Rapid Prototyping using Digital Additive Manufacturing at Solar Turbines

Gas turbines in a carbon-neutral society
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Powering the Future

Solar Turbines
A Caterpillar Company

Solar Turbines

World's Largest Manufacturer of Industrial Gas Turbines
(1 to 23 MW)

Subsidiary of Caterpillar Inc.
Since 1981

16,000+
Gas Turbines Sold

6,500+
Gas Compressors Sold

Installations in
100+
Countries

Direct
End-to-End
Sales and Service

65
Sales and Service Locations

Global Workforce
8,000+
Employees

Solar Turbines Gas Turbine Experience by Package	Units Sold	Estimated Hours (000's)
Compressor Sets	4,930	1,050,000
Mechanical Drives	2,720	630,000
Generator Sets	8,350	1,320,000
Total	**16,000**	**3,000,000**

1 MW → **to** → **23 MW**

Markets: Oil & Gas and Power Generation

Fuels

Gaseous Fuels:
- Natural Gas (Raw/Pipeline)
- Associated Gas
- Landfill & Digester Gas

Hydrogen Containing Fuels:
- Refinery Gas
- Industrial & Process Gases
- Coke Oven Gas
- Waste/Biomass Syngas
- Hydrogen/H2 Blends

Liquid Fuels:
- Diesel
- Jet fuel
- Kerosene
- LPG
- Naphtha
- Condensate (NGL)
- Biodiesel
- Renewable Diesel

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- **Overview:**

In a world of rapidly evolving technology, there are growing demands for faster results as well as a reduction of cost. The time for prototype trials that often require several iterations between engineering, manufacturing, and assembly are being reduced.
The lean solution of Additive Manufacturing (AM) Rapid Prototyping, allows to try many design iterations in a shorter time, providing learning opportunities which in turn allow you to find the best solution quickly.

- **Presentation Outline:**
  - Solar Turbines Prototyping Experience Overview
  - Rapid prototyping Examples

Additive Manufacturing Is More Than Just Metal

Turbine Lab Seal
Overhaul Repair

Substitute Parts
Introduce Mars
20/20 Swirler

Serial Production

Turbine and Rotating Component
Rapid prototyping

T60/T70 SoLoNOx™ (DLE)
Gas Only Injector
DfAM Serial Parts

2012 2014 2015 2016 2017 2018 2019 2020

DIRECTED ENERGY DEPOSITION
Laser Metal Deposition (LDM)

POWDER BED FUSION
Selective Laser Sintering (SLS)
1St ProX300

ProX300

Establishment of
Production Facility

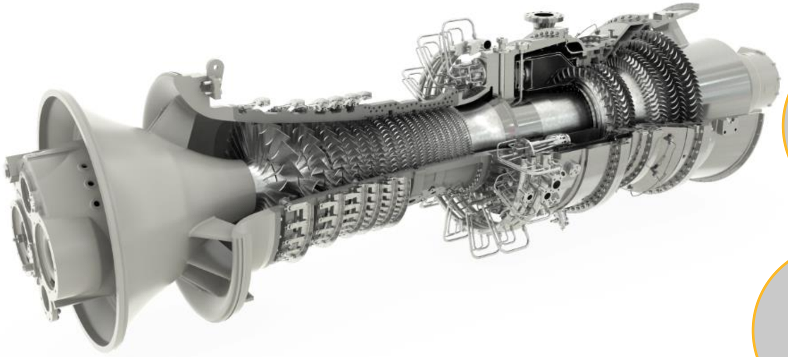
Establishment of
Dedicated Organization

Development and Production Facility Expansion

High potential to improve customer value using Additive Manufacturing

Combustion

- Higher TRIT
- Reduced Emission
- Optimized Injector Fuel Flexibility
- Reduced Development/ Product Cost
- Reduced Development Time



Turbine

- Improve efficiency
- Improved cooling and cooling air reduction
- Reduced Development/ Product Cost
- Reduced Development Time

Rapid manufacturing

CAT - Exhaust Elbow

Rapid prototyping

Mercury Turbine Blade

Substitute parts

Torch Tube

Tooling and gages

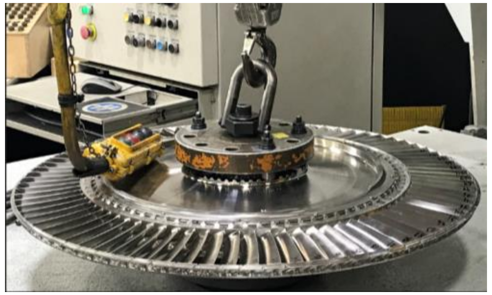
Gage

Design for AM

Fuel Injector

Rapid prototyping

- Rapid learning: Multiple versions in short timeframe
  - Over 2000 development parts were printed at Solar in 2020

Turbine Blade

Turbine Nozzle Segment

Injector Barrels

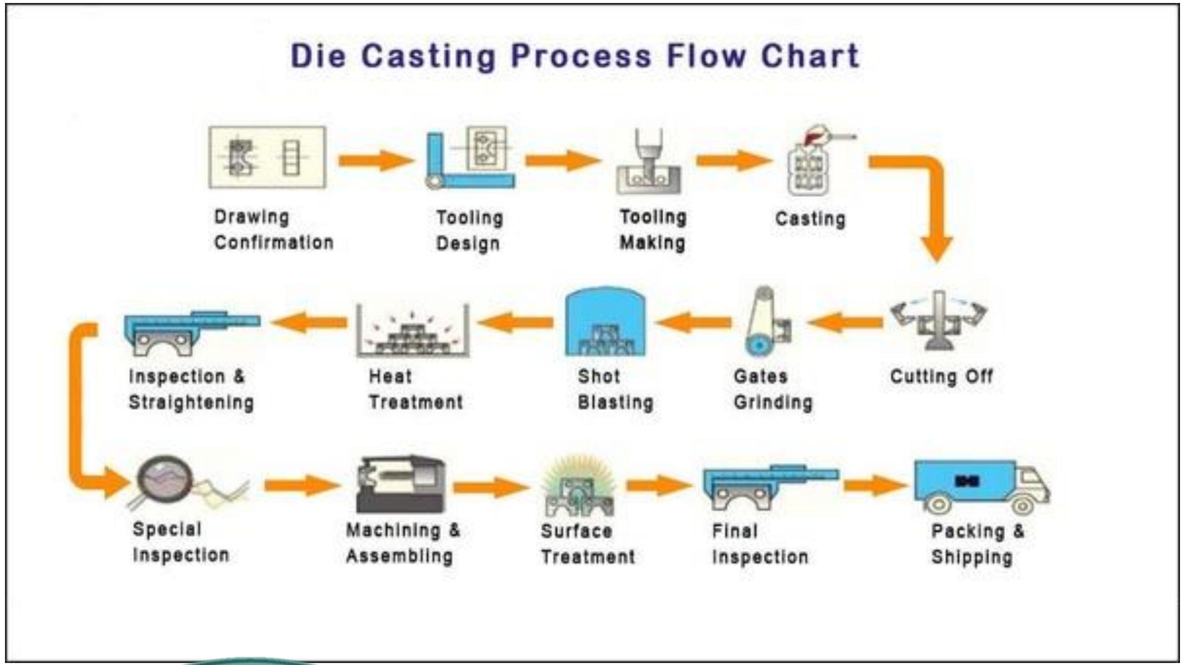
Injector Pilot Assembly

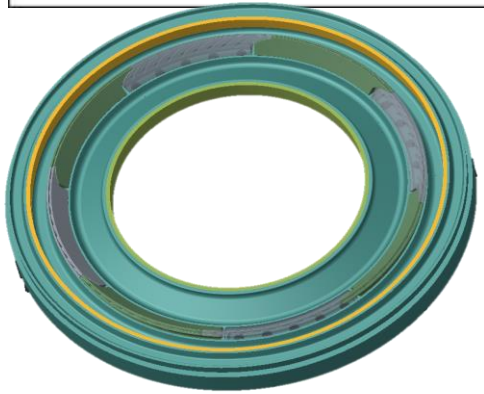
Tip Shoes

Example 1: Preswirlers

- Solar Turbines was faced with an opportunity to utilize rapid prototyping with the development of a new turbine component that would provide cooling flow
- Due to time constraints, Additive Manufacturing (AM) was the only viable solution
- The AM design was required to stay such that casting could be an option for production in the future if it ends up being more cost effective
- Adjustments were needed to adapt for AM with constant feedback from the design team
- AM design met mechanical and manufacturing constraints

Alternative Process to AM:





Component Assembly

Individual AM Segments

Feasibility Print

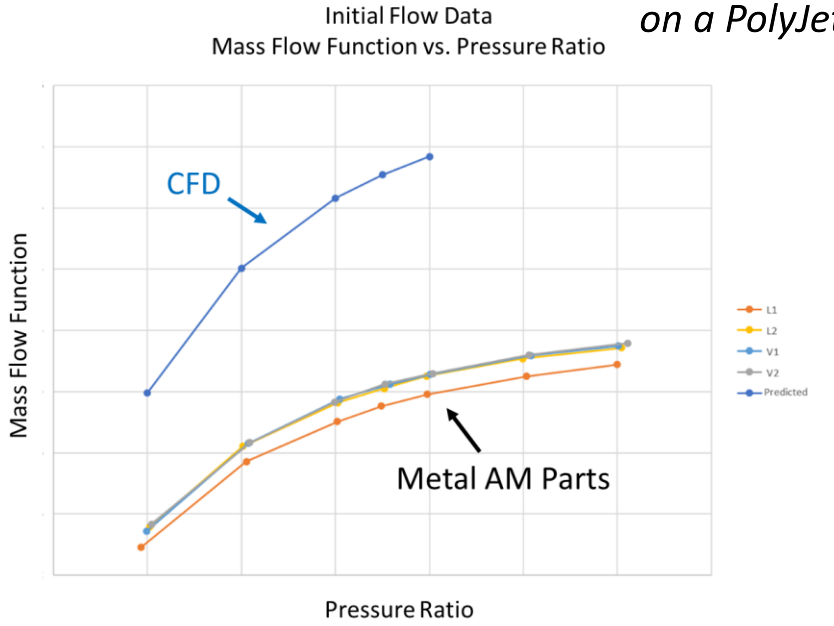
- Looking for the best printing orientation is key for a successful batch (experience based)

- Evaluation of components printed during feasibility print
  - Dimensional checks; Visual inspections

- Flow testing (to verify flow is within Computational Fluid Dynamics analysis limits)
  - lower flow values than predicted (CFD)
  - additional design changes were required to satisfy flow requirements
    - <u>Ideal for AM (rapidly prototyping)</u>

Feasibility Print of multiple orientations

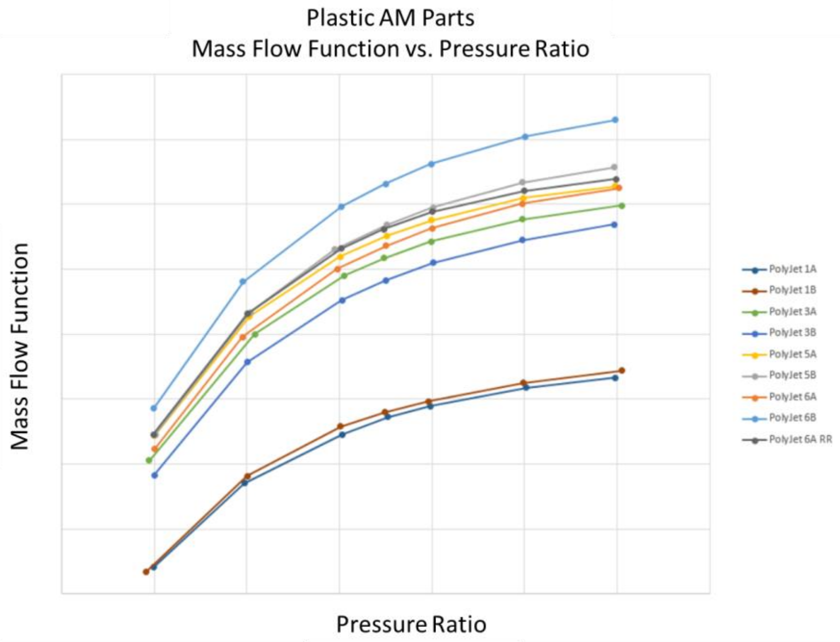
Flow Bench
** Gasket and clamp were printed on a PolyJet printer (plastic)*



Model Adjustments

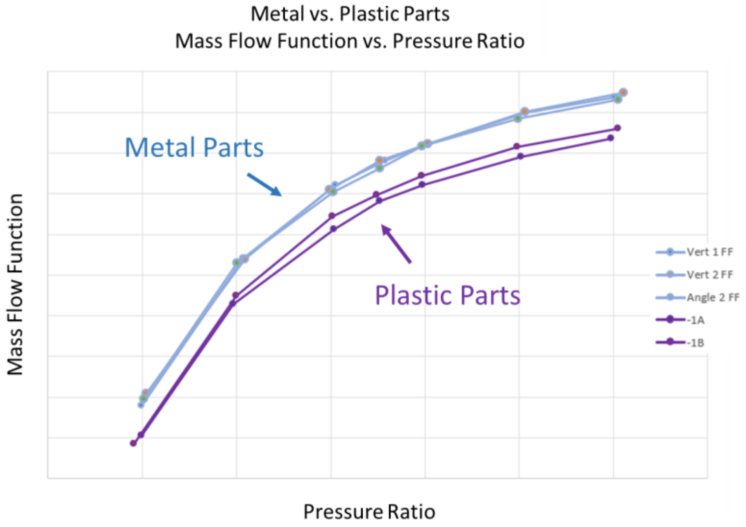
Prototype using Plastic

- Necessary to meet flow rate requirements
- Several model iterations to flow path dimensions
- Decided to print in plastic to reduce cost and time
- Followed by flow testing of plastic parts
- Down-selection of geometry for final engine set (metal)



Metal vs. Plastic Flow Testing

- Identical geometry was printed in metal and plastic
- Metal parts flowed 6% higher on average compared to plastic parts
- Likely attributed to surface finish differences or geometrical shrinkage
- Correlation established for future reference



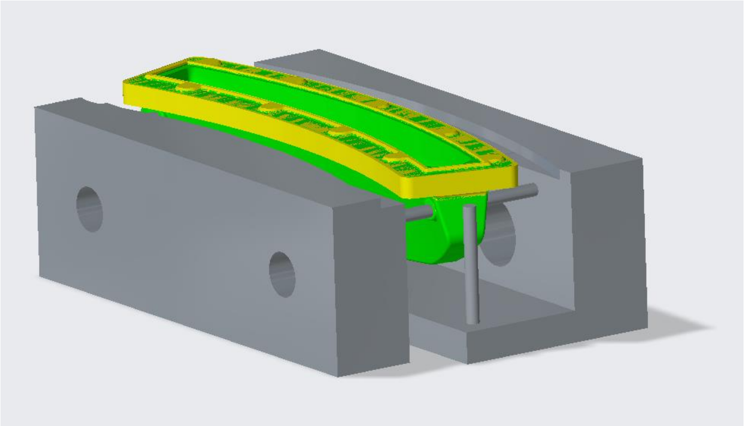
Printing of Engine Set

- Final geometry selected
- Two builds conducted of segments for full engine set

Printed of Engine Set

Post Processing of Engine Set Parts

- Fixturing development was required
- Metal parts were finish machined
  - Removal of AM support material
  - Sealing and mating surfaces required machining
  - Deburring of parts

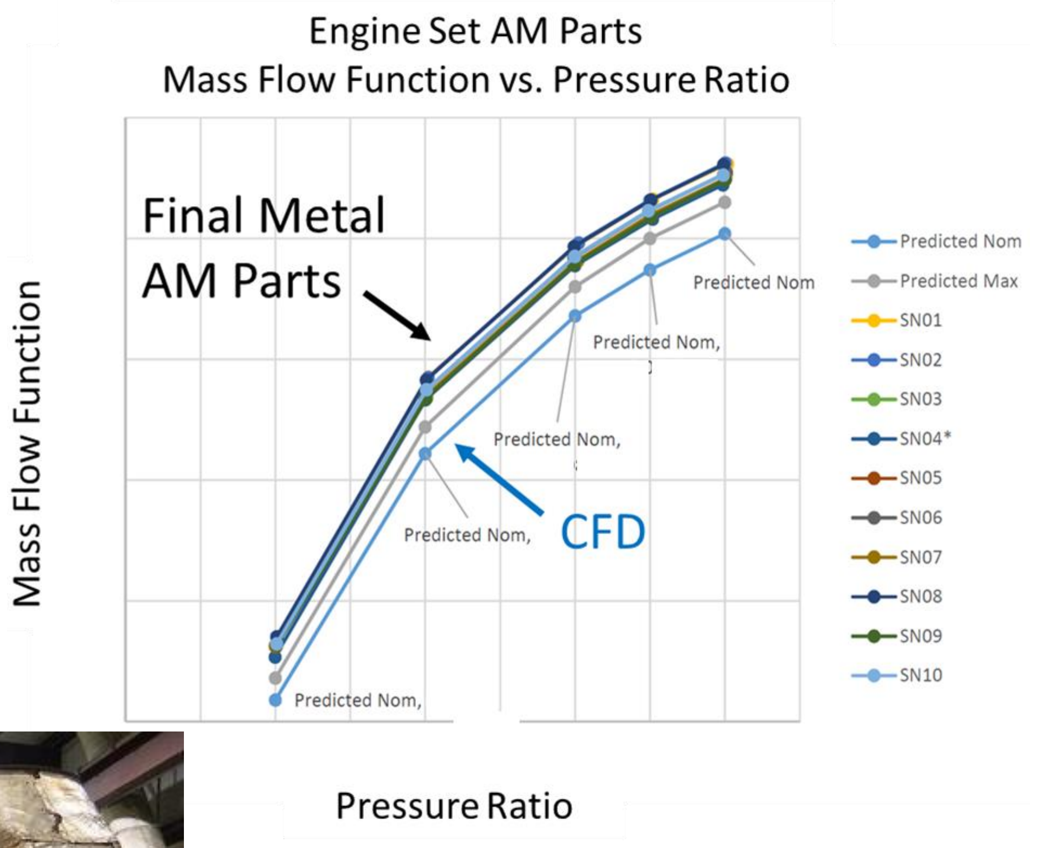


Fixturing for Machining

Machined AM Segment

Final Assembly Performance

- AM parts demonstrated consistent flow values across the engine set
- Comparisons made with Finesse CFD predictions
- Flow rates were slightly higher than predicted values but were within an acceptable range for the application
- Engine test Completed
- Cost analysis Completed

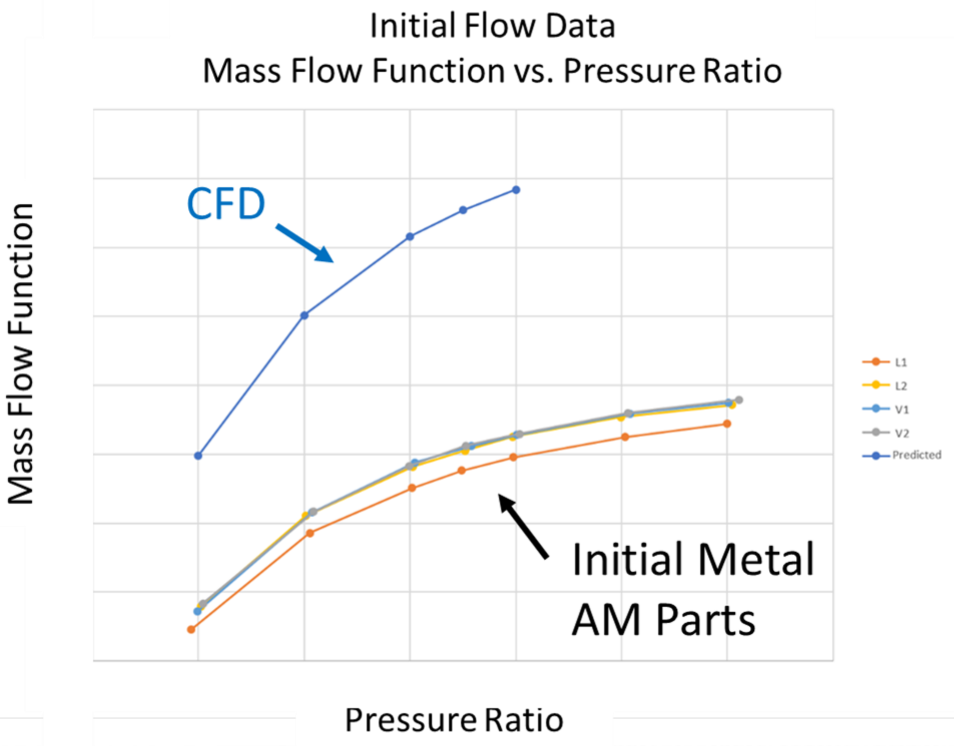


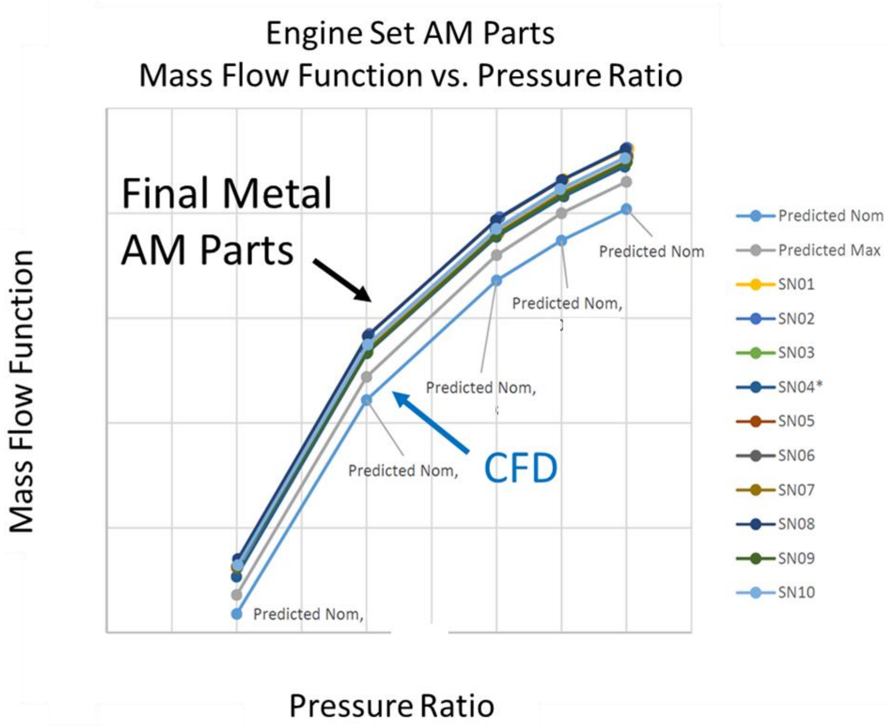
Next Step

- Production planning
- Replication for other products

Takeaways

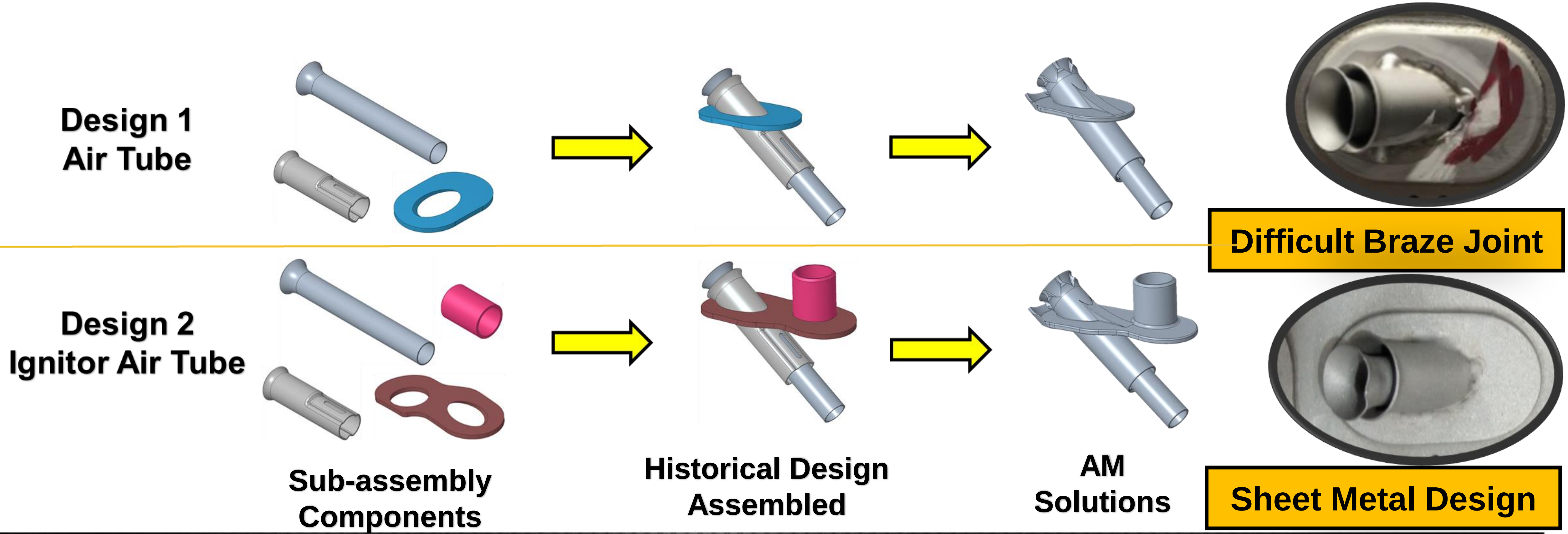
- AM ideal for rapid prototyping applications
  - Provides ability to *'fail quickly' (+ succeed quickly)*
- Plastic printing should be considered during prototyping iteration process
  - Cost and time considerations
  - Room temperature testing (Flow analysis)
- The tooling alone for attempting a cast option would have surpassed the AM development time including all iteration, manufacturing and engine test validation
- AM also viable solution for production





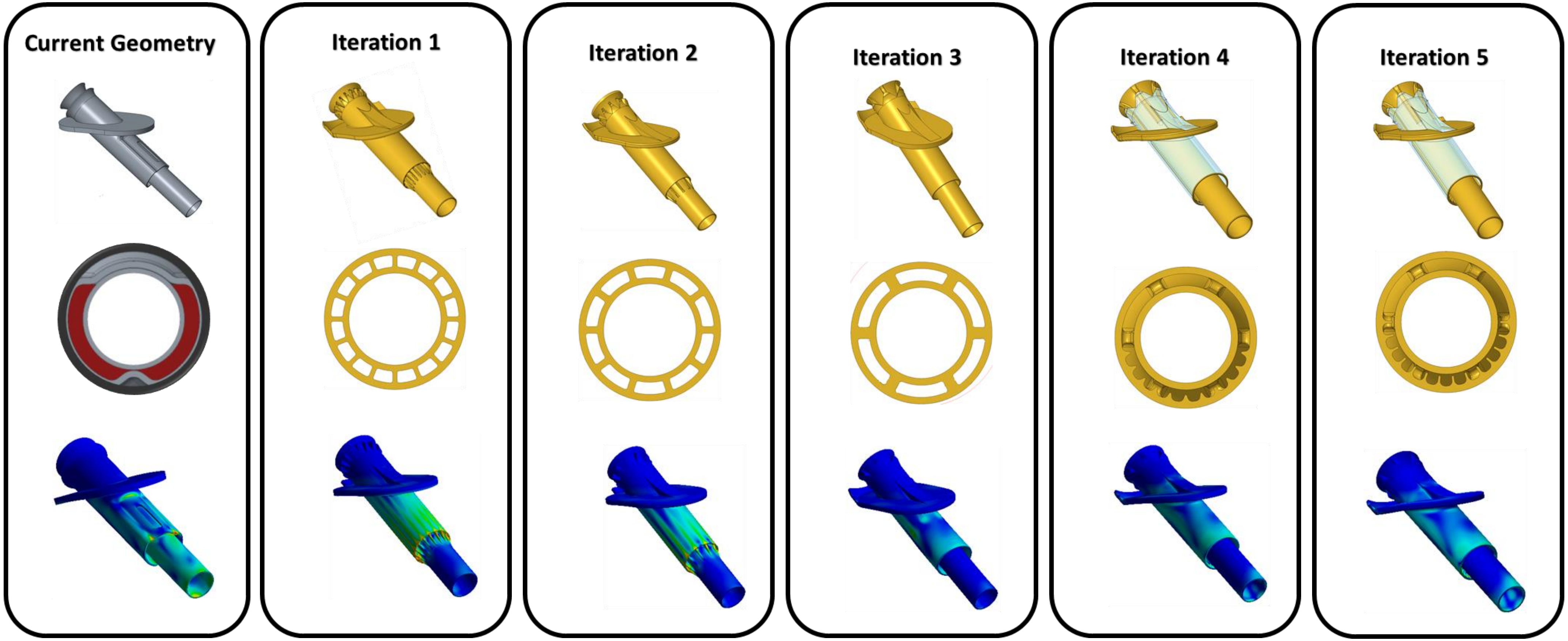
Example 2: Combustor Liner Air Tubes

- Merge and Additively Manufacture (AM) via Laser Powder Bed Fusion (L-PBF) process new designs for the Combustor Liner Auxiliary Air Tubes. New designs intended to reduce part to part cost, address manufacturability concerns, whilst maintaining overall system performance.



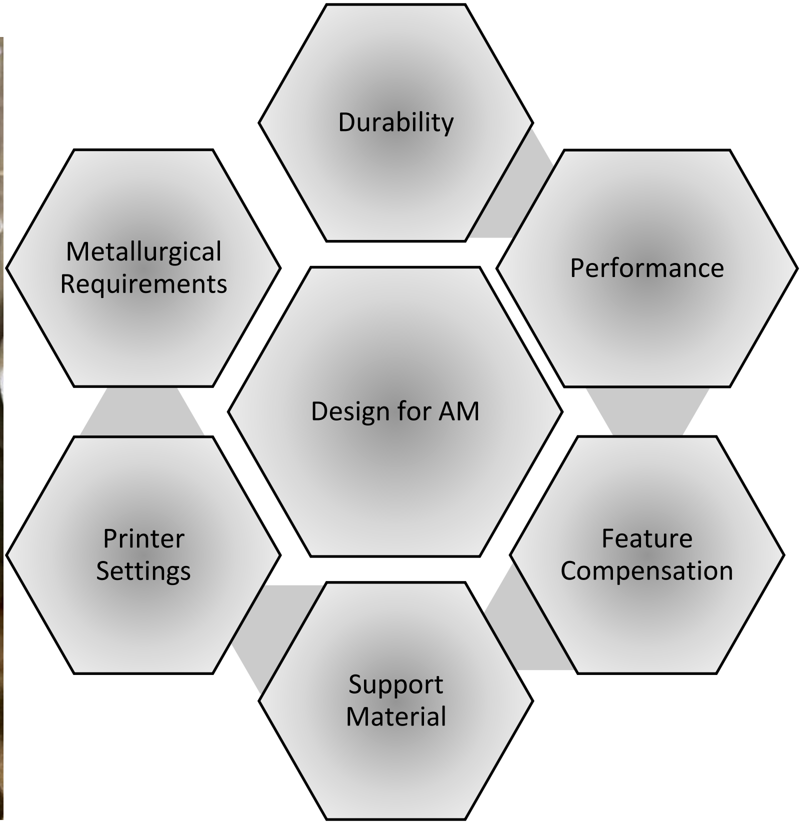
Design Requirements

The subject Air Tubes required a thorough analysis of operating temperatures and stresses for the overall geometry. The design underwent multiple iterations until all criteria was met.



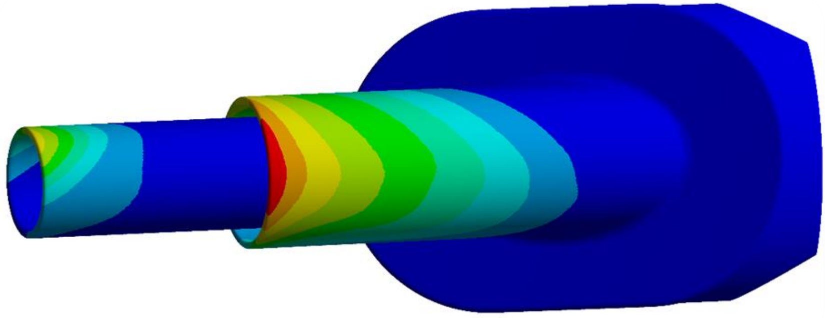
Design for Additive Manufacturing (DfAM)

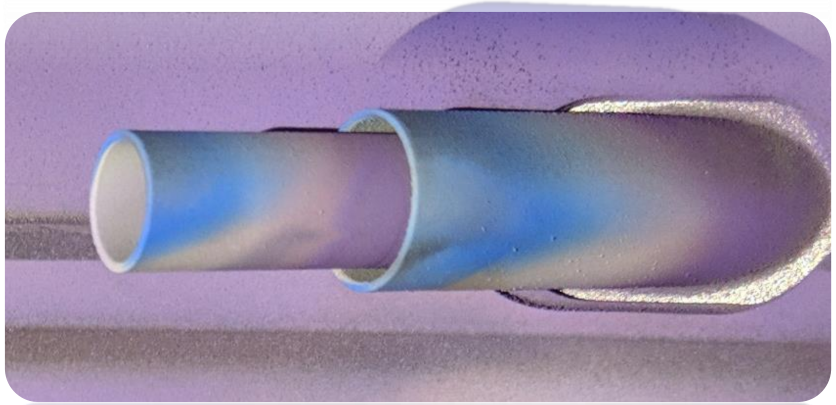
Both Air Tube designs were to be Additively Manufactured (AM) via Laser Powder Bed Fusion (L-PBF) process. Key factors of the process and design were evaluated to validate a stable long term production plan that meets design intent.

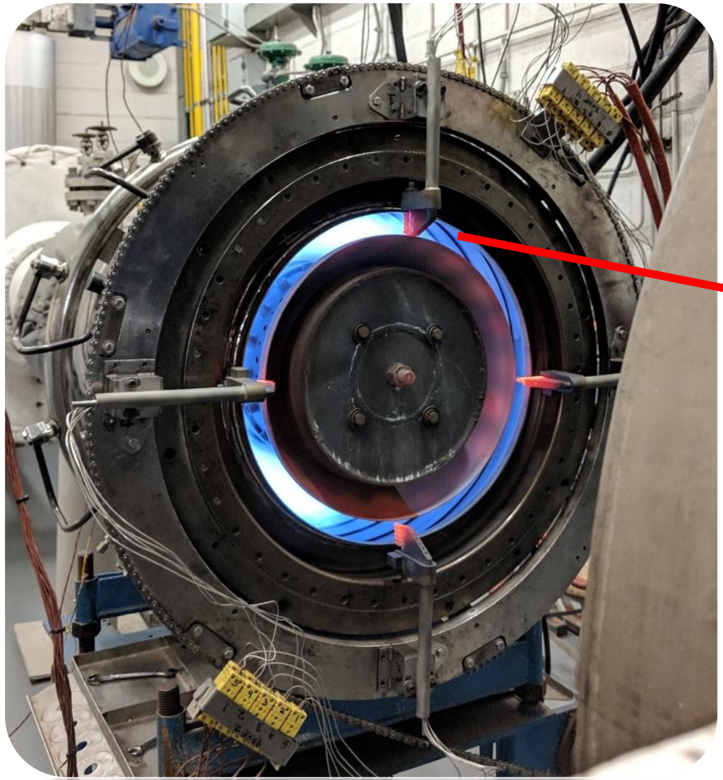


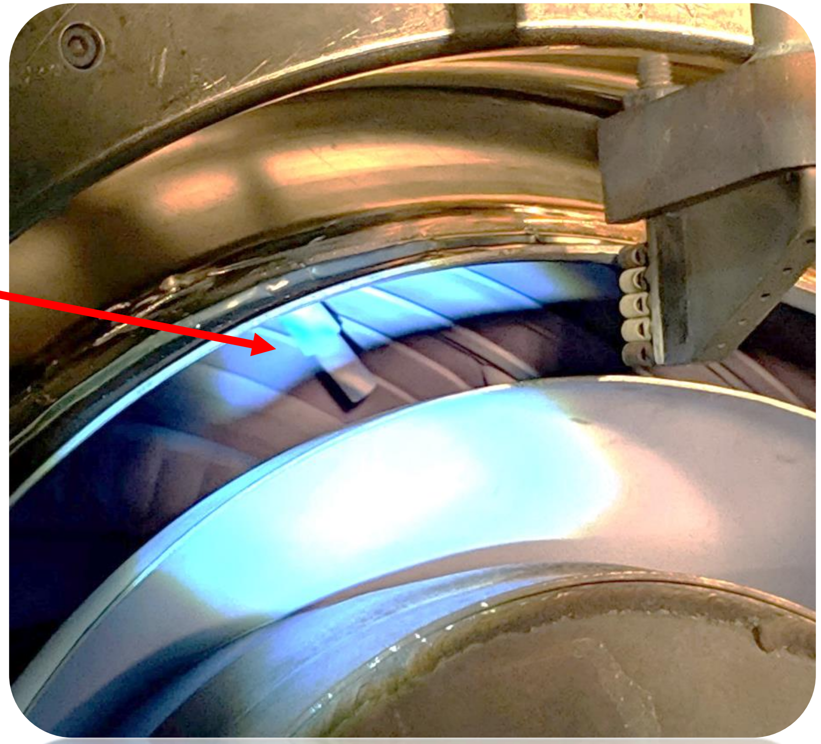
Final Design Validation

A final validation test was conducted on the final geometry selected per the optimization process. This geometry was printed and tested in house to validate the overall system performance.









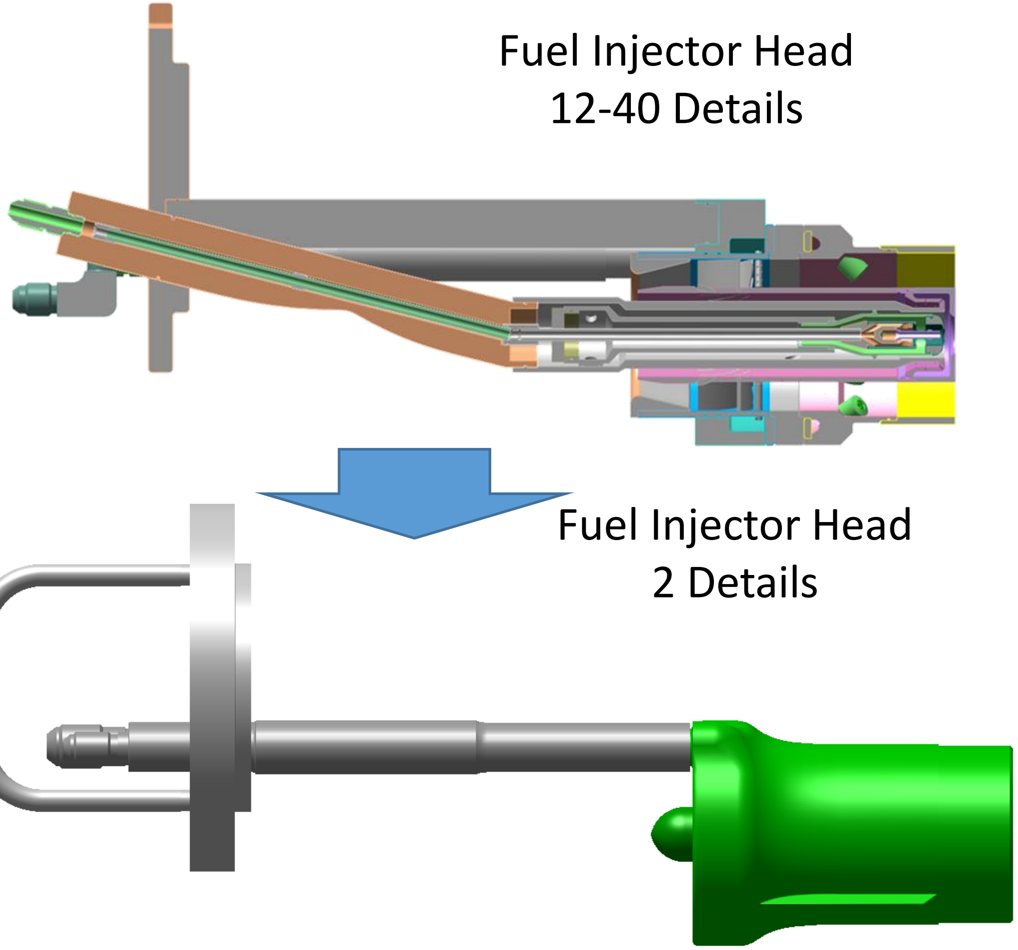
Example 2: Combustor Liner Air Tubes Conclusion

The prototyping and feasibility studies conducted on both Air Tubes designs yielded the following results:

- Consolidation of multiple sub-assembly components can be achieved for both designs
- Successful printing of all Air Tube designs is feasible via AM L-PBF
- Post Processing of the Ignitor Air Tube is feasible
- AM Air Tube designs can be manufactured at a lower cost
- AM Air Tube has the capability of addressing manufacturability concerns
- Part consolidation for sub-assembly components achieved
- Rapid prototyping for multiple design iterations
- DfAM best practices applied
- DfAM optimization using analytical tools

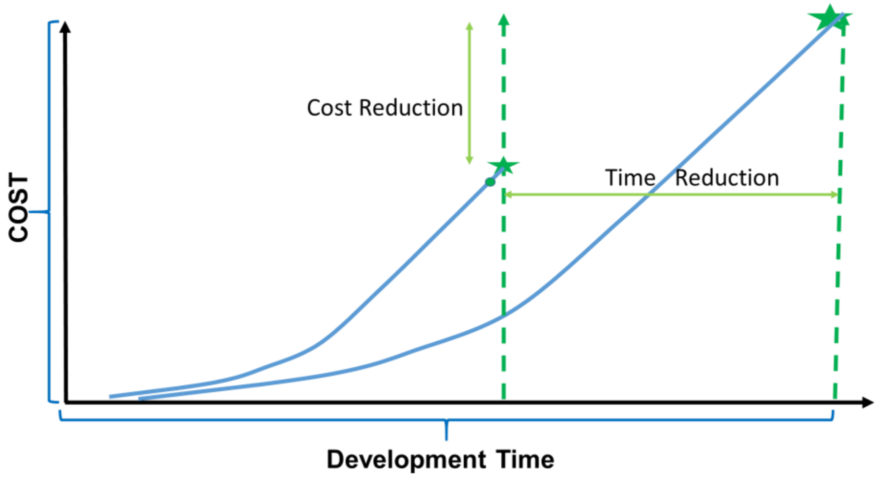
Example 3: Design for AM – DLE Fuel Injector

- Optimized designs
- Simplification of manufacturing
- Reduction of failure modes
- Reduce Development Cost and Cycle Time by 70%
- Reduce Product Cost



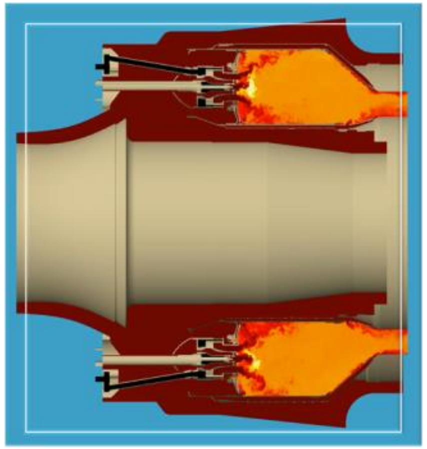
- Rapid manufacturing
- Rapid prototyping
- Substitute parts
- Tooling and gages
- Design for AM

Combustion Hydrogen Technology Enablers



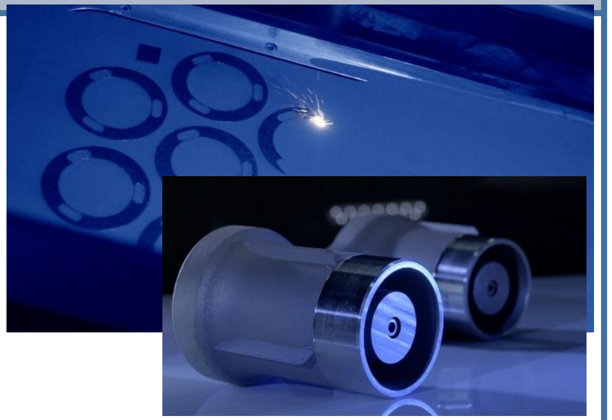
Combustion Digital Platform

- Thermo-acoustic frequencies and mode shapes
- Aero-thermal studies (flow split/ pressure drops)
- Thermal, structural & modal analysis



Additive Manufacturing

- Rapid prototyping
- Rapid manufacturing
- Tooling and gages
- Design for AM (DfAM)



Combustion Test Facility

- Mixing rig
- High pressure single injector rig
- Annular rig atmospheric pressure test
- Engine test
- Field evaluation

THANK YOU

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