JANNAF
Liquid Propulsion Subcommittee and Advanced Materials Panel
Additive Manufacturing for Propulsion Applications
Technical Interchange Meeting

Additive Manufacturing Design Considerations for Liquid Engine Components

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Andy Hissam/Darron Rice/Kevin Baker/David Whitten

MARSHALL SPACE FLIGHT CENTER

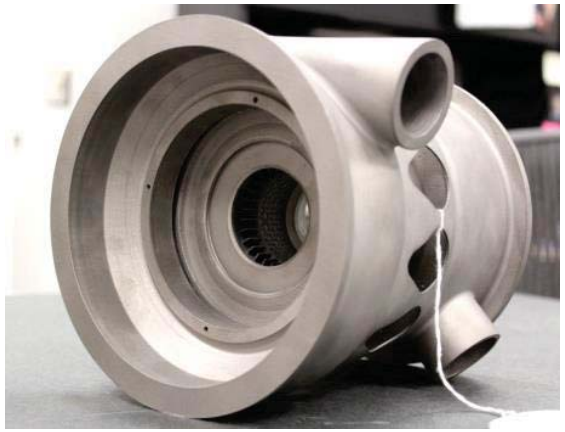
ENGINEERING DIRECTORATE
PROPULSION SYSTEMS DEPARTMENT
PROPULSION COMPONENT DESIGN & DEVELOPMENT DIVISION
PROPULSION DETAILED DESIGN BRANCH

Agenda

- Introduction
- Part Selection
- Part Geometry
- Other Considerations: Build Orientation, Tolerances, Surface Finish, Material Allowances
- Benefits/Drawbacks
- Conclusions

Introduction

- Pump Housings
- Valve Bodies
- Rotating Machinery
- Ducts
- Combustion Devices



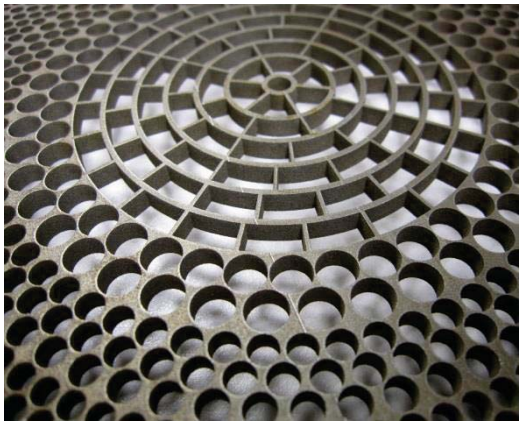
Part Selection

When Does Additive Manufacturing Make the Most Sense?

- Components with large part count
  - Eliminate need for joining: e.g., fasteners and welding. Reduce tooling.
  - Reduce number of sealed joints

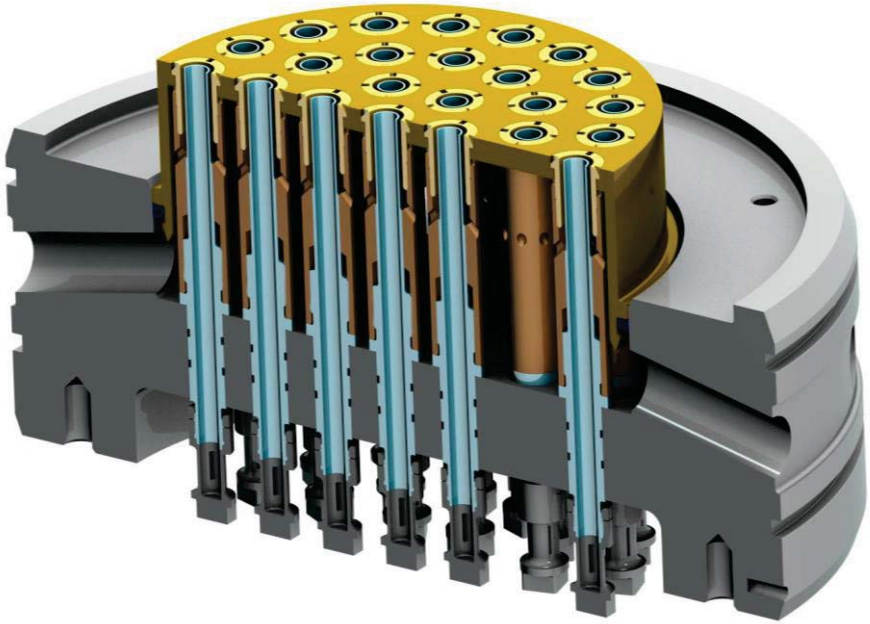
- Parts with Complex Geometry
  - Eliminate costly machining
  - Allows routing of complex internal passages
  - Allows variable passages and wall thickness
    - Coolant channels
    - Flow paths
  - Build parts that cannot be made with traditional machining

- Assess cost savings in terms of individual parts but also at a system level



Part Selection

Components with Large Part Count



INJECTOR,
CONVENTIONAL DESIGN

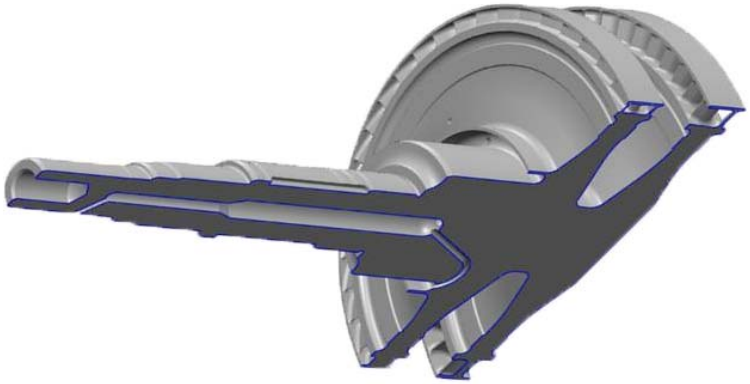
162 pieces

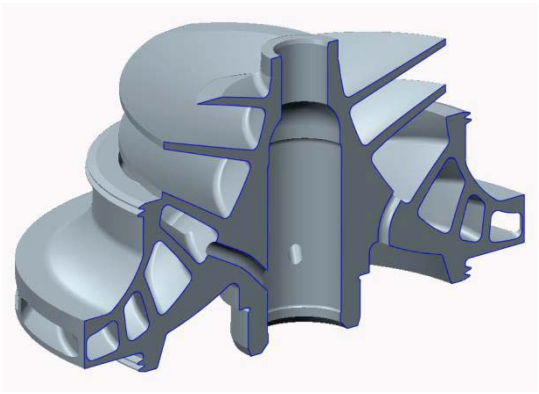
INJECTOR,
ADDITIVE MANUFACURING DESIGN

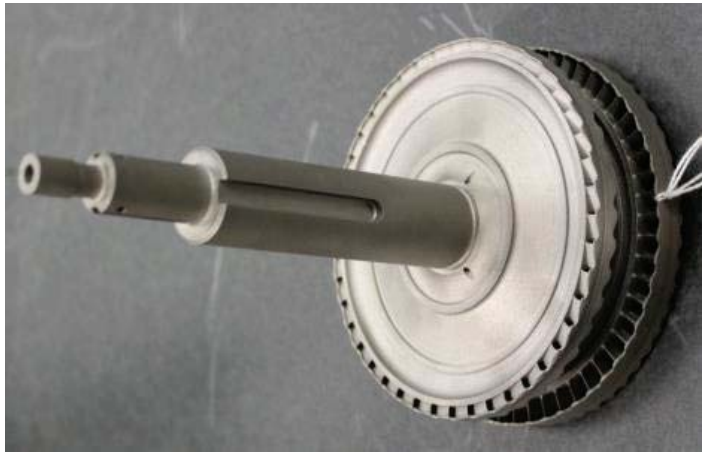
2 pieces

Part Selection

Parts with Complex Geometry







INTEGRAL SHAFT AND TURBINE

IMPELLER

Part Selection

Some parts can be manufactured cheaper using traditional methods

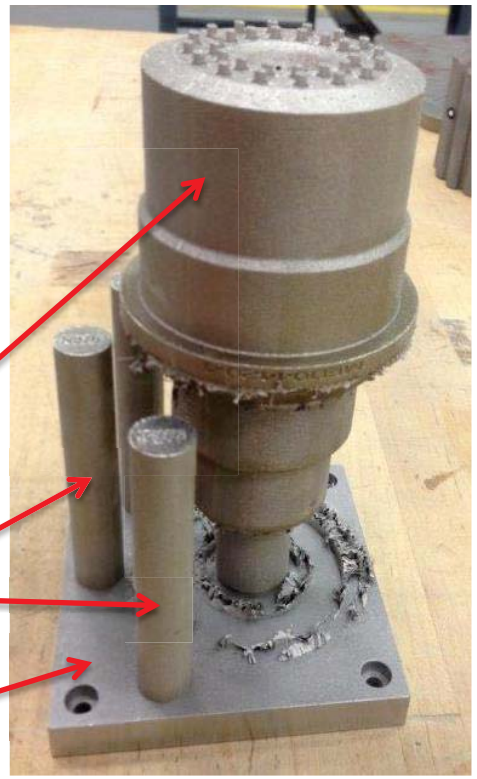
- Vendor A (conventional machining) - $2155
- Vendor B (3D printed) - $3539 + final machining
- Vendor C (3D printed) - $7560 + final machining

INJECTOR LOX STEM

Part Selection

Some Parts Limited by Build Box

- Build Box Varies Between Machines
  - EOS 270 – 9.5” x 9.5” x 7.5” w/1” thick build plate
  - EOS 280 – 9.5” x 9.5” x 11” w/1” thick build plate
  - Concept Laser M2 – 9.5” x 9.5” x 11” w/1” thick build plate
  - Others
- New machines with larger build boxes are becoming available
- Larger parts can be made in several pieces then joined

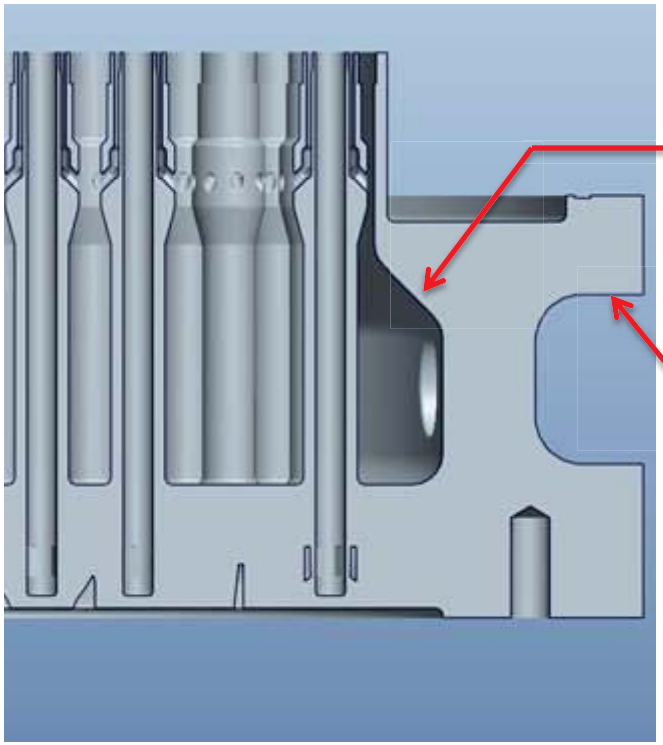


Part Geometry

- Flat Ceilings and Overhangs
  - Require structural support
  - Accessible for post machining
- Angles / Rounds
  - Greater than 45 degrees
  - Optimize round/fillets to minimize material
- Holes
  - A “burn” can occur in holes in vertical plane
  - Consider ovals/teardrops in vertical planes
  - May require support in vertical plane
- Internal passages
  - Powder removal access
  - Support structure removal if required

Part Geometry – Flat Ceilings and Overhangs

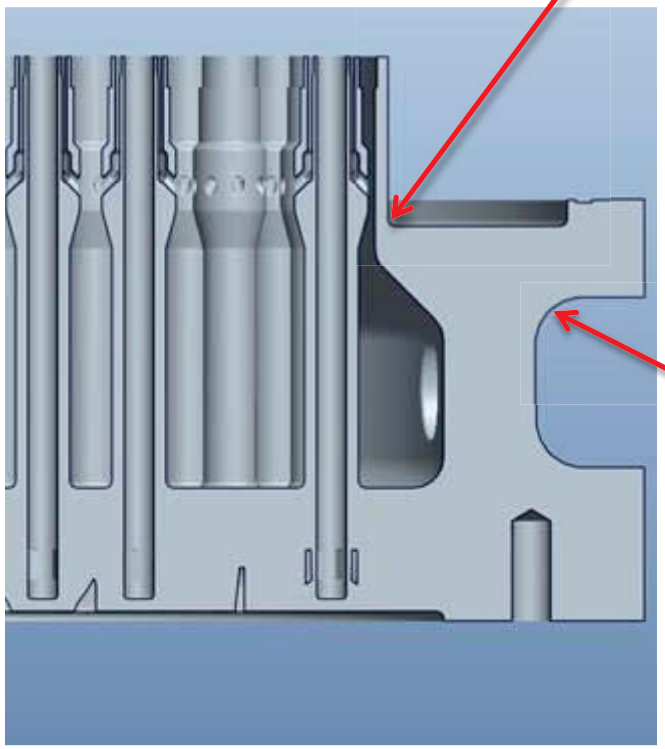
- External flat ceilings are allowed in the design only if supports are used.
- For internal (enclosed) geometry, angles greater than 45 deg. are necessary.
- Arched ceilings also work well.



Angles can be used where support structure will be difficult to remove.

Support structure will be required, requiring post machining for removal.

Part Geometry – Angles/Rounds

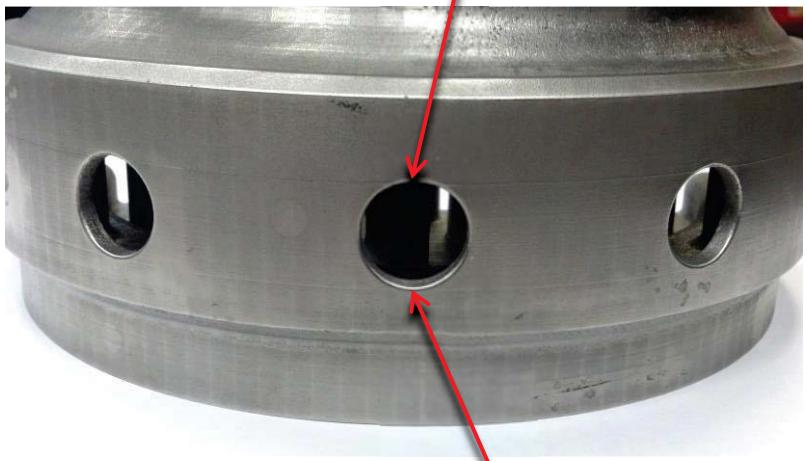


Smaller rounds can be used at floors (stress permitting)

Larger rounds should be used at ceilings

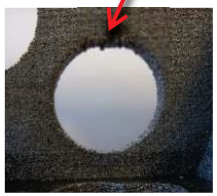
Part Geometry - Holes

Burn (or pill) will occur at top of hole

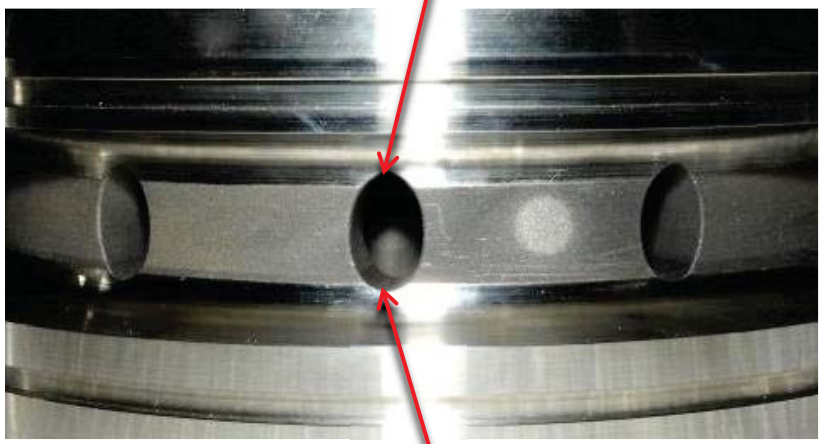


Holes in vertical plane will require structural support (when greater than ~ 1”)

Burn



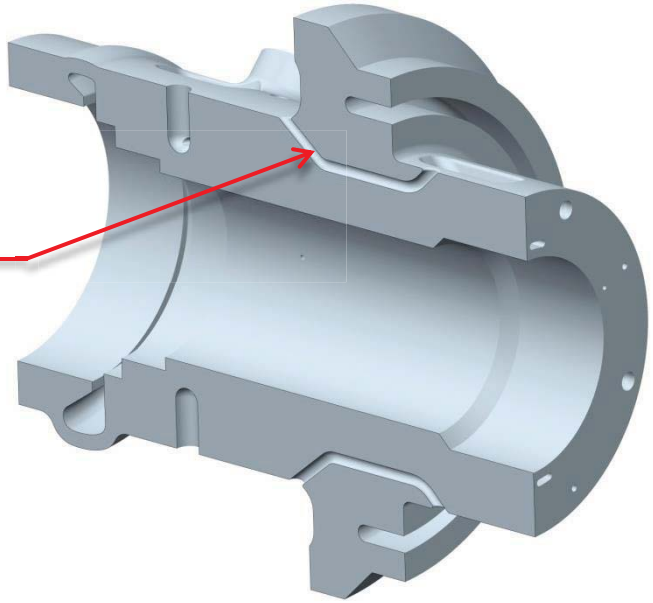
Vertical elliptical holes will reduce burn at top of hole



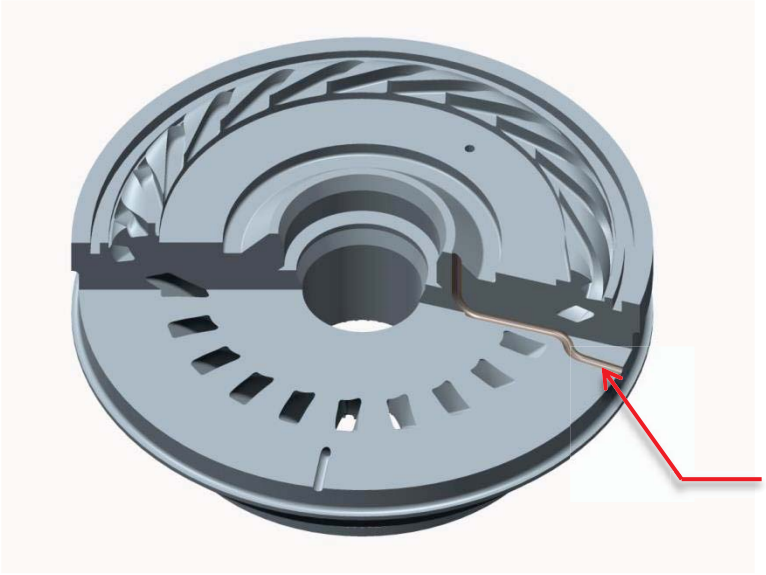
Elliptical holes in vertical plane may eliminate need for structural support

Part Geometry – Internal Passages

Minimum achievable hole diameter 0.020-0.030 inch



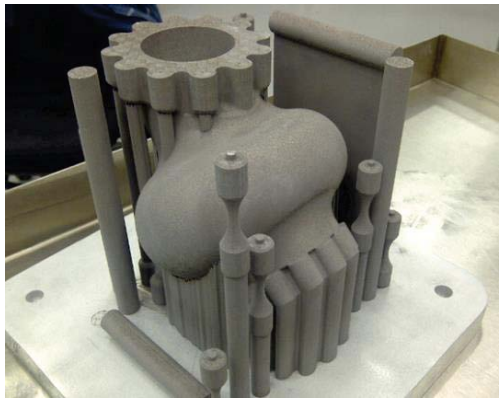
PUMP DISCHARGE HOUSING



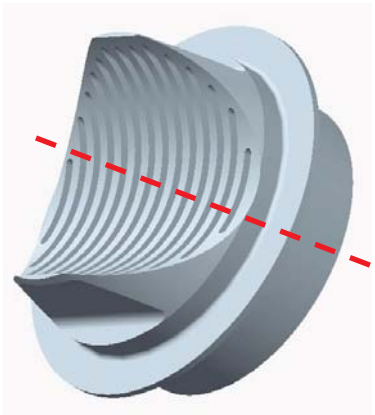
PUMP CROSS-OVER

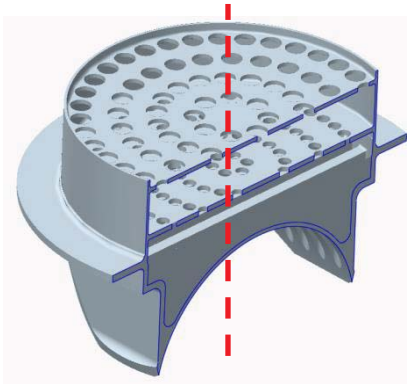
Other Considerations – Build Orientation

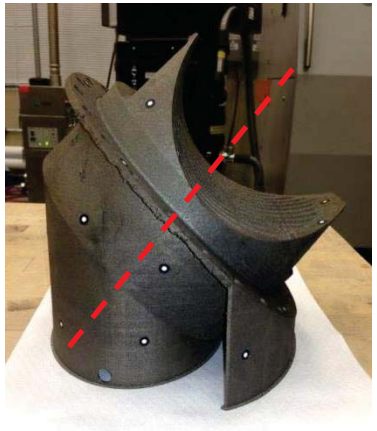
- Ideally, there is a continuous path of solidified metal extending down to the build table
- Features that require build supports should be easily accessible from the outside of the part for removal
- Minimize supported areas. More support structure requires more post processing time.
- Some parts build better in certain orientations



VALVE BODY FOR TURBINE BY-PASS



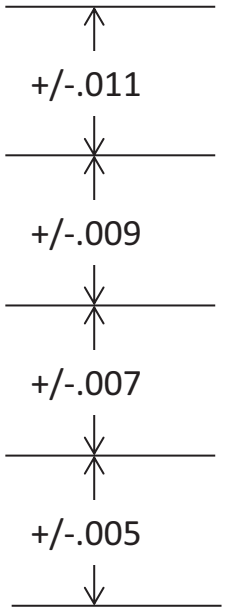


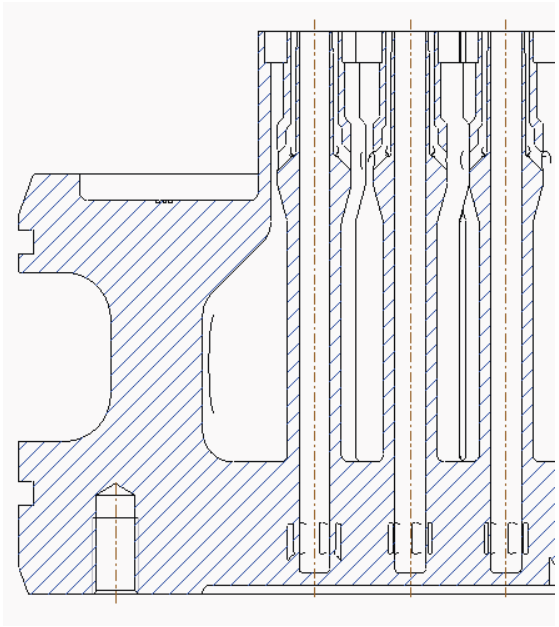


POGO BAFFLE ASSEMBLY

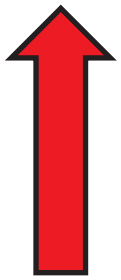
Other Considerations - Tolerances

The achievable part tolerance drops as the part grows, that is, in the build direction.



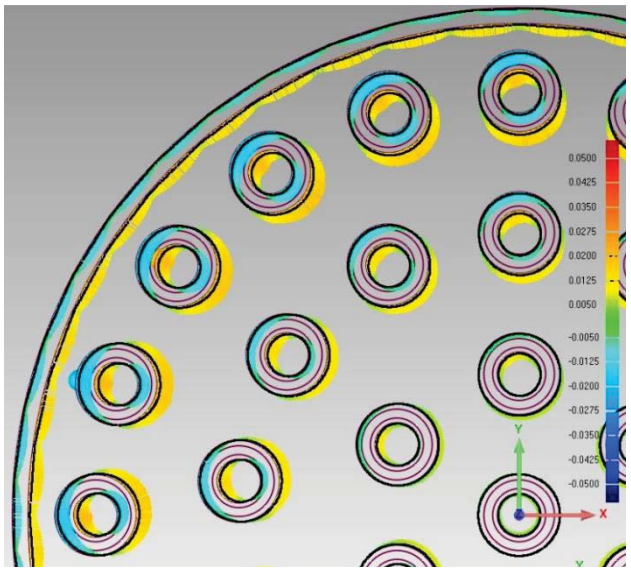


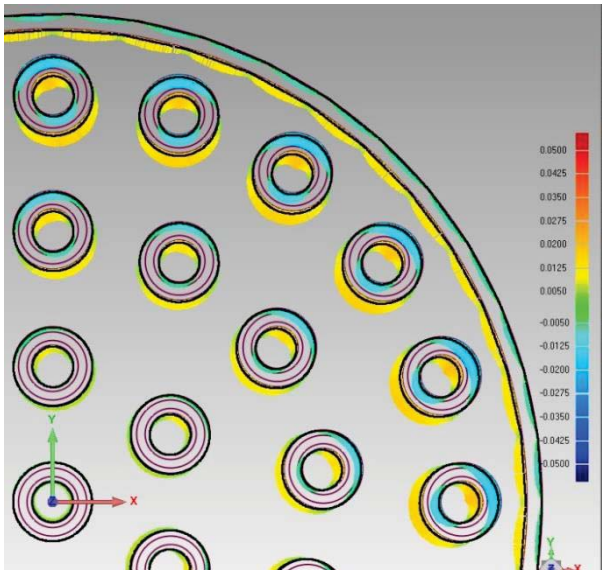
Build Direction



Other Considerations - Tolerances

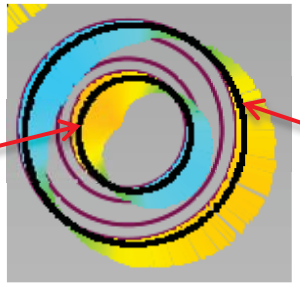
The achievable part tolerance drops moving radially outward.



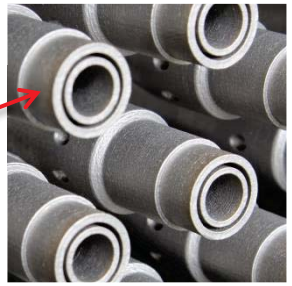


Deviations taken 4.6 inches from build plate

Inner wall of LOX post



Outer wall of fuel sleeve



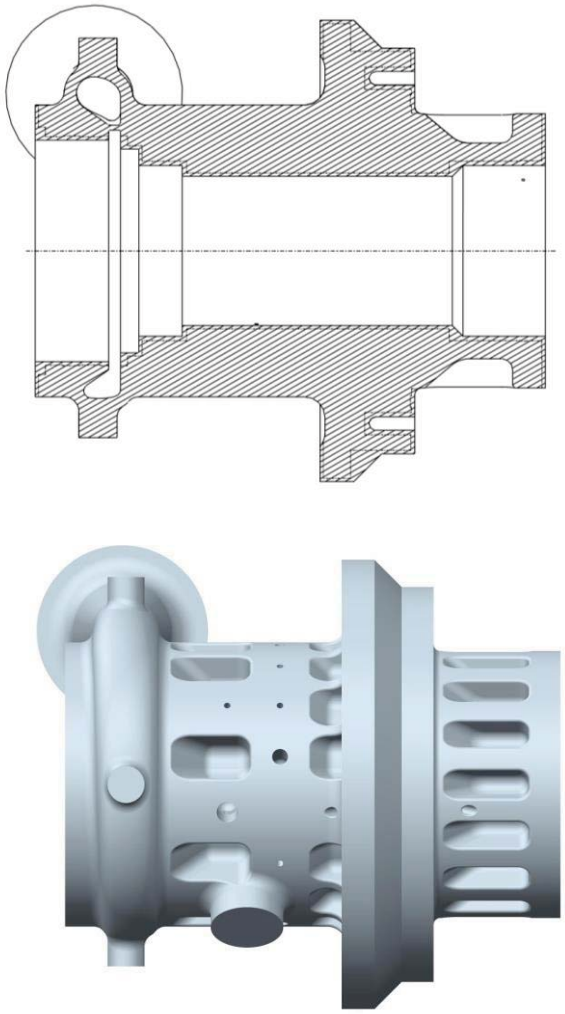
Other Considerations – Surface Finish

- A surface finish of 250-350 µin Ra can be generally achieved directly from the machine.
- Typically, a part can be shot-peened or sand blasted for a smoother finish (100-200 µin).
- This cannot be done to internal passages.
- Post machining may be required to achieve better surface finish (e.g. sealing surface).

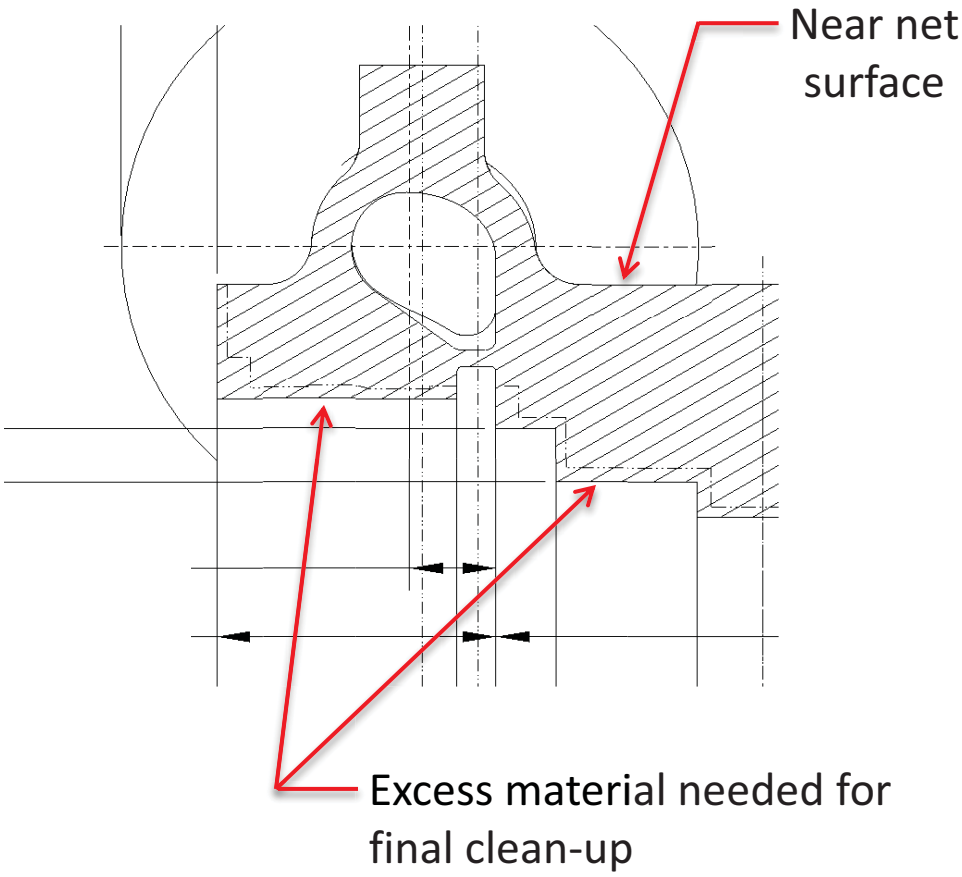
Traditional Machining

Additive Manufacturing

Other Considerations – Material Allowances



PUMP DISCHARGE HOUSING



Excess material may also be needed for part handling (for machining operations)

Other Considerations

- Use external rounds and small internal fillets where design will allow.
  - Decreased build time means less cost.
- Vertical wall thicknesses should be greater than .020”.
  - If a thin wall is required, then extra material is needed.
- Threaded features, O-ring grooves, and tight fits require post machining.
- FOD prevention during post machining.
- Hot Isostatic Pressing (HIP) process may alter part geometry.
- Cannot always inspect internal passages (must ask: is this acceptable?)

Benefits/Drawbacks

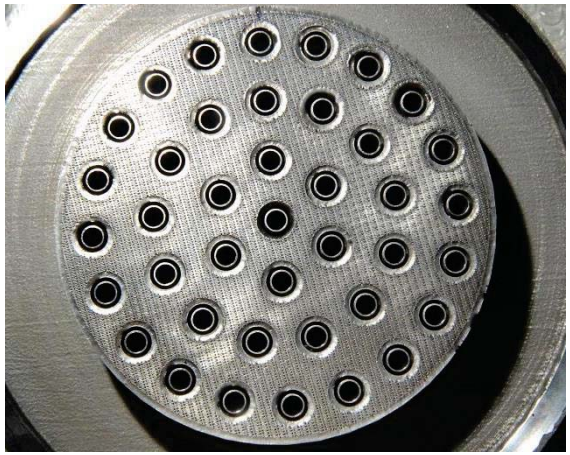
Benefits of AM

- Decreased part count
- Complex parts created for less cost
- Increased design space
- In some cases, schedule benefits
- Increased reliability
- Increased performance (e.g. optimized flow passage geometry)
- Leverages model-based design and analysis

40 Element Injector Test

Drawbacks of AM

- Still requires conventional machining of critical surfaces (sealing surfaces, tight fits)
- Some design features require special accommodation (e.g. overhangs)
- Cannot fully inspect internal passages
- Removing powder from small internal passages
- Limits on size
- Lack of material characterization



40 Element Injector Faceplate

Conclusions

- AM technologies have come a long way in a short time, but are still developing at a rapid pace.
- Many factors must be considered when deciding whether to make a part using AM.
- Many design features must be carefully evaluated when designing for AM (e.g., overhangs, holes, wall thickness).
- Currently, all the parts that we have developed required some final machining. This will likely change in the future.
- As AM technologies continue to evolve and mature, so will our AM design practices.