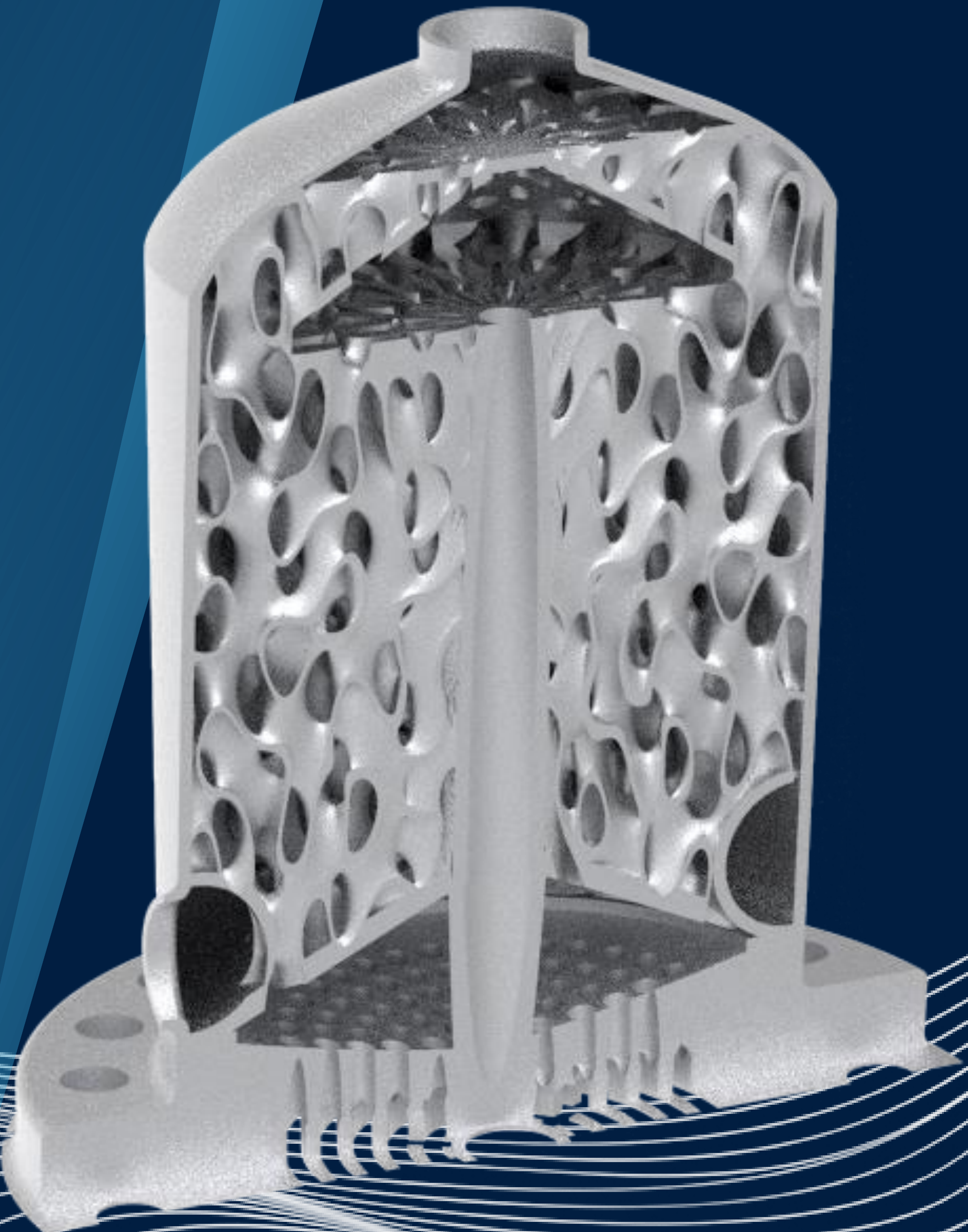
VELO 3D

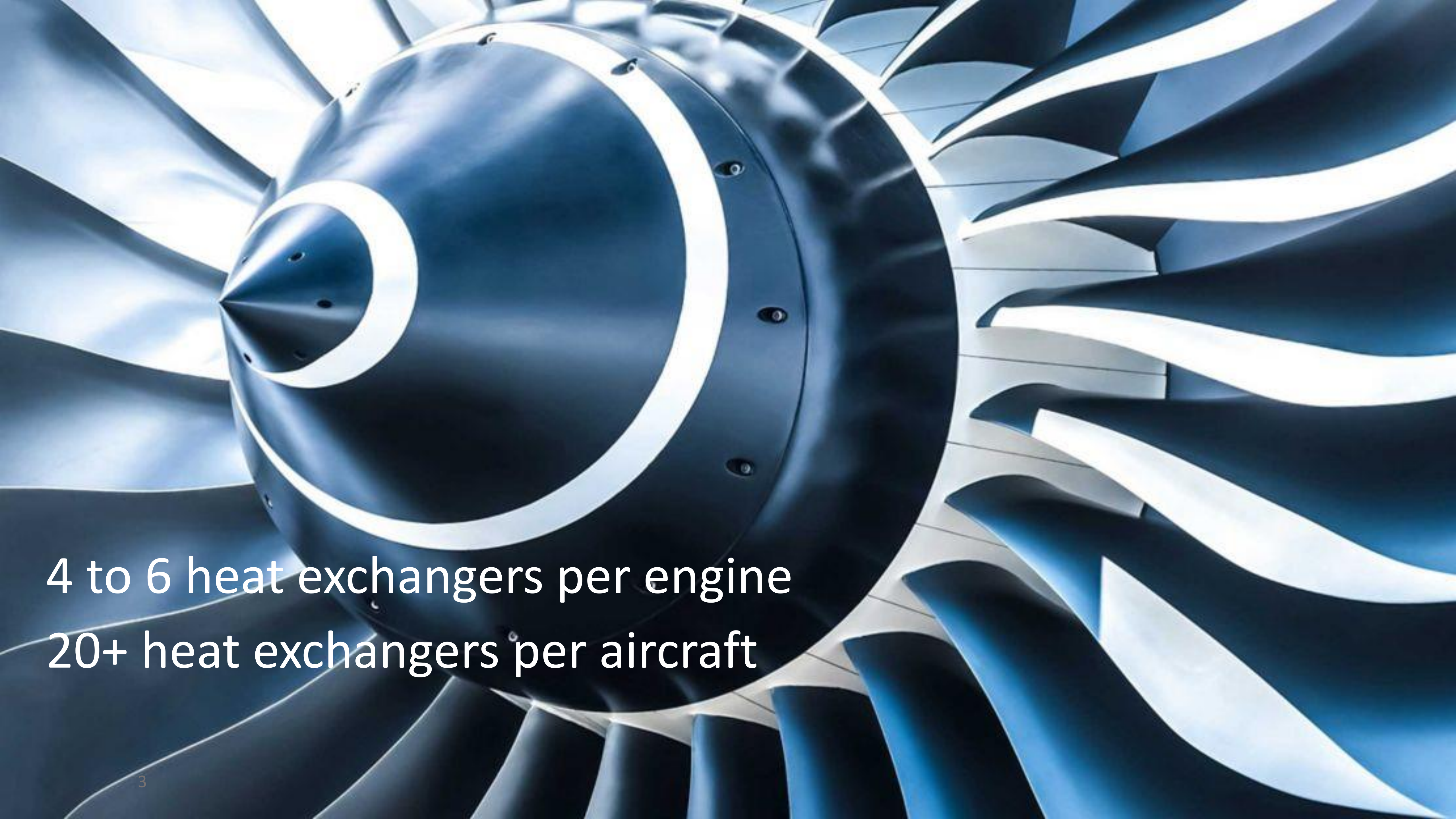
Additive Manufacturing for Heat Exchangers

Will Hasting



Background – Will Hasting, PE

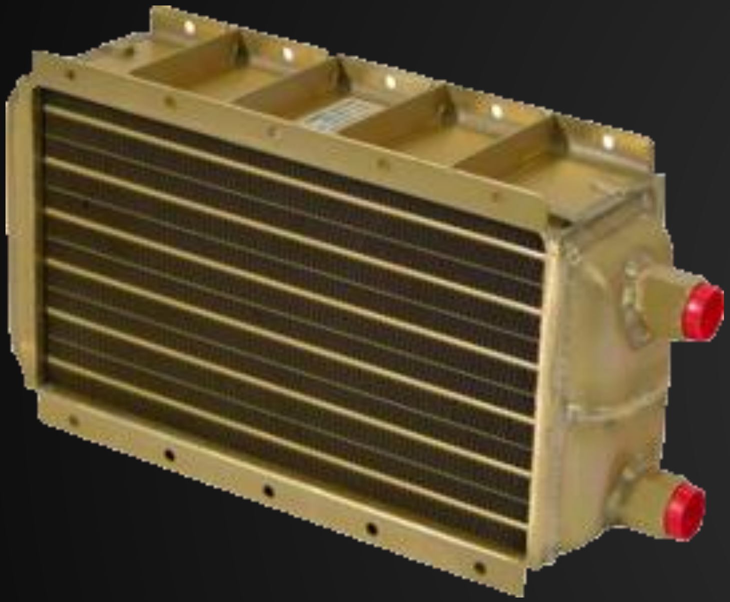
- Director of Aviation & Power Turbine Solutions at VELO3D
- 14 years experience in jet engines, race cars & additive mfg
  - Metals & composite engineering
  - New product design & fielded engine (repair) engineering
- 18 Patents
- Professional Engineer, State of Ohio, USA
- MS, Mechanical Engineering – University of Cincinnati
- BS, Aerospace Engineering – Embry-Riddle Aeronautical University
- US Navy – Nuclear Plant Operator

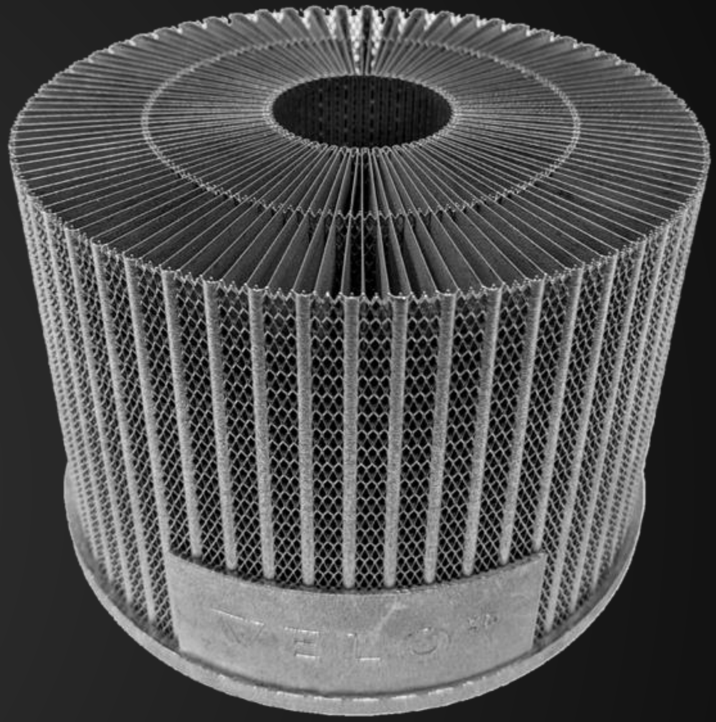


4 to 6 heat exchangers per engine

20+ heat exchangers per aircraft

Heat Exchanger Evolution





Conventional

First Generation Additive

Next Generation Additive

Traditional Fabrication is a Legacy, Analog Process

4000BC – First Method of Casting

2400BC – First Method of Brazing

1893 – First Method of Welding

1915 – First Diffusion Pump for Brazing

Many operations in heat exchangers pre-date or are from the first industrial revolution.

The world relies (and flies) on these legacy processes with variation – between sites, technicians, etc.

1959 – First Computer Chip

1995 – First LPBF System

Additive manufacturing offers a way to harness the technology enhancements of the last 70 years to drive performance & quality

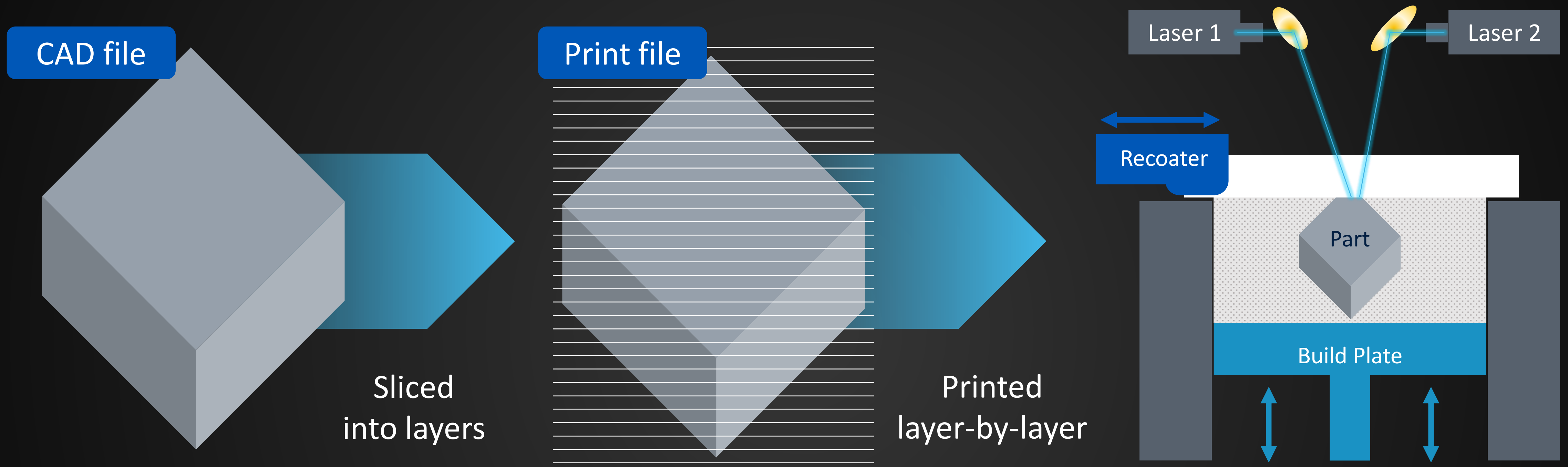
Environmental, Healthy & Safety Concerns

Brazing and welding produce toxic substances as a by-product:

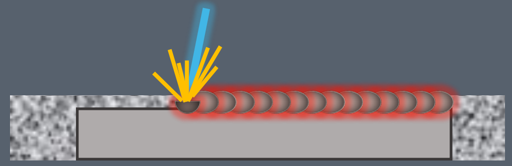
- Trichlorethylene
- Hydrofluoric acid
- Hexavalent chromium

Most of these are banned by environmental agencies

What is Additive Manufacturing (LPBF)



Metal powder is melted in 50 micron layers
based on the CAD file geometry



Laser melts powder onto
solid metal substrate.

Conventional Heat Exchangers

Time
- Delivery (WIP)
- Development (Cast lead time)

Environment
- Chemicals used – regulatory restrictions
- Braze process – Flux, vacuum or other
- Chromium

Cost
- Skilled labor - 400k welder shortage
- First time Yield vs rework
- Braze alloy – Gold or other precious metals potentially

Tooling
- Dedicated equipment for different materials
- Batching for qualified process
- Upkeep/ Storage

Quality
- FOD (Foreign Object Damage)
- Technician-to-technician variation

Why Additive Manufacturing

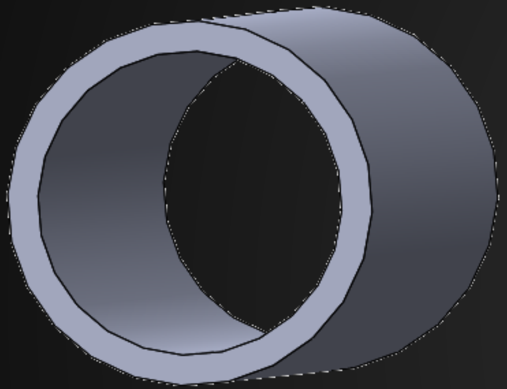
Flexibility	• No tooling, fixtures or pre-cleaning • Multiple iterations printed simultaneously
Speed	• Finished heat exchanger in weeks
Performance	• Integration with surrounding systems • Shaped holes and tubes
Quality	• Automated process drives consistency across supply chain
Vertical Integration	• Decreased vendor reliance

Performance drivers for heat exchangers

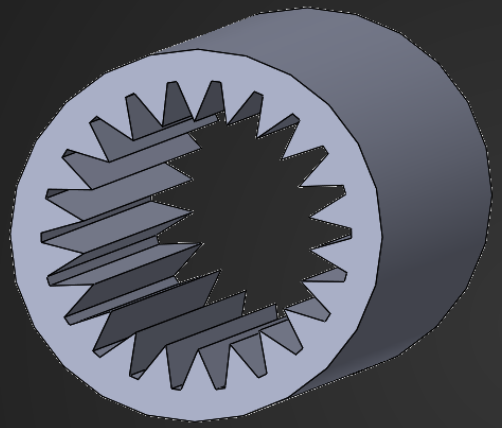
Performance Targets	How design & mfg help meet targets
Heat Transfer Rate	Surface area optimization
Pressure Drop	Surface Roughness
Weight	Wall thickness
Footprint	Material choices
Cost	Design optimization

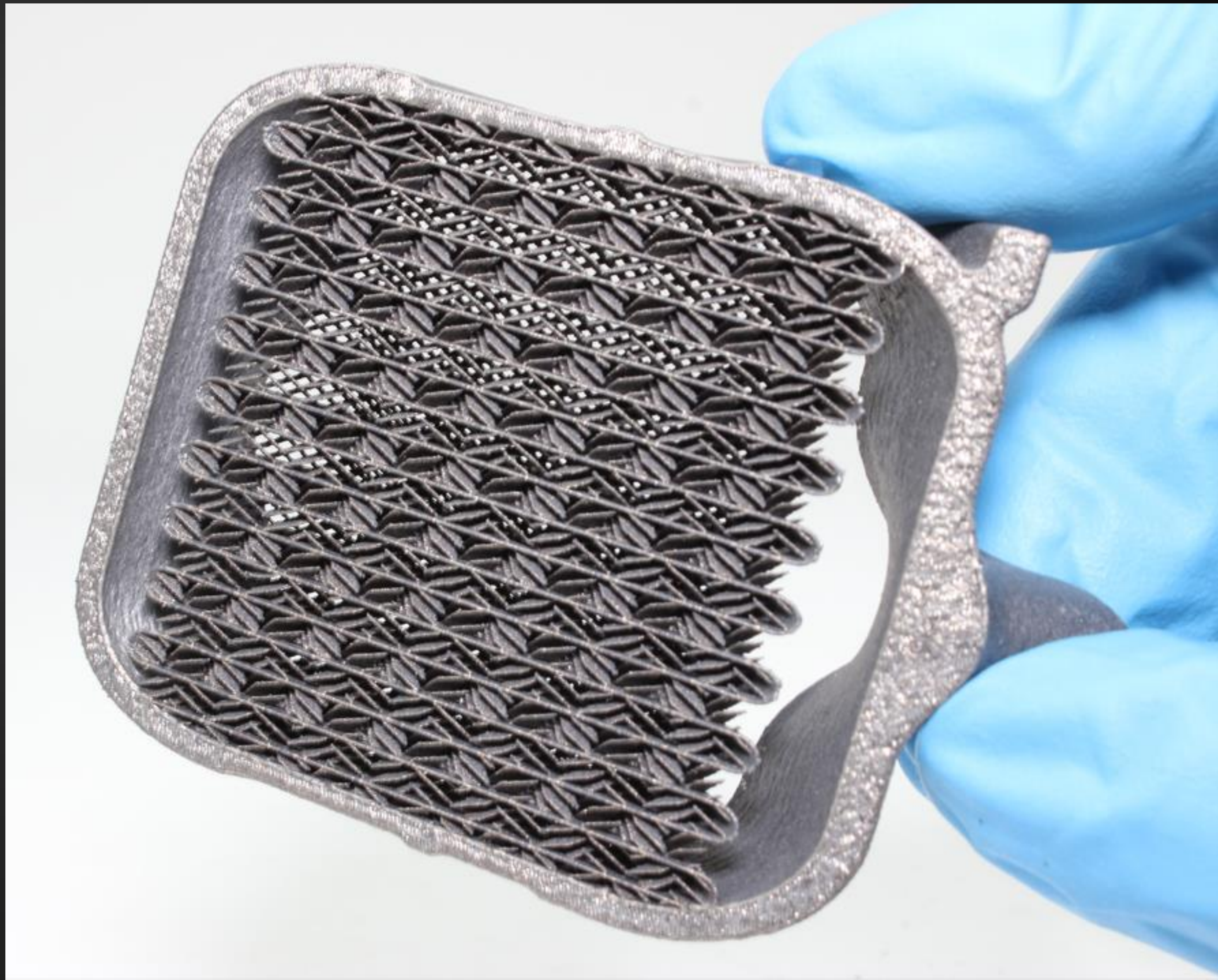
Design freedom for heat exchangers

Simple Tube



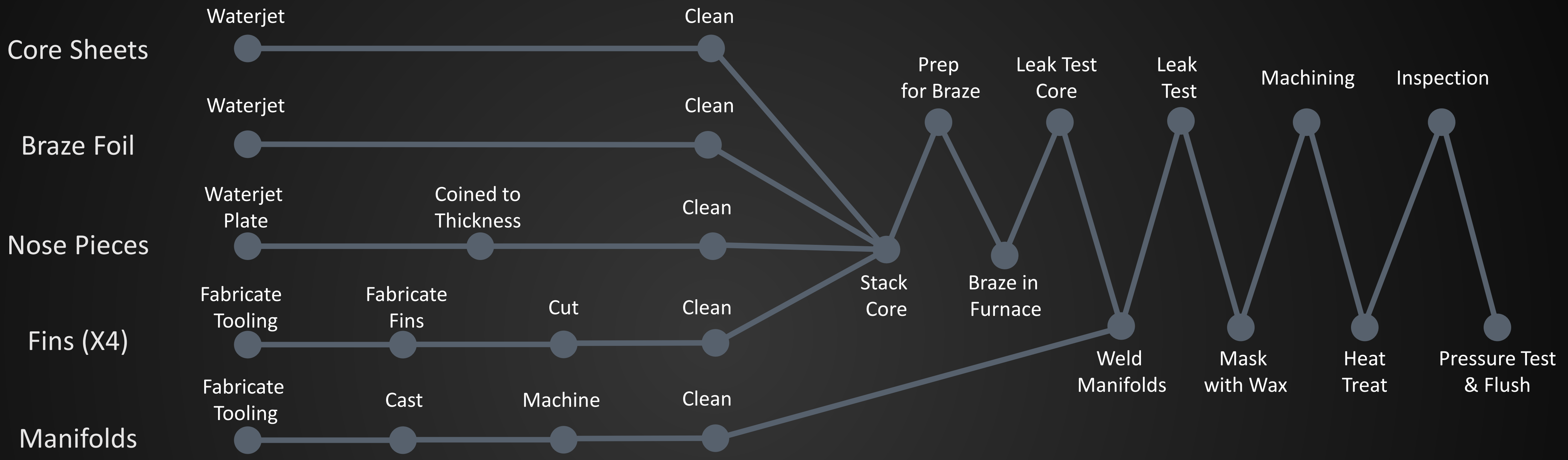
60% more surface area

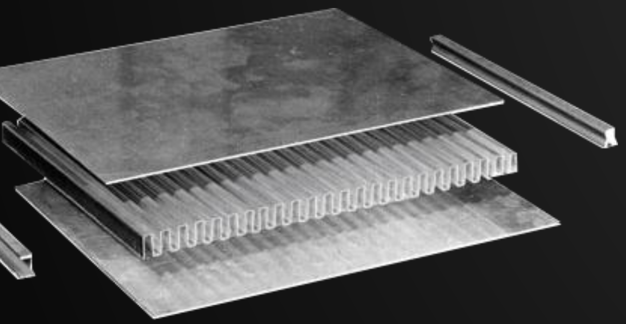


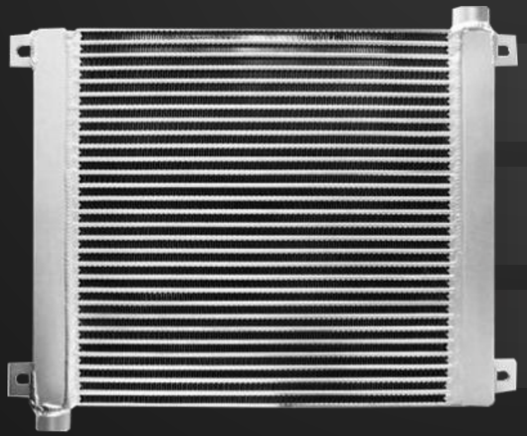


- Flexibility to easily increase mm^2/mm^3
- Improved efficiency
- Light weighting
- Traditional & new materials
- Iteration speed

Conventional Plate-Fin Heat Exchanger





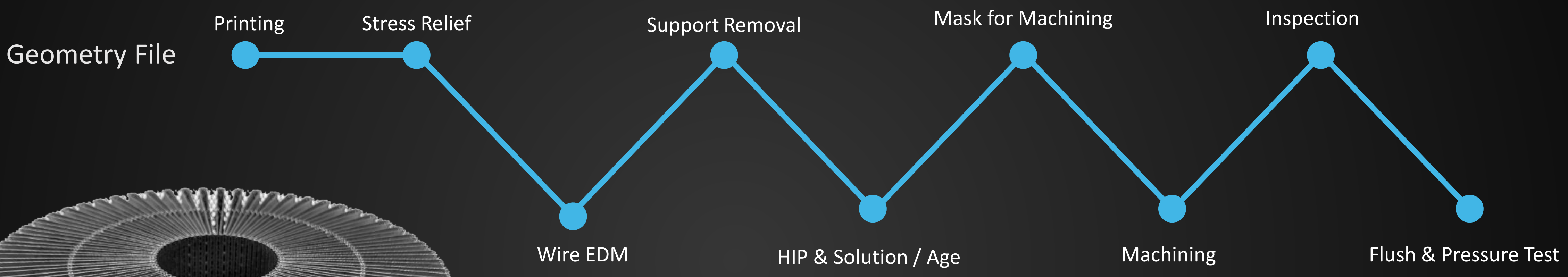


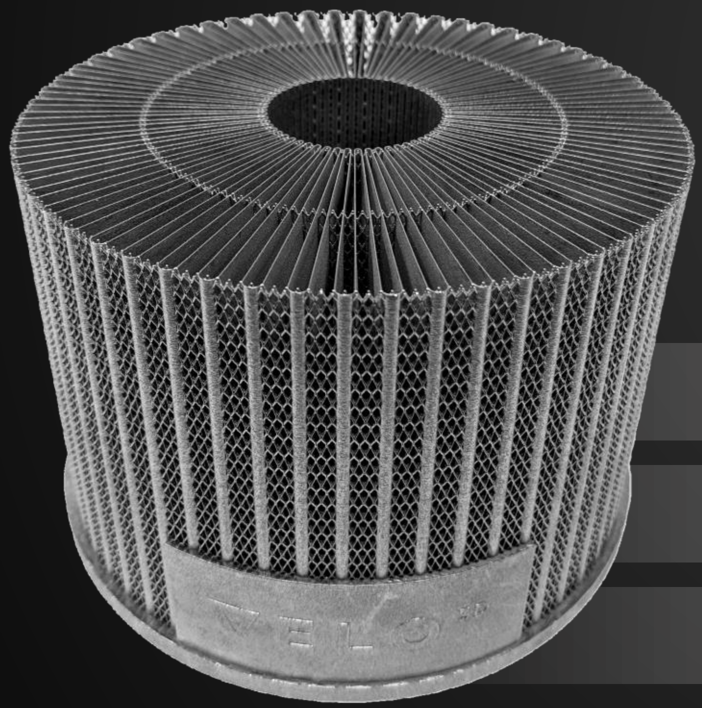
12 - 18 months per design iteration

Fabrication methods limit design

Highly manual process (subject to variation)

Metal AM Heat Exchanger



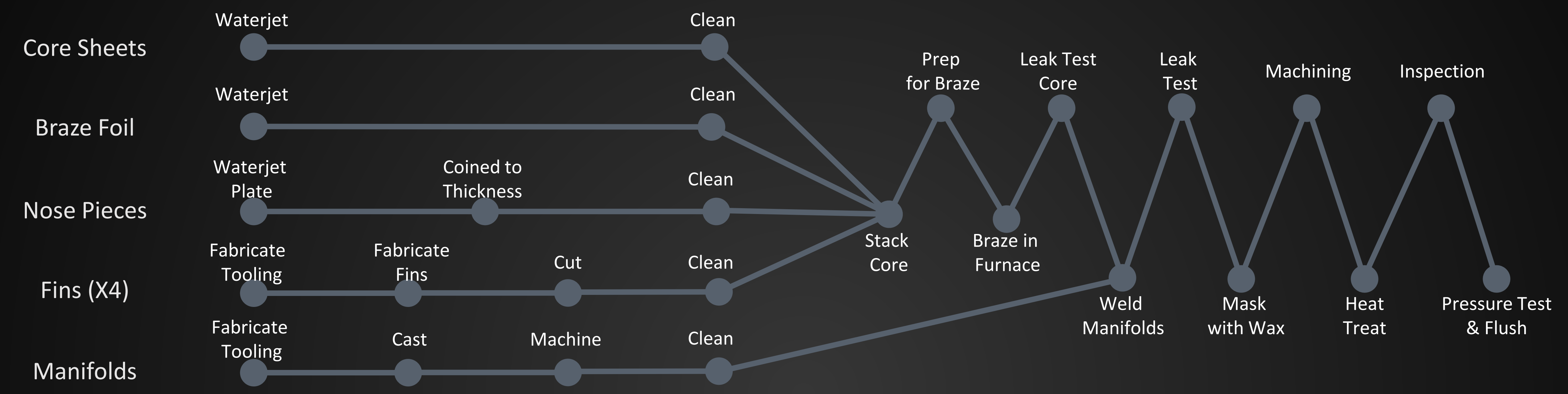


4-6 weeks per design iteration

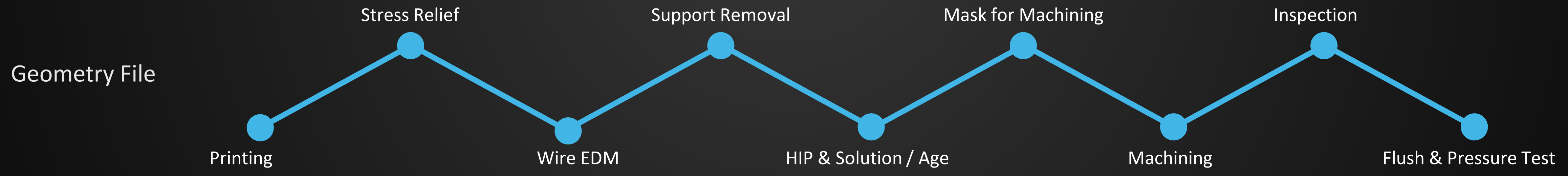
Print multiple iterations simultaneously

Automated/ repeatable process

Conventional Plate-Fin Heat Exchanger

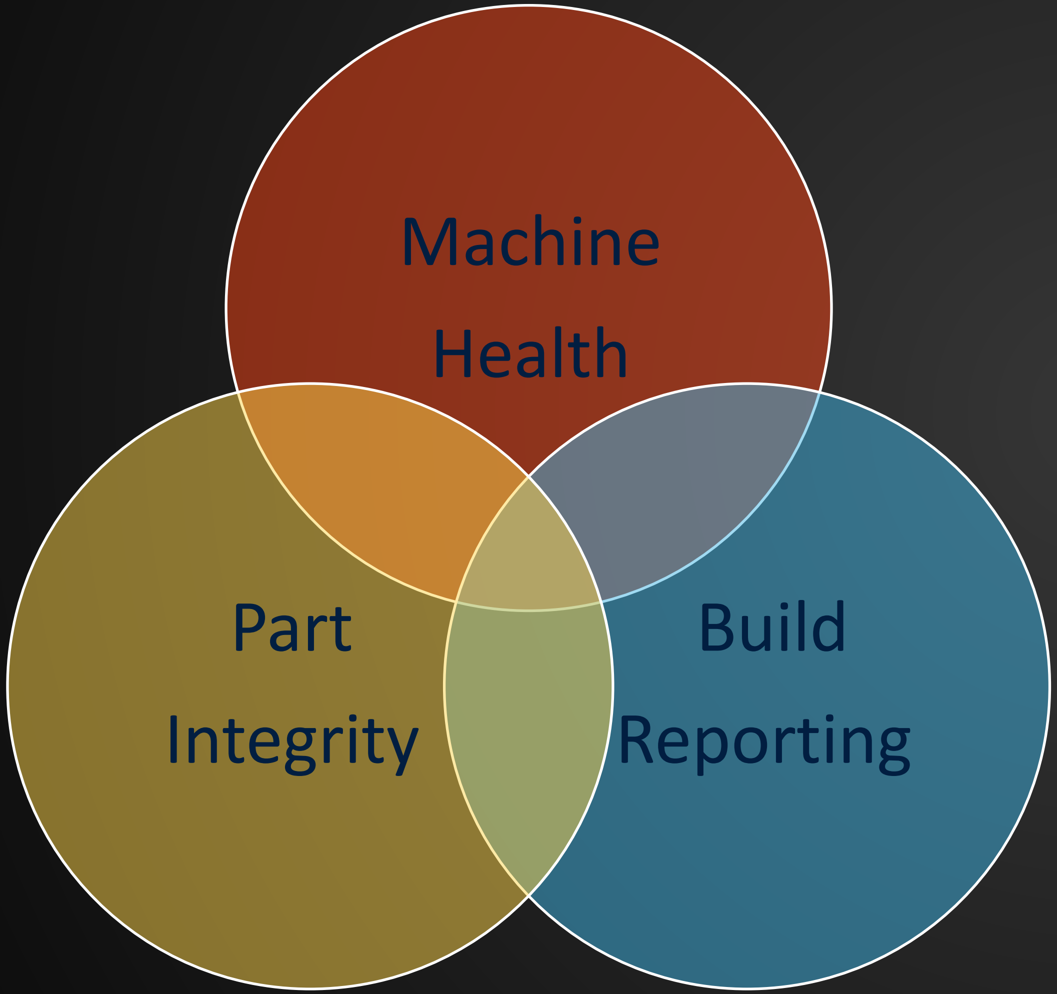


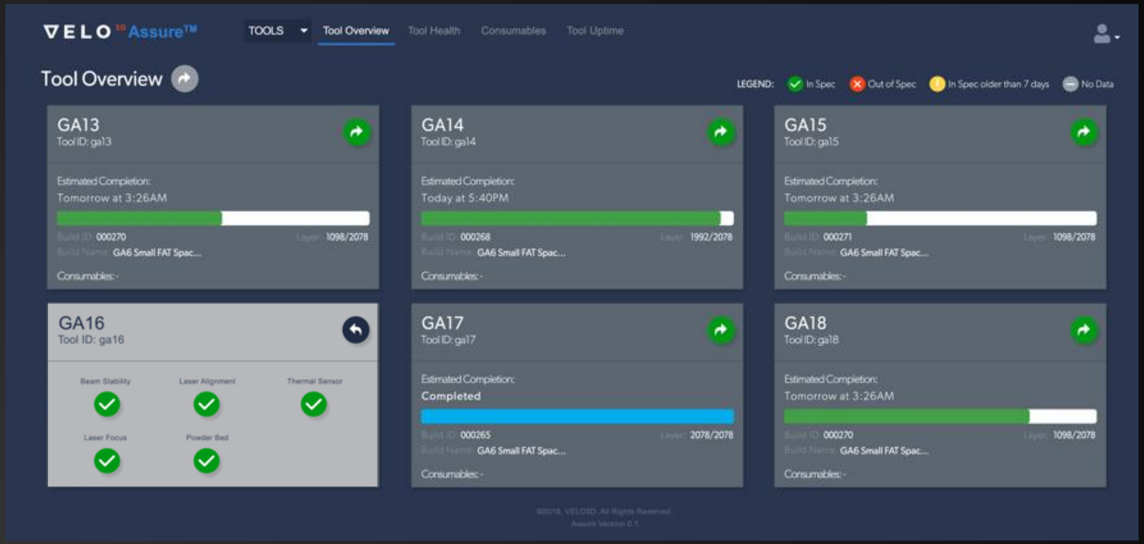
Metal AM Heat Exchanger

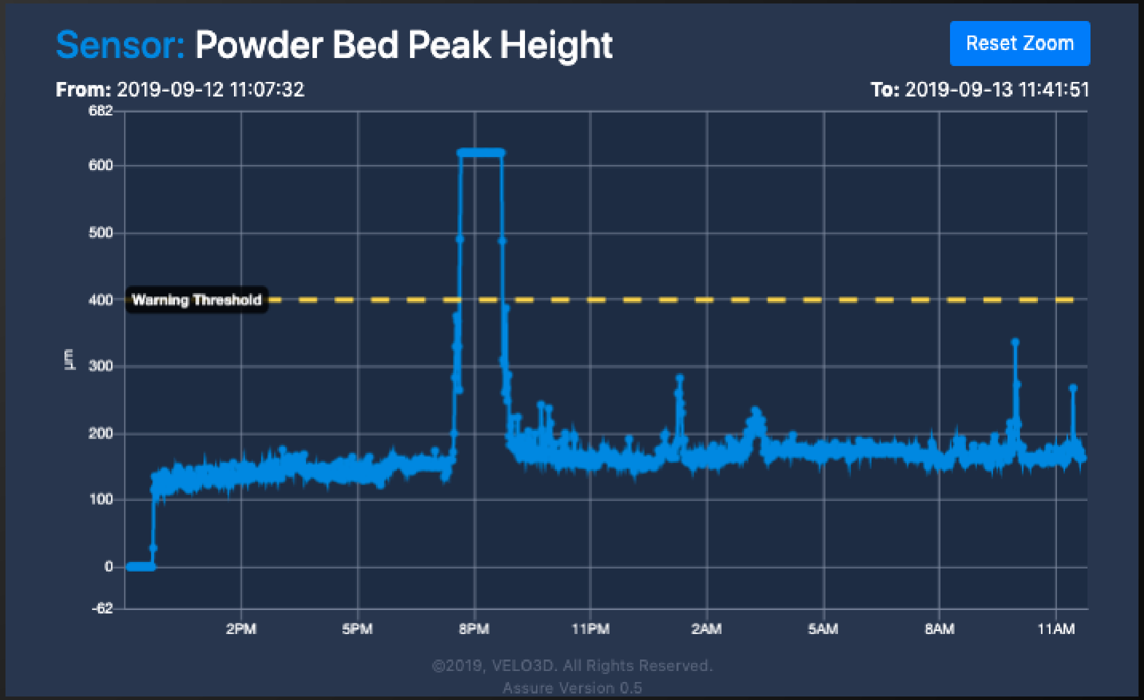


100+ parts ➔ 1 part | Months ➔ weeks per iteration | 10x+ design iterations

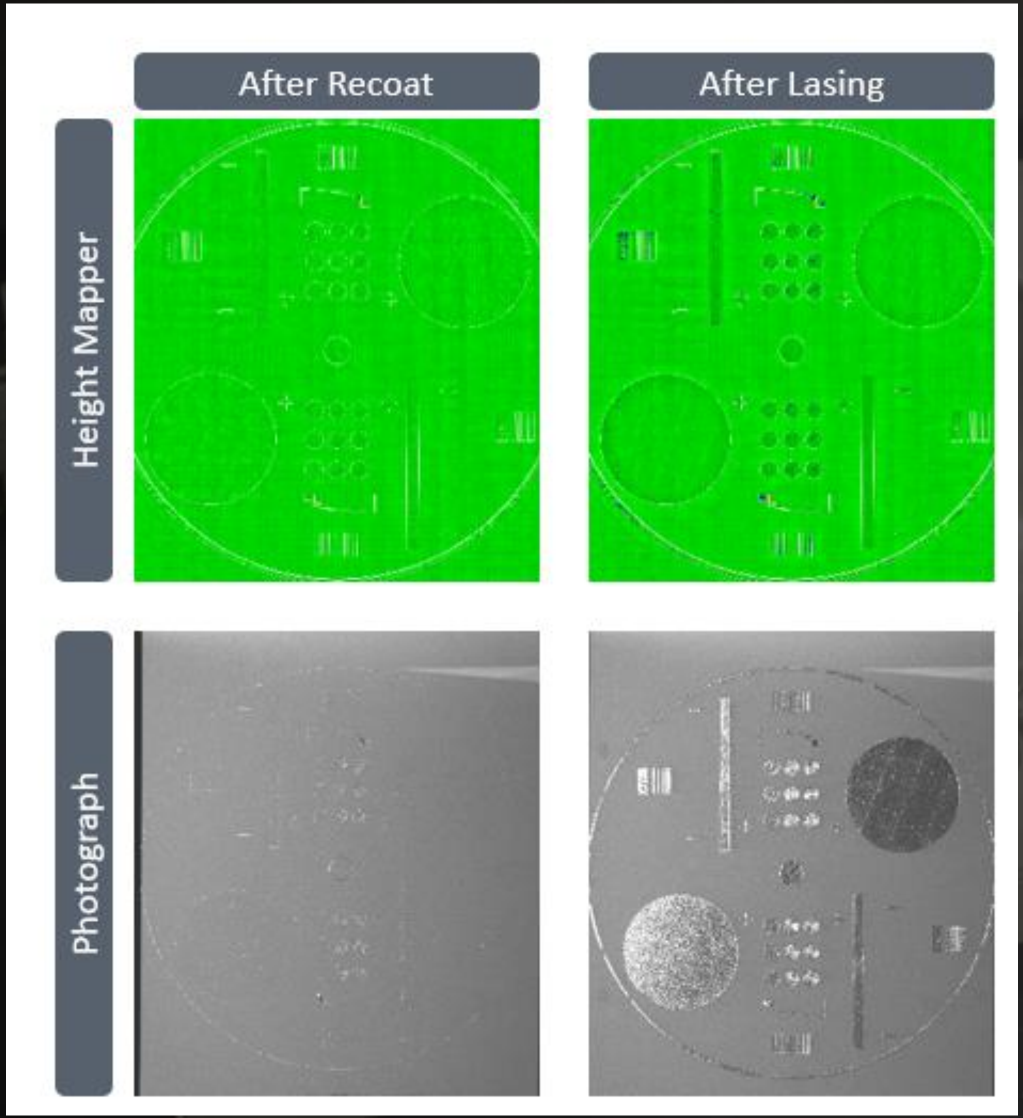
Quality Assurance for Predictable Outcomes







Next Generation Additive Quality & Scalability



- Full heat exchanger printed (vs core only)
- Weekly machine calibration
- Continuous Process monitoring during the build via multi sensor analytics
- Enterprise-wide buildability
- Reduced inspection based on process capability (varies by system)

Getting started with metal AM

Finding the right first part for production

✓Size: Smaller than 315mm ⌀ X 400mm tall

✓Material: IN718, IN625, F357, Ti-64, Hast-X

✓Part value: Improved performance required
- Reduced weight
- Combined assemblies, consolidated processes

✓Assembly value: Supply chain flexibility required
- Lead time reduction
- High barrier to entry production

Further Questions

Will Hasting
Director, Aviation & Power Turbine Solutions
Will.Hasting@velo3d.com

VELO3D
www.velo3d.com
511 Division St. Campbell, CA 95008

Backup Slides

Additive (LPBF) Heat Exchanger Technology Progression

First Generation Additive

- >500 micron (.020”) leak tight features
- 8:1 Aspect ratio
- >45^{o} overhangs
- Directionality with respect to recoater
- Single Laser
- Little-to-no in-process monitoring available
- Machine to machine variability

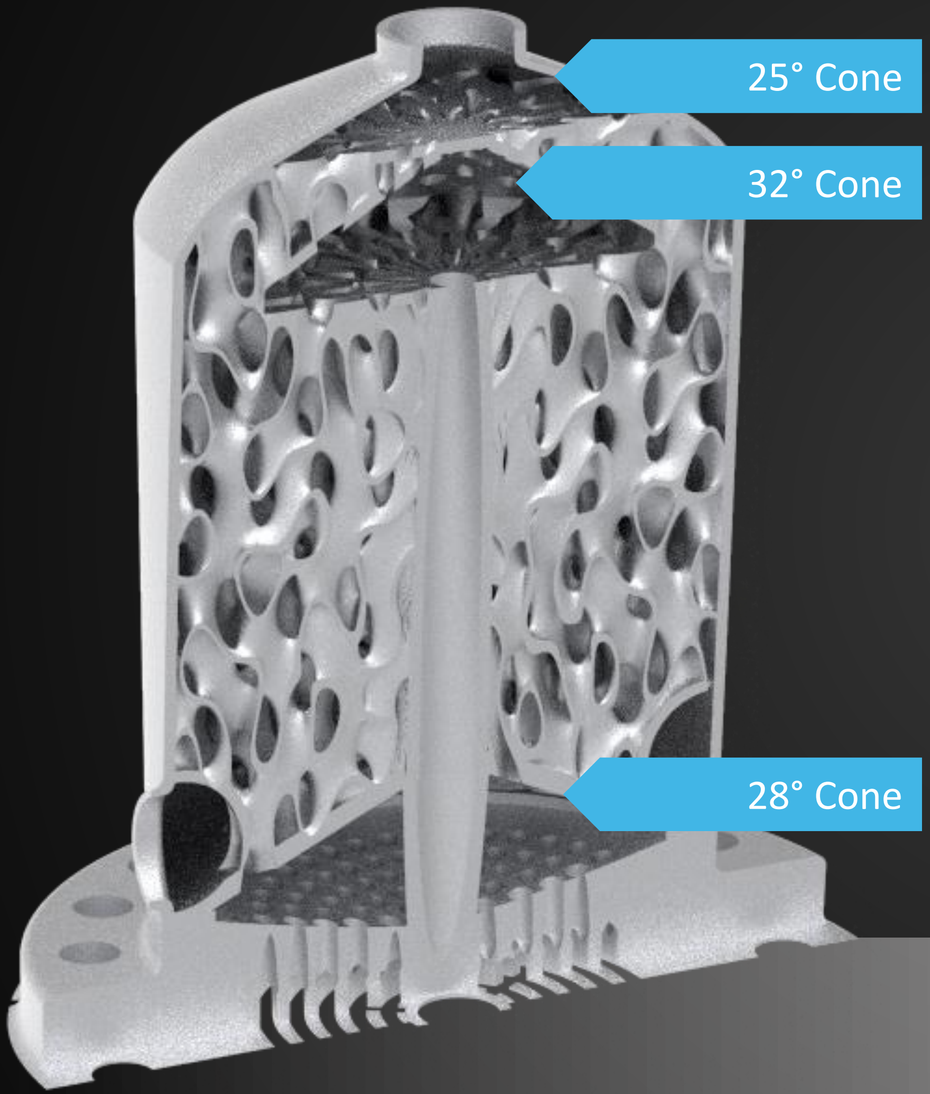
Next Generation Additive

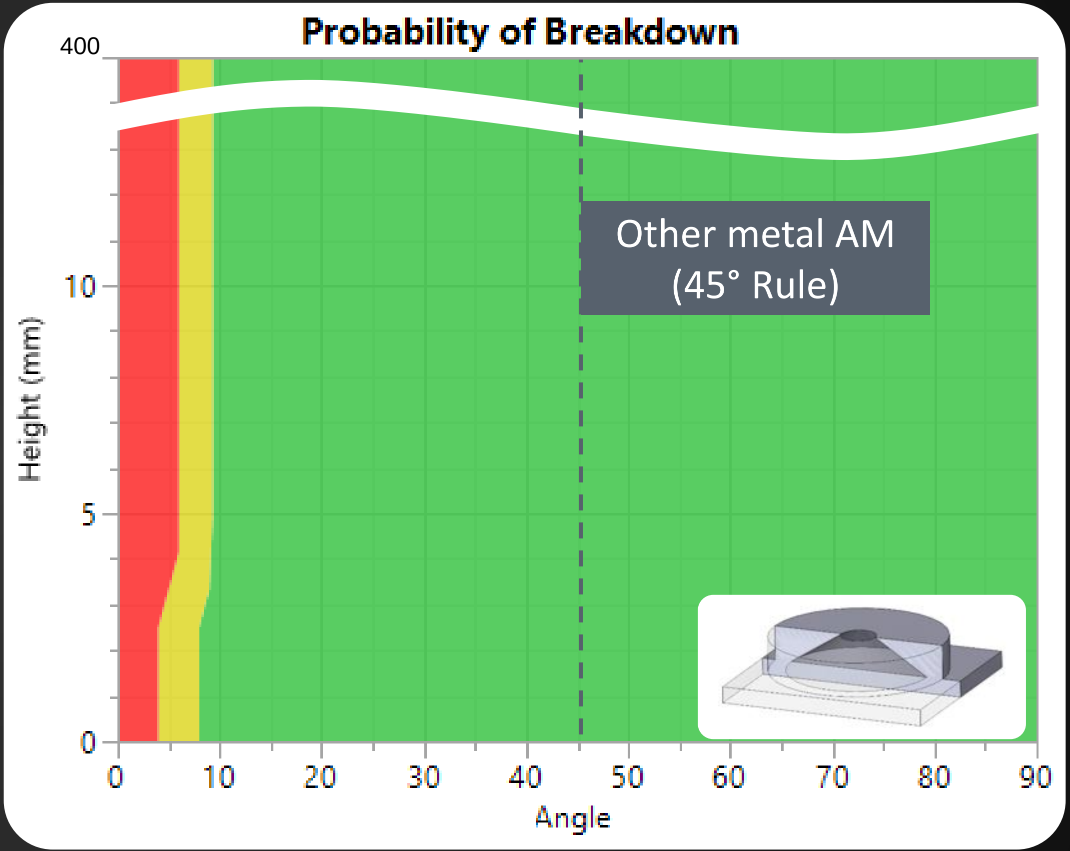
- >300 micron (.012”) leak tight features
- Infinite (>500:1) Aspect ratio
- 0^{o} overhangs
- Non contact recoater
- Multiple lasers
- Continuous monitoring of printing process
- Quality parts regardless of location in chamber

Enabling tighter packaging

Probability of Breakdown

- High
- Moderate
- Low



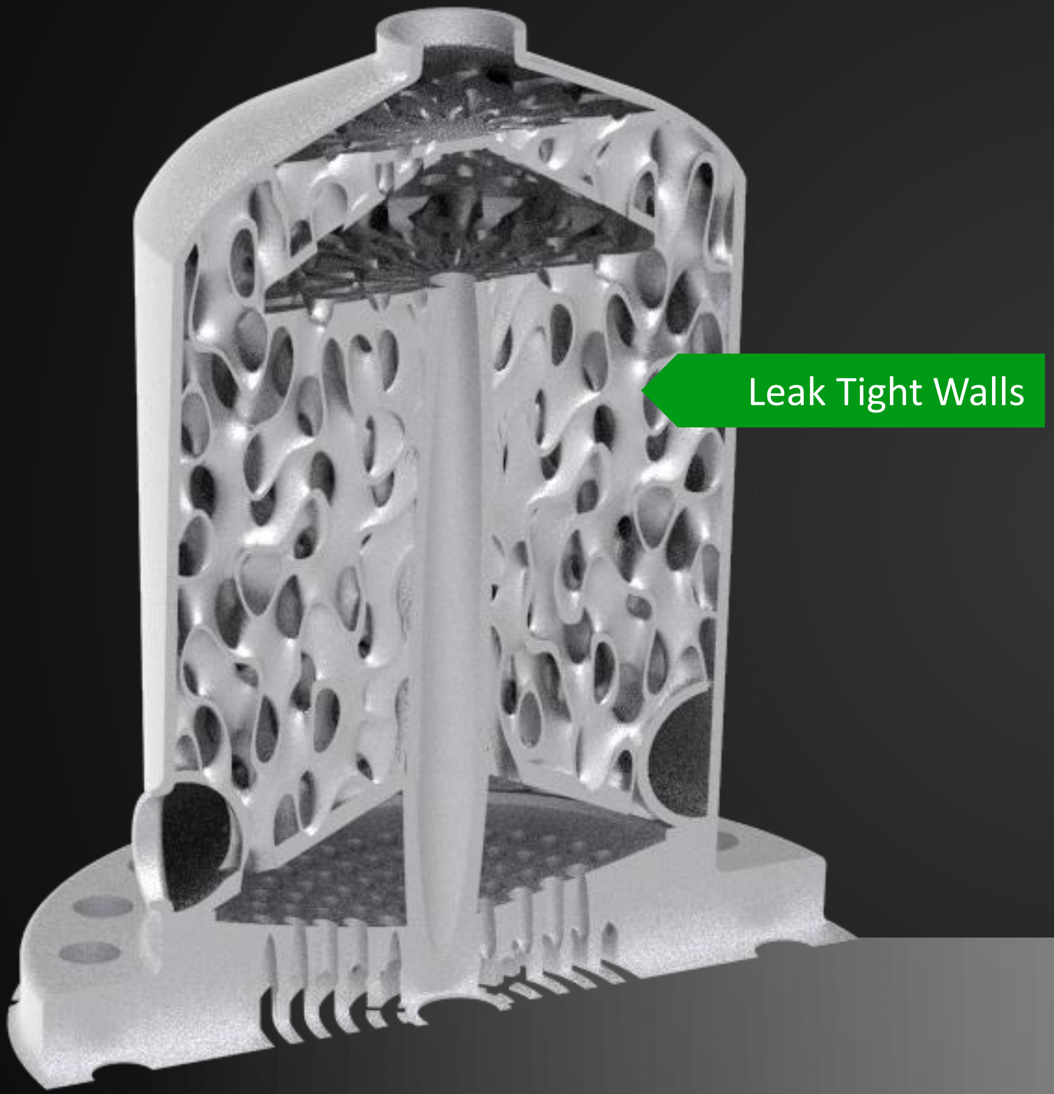


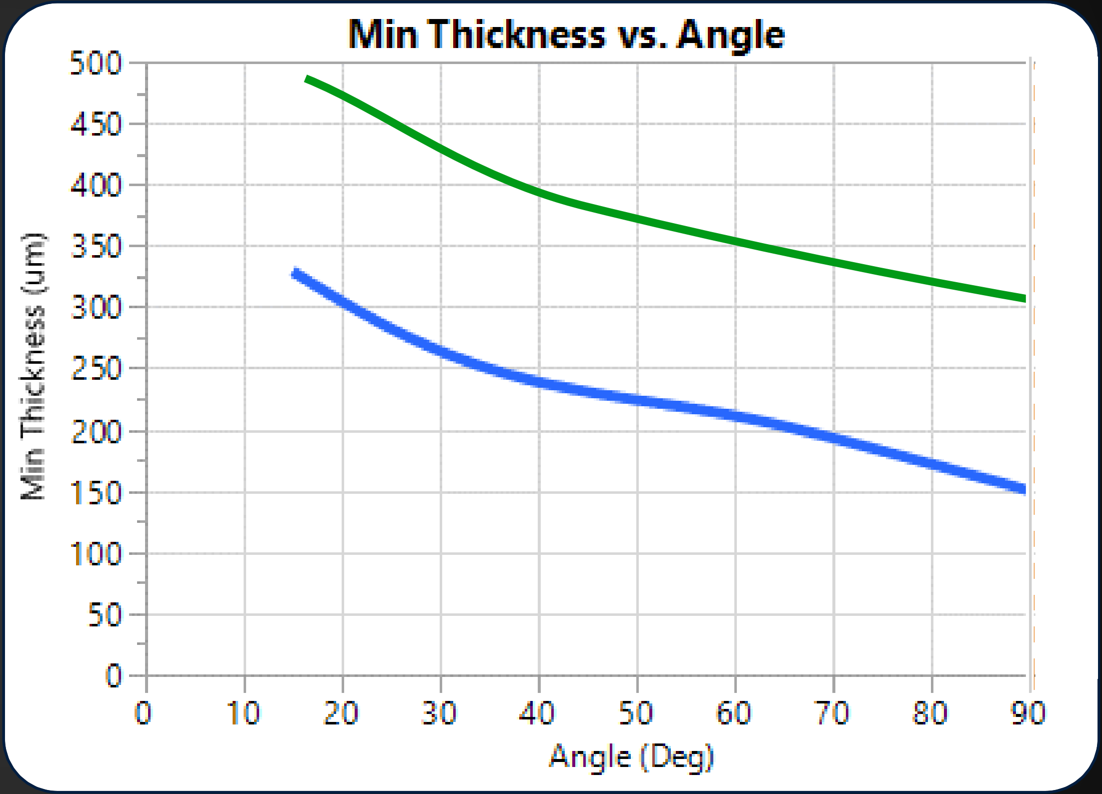
VELO3D's capabilities allows a more efficient use of the volume

Enabling higher thermal performance

Leak Tight Walls

Non-Leak Tight Walls

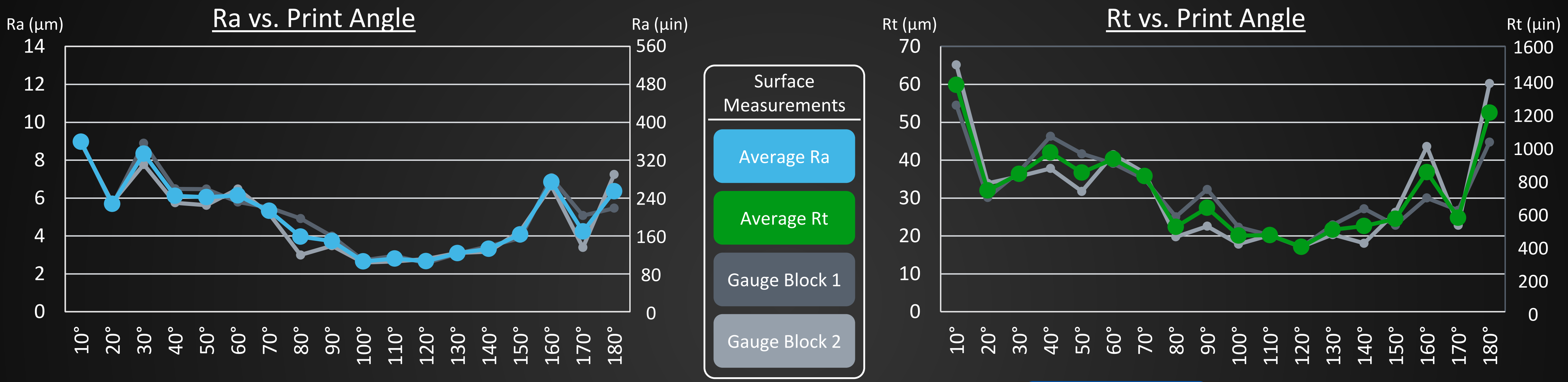


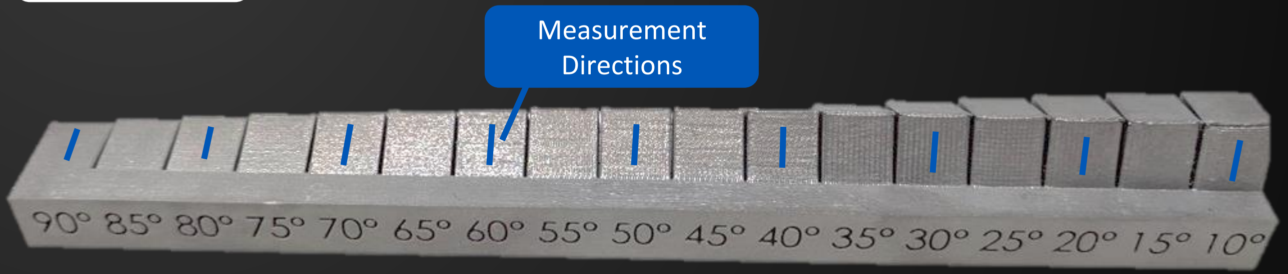


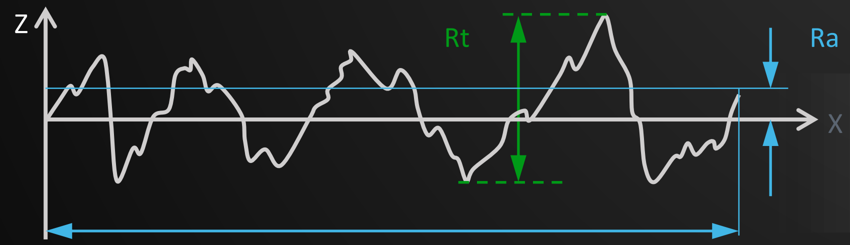
VELO^{3D}'s capabilities enables thinner plates and fins

Enabling lower pressure drop

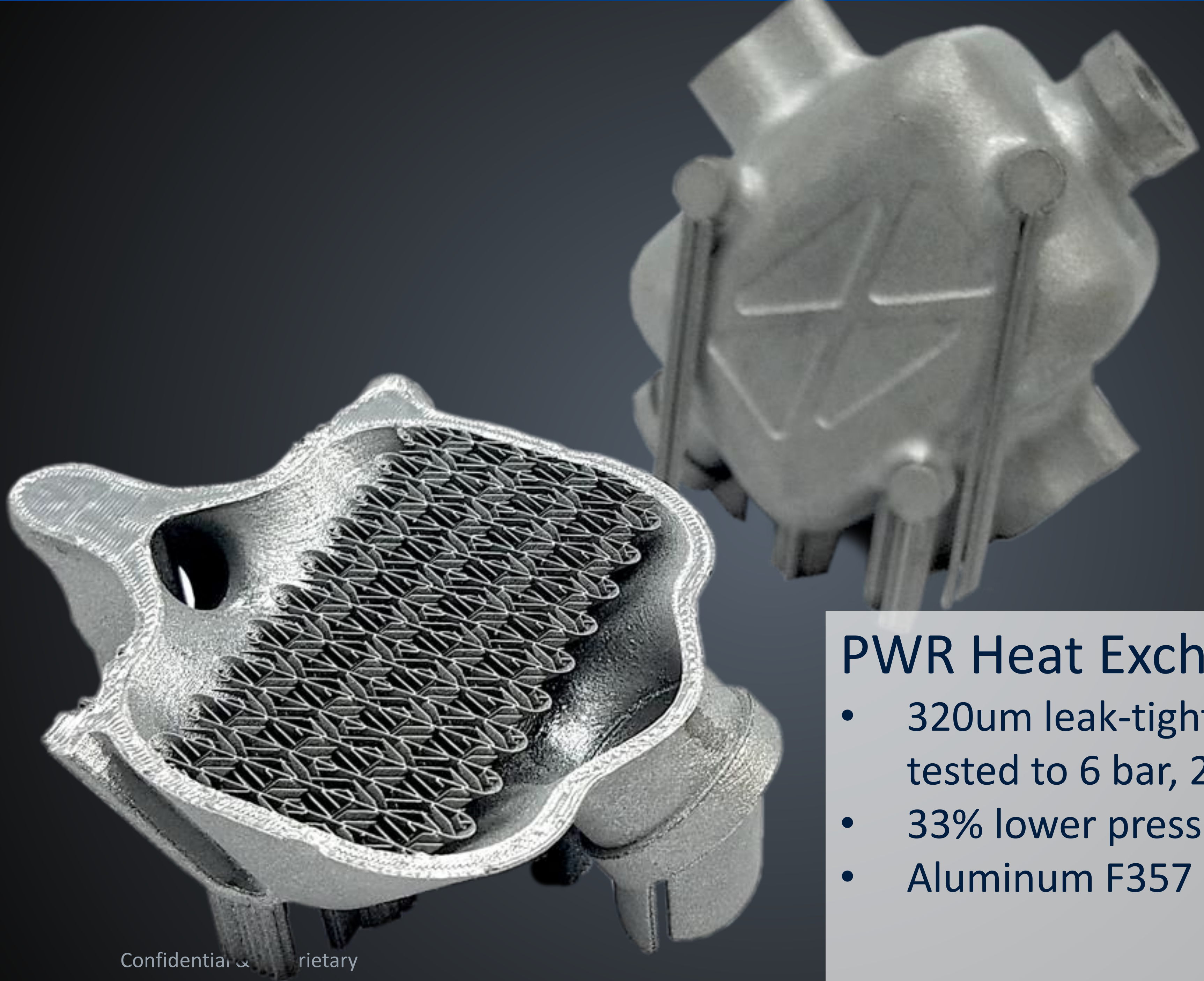
Taken with a Profilometer at MicroTek
- 5 um Stylus Tip Radius/ 90 Tip Angle
- Gaussian Filter
- Sample Length: .050 inches







VELO3D's capabilities enables smoother surfaces



PWR Heat Exchanger

- 320um leak-tight walls pressure tested to 6 bar, 220um turbulators
- 33% lower pressure drop
- Aluminum F357

Agility and Responsiveness – Value Drivers of Metal AM

When changing from castings to metal AM, there is an introduction of new variables and risk – how can that risk be worth it?

- Each weld joint costs an average of $100, but what does it cost you if that joint fails?
- How much would you be fined by your customer for a field shutdown?
- How much does a late shipment/day, quality escape, or in-field replacement cost you?