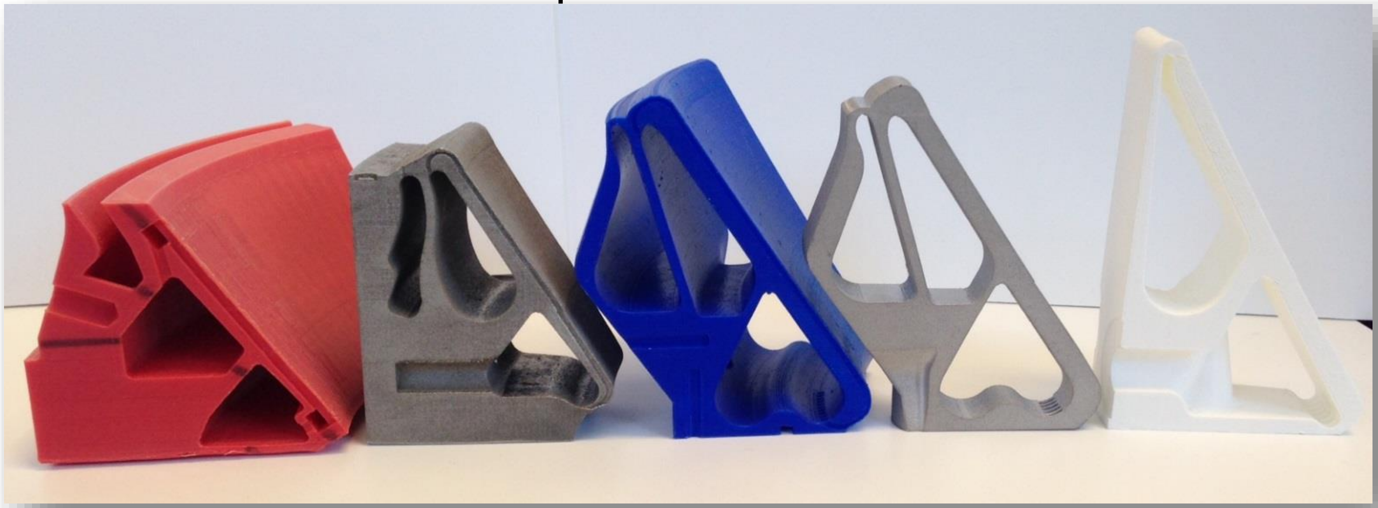
- Design and analysis needs to consider surface finishes for internal and external features
- Internal passages may need to be oversized to account for burn-thru or undersized hole
- Support material should be understood in design phase
  - Placement of support material is important
  - How support material is removed is equally important
  - Ask your operator or vendor
  - Support material highly dependent on print orientation





Considerations in Design and Printing

- Print orientation is critical – evolve the CAD design with AM machine operator or vendor
  - Print orientation is not always obvious; supports may be minimized in a complex angled orientation
- Print volume should be considered
  - Bolt holes required for the build plate
  - Build plate (~1" thick) takes up part of the build height
- Test print in plastic during design phase
  - Inexpensive method to identify issues with design and model
  - Determine design issues, bad design features and actual feature issues can be resolved with test prints

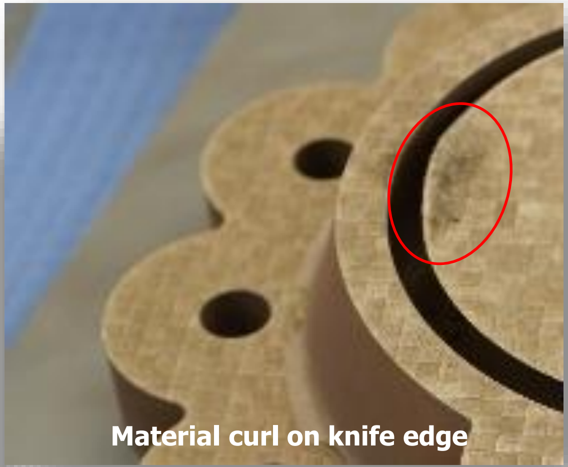


Considerations during Pre-processing and Printing

- Heat control is critical and can cause significant deformations or failures
  - May be driven by original design (too thick or thermal gradients too high across varying cross sections)
  - May be impacted by adjacent parts or witness specimens
- Material curl caused by coater arm damage
  - Based on knife edges during design
- Stops and starts are also common in 3D prints, causes knit lines
  - Refill of powder in dose chamber
  - Issue observed that requires visual

Cracking from Residual Stresses during build

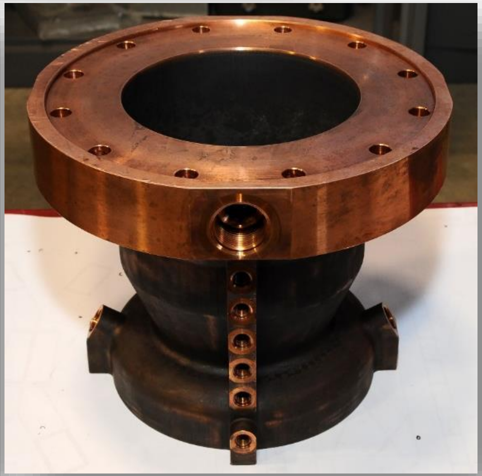
Knot line observed post-build



Material curl on knife edge

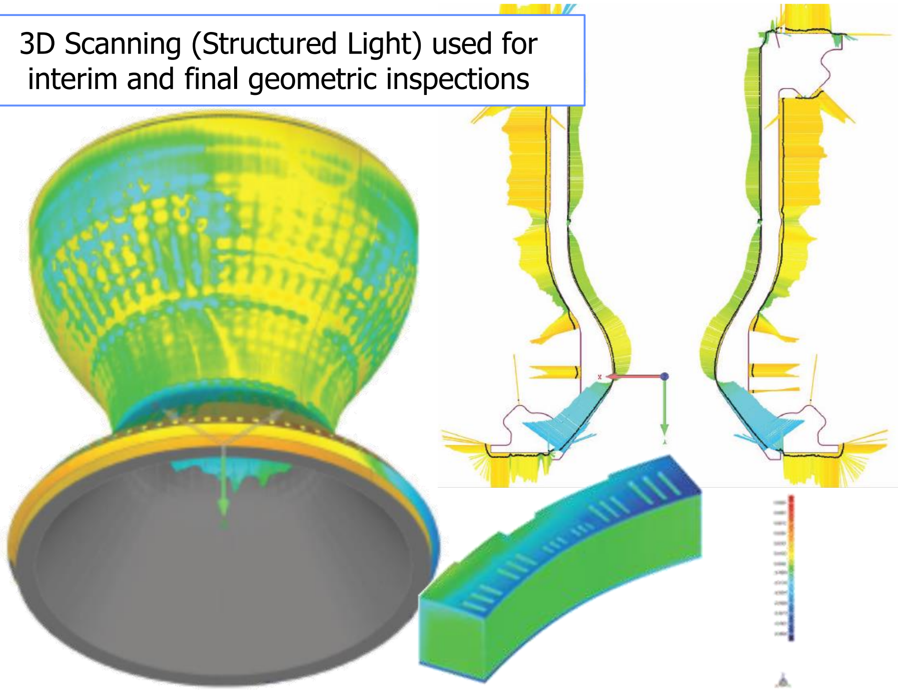
Considerations during Design and Post-Processing

- **Geometric Dimensioning and Tolerancing (GD&T) needs to be considered during design for ease of post-processing**
  - Cylinders for better positional tolerance at feature level
  - Grooved for axial location
  - Flat surfaces for datums
  - Extra holes for powder removal
  - Additional stock material for critical features that will be post-machined
- **Holes only when required or in softer materials**
  - Existing printed holes can cause machine tools to "walk"
  - Do not print threads; post-machine
  - Undersize holes for reaming and tapping

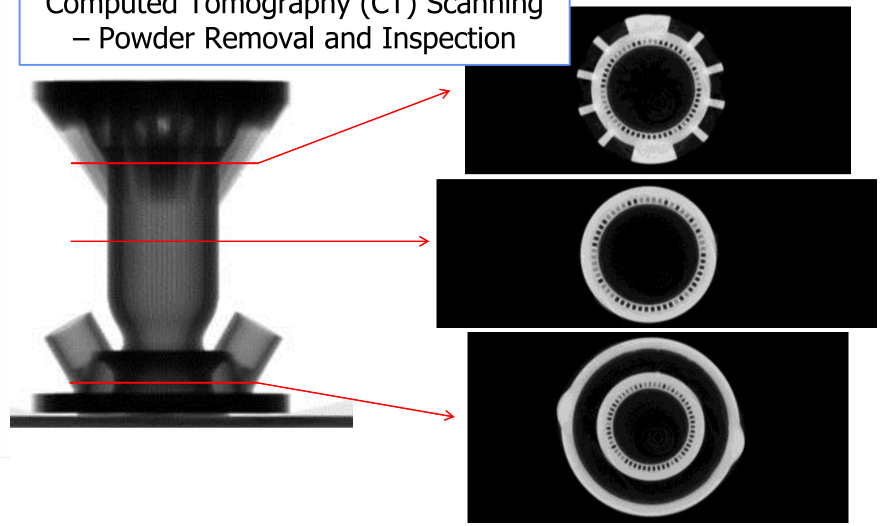


Considerations in Post-processing and Inspections

3D Scanning (Structured Light) used for interim and final geometric inspections



Computed Tomography (CT) Scanning – Powder Removal and Inspection

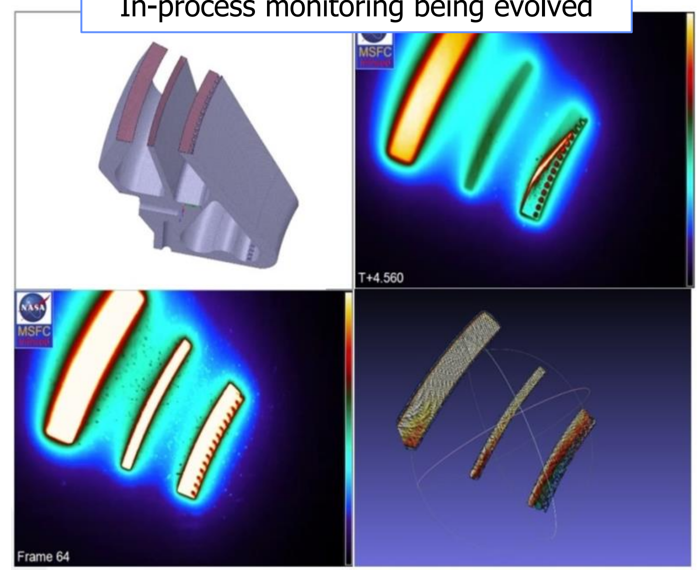


Borescope Inspection – Powder Removal and Verification

Other NDE options:

- Visual
- Ultrasonic Testing
- X-Ray
- Penetrant inspection
- Eddy Current

In-process monitoring being evolved



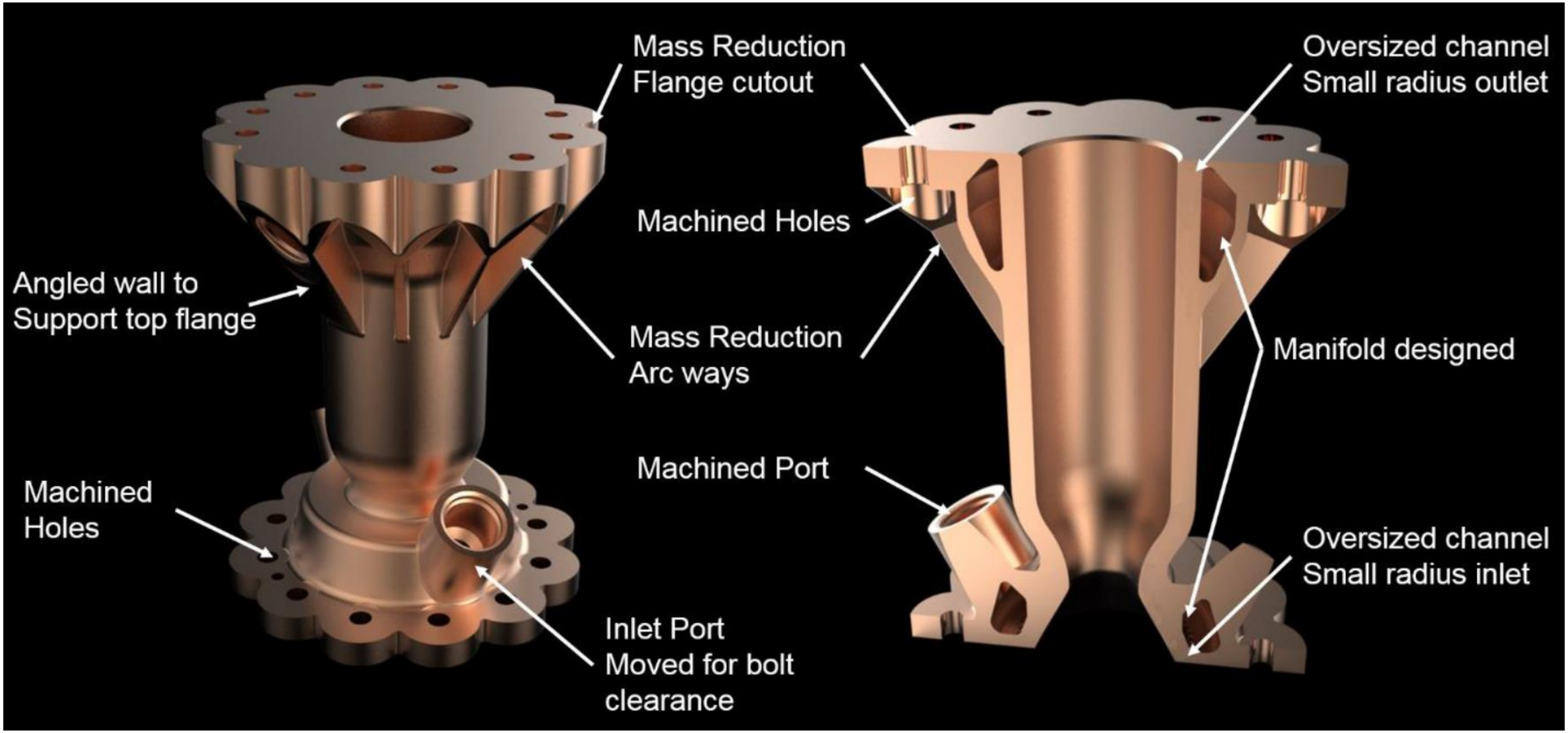
Ref: Waller, J., Parker, B., Hodges, K.L., Burke, E., Walker, J.L. Nondestructive Evaluation of Additive Manufacturing: State of the Discipline Report, NASA/TM-2014-218560. "https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140016447.pdf

Other Questions to Ask

- Should this part be printed or traditionally manufactured?
- Is the print accuracy adequate for the design?
- What is the build orientation?
- How am I going to remove all the powder?
- Will support structure be used in the build?
- What kind of post machining needs to occur after the print?
- How do I verify powder removal?
- How is this part being removed from the build plate?
- Is my deliverable file accurate?
- Will there be any material processing after the print?

Example of Design for Additive

1.2K-lbf Workhorse combustion chamber



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Combustion Chamber Lessons Learned

- Optimized AM design may not be single-piece
  - Welding multiple AM pieces
    reduces risk, eases powder removal, allows inspection of unique features
  - Inlet/outlet ports can easily be welded on;
    protruding features often experienced print failures

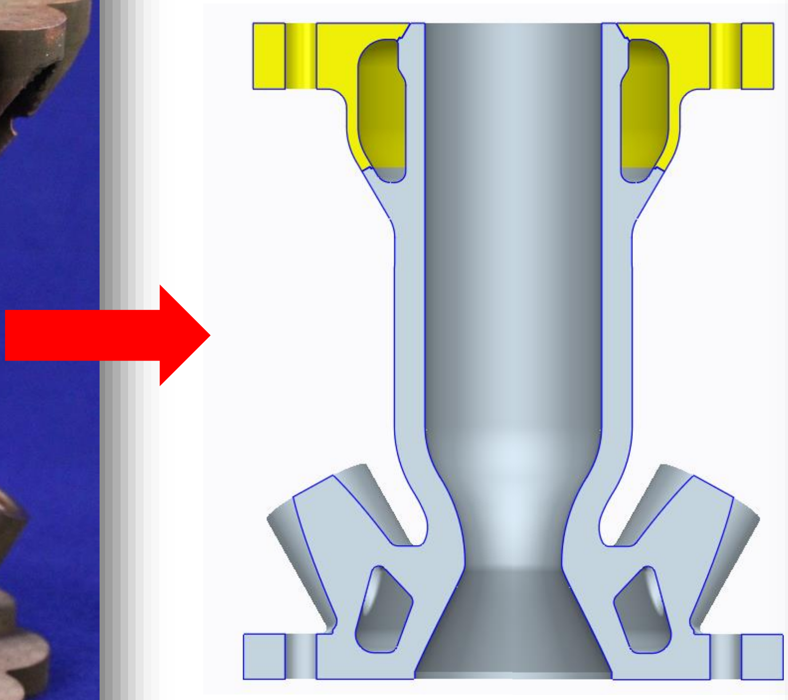
- Coolant channels –
  - Leave access for powder removal
  - Increase effective area to account for rough surfaces…
  - Maintain access for interior powder removal
- Design copper EB weld joints for excess penetration and material heating
- Minimize thick areas to eliminate residual stresses (thick flanges can lift off the build plates)
- Part orientation is critical for coater blade, so optimize design to minimize potential damage
- Include enough stock for secondary bonding ops, run-outs, &/or final machining
- Builds can deform as vertical height increases further from the build plate
- Compare exported CAD files back to original model

Combustion Chamber Lessons Learned

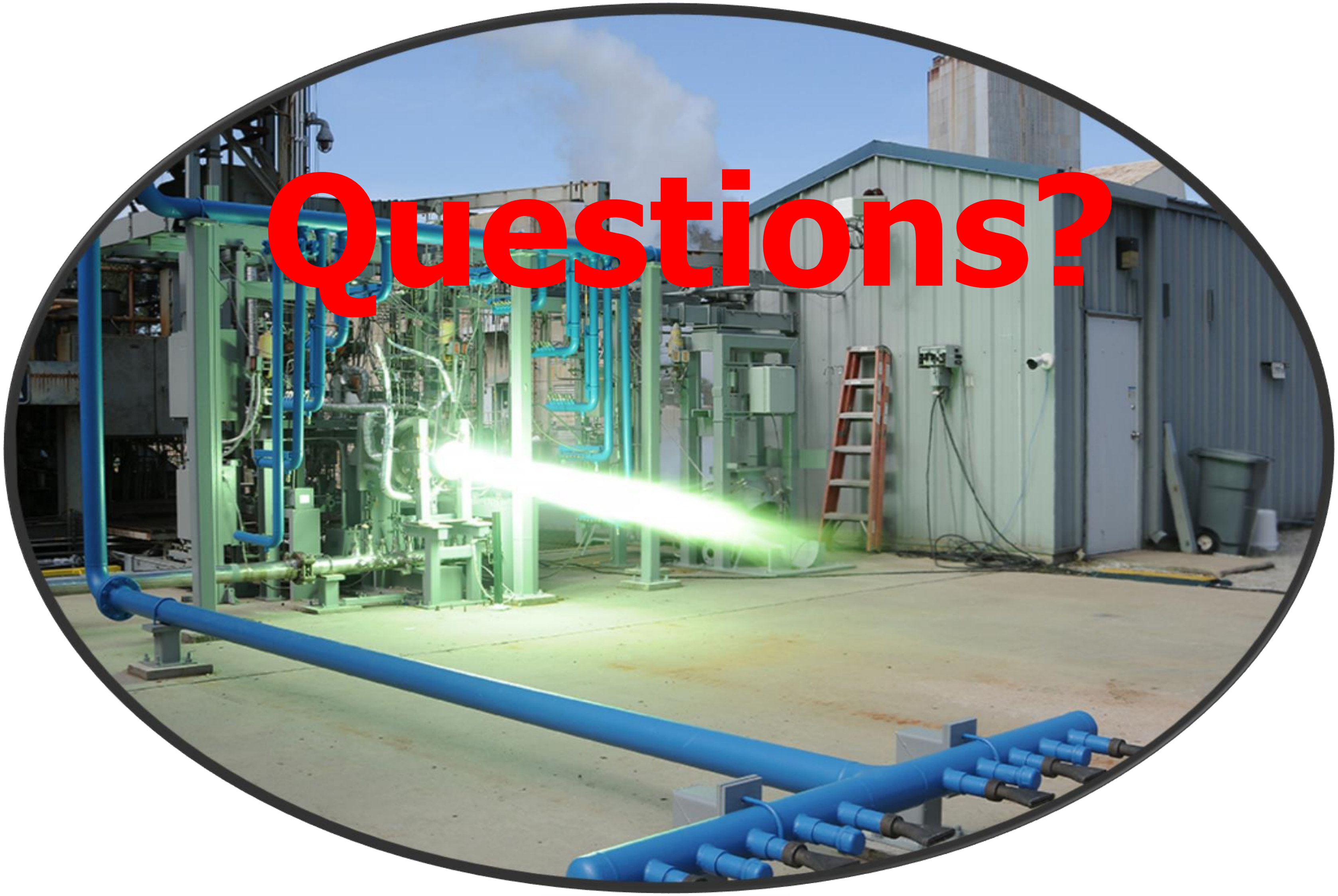
- Powder dose factor is critical as parts get taller.
- Design for Powder Removal
  - Physical efforts for powder removal can cause stress on the part.
    Mallet blows created microcracks in some components prior to HIP
  - High pressure (>500 psi) air/GN2 aided in powder removal
  - Alcohol evaporates and helped remove powder from select channels (although residual powder might clump when exposed to this fluid).
  - Include threaded ports that can be blocked off during powder removal to seal air flow properly (dry state/no oils).
  - CT scan continuously to verify powder removal.
  - Removing prior to HIP is ideal, but it can be removed after, since it does not all consolidate.
  - Build direction is critical and overhangs may fail; 45 deg max build angles possible.
- Creating plastic models or building small wedges/slices to demonstrate parameters prior to metal designs can be helpful; identify potential issues prior to actual component builds.
- TIG braze repairs for debonds worked well; identical filler material is ideal.
  Include 0.030"/0.045" dia during AM builds to create matching welding rods.
- Design for shrinkage/deformation in all process steps, such as welding and metal deposition.

Chamber Lessons Learned, 1-piece to 2-piece

Allowed for easier removal of powder, simplified design, simplified inspections, and reduced overall processing time



Designs will evolve with additive through print trials, testing, and design and analysis tools



Questions?

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