Metal 3D printing of Low-NOx Fuel Injectors with Integrated Temperature Sensors

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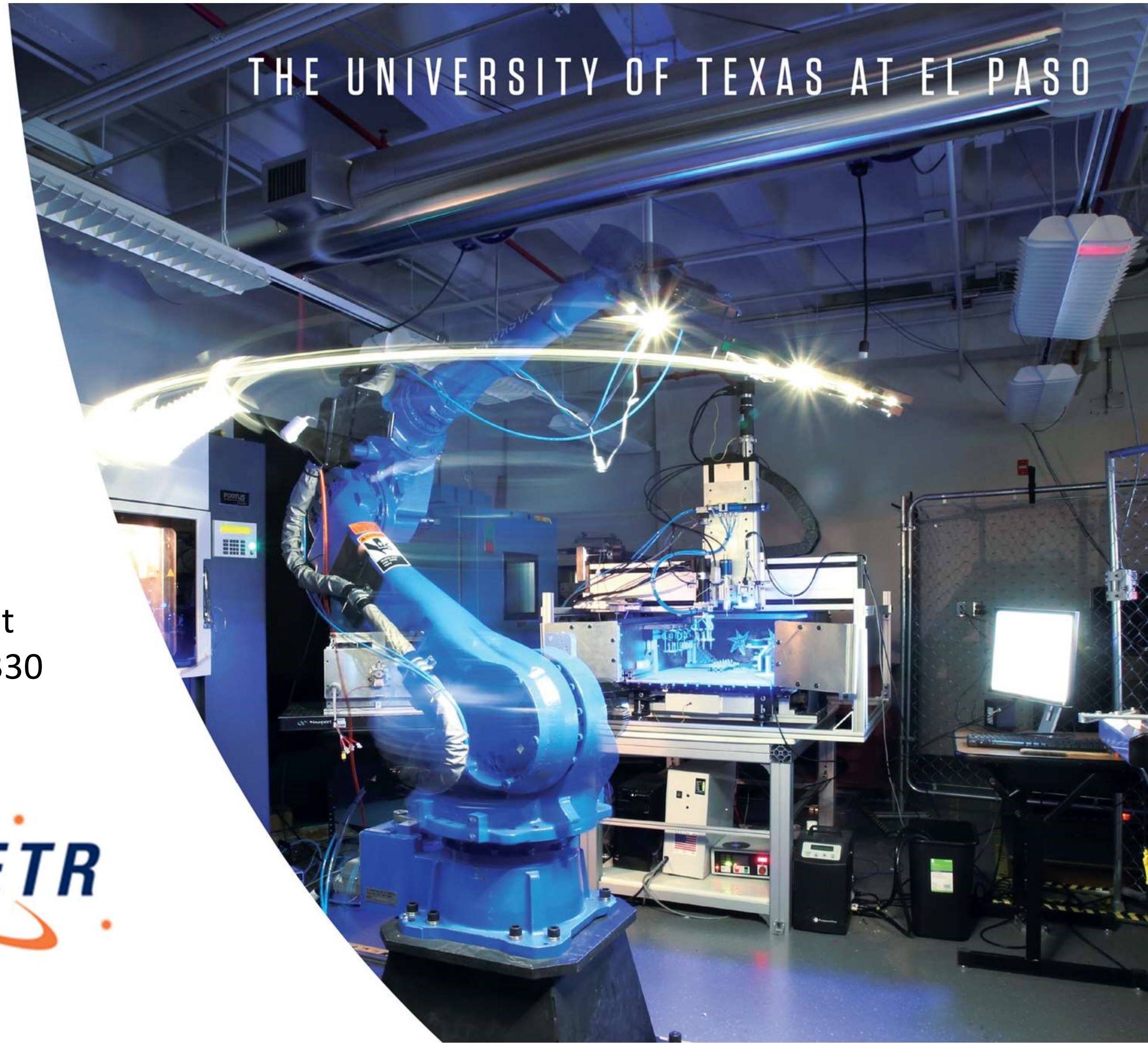
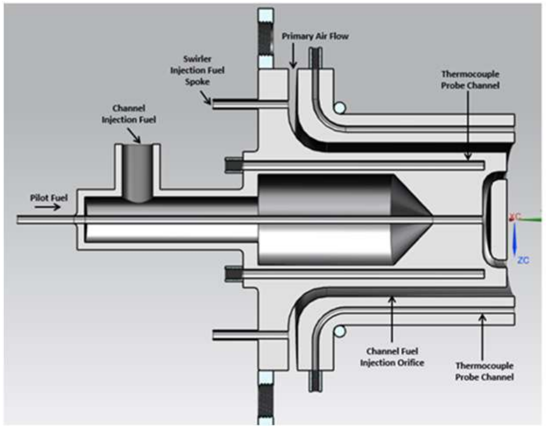


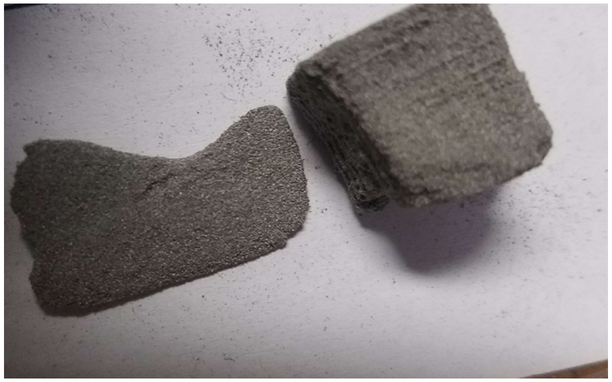
Motivation

- The purpose of the project is to fabricate a low NO_x fuel injectors for power generation power plants
- Additive manufacturing (AM) allows the fabrication of complex internal channels and cavities required for injector design
- AM allows the integration of temperature sensors



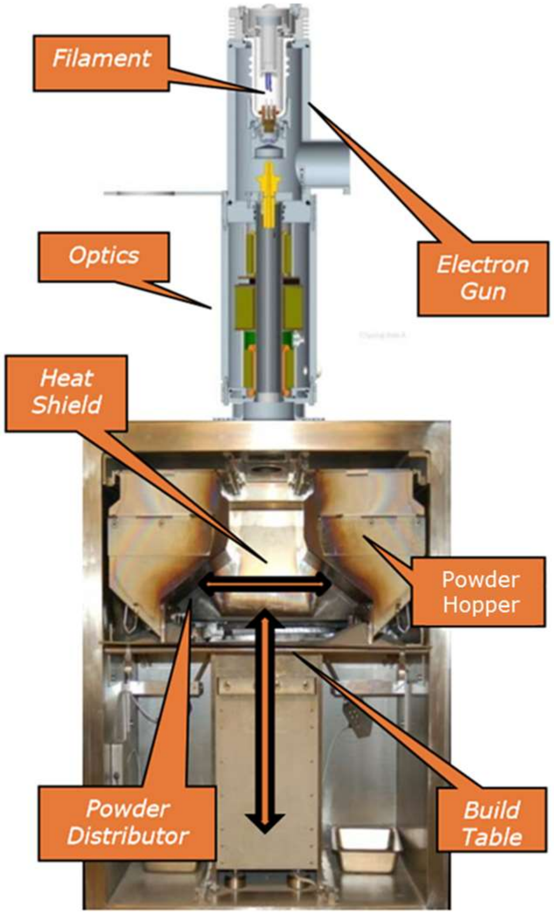
Problem Statement

- Precursor powder used in powder bed fusion remains trapped within internal cavities and channels after fabrication
- Some processes result in sintered powder which is a challenge for removal



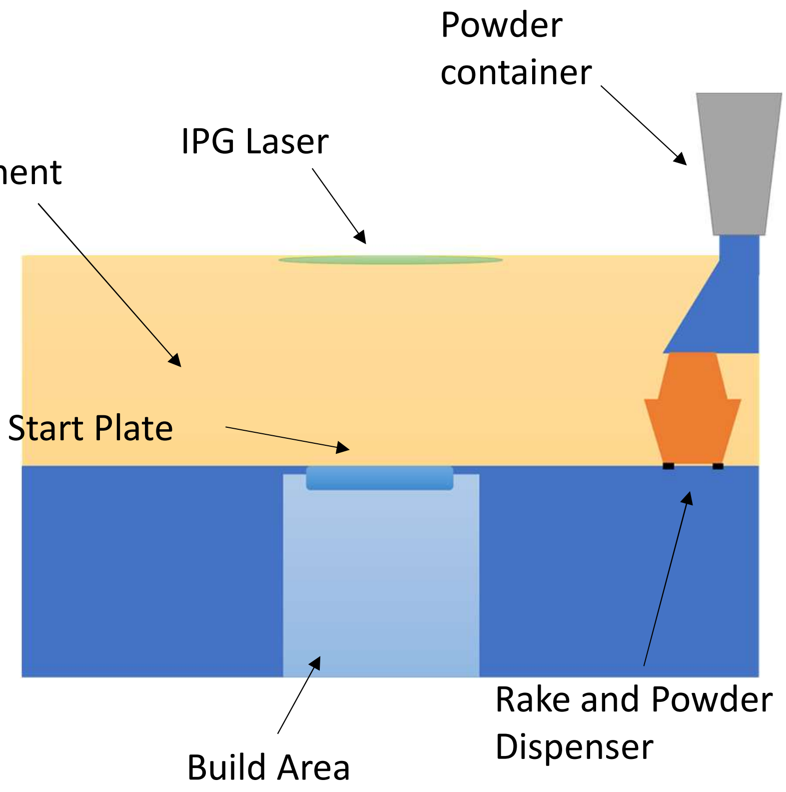
EBM (Electron Beam Melting)

- Builds at elevated temperature
- Machine: Arcam A2
- Ultra high vacuum environment (~10^{-3} torr)



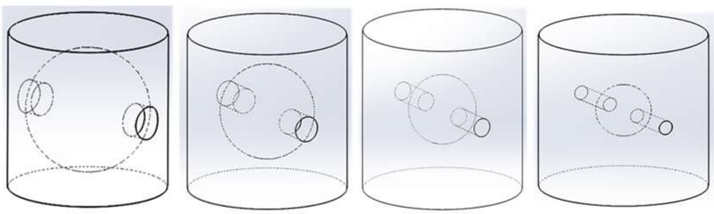
SLM (Selective Laser Melting)

- Builds in low temperature
- Machine: SLM Solutions 125 HL
- Environment can be with Argon or Nitrogen gas

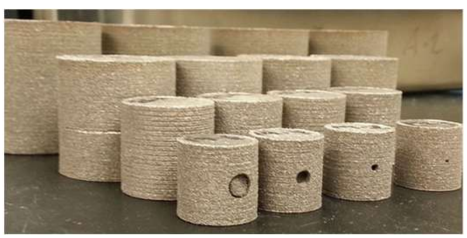


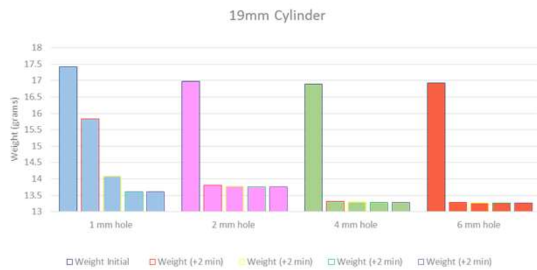
Preliminary Powder removal evaluation

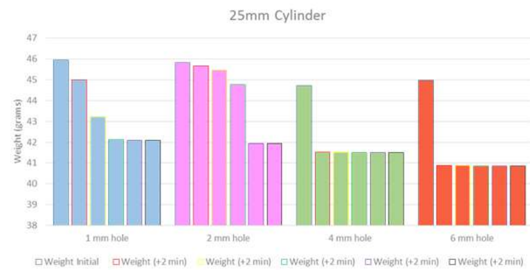
- Ultrasonic vibration was tested on samples of various wall thicknesses and orifice diameters

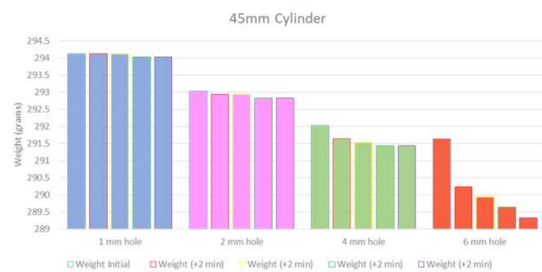


19mm cylinder (4mm channel) | 25mm cylinder (4mm channel) | 35mm cylinder (4mm channel) | 45mm cylinder (4mm channel)









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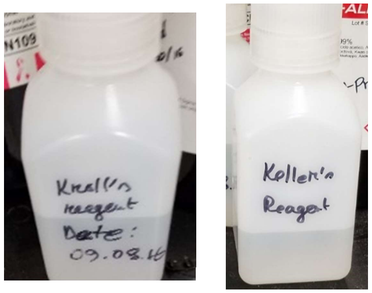
Powder Removal Methods

- Powder Recovery System (PRS)
- Vapor Blast
- Ultrasonic
- Ultrasonic & Hammering
- Liquid Nitrogen & Ultrasonic
- Chemical Etching

Vapor Blast

PRS

Liquid Nitrogen



Chemical Etching

Hammering

Ultrasonic

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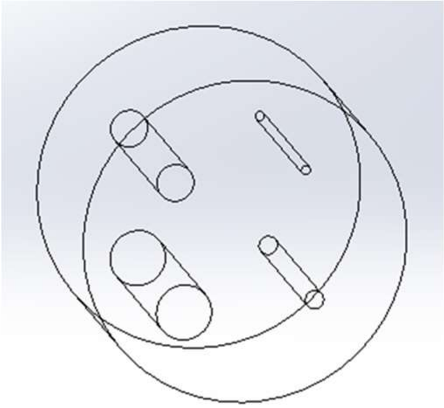
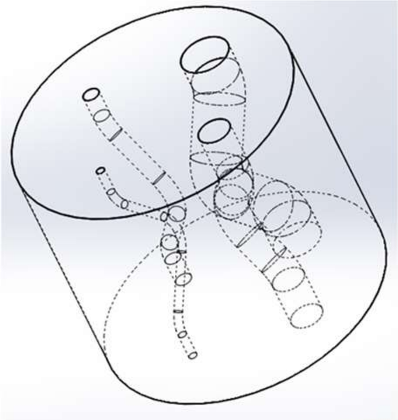
Test articles

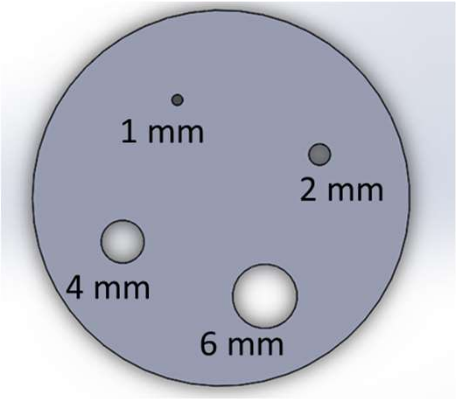
- Sample parts were tested in pairs



Straight Holes

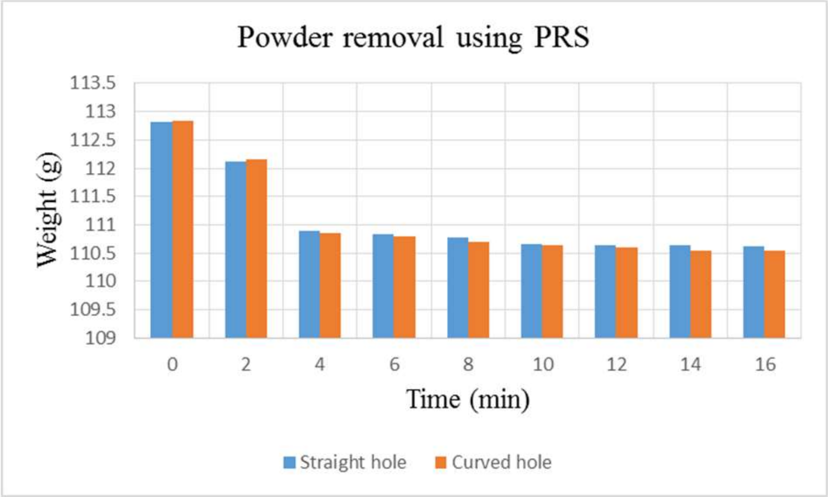


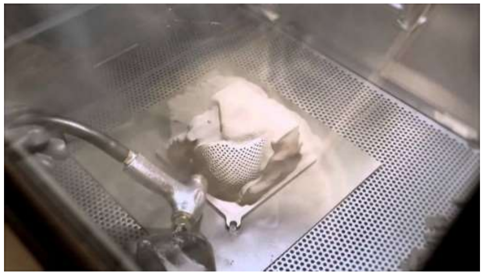
Curved Holes



Powder Recovery System

- Pressurized air blasts metal powder
- Powder is recovered and reused
- Part was clean after 6 minutes





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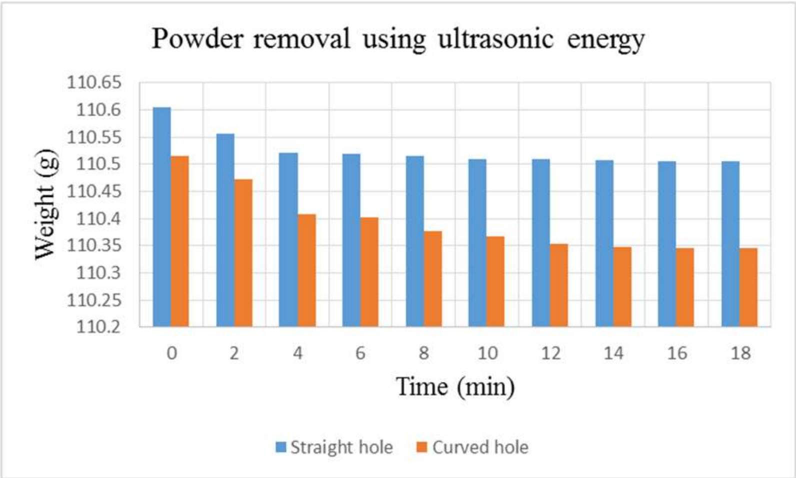
Ultrasonic vibration

- Ultrasonic vibration is applied to break up sintered powdered
- After 6-8 minutes part was clean

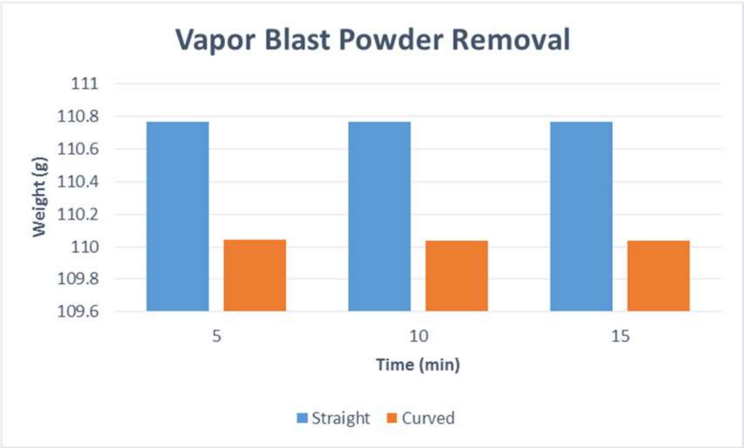
Ultrasonic controller



Ultrasonic application wand

Vapor Blast

- Parts were blasted with a slurry of sand and water
- This method was found ineffective



Parts after blasting

Vapor Blast Station

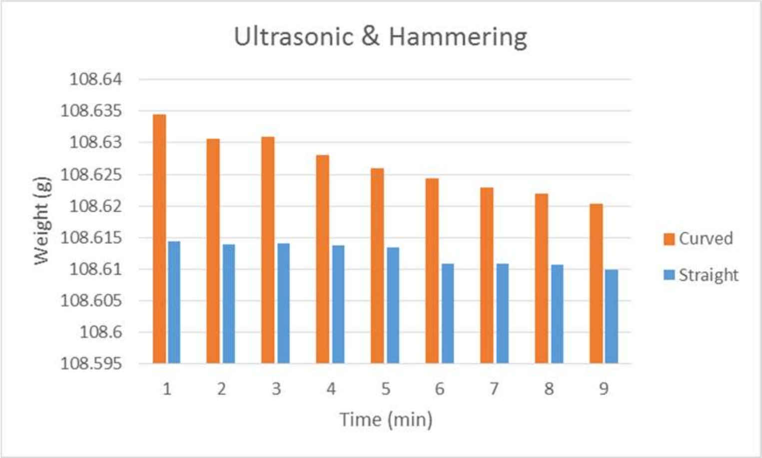
Ultrasonic vibration and Hammering

- Testing consists of 1 minute ultrasonic vibration followed by 1 minute of hammering
- Effective after the first application for straight channels
- Effective after 6 minutes in curved channels

1 minute ultrasonic vibration

1 minute rubber mallet

Light was shown through the holes to assess powder removal



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Chemical etching

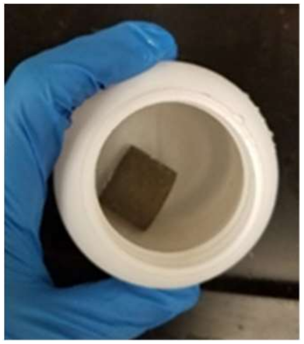
- Two etchants were tested, Kroll's reagent and Kellers etch
- Solutions were applied directly to specimen, no change was observed after 60 seconds
- Specimens were placed in both solutions for 22 hours; no effect

Kellers Etch
- 190 mL Distilled water
- 5 mL Nitric acid
- 3 mL Hydrocloric acid
- 2 mL Hydrofluoric acid

Kroll's Reagent
- 92 mL Distilled water
- 5 mL Nitric acid
- 2 mL Hydrofluoric acid

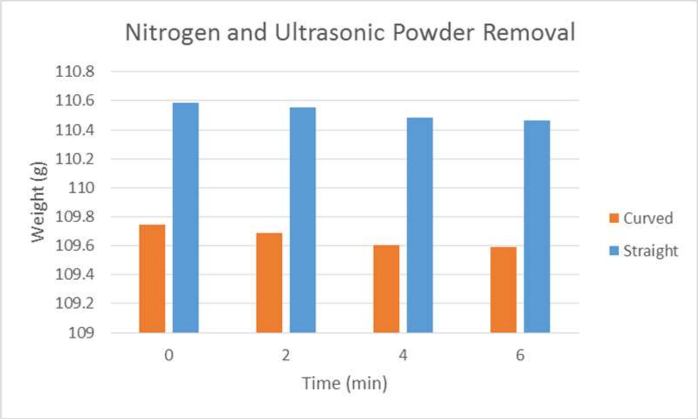

After Kellers etch


After Kroll's reagent

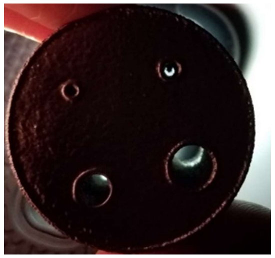
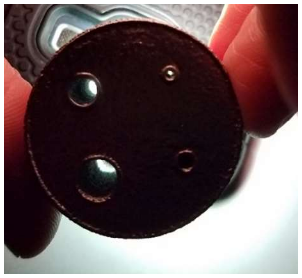


Liquid Nitrogen and Ultrasonic

- Parts were placed in liquid nitrogen for 30 seconds and followed by 2 minutes ultrasonic vibration
- All the holes were cleared after the first application




Parts dipped in liquid nitrogen

Holes after liquid nitrogen and ultrasonic vibration

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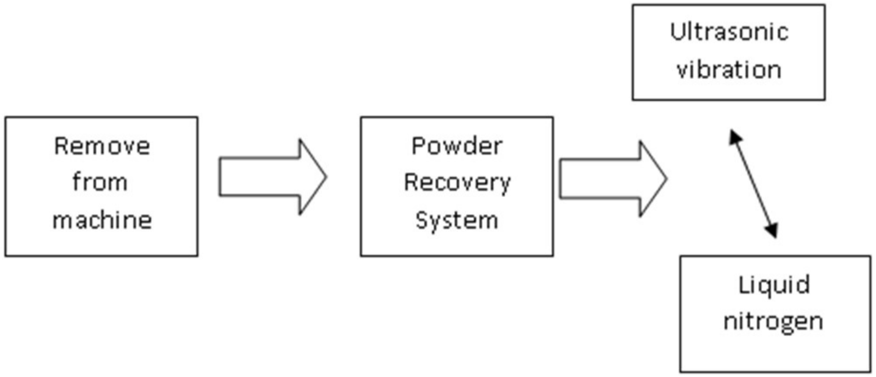
Powder Removal: Conclusion

- Design complexity and wall thickness can inhibit these methods

Testing Method	Results
Nitrogen & Ultrasonic	Effective-Best
Powder Recovery System (PRS)	Effective-Big orifices & Line of sight
Ultrasonic	Effective-Time Consuming
Ultrasonic & Hammering	Effective-Time Consuming
Vapor Blast	Ineffective
Chemical Testing	Ineffective

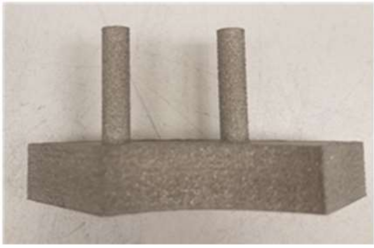
Powder Removal Process

- Powder Removal procedure was finalized
- An article was designed to test the procedure



Powder removal procedure flow chart

Test article with an internal channel




Sample Part	Weight (g)
Before PRS	88.6
After PRS	88.33
After PRS 2	88.05
After Ultrasonic	84.64
After Liquid Nitrogen	84.44

Sectioned the part for visual inspection

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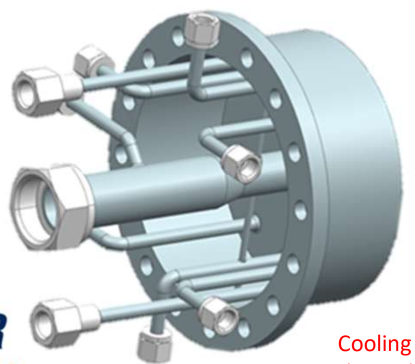
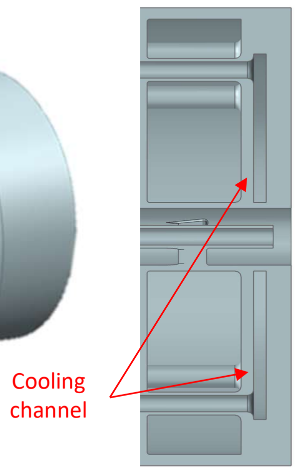
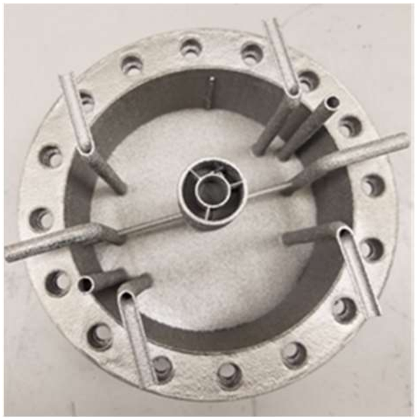
Powder Removal Process

- The procedure was performed on an EBM fabricated injector with an internal cooling channel





Cross section view



EBM fabricated fuel injector

Injector submerged after LN_2 pour

Weight Of Sample Injector	Weight (lb)
With Supports	3.144
After Support	2.3
After PRS	2.222
After Ultrasonic	2.0922
After Liquid Nitrogen	2.076

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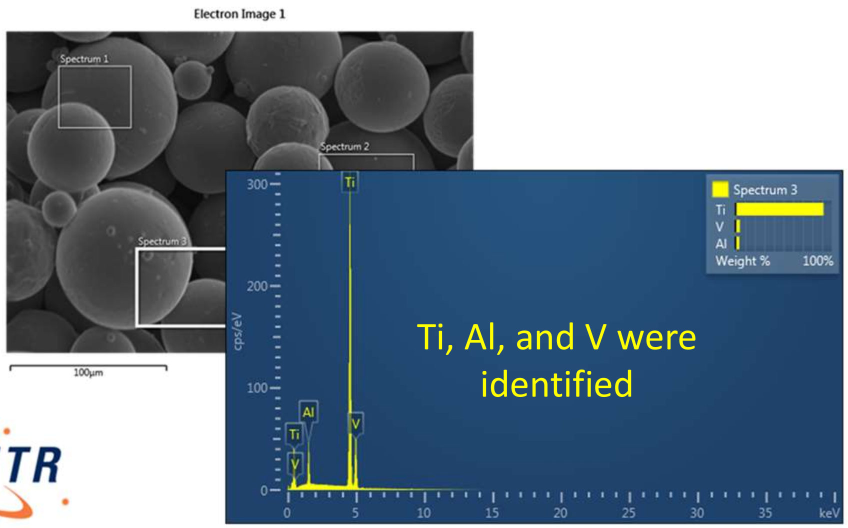
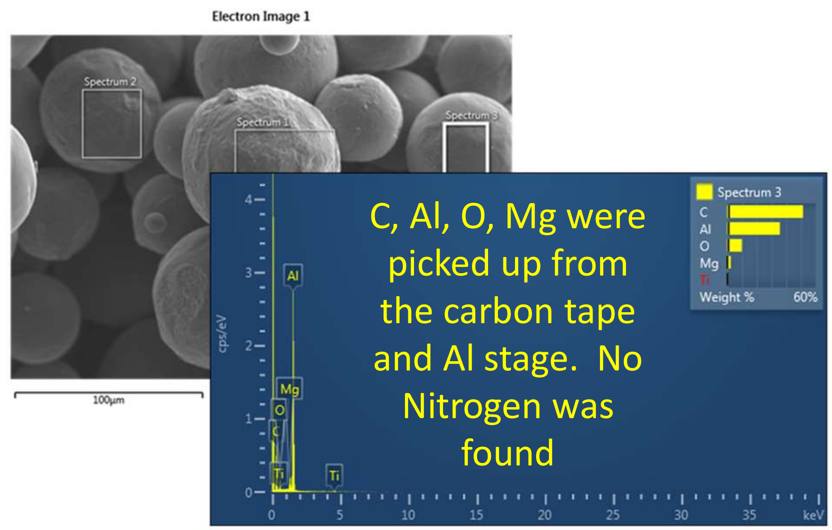
Powder Characterization

- Energy-dispersive X-ray spectroscopy (EDS) was used to check powder for nitrogen contamination



Sintered Ti-6Al-4V powder – no liquid nitrogen exposure



Ti-6Al-4V powder – after liquid nitrogen exposure

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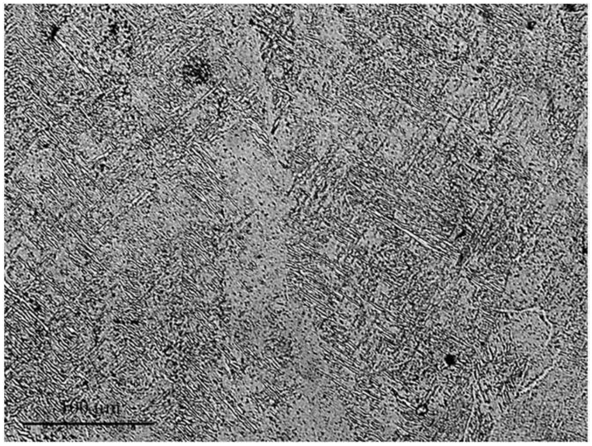
Powder Characterization

	Measured by manufacturer	Mean measured control group	Mean measured LN2
Flow rate (sec/50g)	24	21.8	21.6
Apparent Density (g/cc)	2.54	3.00	3.02

- Powder properties were measured
  - Flow rate following ASTM B213
  - Apparent density ASTM B212
- Microstructure was analyzed – samples were etched with Kroll's reagent

Not exposed to liquid nitrogen



Exposed to liquid nitrogen

Mechanical Testing

- Tensile test samples were machined and tested according to ASTM E8/E8M
- Two groups were tested, not exposed to liquid nitrogen and exposed
- Each group consisted of six samples

Tensile test specimen

No Liquid Nitrogen	Mean	Standard Deviation
Elastic Modulus (GPa)	115.50	5.99
Yield Strength (MPa)	962.12	26.14
Ultimate Tensile Strength (MPa)	1007.12	10.81
Percent Elongation (%)	8.63	2.70
Liquid Nitrogen Exposure	Mean	Standard Deviation
Elastic Modulus (GPa)	116.33	3.59
Yield Strength (MPa)	972.83	38.40
Ultimate Tensile Strength (MPa)	1015.33	3.86
Percent Elongation (%)	9.23	2.95

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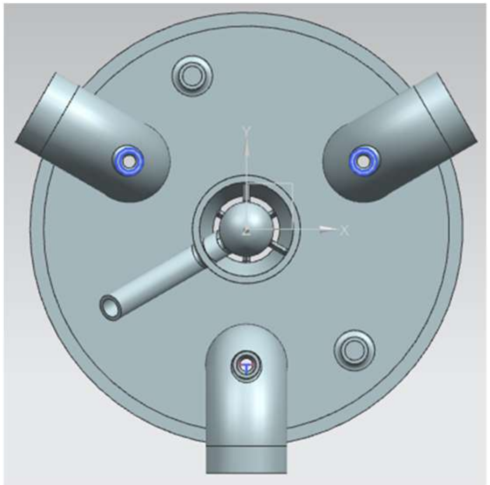
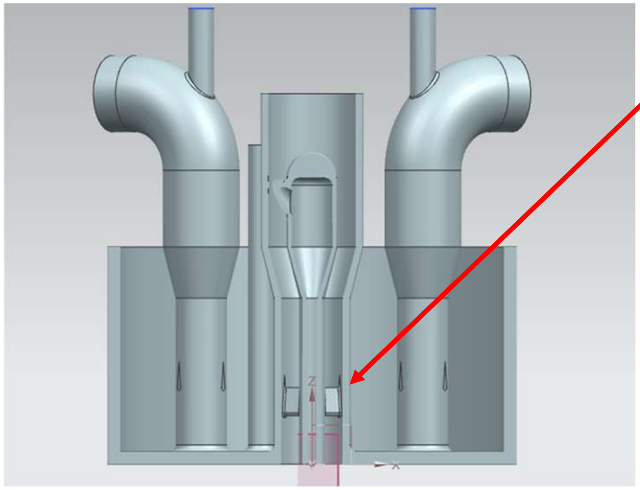
Low NO_x Injector v1.0

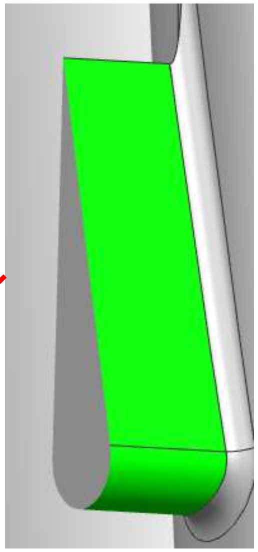
- Designed in serial
  - Conventionally designed for fluid considerations
  - Features to improve manufacturability were additions



Top view of Injector



Cross section of Injector



Airfoil spoke design difficult to fabricate conventionally

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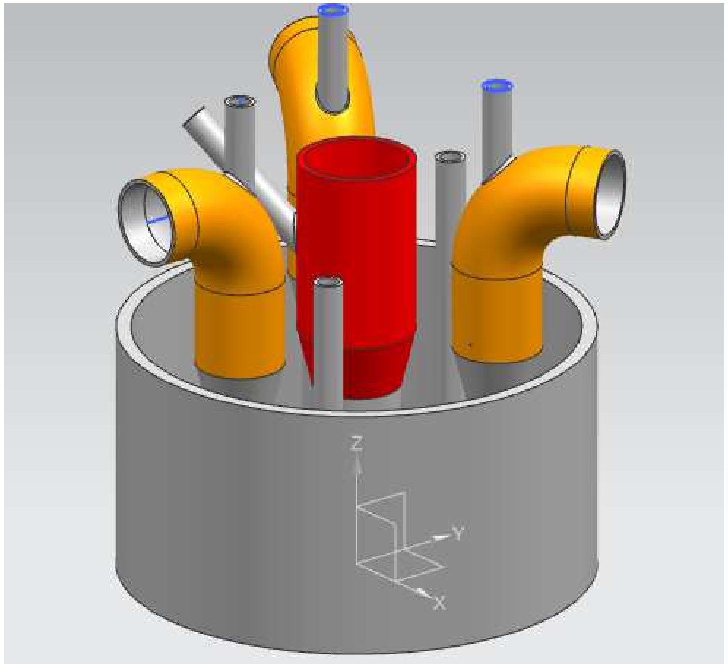
Design v1.0

- Fuel inlets in orange are difficult to additively manufacture and required modifications
  - The 90° turn require internal support
- Main fuel inlet in red is a good design for AM
- Nozzles were included in the design to prevent flash back



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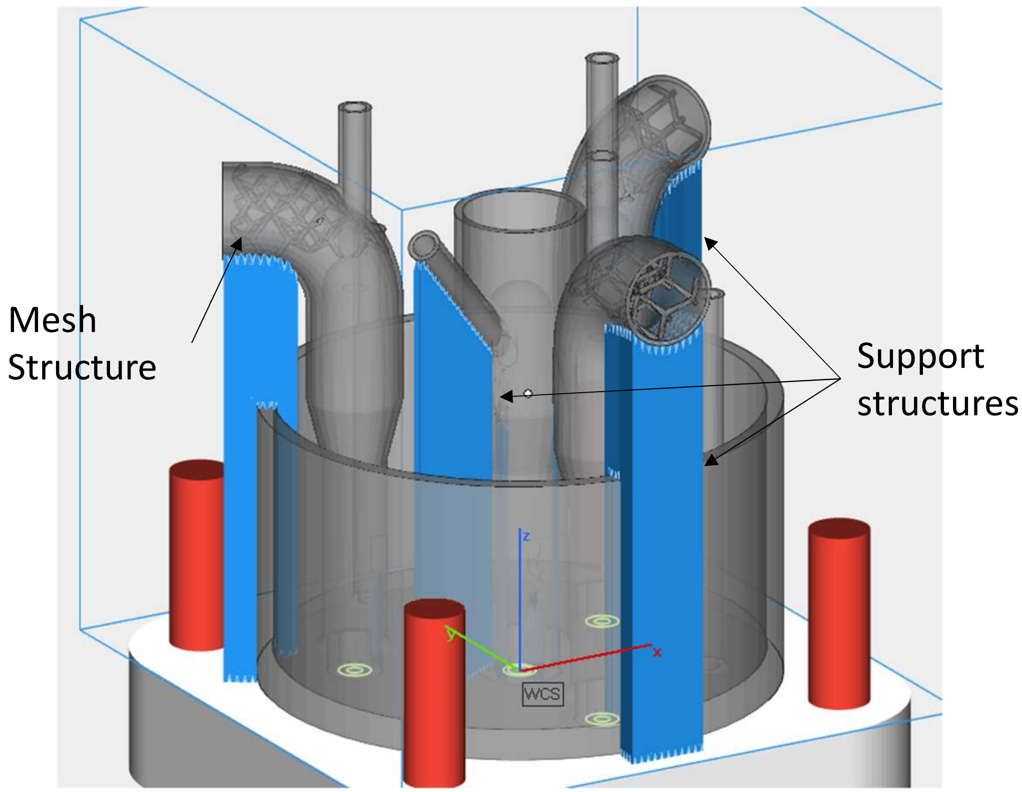
Design v1.0 - Supports

- Materialise Magic's was used for build preparation
- Mesh structures were added eliminate the need for internal supports
- Supports were modified for easier removal



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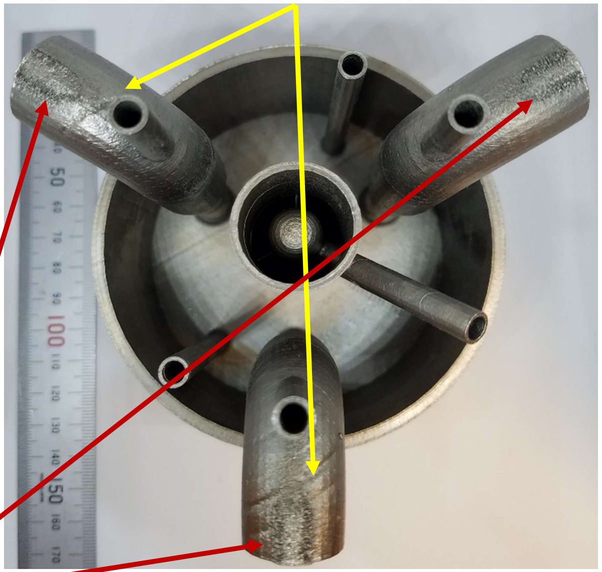
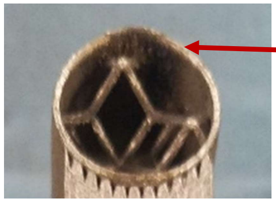
Design v1.0 - Printing

- Parameters were not optimized for the mesh structure and damaged the powder dispenser
  - The mesh overheats and warps
- The mesh did not provide enough support to prevent warping

Defects caused by damaged powder distributor





Warping from insufficient support

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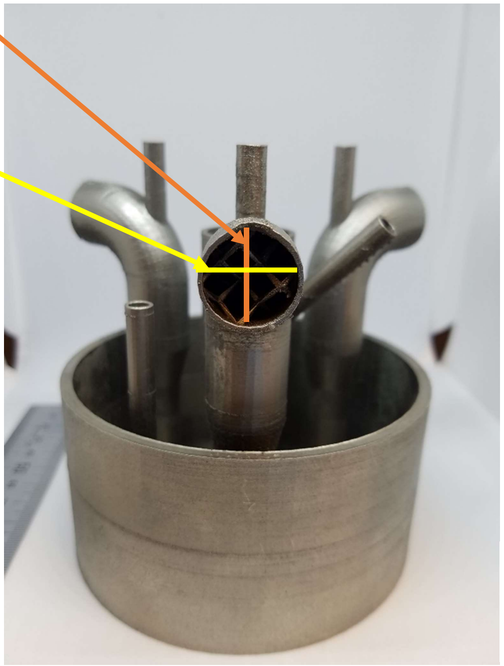
Design v1.0 - Metrology

Big diameter (mm)	Small diameter (mm)	Design diameter (mm)	Big error %	Small error %
19.45	18.65	19.05	2.1	2.1
19.33	18.46	19.05	1.47	3.10
19.35	18.35	19.05	1.57	3.67



Side View

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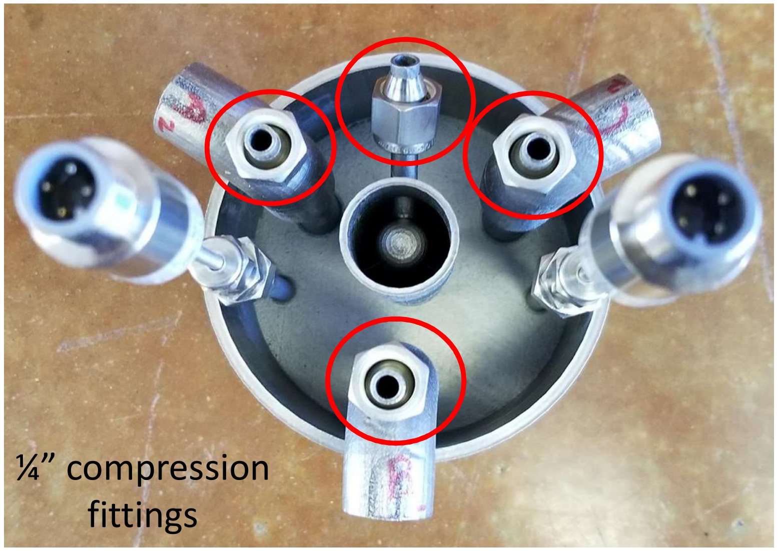
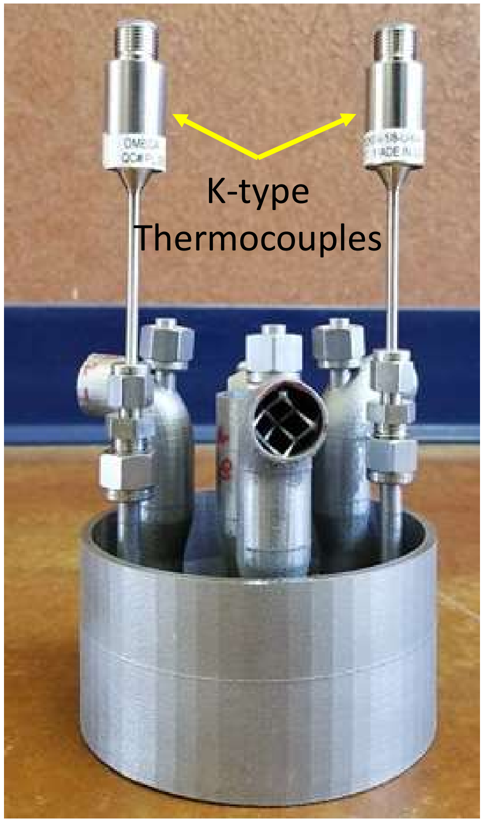
Design v1.0 – Fittings and Sensors

- K type thermocouples were installed
- ¼" compression fittings were installed on all oxidizer inlets





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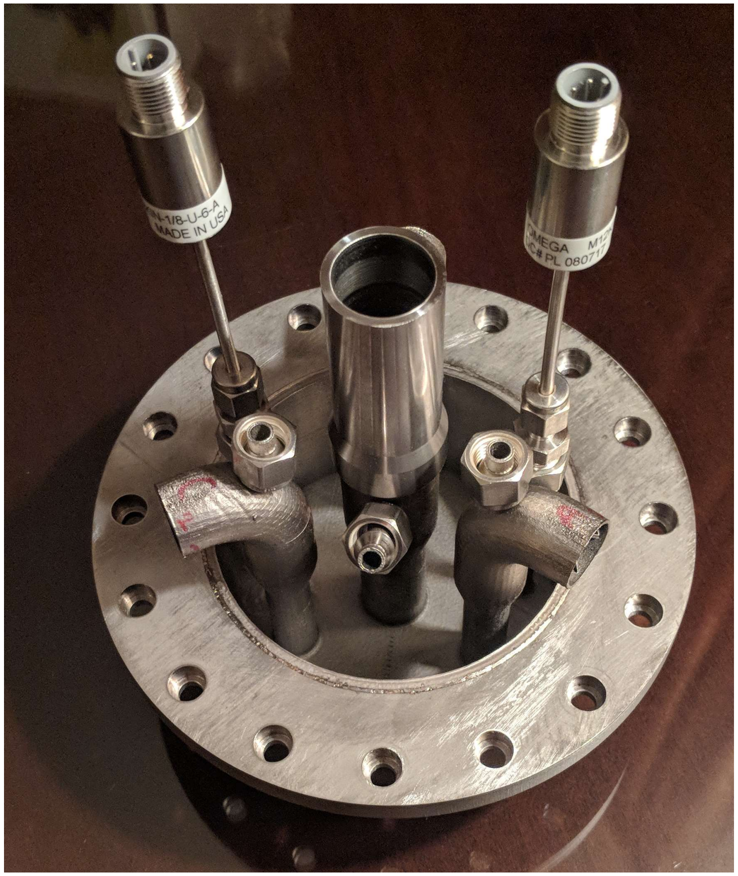
Design v1.0 – Flange

- A flange was welded on the injector to fit the test set up



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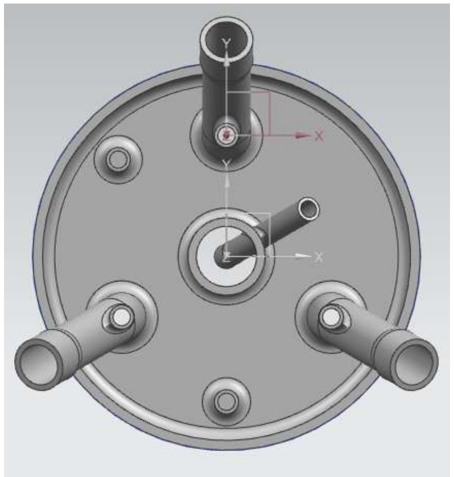
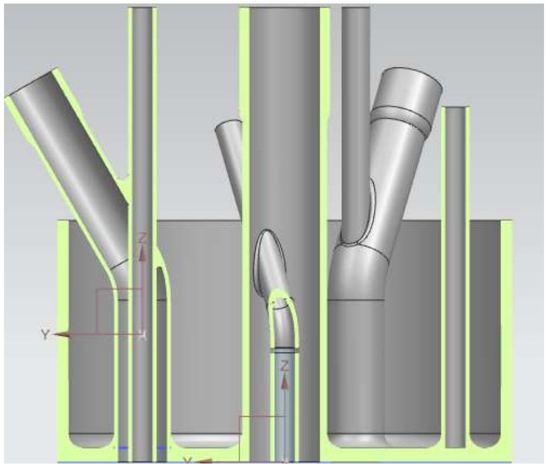
Low NO_x Injector v2.0

- Collaboratively designed – accounted for AM manufacturing constraints



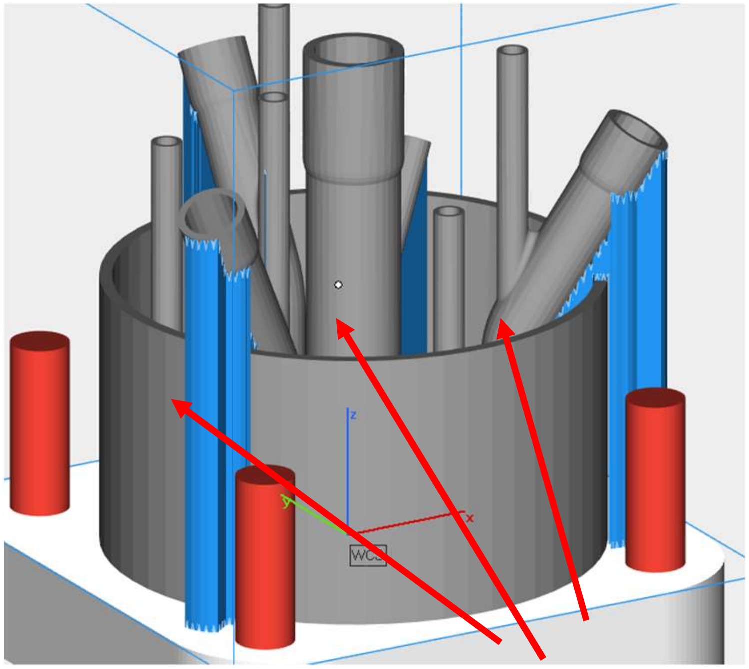
Top View



Cross Section of Injector

Design v2.0 - Supports

- External supports were added
  - Internal supports were not required
- No mesh structures or other additions were required



Supports

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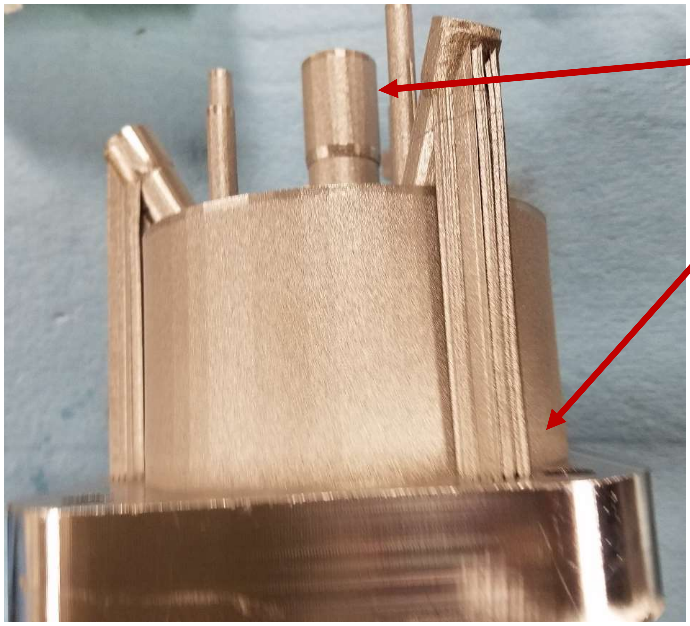
Design v2.0 - Printing

Top View



Side View

Conclusion

- The most effective powder removal method is a combination of liquid nitrogen and ultrasonic
- Liquid nitrogen exposure did not effective the mechanical properties, or microstructure of Ti-6Al-4V
- Collaborative design is the best path forward to unlock the potential of additive manufacturing

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Future Work

- Develop test plan for injector design v1.0
- Test injector design v1.0
- Finish fabrication and injector design v2.0
- Test injector design v2.0

Acknowledgements

PI: Dr. Ahsan Choudhuri

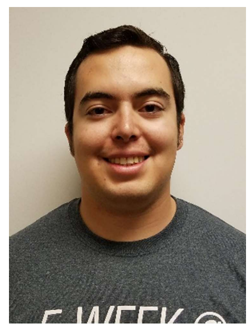
Co-PI: Dr. Ryan Wicker

Manager: Philip Morton

Post Doc: Mohammad Hossain

Masters student: Syed Zia Uddin

Former Manager: Jorge Mireles



UG to grad student: David Saenz

Undergrad student: Jaime Torres

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THANK YOU
QUESTIONS?

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