3-D Printed High Temperature Centrifugal Impellers for Low Cost SOFC Recycle Blower

(SBIR Phase II—Proj. No.: DE-SC20793)

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Mohawk Innovative Technology, Inc., Albany NY, 12205, USA

2023 FECM / NETL Spring R&D Project Review Meeting

Sheraton Station Square Hotel
Pittsburgh, PA
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About Mohawk Innovative Technology, Inc.

Mohawk Innovative Technology, Inc. (MiTi®) was founded in 1994 to advance oil-free bearing technologies and apply them in production machinery.

Located in Albany, New York, USA, MiTi specializes in the development of ultra-high speed, oil-free, energy efficient and environmentally friendly rotating machinery for energy and power applications, as well as defense and aerospace.

Project Team

José Luis Córdova, PhD

- President & Technical Director
- Principal Investigator

Rochelle Wooding

- Mechanical Engineer
- Aerodynamic Design/Program Manager

Hannah G. Lea

- Mechanical Engineer
- FEA Design/Data Analysis

Zach Walton

- Technical Sales Manager

Matt Karesh & Dan Lavertu

- Technical Business Development

Sapphire Printer

"VELO3D addresses the most difficult additive manufacturing challenges, delivering a comprehensive end-to-end solution that enables on-demand manufacturing of production quality parts with unprecedented design freedom."

Motivation: Reduction of Cost of SOFC-Based Electricity

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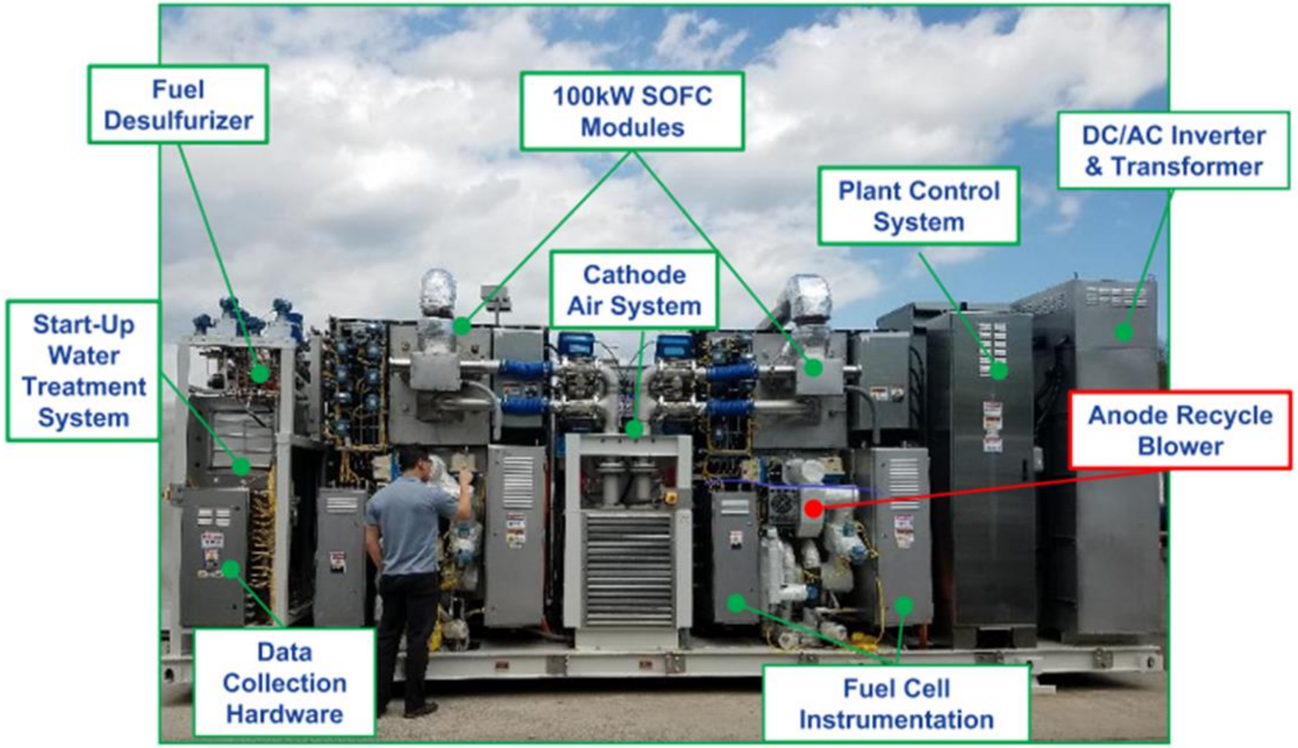
- U. S. Department of Energy (DOE) ambitious goal for reduction of solid oxide fuel cell (SOFC) cost of installation, from the current \$12,000US/kWe to \$900US/kWe by the year 2030
- To enable commercial generation of low-cost electricity in modular natural gas-fueled SOFC power plants by reducing the cost of *balance of plant* (BOP) components
- To incorporate Additive Manufacturing (3D printing) methods into the development of impellers for high and ultra-high temperature anode offgas re-cycle blowers (**AORBs**) for SOFC BOP applications

FuelCell Energy



Precursor Programs: Fuel Cell Enabling Technology

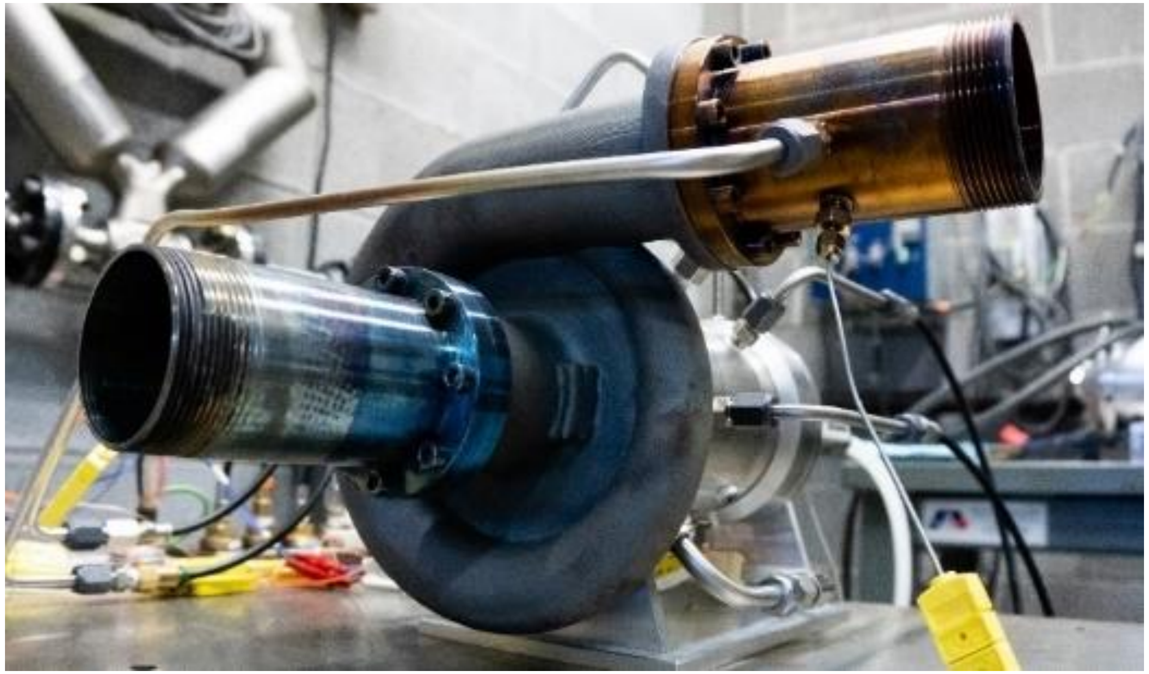
Anode Offgas Recycle Blowers (AORBs) for Solid Oxide Fuel Cell Power Plants

High Temperature (~200ºC)

- DOE Award No.: FE0027895
- Collaboration with FuelCell Energy, Inc. (Danbury, CT)
- Demonstrated ~1200 hours of TRL-6 testing.
- ***Completed over 1800 hours of TRL-8 testing in FCE's 200 kW power plant***

Ultra-High Temp. (700ºC)

- DOE Award No.: FE0031148
- Successful laboratory demonstration of prototype operation at 700ºC for 12 hours



- **R. S. Wooding, H. G. Lea, and J. L. Córdova, "Development of Oil Free Centrifugal Blower as Enabling and Cost Reducing Technology for Solid Oxide Fuel Cell Anode Gas Recycling," Proc. of ASME Turbomachinery Tech, Conf. and Expo (Paper No. GT2022-82294), Rotterdam, 2022**

Reduction of Development Cost of BOP

- ***Market conditions to achieve full cost reduction by taking advantage of economies of scale are* not *yet available.***
- ***MiTi estimates that the most probable cost of installation for fewer than 100 AORBs (for 100 kWe MPBs) is \$110 per SOFC-generated kW_e. This may represent as much as 17% of the current cost of major SOFC balance of plant equipment.***
- ***By introducing additive manufacturing methods into AORB integration, the installation cost of AORB could be brought down to \$91 per SOFC-generated kW_e.***

Some Questions MiTi Set Out to Answer

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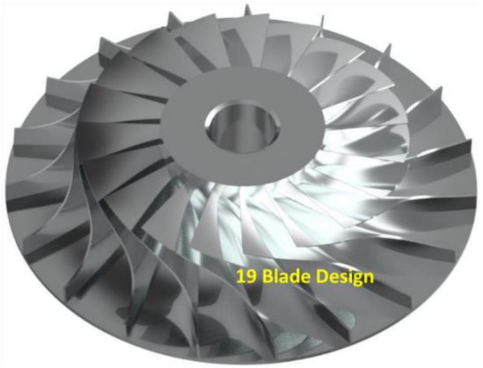
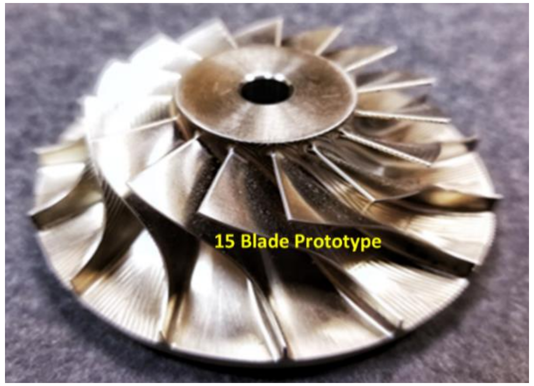
- ***What improvements can be derived from 3D printing?***
  - ***Fabrication cost?***
  - ***Aerodynamic improvement?***
- ***Are 3D-printed materials mechanically sound for the application conditions?***
  - ***Characterization of mechanical properties***
- ***Is it possible to achieve the required impeller geometries?***
  - ***Meet mechanical/manufacturing drawing dimensions***
  - ***Achieve acceptable surface finish***

Benefit: Impeller Cost Reduction

- For prototype development and at low count production runs, centrifugal impellers made by traditional manufacturing methods are the highest cost mechanical component in AORBs and other turbomachinery.

Inconel 718 or Rene 41 impeller for UHT AORB



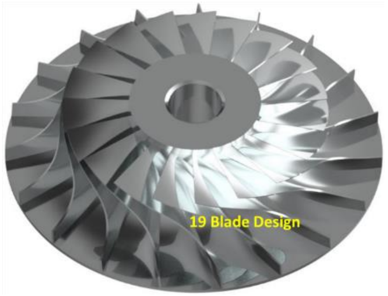


Cost per unit of Inconel 718 impeller for UHT-AORB (up to 700^{O}C)			
Quantity	**Manufacturing Method**	**Number of Blades**	**Unit Cost**
1 or 2	5 Axis Machining	19	$18950
1 or 2	5 Axis Machining	15	$15845
5 to 10	Investment Casting	15 or 19	$3800 to $1900
2	SLM-3D Printing	15 or 19	$1005
12	SLM-3D Printing	15 or 19	$614

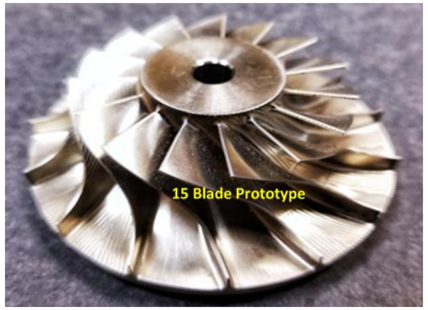
Benefit: Aero Efficiency/Geometry Innovations

- *Traditional manufacturing methods impose geometric limitations that result in aerodynamic performance trade-offs and efficiency penalties.*

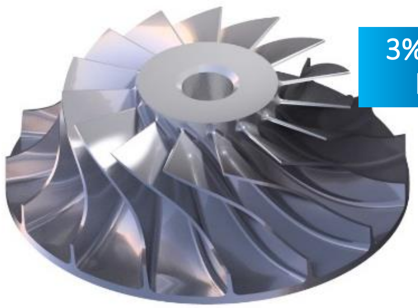
Theoretical Design



Actual Prototype



Open Impeller



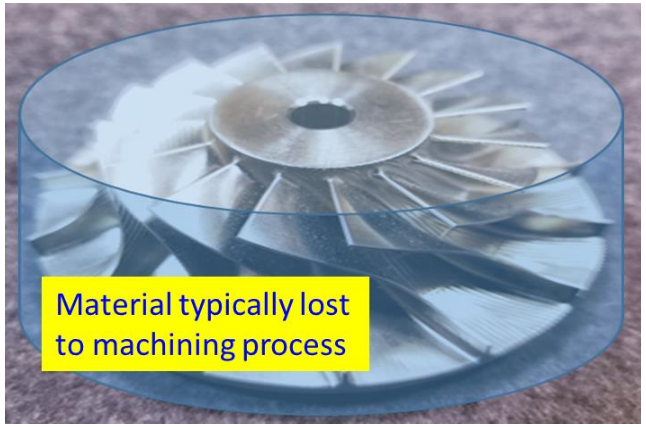
3% Efficiency Increase

Shrouded Impeller

Tool availability limits number, depth, and back-sweep angle of blades.

Benefit: Efficient Material Utilization

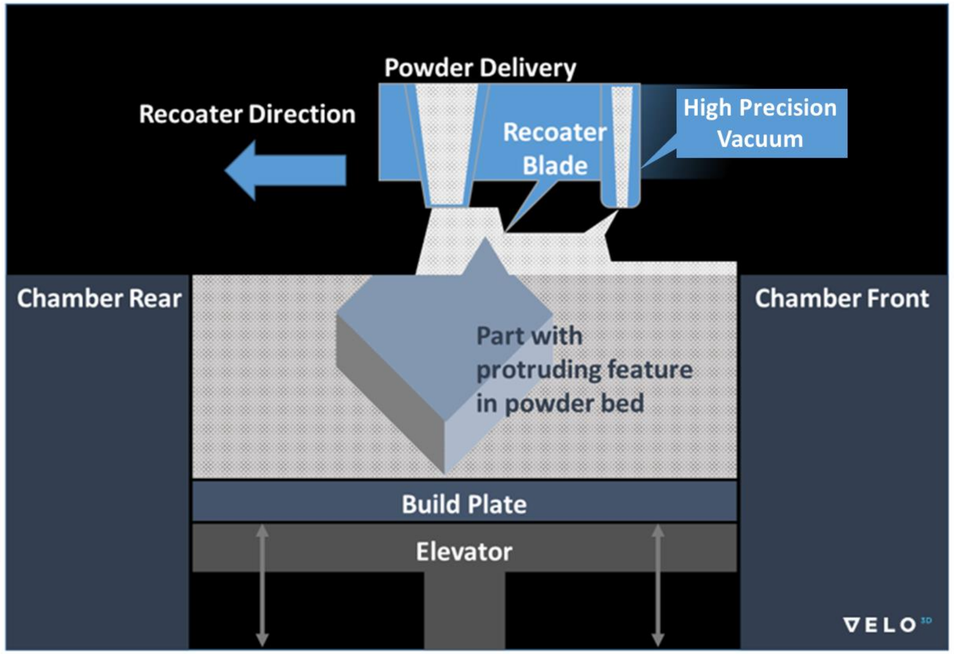
- CNC machining of prototype results in approximately 60 to 70% loss of material volume (or mass).
  - ***Mass of finished impeller: 730 g***
  - ***Material waste: 1100 g to 1700 g.***
  - ***Cost of forged Inconel 718 for CNC: $130/kg***
    - ***Total material cost: $238 to $316 per impeller***
    - ***Material waste: $143 to $221 per impeller***
  - ***Cost of powdered Inconel 718 for SLM-3D process: $97/kg***
    - ***Total material cost per impeller of $71/impeller***



3D Printing Process & Material Characterization

VELO 3D State-of-the-Art 3D Metal Printers Assure Software

Process: modified implementation of the Laser Bed Powder Fusion (LPBF) method



Mechanical property data for 3D-printed super alloys is not broadly or even publicly available, especially at high temperatures.

- ***Yield stress, hardness, surface finish, fatigue/creep are critical for design of high speed, high temperature aero components.***
- ***Program has significant impact beyond SOFC BOP, serving much broader energy, defense, and aerospace needs.***

- **H. G. Lea, R. S. Wooding, Sam Kuhr, John Rotella, and J. L. Córdova, "Characterization of Properties of Laser Powder Bed Fusion 3D-Printed Inconel 718 for Centrifugal Turbomachinery Applications," Proc. of ASME Turbomachinery Tech, Conf. and Expo (Paper No. GT2022- 83474), Rotterdam, 2022**

3D-Printed Impeller Fabrication

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First trial:
- **Fabricate material samples for mechanical property testing**
- **Establish baseline impeller geometry achievable**

Second trial:
- **Implement 3D printing process improvements based on results of first print**

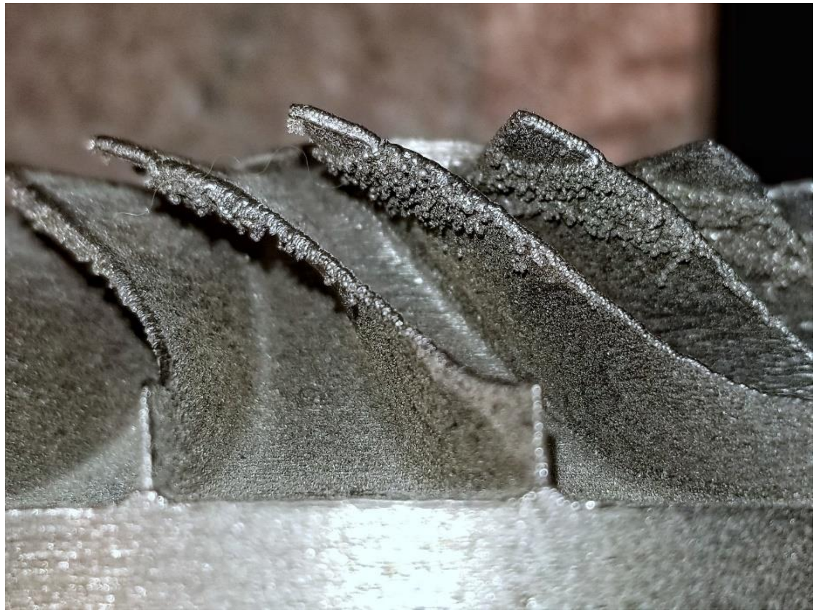
Third trial:
- **Implement design impeller changes to accommodate 3D printing capability**

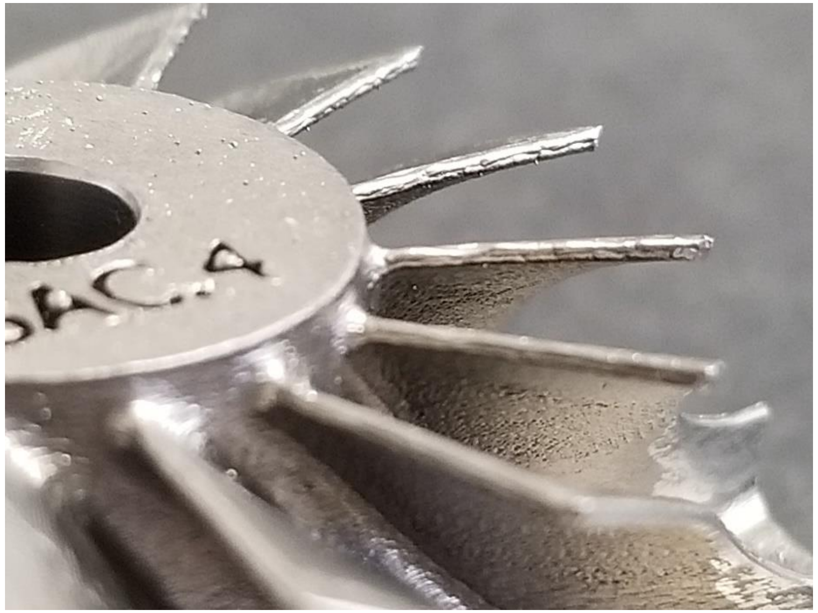
Evolution of 3D Printing Process

First trial:
- Excessive material build up in bottom face of blades
- Poor axial symmetry

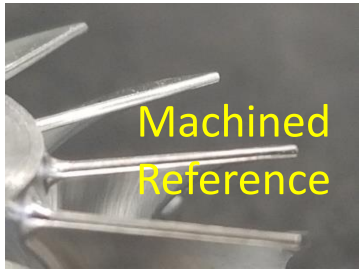
Second trial:
- No excess material build up
- Better axial symmetry
- Problems with blade sag

Third trial:
- All critical geometries adhere to the manufacturing drawing dimensions



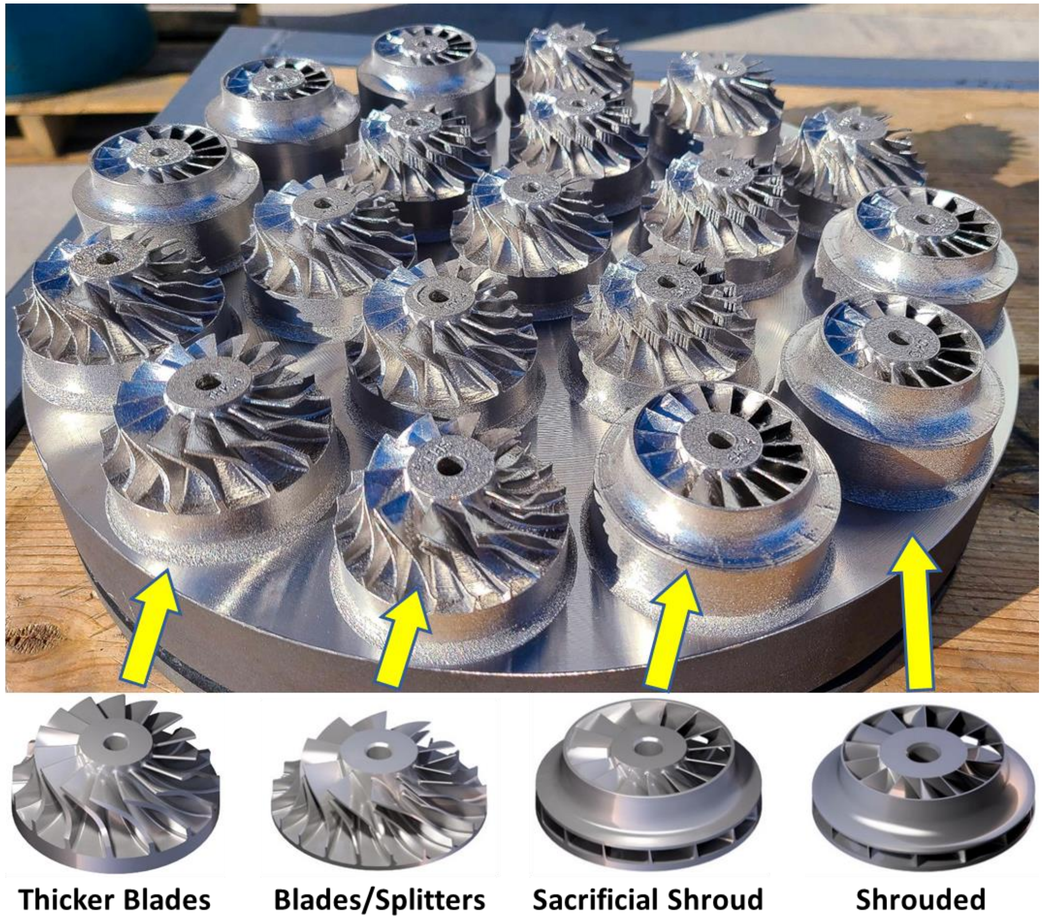


- ***Between the first and second trial, VELO3D developed a new set of "thin edge" process parameters that yielded the cleaner print.***
- ***For the last step, MITI conducted design adjustments to better suited to VELO3D's capability.***



Third Trial 3D-Printed Impellers

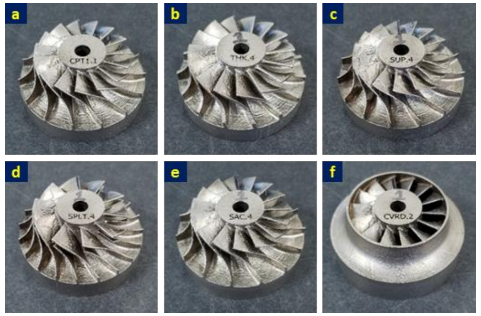
- *The impellers were 3D-printed*
- *Then, they were cut from plate, and subject to stress-relief treatment*
- *Secondary machining of selected wheels was done*



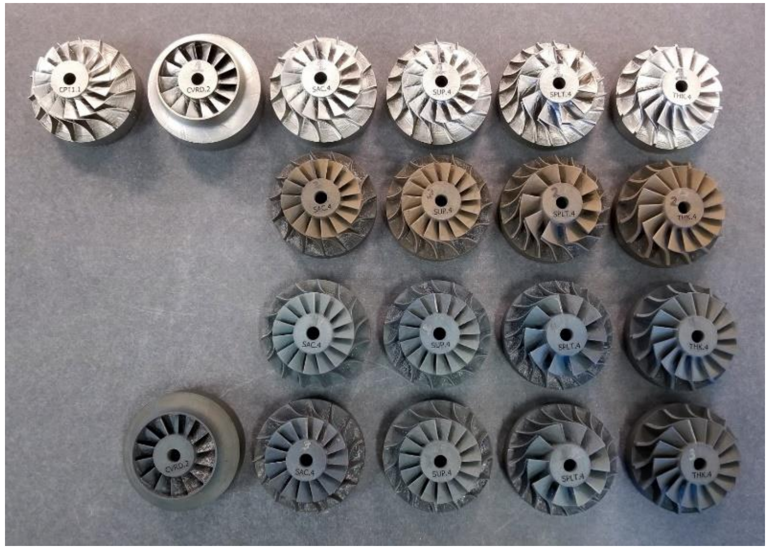
Impeller Heat Treatment & Secondary Machining

Is it possible to achieve the required impeller geometries?* *Yes it is!

Different Designs

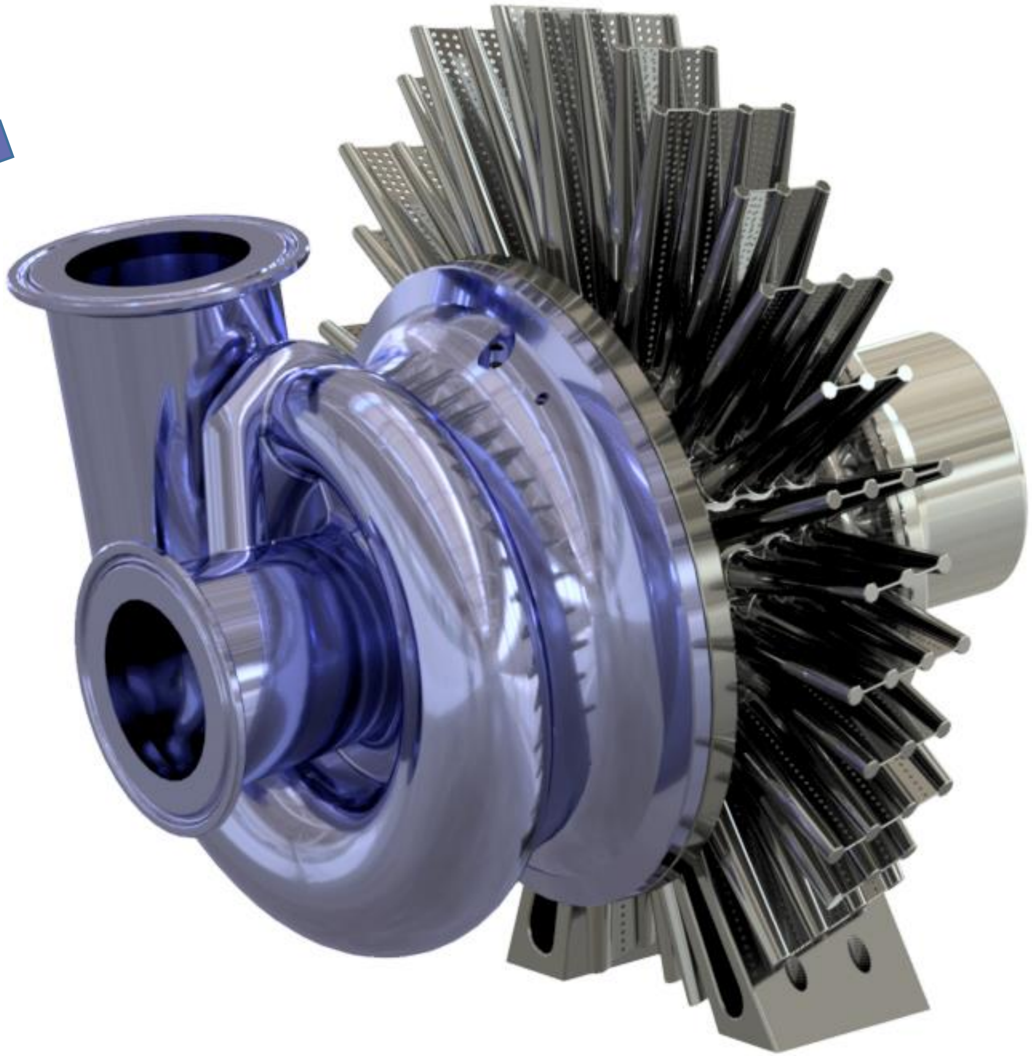


Impellers at different heat treat stages



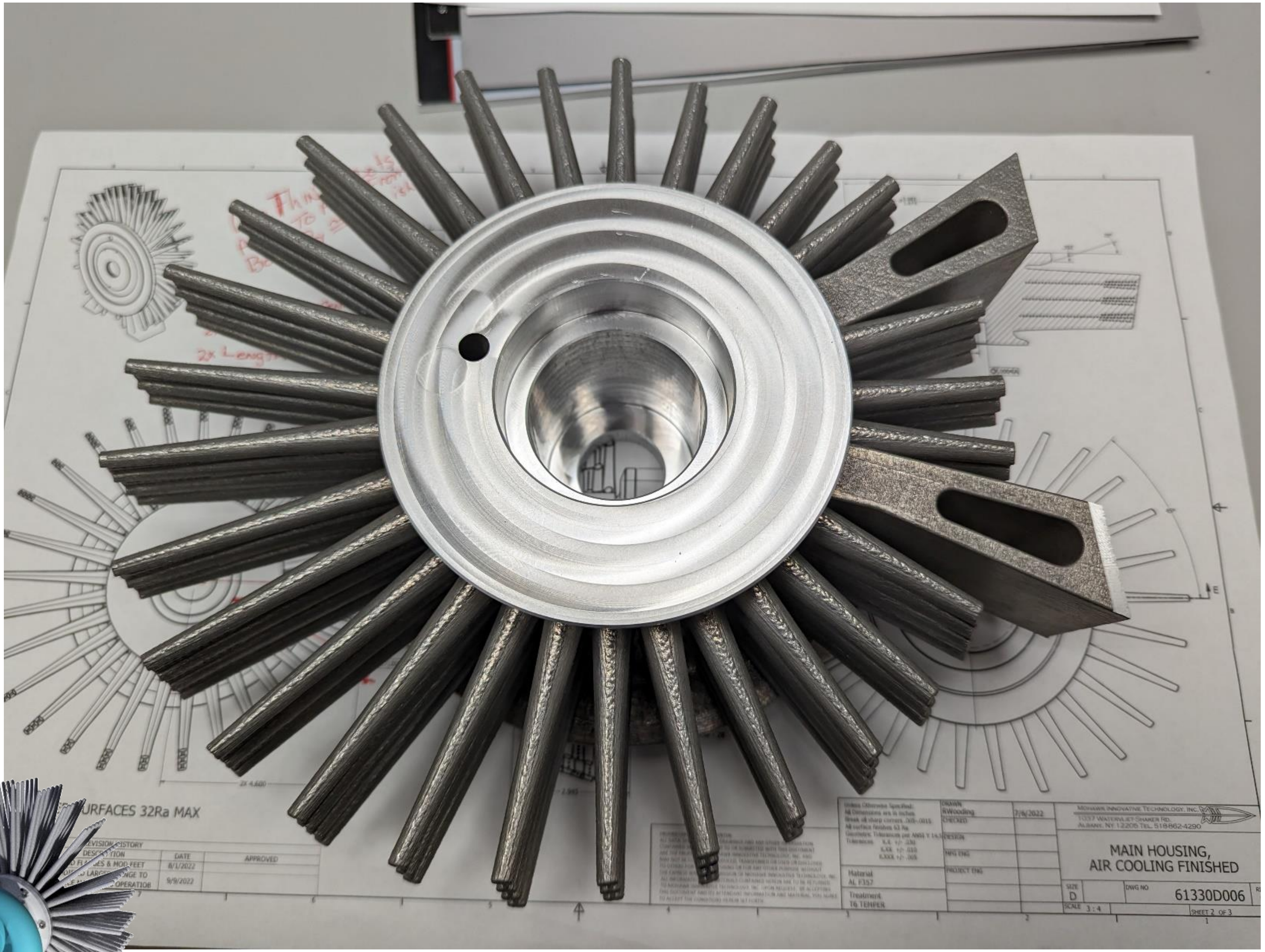
Design of New Housings for 3D Printing

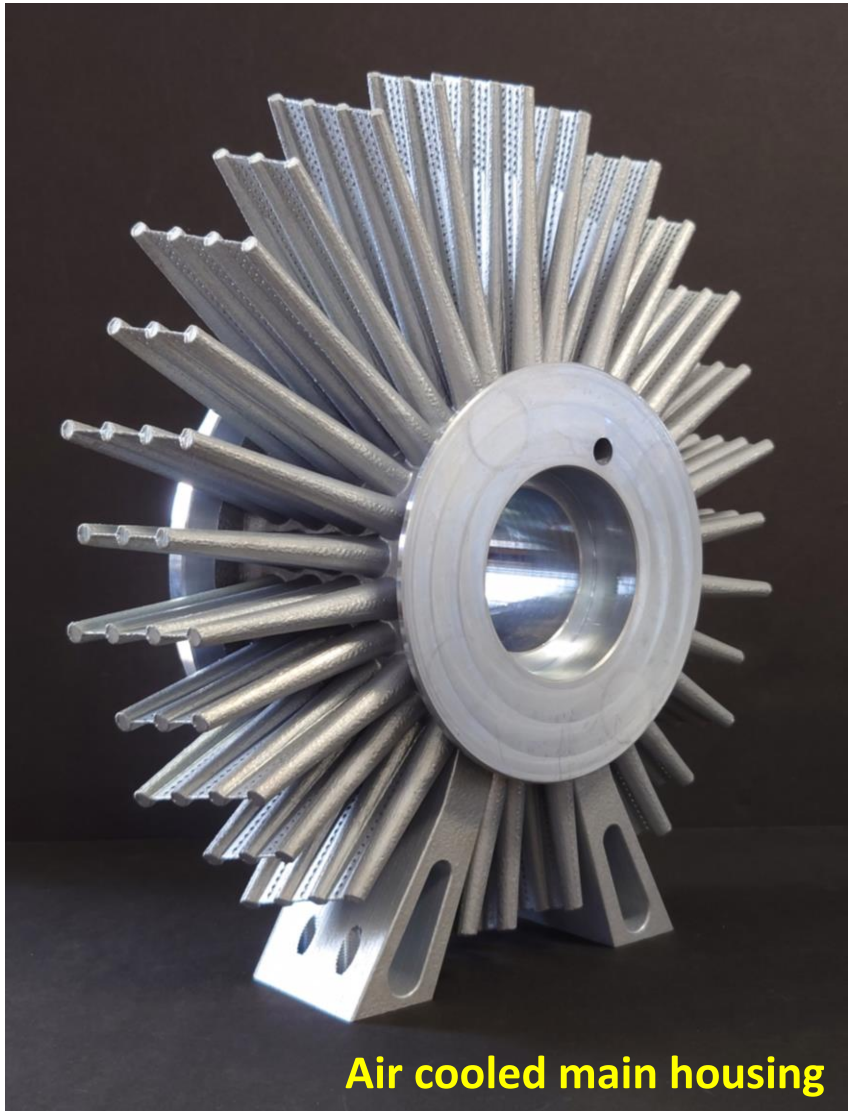
Air Cooled Version



Water Cooled Version

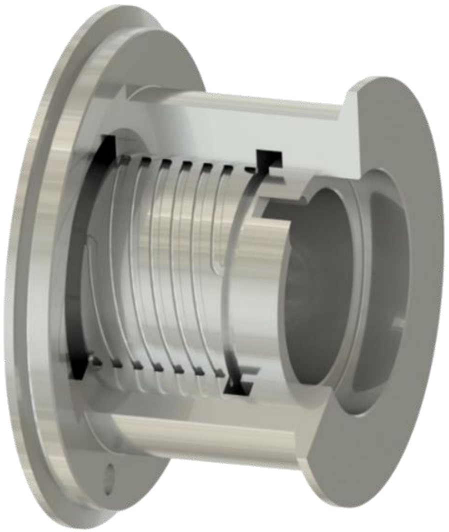
Air Cooled Housing Complete

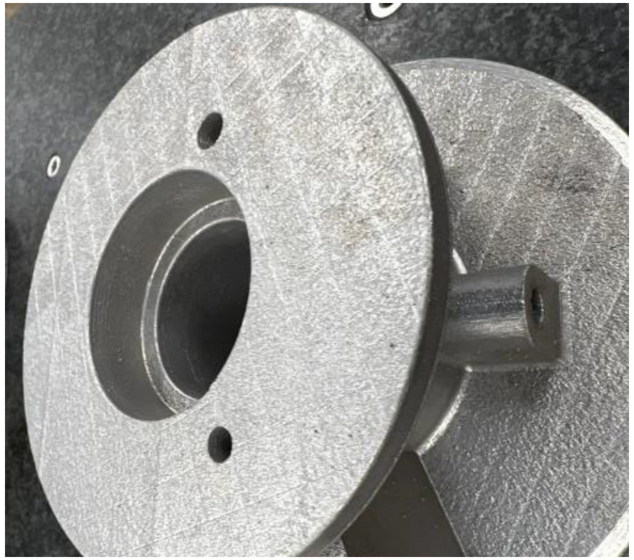


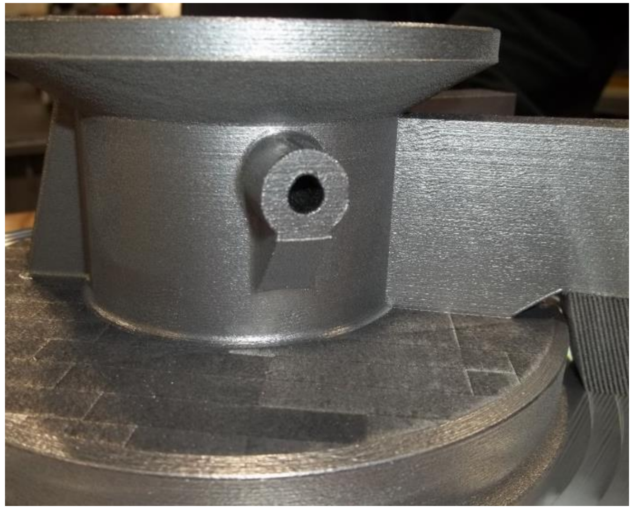


Air cooled main housing

Liquid Cooled Housing Complete







Volutes Complete

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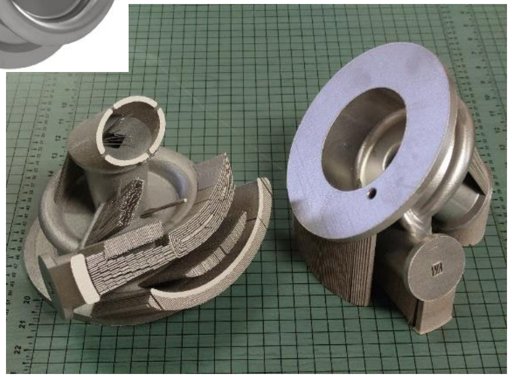
Volute for original FCE AORB with covered Impeller

Volute for 65 mm impeller for INL SOEC



Volute for 45 mm impeller for INTEGRATE SOFC

Drop-in Replacement Volute for Original AORB

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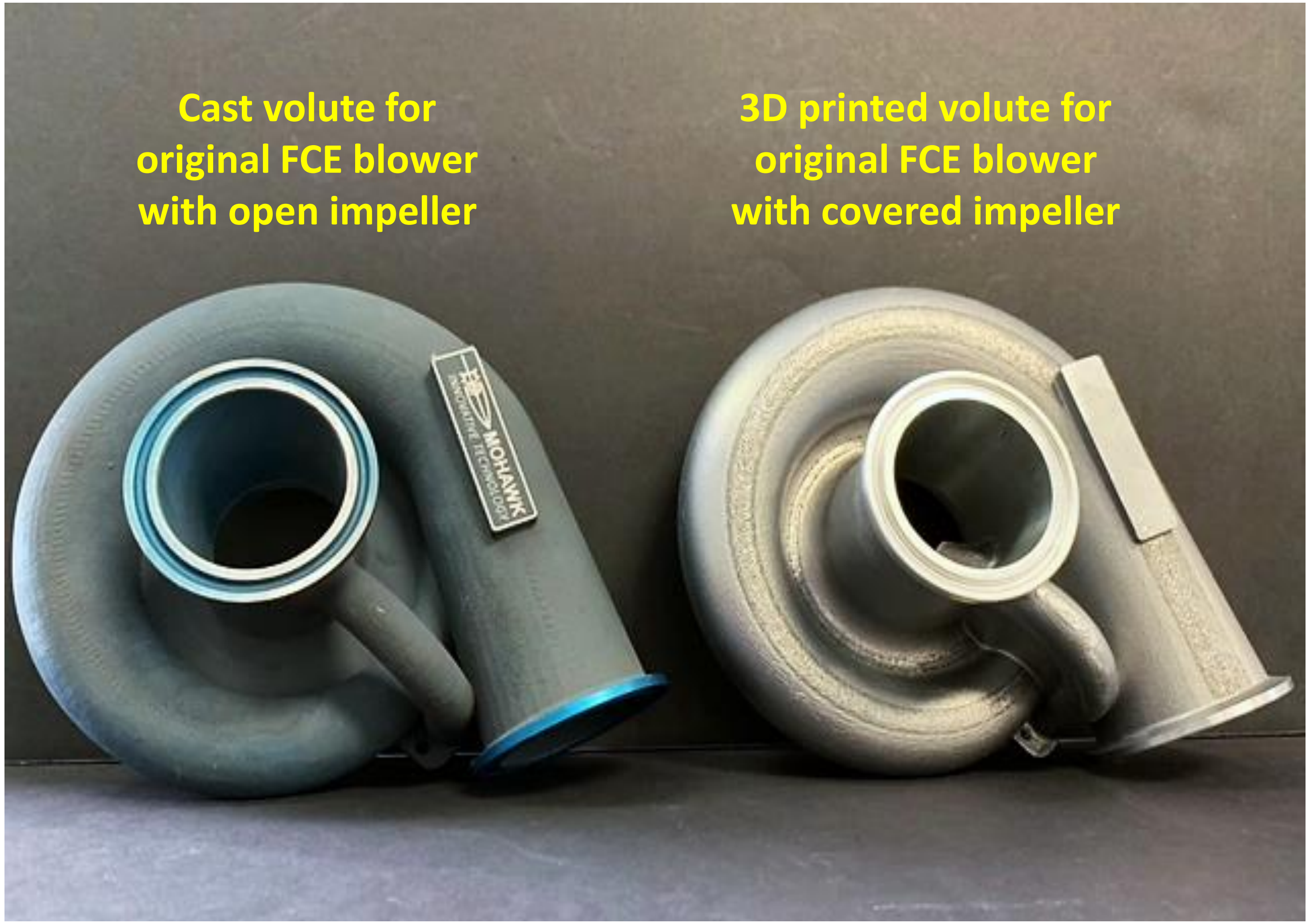
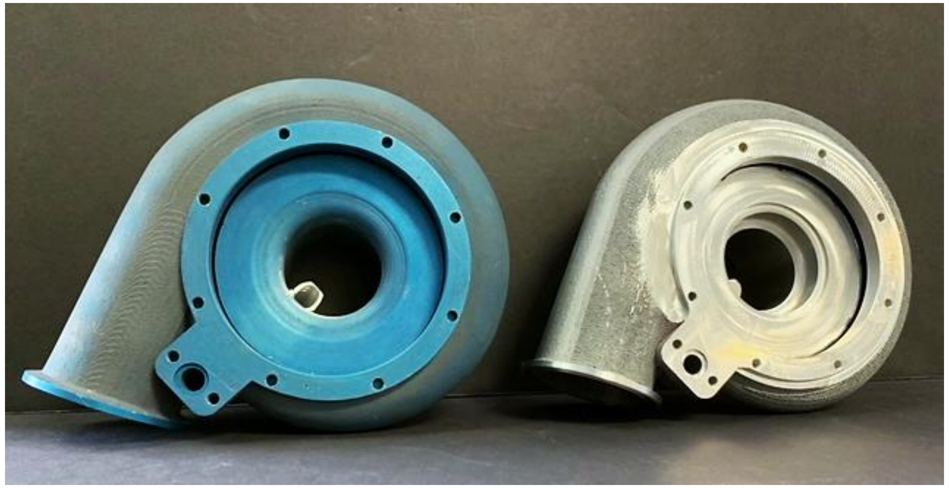
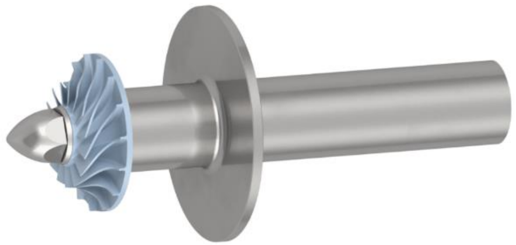




Other Parts Complete or Nearing Completion

45 mm INTEGRATE SOFC

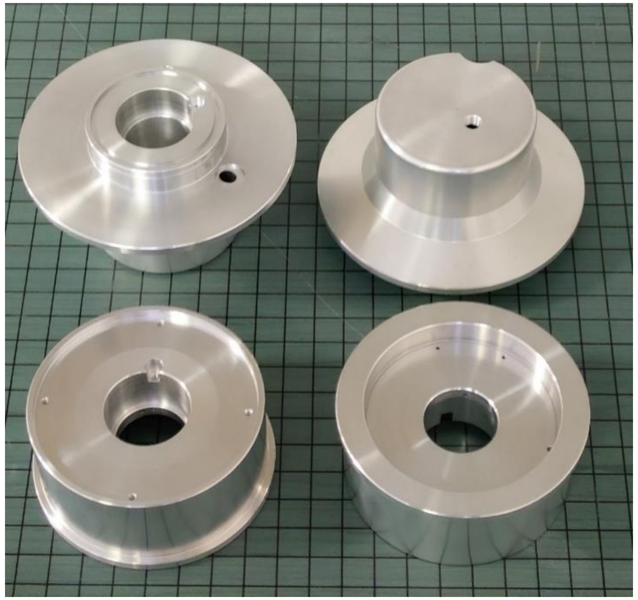


65 mm INL SOEC

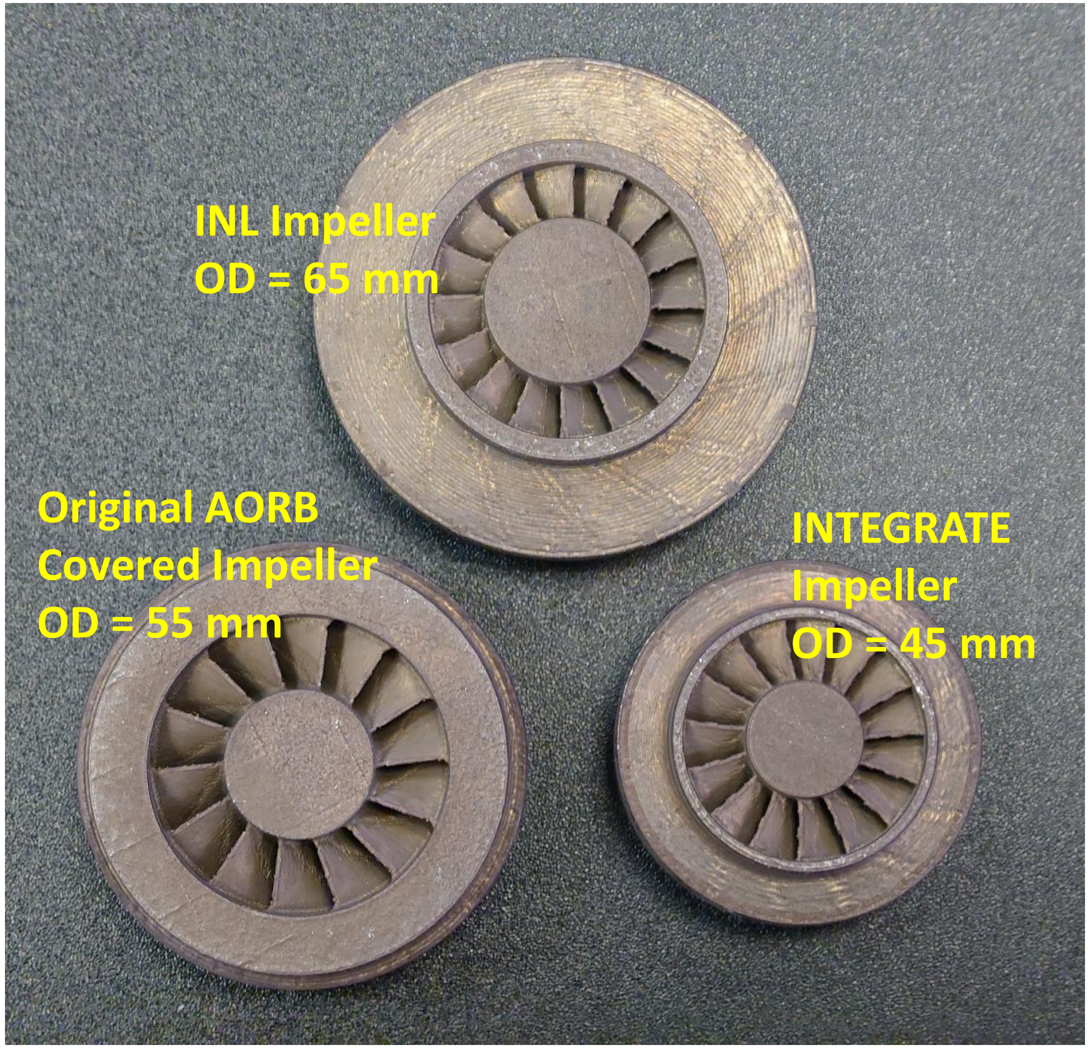
55 mm (Shrouded) Original FCE SOFC

Shafts with Embedded Magnets

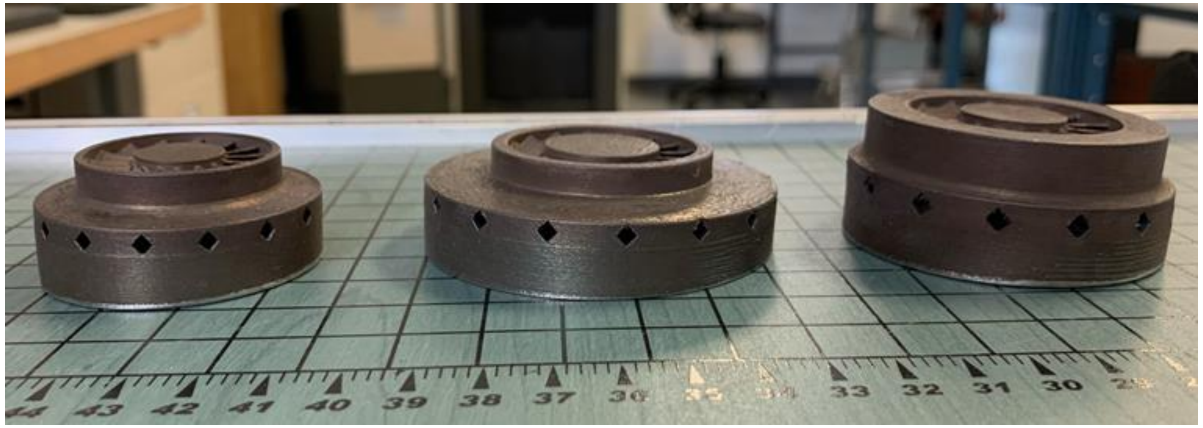
Bearing Housing and Rear Caps



Has it Been Smooth Sailing? Of Course Not!!



Secondary Machining Error After Successful 3D Printing



Part Kit – So Far

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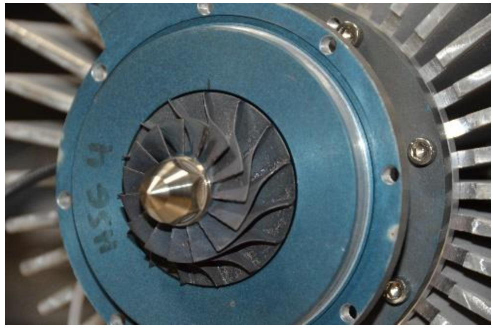
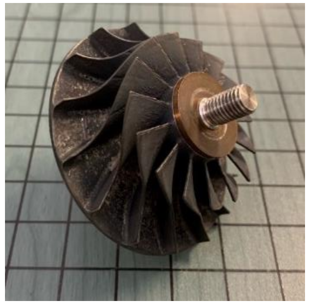
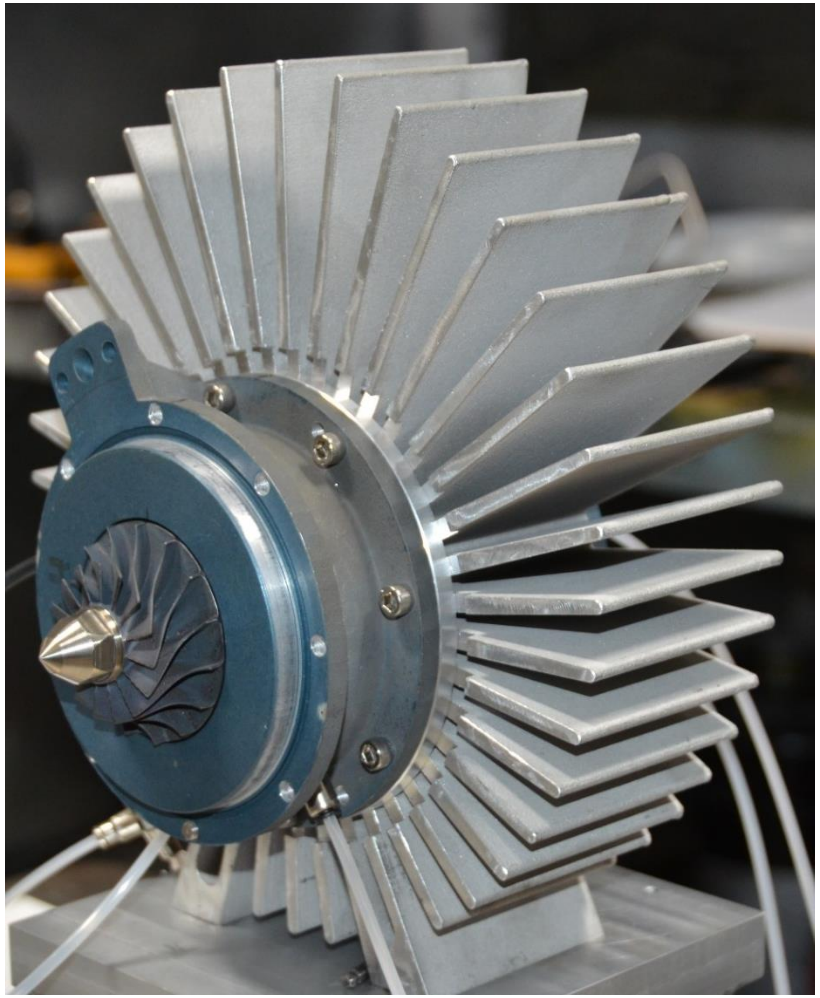
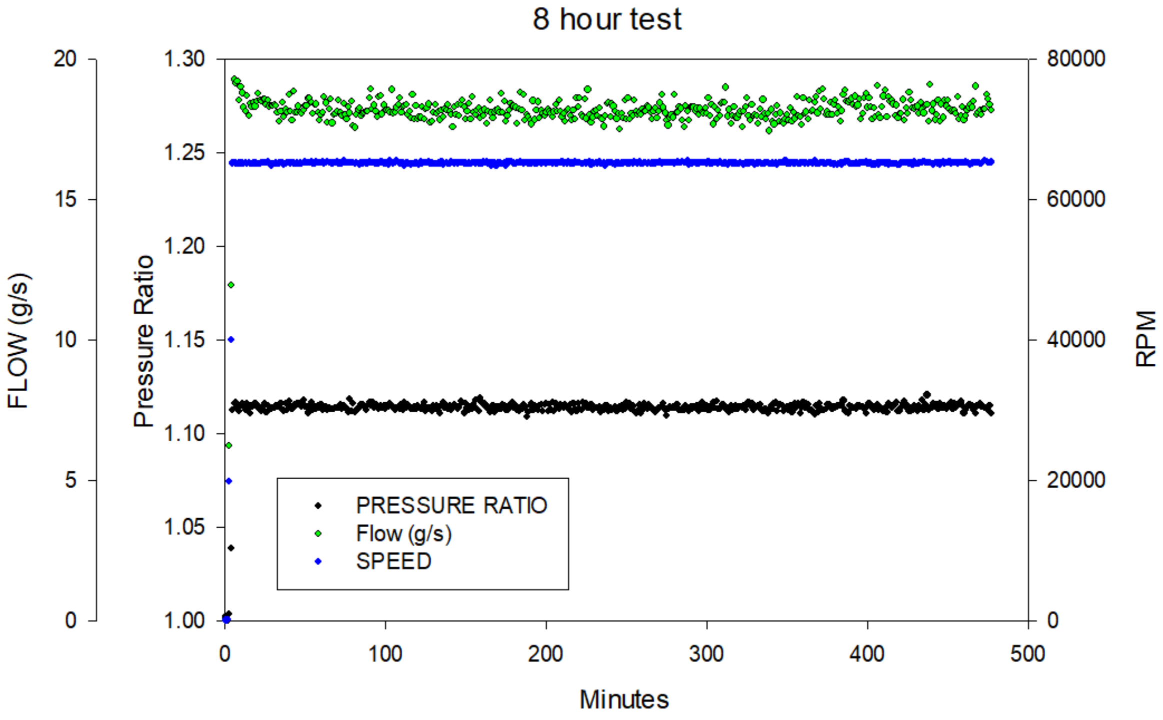
Preview of Next Steps





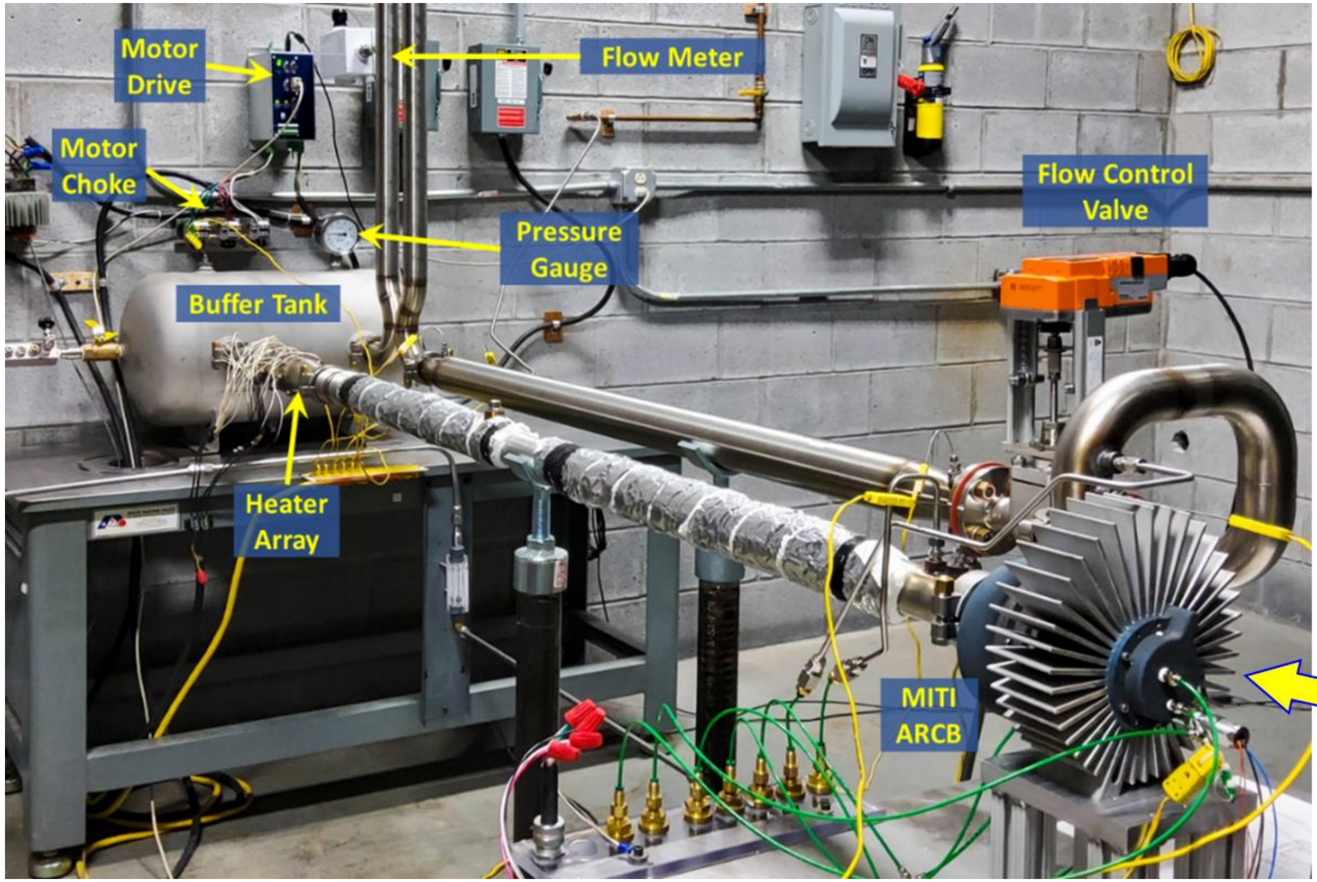


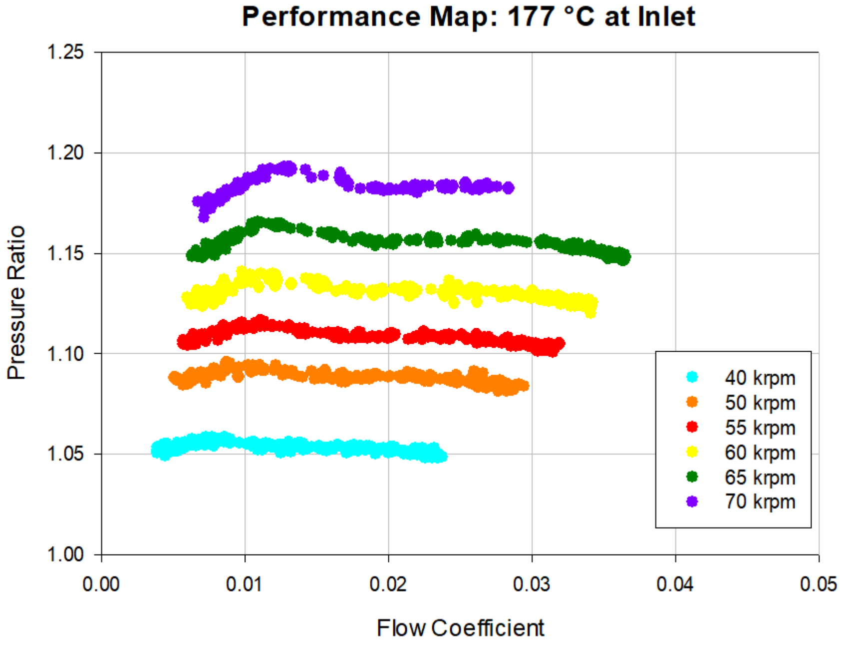
First Successful Spin Test!



Preview of Next Steps

Goal: Demonstrate adequate performance of AORBs equipped with 3D-printed parts





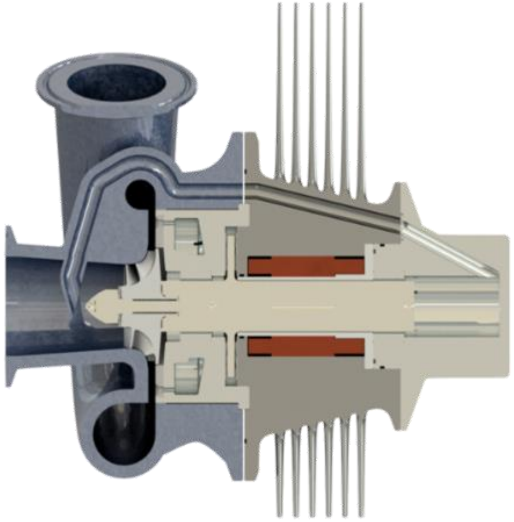
MITI ARCB

Note on Modularity

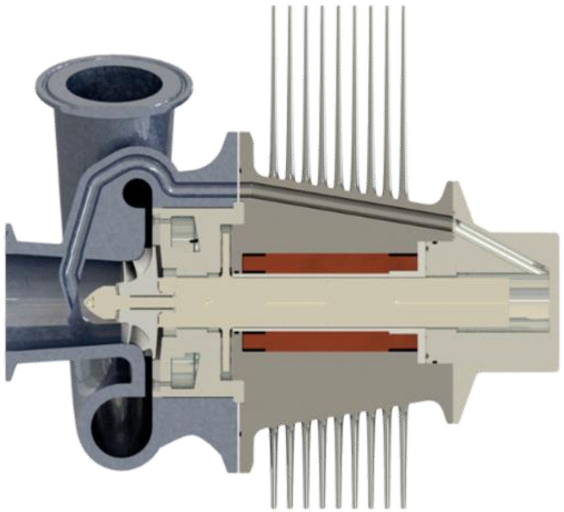
Two Platforms Defined:

- <1 to 1.5 kW and 1.5 to 3 kW
  - SOFC Anode Offgas Recycle Blower
  - SOEC Fuel Blower
  - Hydrogen Blowers/Compressors
- Leverage commonality of components for quick “on demand” prototyping

<1 to 1.5 kW Platform



<1.5 to 3 kW Platform



Common Parts
- Tie-bolt/Washer/Nut
- Bearing Housings
- Thrust Runner/Front Shaft
- Thrust Housing (3D-P)
- Bearings
- Rear Housing (3D-P)
- Clamps/Fasteners

Platform-Specific Parts
- 1.5 or 3 kW Stator
- 1.5 or 3 kW Magnet
- Short or Long Main Housing - Air or Water Cooling Option (3D-P)

Fully Customized Parts
- Impeller (3D-P)
- Volute (3D-P)
- Aft-shaft
- Diffuser Plate

Quick Note on Customization

It is not possible to use the same blower for different gas conditions even if the flow or pressure ratio requirements are similar.

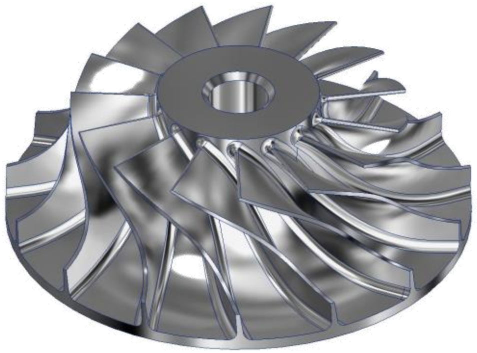
- Gas Composition – Molar Mass/Density
- Inlet Pressure
- Inlet Temperature

Even if the power is the same, the aerodynamic components (impeller and volute) have unique characteristics to work optimally or even to work at all!

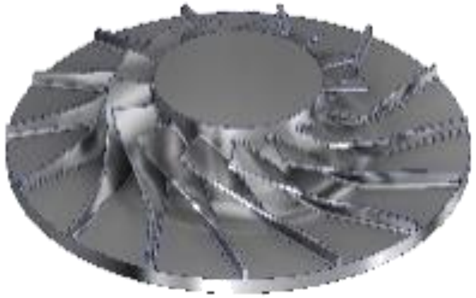
Case Study: Two Anode Recycle Blower Impellers for Different SOFC blowers

- Same gas composition
- Same flow rate
- Same inlet temperature
- Same pressure ratio
- Same diameter/operating speed

Inlet pressure: 1 atm



Inlet pressure: 4 atm



Publication

- Parts of this work have been published in:
  - J. L. Córdova, "Additive Manuf. of Centrifugal Impellers for SOFC Anode Gas Recycle Blowers," in *Proc. of ASME Turbomachinery Tech, Conf. and Expo.*, Rotterdam, 2022.
  - R. S. Wooding, H. G. Lea, J. L. Córdova, "Development of Oil Free Centrifugal Blower as Enabling and Cost Reducing Technology for SOFC," in *Proc. of ASME Turbomachinery Tech, Conf. and Expo.*, Rotterdam, 2022.
  - *H. G. Lea, R. S. Wooding, Sam Kuhr, John Rotella, and J. L. Córdova, "Characterization of Properties of Laser Powder Bed Fusion 3D-Printed Inconel 718 for Centrifugal Turbomachinery Applications," Proc. of ASME Turbomachinery Tech, Conf. and Expo (Paper No. GT2022- 83474), Rotterdam, 2022

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- Finally, the authors acknowledge the support of MiTi's now retired founder, Dr. Hooshang Heshmat, whose long term vision and perseverance have made this work possible.

Questions & Feedback

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Thank you for your attention!

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