High Temperature Anode Recycle Blower for Solid Oxide Fuel Cells

Projects:

DE-FE0027895 and DE-SC0020793 (SBIR Phase II)

Prepared by:

Mohawk Innovative Technology, Inc. (MiTi®)

PIs: Hooshang Heshmat, PhD and Jose Luis Cordova, PhD

For :

22nd Annual Solid Oxide Fuel Cell Project Review Meeting

U. S. Department of Energy – Office of Science

DOE Project Officer: Sarah Michalik

High Temperature Anode Recycle Blowers for Solid Oxide Fuel Cell

DOE Award No.: DE-FE0027895

Overall Program Objectives (FE0027895)

- To develop scalable Oil-Free High-Temperature Anode Recycle Blower (ARCB) technology for SOFC power plants
- Demonstrate TRL 7 by characterizing performance and life via testing in a real SOFC power plant

Team

U.S. Department of Energy

Sarah K. Michalik
- Project Manager

Mohawk Innovative Technology

Hooshang Heshmat, PhD
- CEO & Technical Director
- Principal Investigator

Jose Luis Cordova, PhD
- Vice President of Engineering
- Program Manager
- Aero-Thermal Analysis

Rochelle Wooding
- Mechanical Engineer
- Testing

FuelCell Energy

Hossein Ghezel-Ayagh, PhD
- Director SECA Program
- FCE Project Manager

Stephen Jolly
- SOFC systems engineering
- Operations manager

Andrew Ethier
- Process Engineer

MiTi's Anode Recycle Blowers for SOFCs

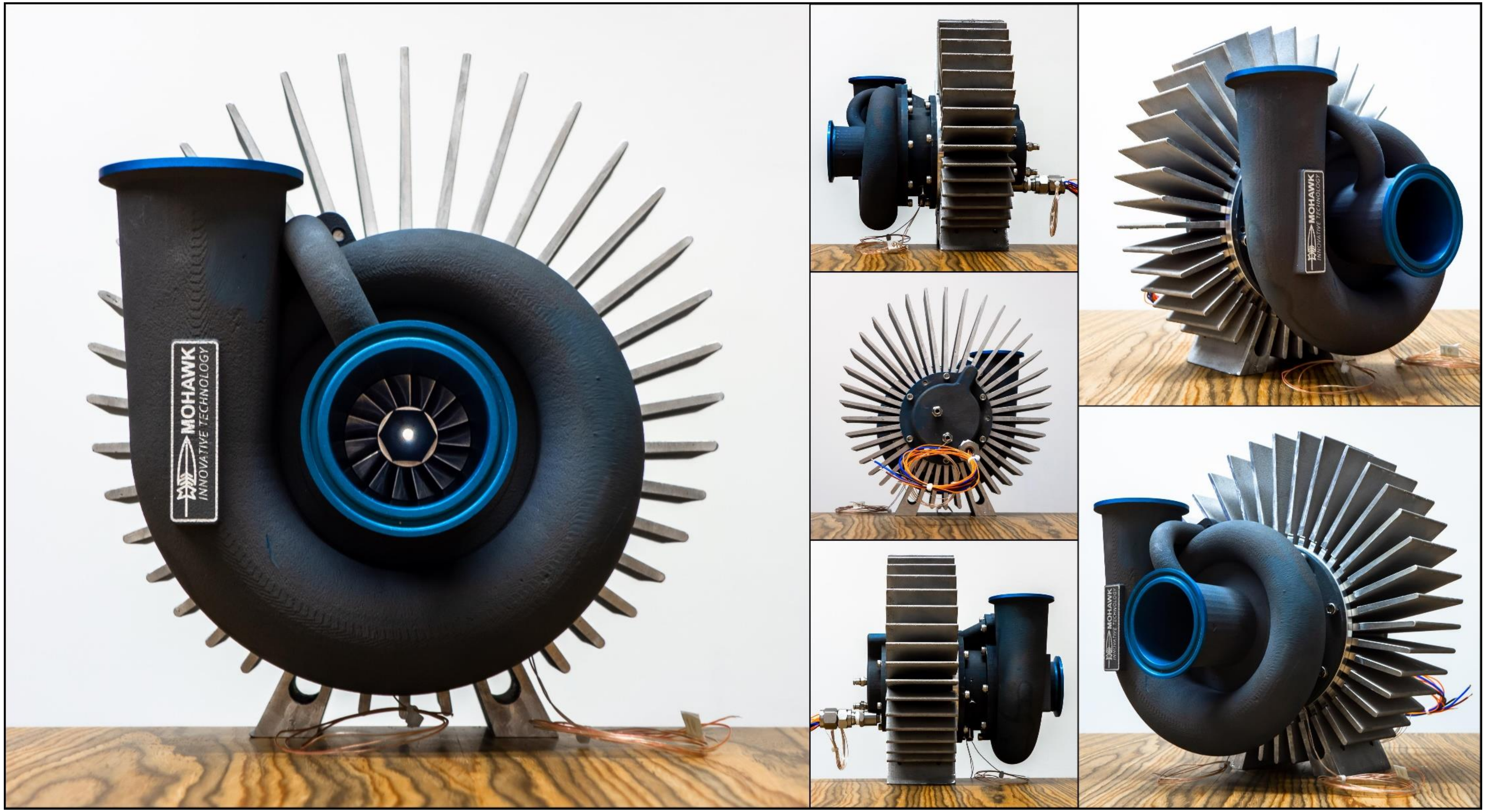
- **High Temperature (HT) Anode Recycle Blower for Solid Oxide Fuel Cell—Phase II**
  - Award No.: FE0027895
  - Performance Period: 10/01/2016 - 03/31/2022
  - Total Phase I & II Budget:
    - DOE: $2,098,408
    - MITI Cost Share: $ 569,443

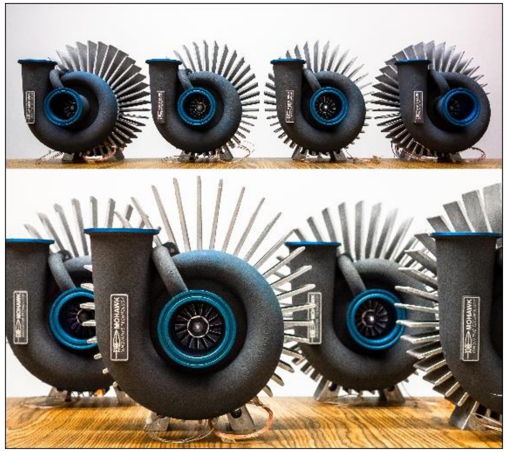
Phase II Deliverable Unit

Phase I Prototype and Testing

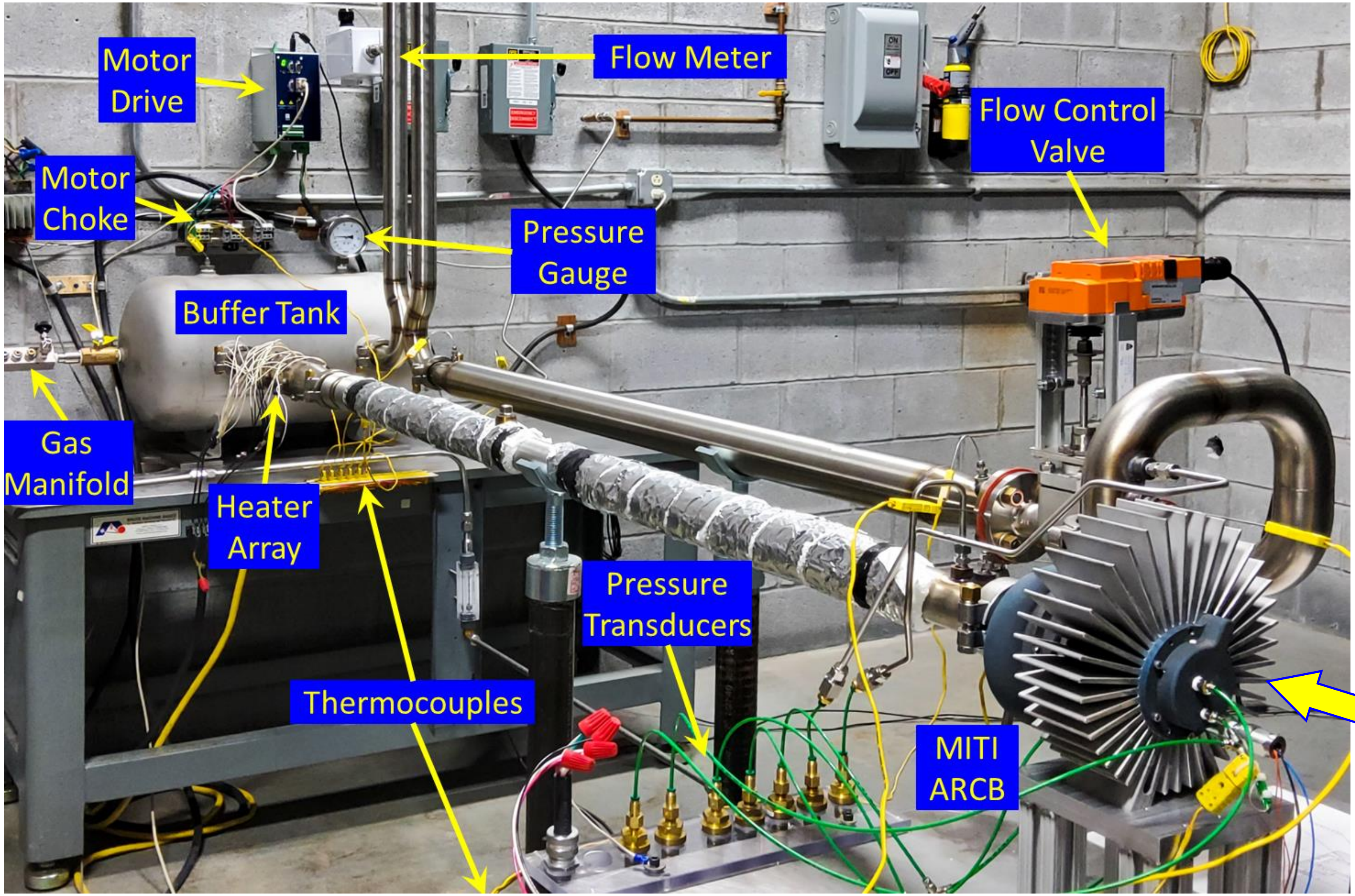
HT ARCB Full Assembly

4 X Production Prototypes Completed





Accelerated Life Test Loop Design

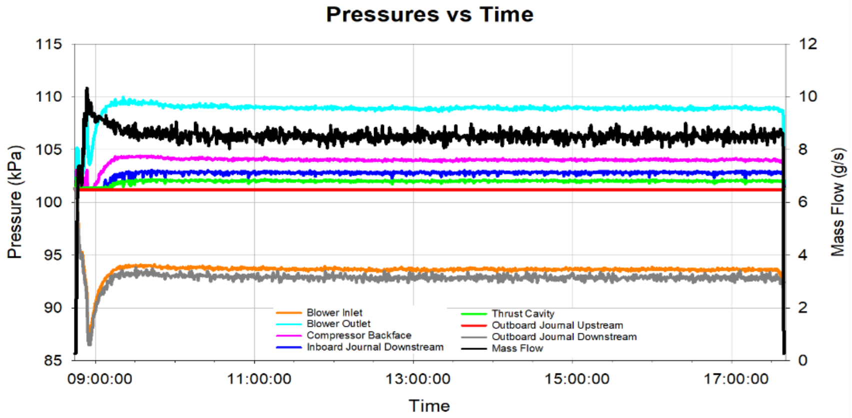


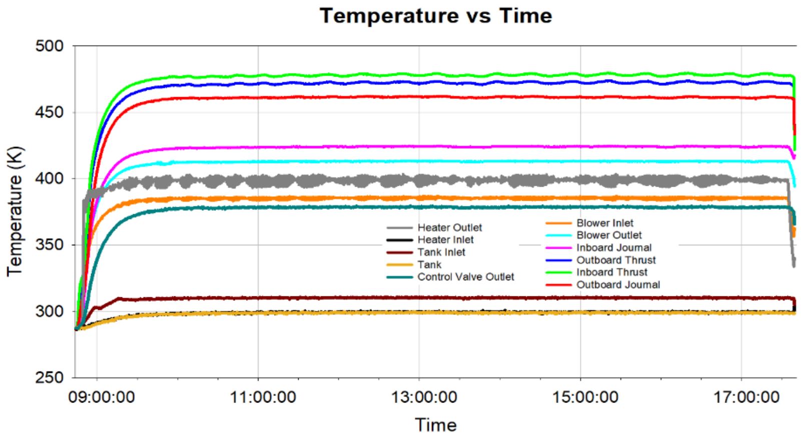
- **Beginning of testing mid-August 2020**
- **Completed approximately 1200 hours of testing at realistic conditions.**

MITI ARCB

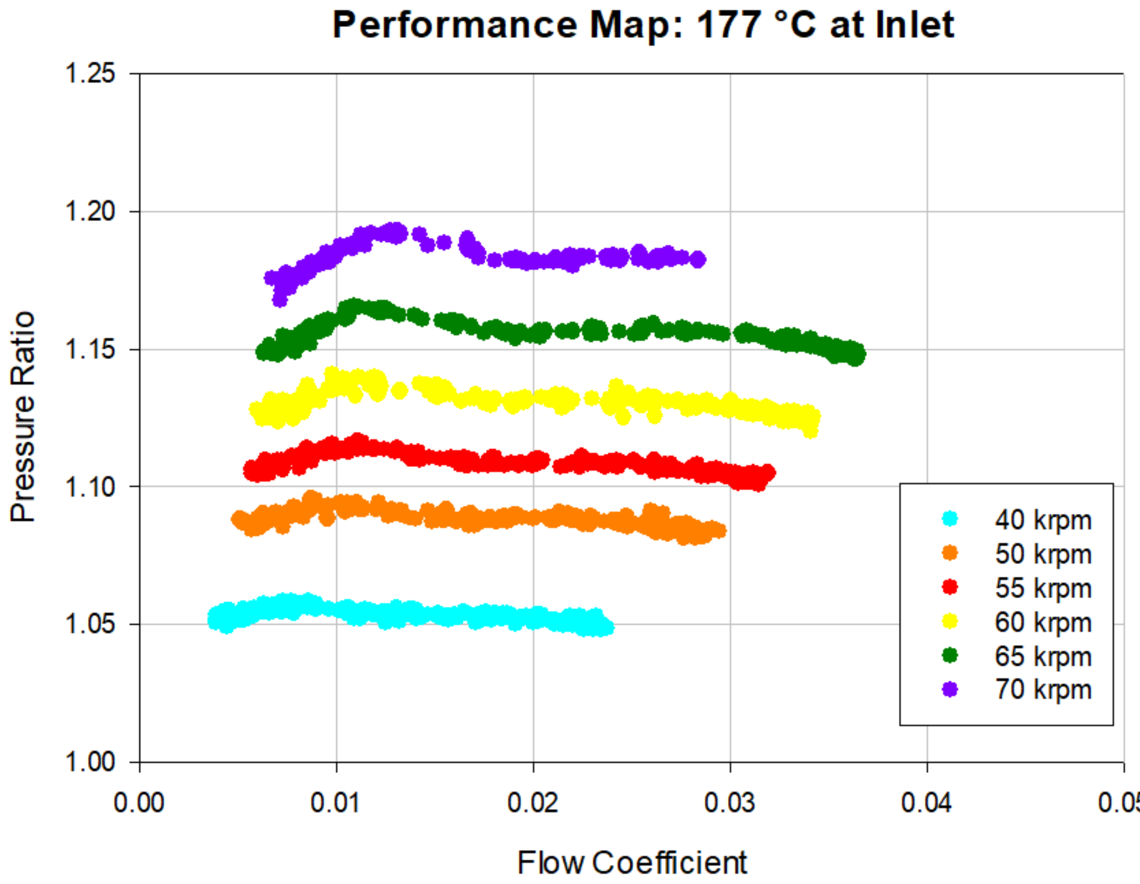
1000+ Hours Laboratory Test Data

Typical Test Run Raw Data



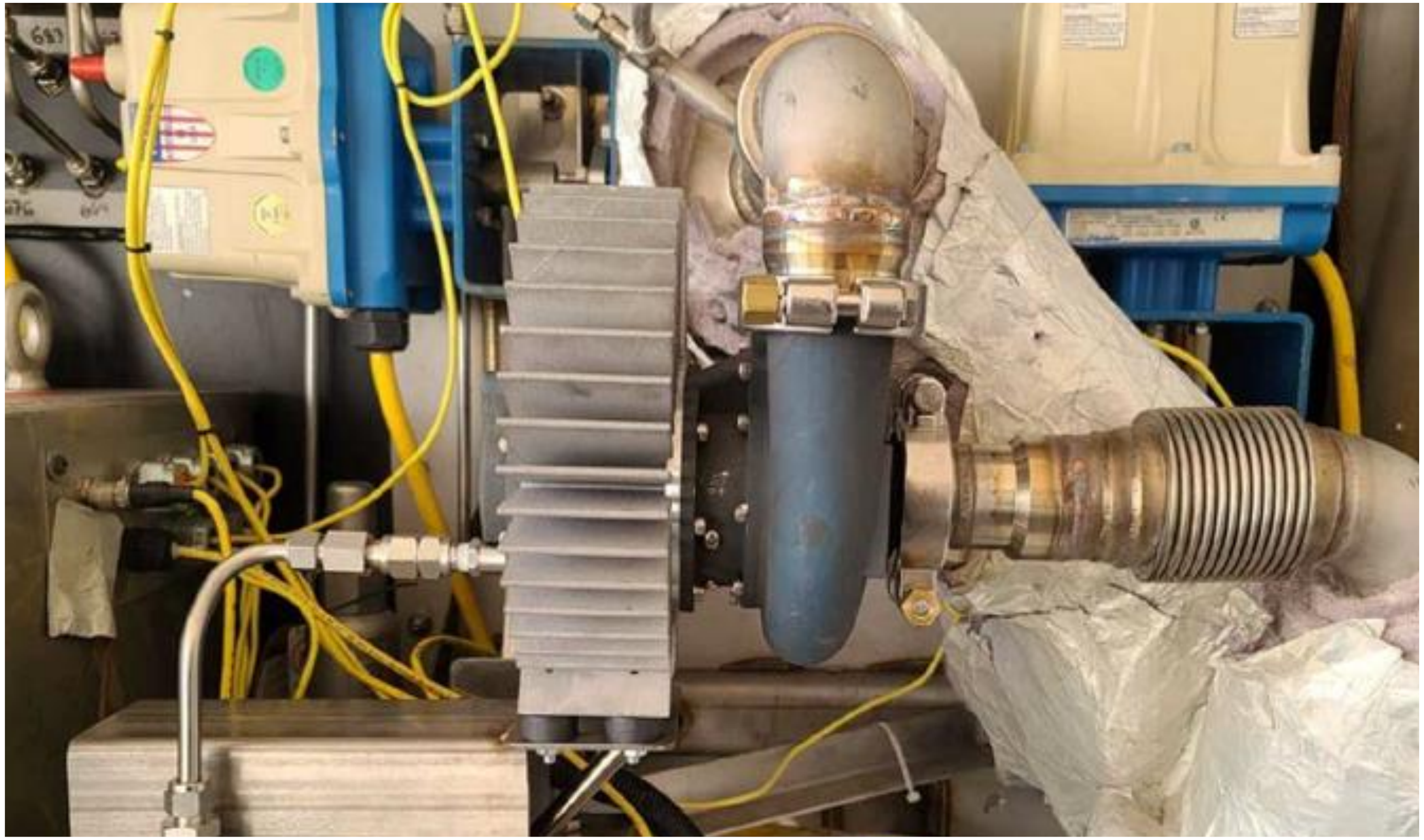


Typical Compressor Performance Map



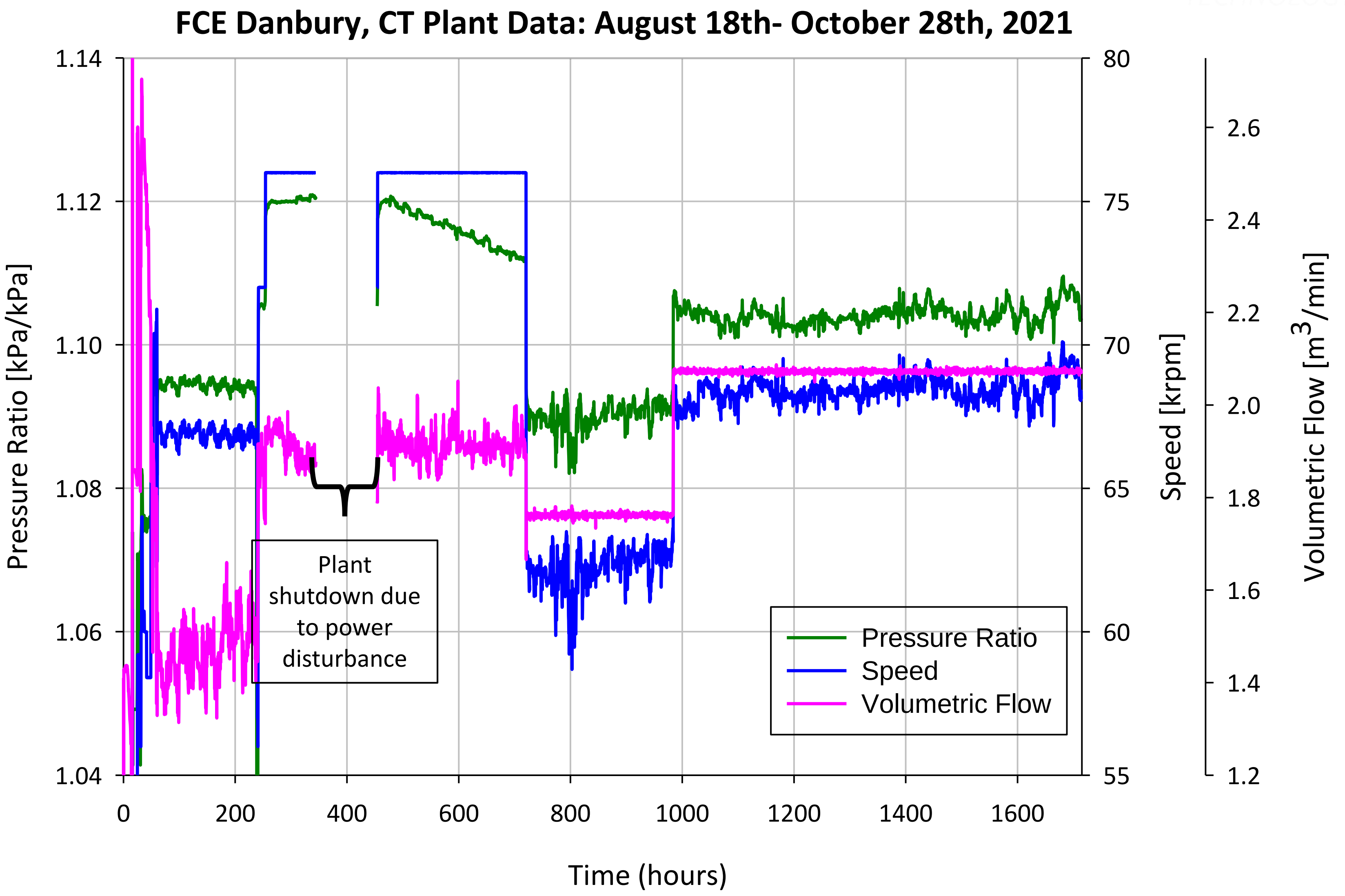
Operation in FuelCell Energy's 100 kW Module

1000 hours on 9/29/2021 → ***TRL-7 Demonstrated. Final Milestone Achieved!***



Operation in FuelCell Energy's 100 kW Module

MiTi's TRL-7 ARCB performance data in FCE's plant



Current Status of Project DE-FE0027895

- All project milestones concluded
- TRL-7 achieved through testing in FCE’s system
- Blower in testing at FCE will achieve upwards of 3000 hours
- Testing end date: 1/31/2021
- Wrapping up scalability, commercialization, and final reporting tasks
- Despite two no cost time extension (NCTEs), project budget is under control.
- Project end-date: 3/31/2021

Additive Manufacturing of High Temperature Centrifugal Impellers for Low Cost SOFC Recycle Blower

DOE SBIR Phase II Award No.: DE-SC0020793

Overall Program Objectives (SBIR Phase II DE-SC0020793)

- To enable generation of low-cost electricity in modular natural gas-fueled solid oxide fuel cell (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 gas re-cycle blowers (**ARCB**) for SOFC BOP applications

Project Team

José Luis Córdova, PhD

- Vice President, Engineering
- Principal Investigator/Thermal Sciences

Rochelle Wooding

- Mechanical Engineer
- Aerodynamic Design/Program Manager

Hannah G. Lea

- Mechanical Engineer
- FEA Design/Data Analysis

Luke A. Montesano

- Mechanical Design
- Test Engineer

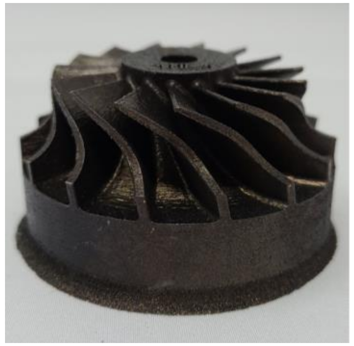
Zach Walton

- Technical Direction, Energy Applications

Zach Murphree, PhD

- Vice President, Technical Partnership

Sapphire Printer



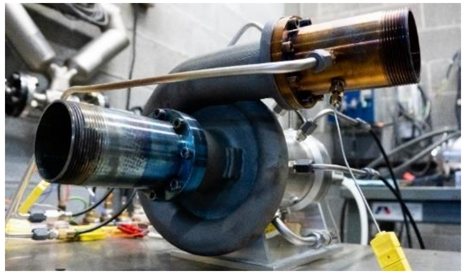
"VELO3D addresses the most difficult additive manufacturing challenges, delivering a comprehensive end-to-end solution that enables on-demand manufacturing of production quality parts with unprecedented design freedom."

Background

Anode Recycle Blowers (ARCBs) for SOFCs

High Temperature (180°C)—Phase II
- DOE Award No.: FE0027895
- Collaboration with FuelCell Energy, Inc. (Danbury, CT)
- Demonstrated ~1200 hours of TRL-6 testing.
- Completed over 600 hours of TRL-7 testing in FCE's 200 kW power plant

Ultra-High Temp. (700°C)—Phase I
- DOE Award No.: FE0031148
- Performance Period: Oct 2017-Mar 2019



Supercritical CO_2 Blower w. 3D-Printed Housing

Heat Transfer Fluid (HTF) Circulator for Gas Phase Pathway CSP Systems
- DOE Award No.: DE-EE0008374
- Operating Conditions
  - Supercritical CO_2
  - 1.5 MW Thermal Load HTF Circulator
  - Pressure: 127 bar to 240 bar
  - Temperature ~550°C up to 700°C

Phase I results: impellers successfully made via additive manufacturing

Phase I Objectives (DE-SC0020793)

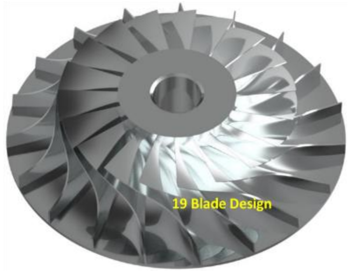
MOHAWK INNOVATIVE TECHNOLOGY

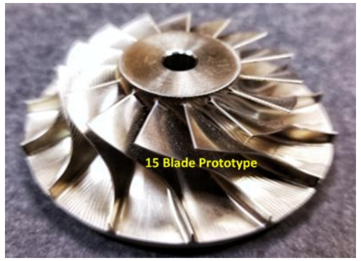
During Phase I, MiTi set out to answer the following questions:

- ***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***

Improvements Derived from Additive Manufacturing

Potential Cost Benefits





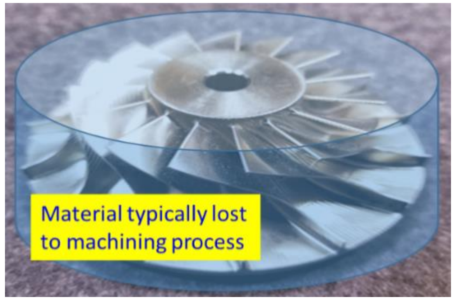
- **At prototype or low count production runs, centrifugal impellers are the highest cost mechanical component in turbomachinery.**

Cost per unit—Inconel 718 impeller for SOFC Blower (700^{o}C gas)

Quantity	Manufacturing Method	# 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	$578
12	SLM-3D Printing	15 or 19	$353

- **CNC prototype machining results in approximately 60 to 70% loss of material volume (or mass).**

Blank initial mass	2.43 kg
Finished impeller	0.73 kg
Material wasted	1.67 kg
Cost of forged Inconel 718	$130/kg
Cost of powdered Inconel	$97/kg
Material cost—machined	$316.00
Material cost—3D printed	$71.00



Potential Aerodynamic Benefits

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

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

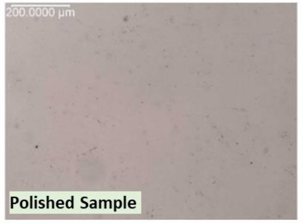
Open Impeller **Shrouded Impeller**

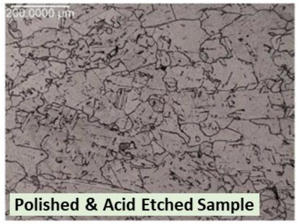
3D-Printed Inconel 718 Mechanical Properties

MOHAWK INNOVATIVE TECHNOLOGY

Under the s-CO2 circulator program (DOE DE-EE0008374)

Metallography





Chemical Composition

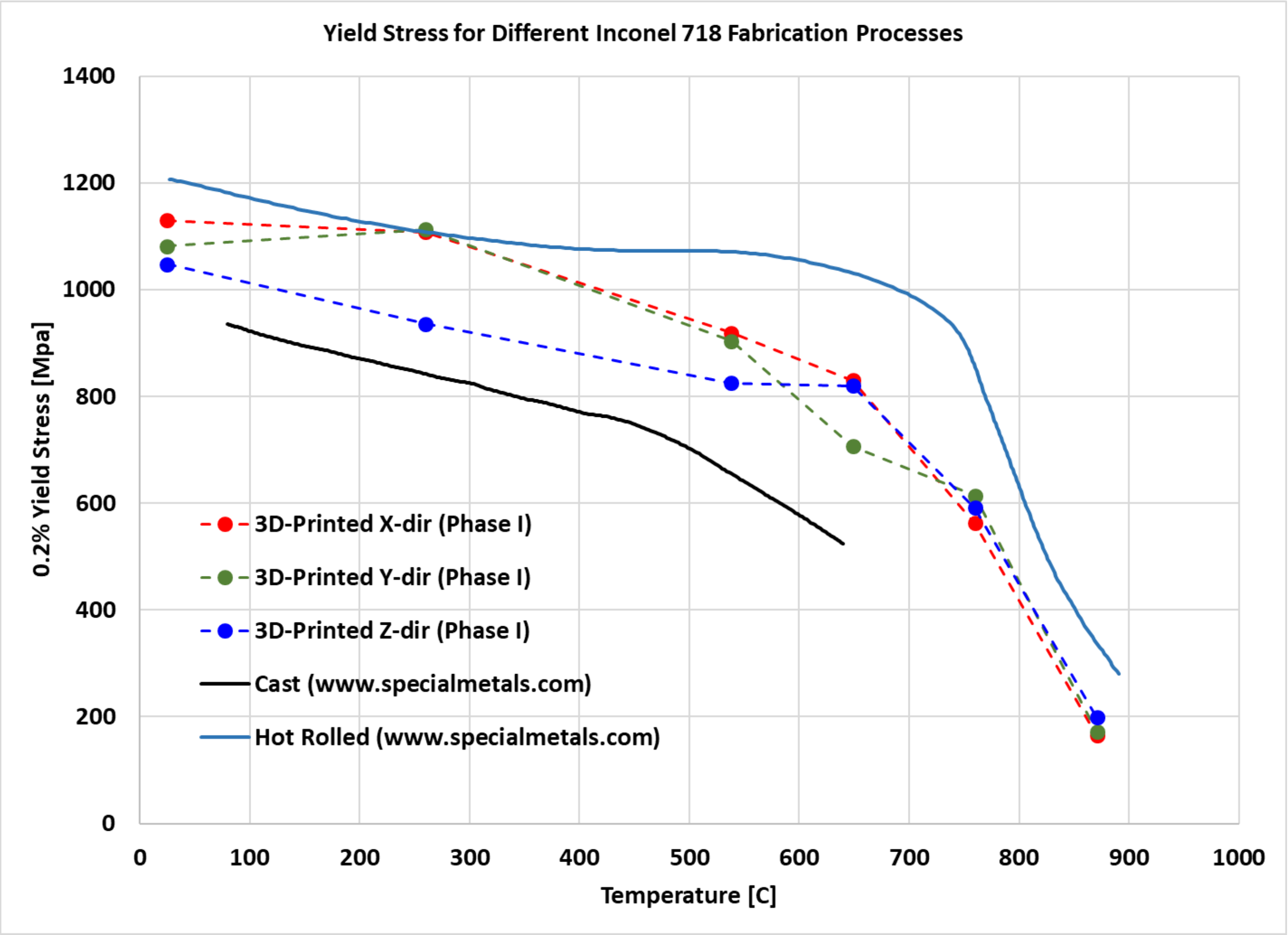
Element	Block 1, Wt %	Block 2, Wt %	Block 3, Wt %	UNS N07718
Carbon	0.037	0.039	0.034	0.08 max
Silicon	<0.0020	<0.0020	<0.0020	0.35 max
Manganese	0.039	0.040	0.042	0.35 max
Phosphorus	0.012	0.013	0.013	0.015 max
Sulfur	0.0039	0.0012	0.0018	0.015 max
Chromium	19.01	17.49	18.03	17.0-21.0
Nickel	52.8	54.1	53.8	50.0-55.0
Molybdenum	3.16	3.18	3.10	2.80-3.30
Aluminum	0.52	0.53	0.52	0.20-0.80
Copper	0.040	0.041	0.040	0.30 max
Cobalt	0.268	0.289	0.233	1.00 max
Titanium	0.99	1.01	0.96	0.65-1.15
Niobium	5.325	5.330	5.310	4.75-5.50
Boron	0.0029	0.0031	0.0029	0.006 max
Vanadium	0.023	0.021	0.022	--
Tungsten	<0.010	<0.010	<0.010	--
Lead	<0.0030	<0.0030	<0.0030	--
Magnesium	0.032	0.032	0.032	--
Tin	0.015	0.011	0.011	--
Zinc	0.036	0.036	0.036	--
Arsenic	<0.0010	0.0044	0.0010	--
Bismuth	0.025	0.025	0.025	--
Calcium	0.0002	0.0002	0.0002	--
Cerium	0.065	0.060	0.063	--
Zirconium	0.025	0.025	0.025	--
Lanthanum	0.0077	0.0069	0.0071	--
Iron	*Remainder*	*Remainder*	*Remainder*	*Remainder*

Tensile Strength (12 samples)

Material Property	3D Printed Average (Ambient)	3D Printed Average (1100 °F)
Young's Modulus (ksi)	2.89E+04	2.12E+04
Yield Strength (ksi)	156.9	130.0
Ultimate Strength (ksi)	190.8	156.3

Material Property	Bar Stock AMS 5662/5663 (Ambient)	Bar Stock AMS 5662/5663 (1200 °F)
Young's Modulus (ksi)	2.90E+04	2.37E+04
Yield Strength (ksi)	150.0	125.0
Ultimate Strength (ksi)	185	145

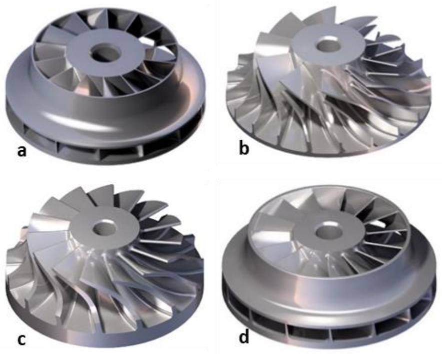
Phase I results: obtained 0.2% yield stress, modulus of elasticity, ultimate stress, & elongation, for different print orientations.



3D-Printed Impeller Fabrication

Is it possible to achieve the required impeller geometries?

Yes it is!



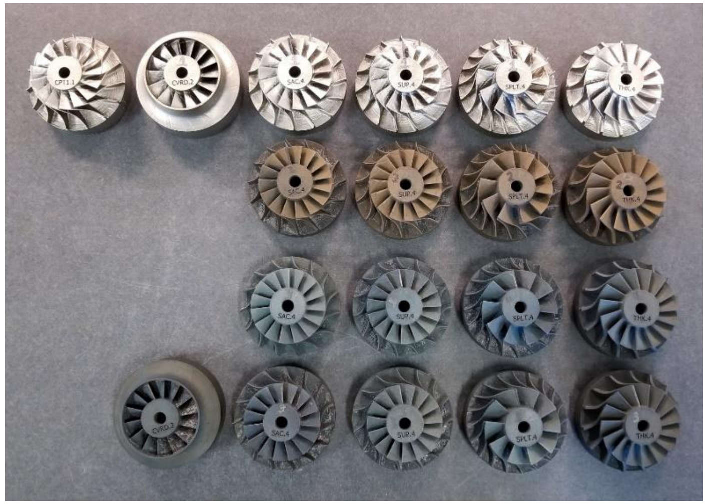
Evolution of process during Phase I:

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

Impellers at different heat treat stages:



Phase II Goals

The Phase II goals are to:

- ***Continue characterization of mechanical properties, e.g. fatigue and creep***
- ***Fabricate impellers and other suitable components using 3D-printing-enabled geometry***
- ***Integrate new or recommission used ARCB prototypes, and install impellers/volutes for testing***
- ***Test component and system performance, including accelerated life***
- ***Demonstrate through techno-economic analysis the cost reduction for SOFC BOP and in general for other applications***

Phase II Program Tasks

- ***Task 1. Project Management***
- ***Task 2. Characterization of Mechanical Properties of Additive Manufacturing Materials***
- ***Task 3. ARCB Scaling and Design Modifications for Additive Manufacturing***
- ***Task 4. Manufacture by 3D Printing of Impellers, Volutes, & Selected Parts for ARCBs***
- ***Task 5. Modification/Integration of ARCBs for Incorporation of 3D-Printed Components***
- ***Task 6. Testing of ARCBs Equipped with 3D-Printed Impellers and other Parts***
- ***Task 7. Techno-Economic Analysis***

Current Status of Project DE-SC0020793 (SBIR Phase II)

MOHAWK INNOVATIVE TECHNOLOGY

- Planned project timeline is 24 months long.
- Project start date: 8/23/2021
- Planned end date: 9/22/2023
- Held Kick-Off Meeting on 10/19/2021.
- Task 2 (first technical task) is underway.
- Project is on time and on budget.

Questions & Feedback

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Thank you for your attention!

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