High Temperature Anode Recycle Blower for Solid Oxide Fuel Cell

Department of Energy Award No. DE-FE0027895

Prepared for DOE Kickoff Meeting
By Mohawk Innovative Technology, Inc.

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Project Team

Mohawk Innovative Technology, Inc.

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

MiTi

- Hooshang Heshmat, PhD
  - Principal Investigator
- Jose Luis Cordova, PhD
  - Program Manager
  - Thermal Management
- James F. Walton II
  - Rotordynamics
- Andrew Hunsberger
  - Aerodynamics
  - Motor/Drive

FCE

- Hossain Ghezel Ayagh, PhD
  - FCE Lead
- Stephen Jolly
  - Systems Design Engineer
- Micah Casteel, PhD
  - Mechanical Engineer

Team Background

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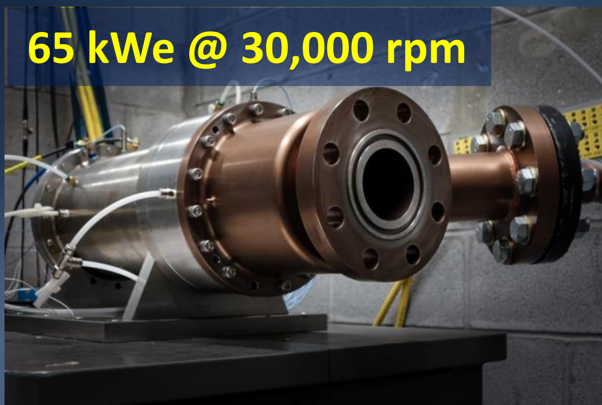
- **MiTi**: Specializes in High-Speed Oil-Free Rotating Machinery and Green Technology
  - Blowers, Compressors, Turbo-alternators, Gas-Turbine Engines, Flywheel Energy Storage, and more
- **Fuel Cell Energy**: is an integrated fuel cell company that designs, manufactures, installs, operates and services stationary fuel cell power plants.

Oil-Free Turbomachinery

ORC Turbogenerator



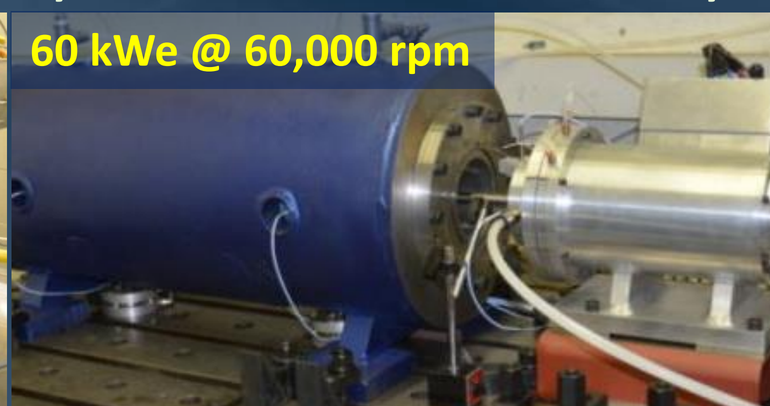
Air Cycle Machine

Hydrogen Blower

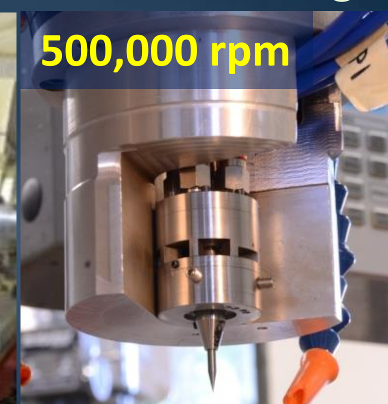
Fuel Cell Compressor

Hydrogen Pipeline Compressor

Flywheel Electromechanical Battery



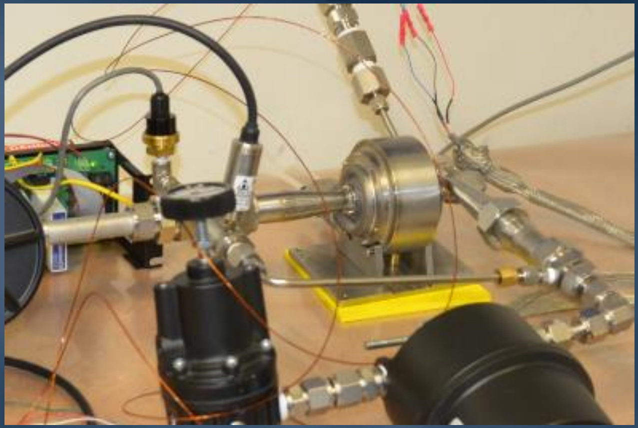
Micro Machining



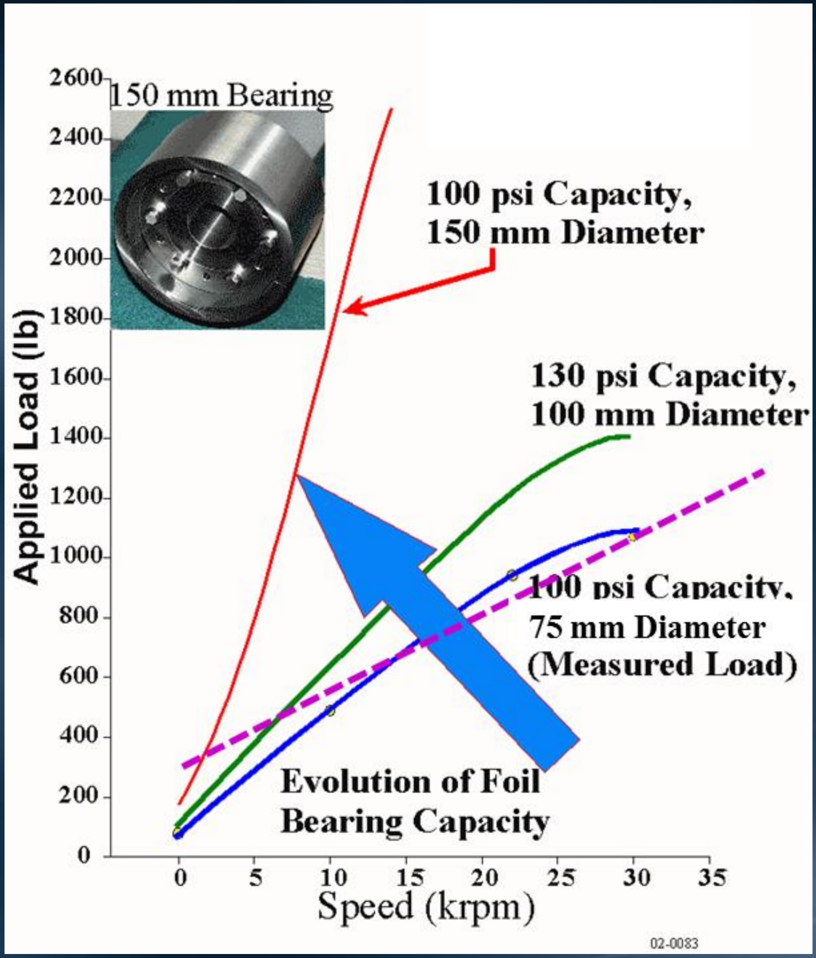
MiTi's Broad Blower and Compressor Experience

200 kW H_2 compressor

1.5 kW H_2 blower



MiTi® Foil Journal Bearings Gen-V (High Load & Temp)



- Sizes from 6 to 200 mm Diameter
- DN to over 6 Million
- Speeds greater than 700,000 RPM

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Company Overview

- >50 sites operating on 3 continents
- > 5 billion kWh's ultra-clean power generated
- Global manufacturing
- Robust intellectual property portfolio

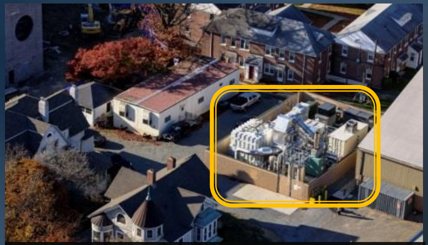
Design & Manufacture

Project Development

Turn-key Project Delivery

Plant Operation

Energy Supply

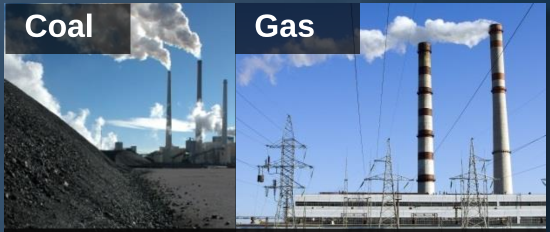


Micro-grid CHP

Utility Grid Support

Distributed Hydrogen Tri-Gen

Energy Recovery

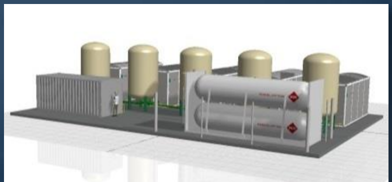


Carbon Capture

Gas Pipeline

H_2 Recovery *(EHS)*

Energy Storage



Long duration storage

Power-to-Gas

NASDAQ: FCEL
www.fuelcellenergy.com

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FCE SOFC Overview

- FCE is developing Solid Oxide Fuel Cell (SOFC) for stationary power generation and electrolysis applications for Department of Energy (DOE)
- Initially demonstrated the operation of a 50 kW SOFC system
- FCE has selected 200kW as the commercialization platform for stationary power generation based on cost studies and voice of the customer studies
- Recent DOE project includes demonstration of a 400 kW system (2x 200kW units) at a third party site

50 kW Powerplant

200kW Powerplant

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400kW SOFC System

- The 400 kW SOFC system consists of two 200 kW SOFC power plants
- Each 200 kW skid is sized as standard ISO 20’ x 8’ shipping container
- Thermally integrated modules enable compact and lower cost system
- Unattended Operation with Remote Monitoring
- >60% Electrical Efficiency
- >5000 hours of operation
- Heat recovery capability for > 80% total thermal efficiency

Project Objective

- To develop a scalable Oil-Free High Temperature Anode Recycle Blower (A-RCB) for Solid Oxide Fuel Cell (SOFC) power plants.
  - Design of a scalable oil-free high temperature SOFC recycle blower
  - Verify the technology through prototype proof of concept testing
  - Validate economic viability through cost-benefit analysis

Technical Approach

Project Structure

- Task 1: Project Management and Planning
  - Task 1.1: Report Preparation
- Task 2: Definition of Requirements
  - Performance
  - Economic
- Task 3: Design of Proof of Concept System
  - Task 3.1: Preliminary Design
  - Task 3.2: Preliminary Design Review
  - Task 3.3: Detailed Design
- Task 4: Hardware Fabrication and Integration
- Task 5: Blower Performance Test
- Task 6: Assessment of Outcome and Plan Forward

Task 2: Definition of Requirements

- Operating conditions specified with input from subcontractor Fuel Cell Energy Inc.
- Three sets of conditions to consider
  - Start Up Transient
  - Nominal Operation
  - Rated Operation

Task 2: Operating Conditions

Three main operating regimes:

			Operating Condition		
			Nominal	Rated	Start-Up
Temperature	T	[°C]	101	130	180†
Inlet Pressure	P	[kPa]	103.9	103.9	103.9
Mass Flow	$\dot{m}$	[kg/s]	0.033	0.036	0.022
Pressure Increase	DP	[kPa]	7.2	8.7	TBD
Mixture Components					
Hydrogen	H_2	mol %	11.87	11.86	51.2
Methane	CH_4	mol %	12.85	12.85	5.62
Carbon Monoxide	CO	mol %	5.13	5.17	8.54
Carbon Dioxide	CO_2	mol %	24.36	24.34	7.23
Water	H_2O	mol %	44.36‡	44.4‡	24.92
Other		mol %	1.43	1.38	2.49

‡*Requires encapsulation of electrical components.*

†*May require enhanced thermal management*

Overall very low risk operating conditions.

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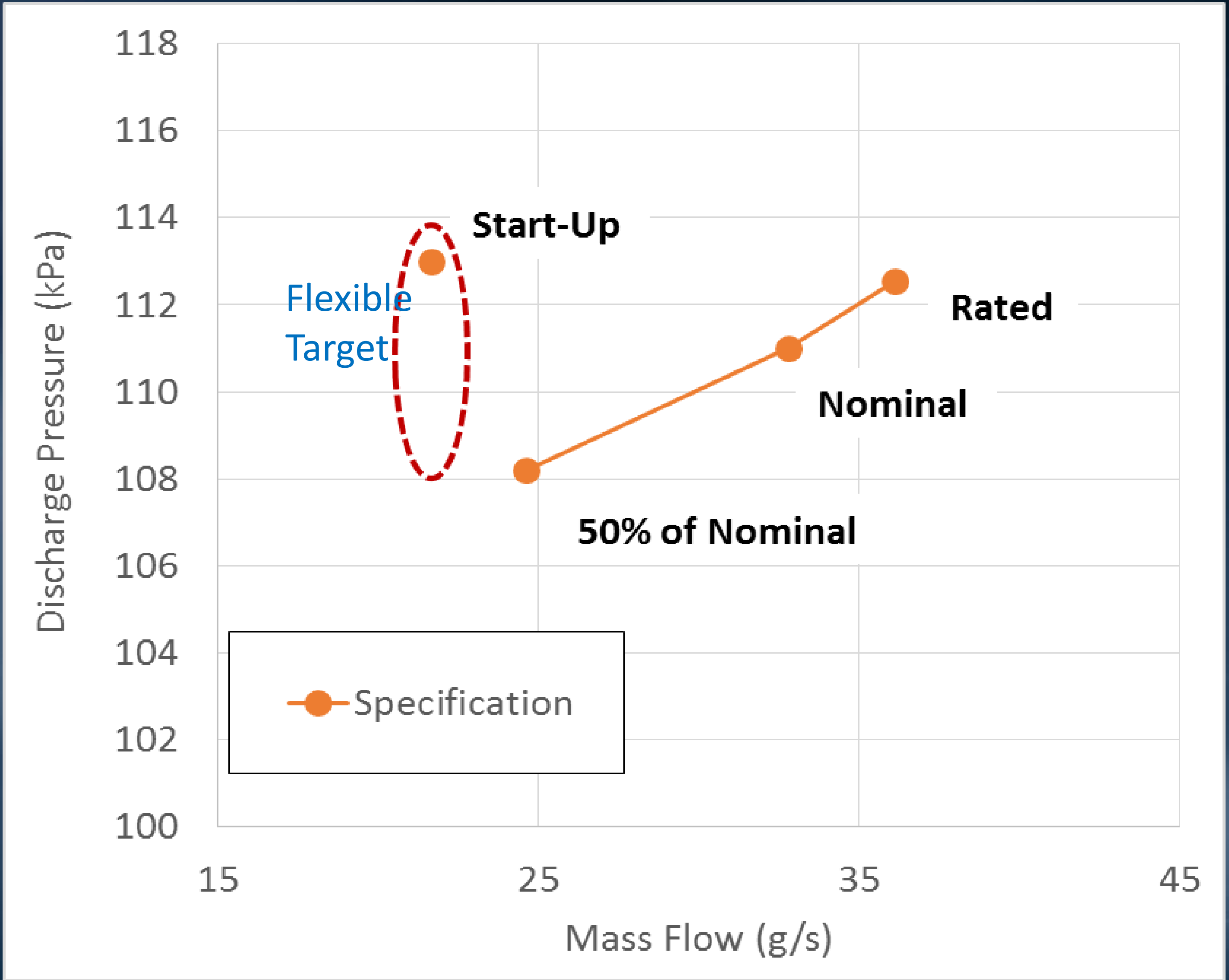
Task 2: Pressure-Flow Requirements



Task 2: Design Considerations

- Net Power Input < 1.5 kW
- Oil-Free Foil Bearing Design
  - No Lubricant Contamination
  - Low Power Loss Bearings
- Air Cooled if Possible
- Economical Design
  - Low Capital Cost
  - Low Maintenance Cost
  - Low Operating Cost

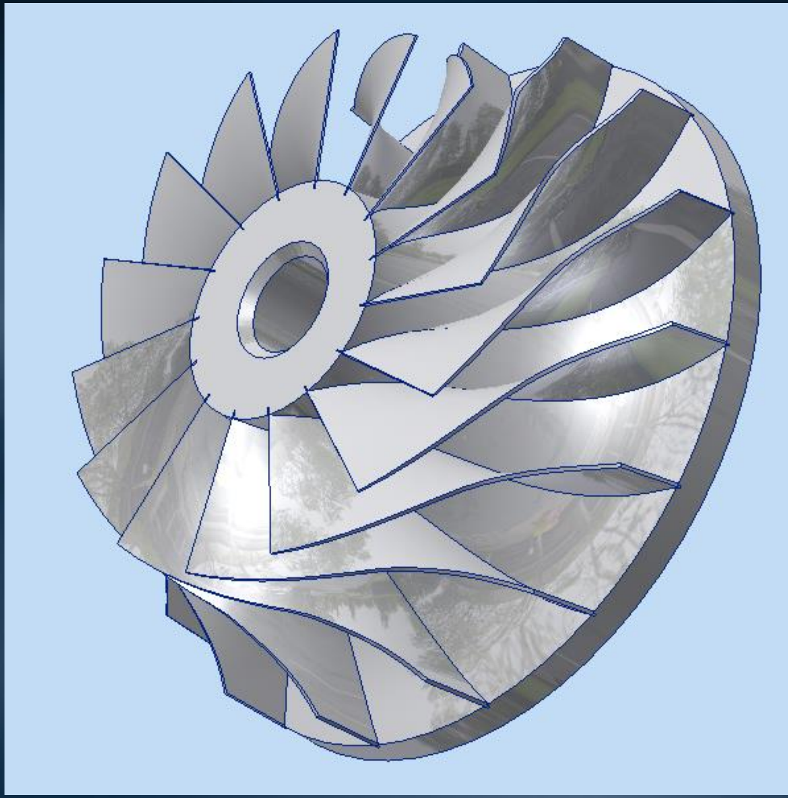
Task 3: Prototype Design

- Oil-Free System Design Approach
  - Aerodynamics
  - Identification of Motor
  - Power Electronics Integration
  - Rotor-Bearing Design and Dynamics
  - Thermal Analysis

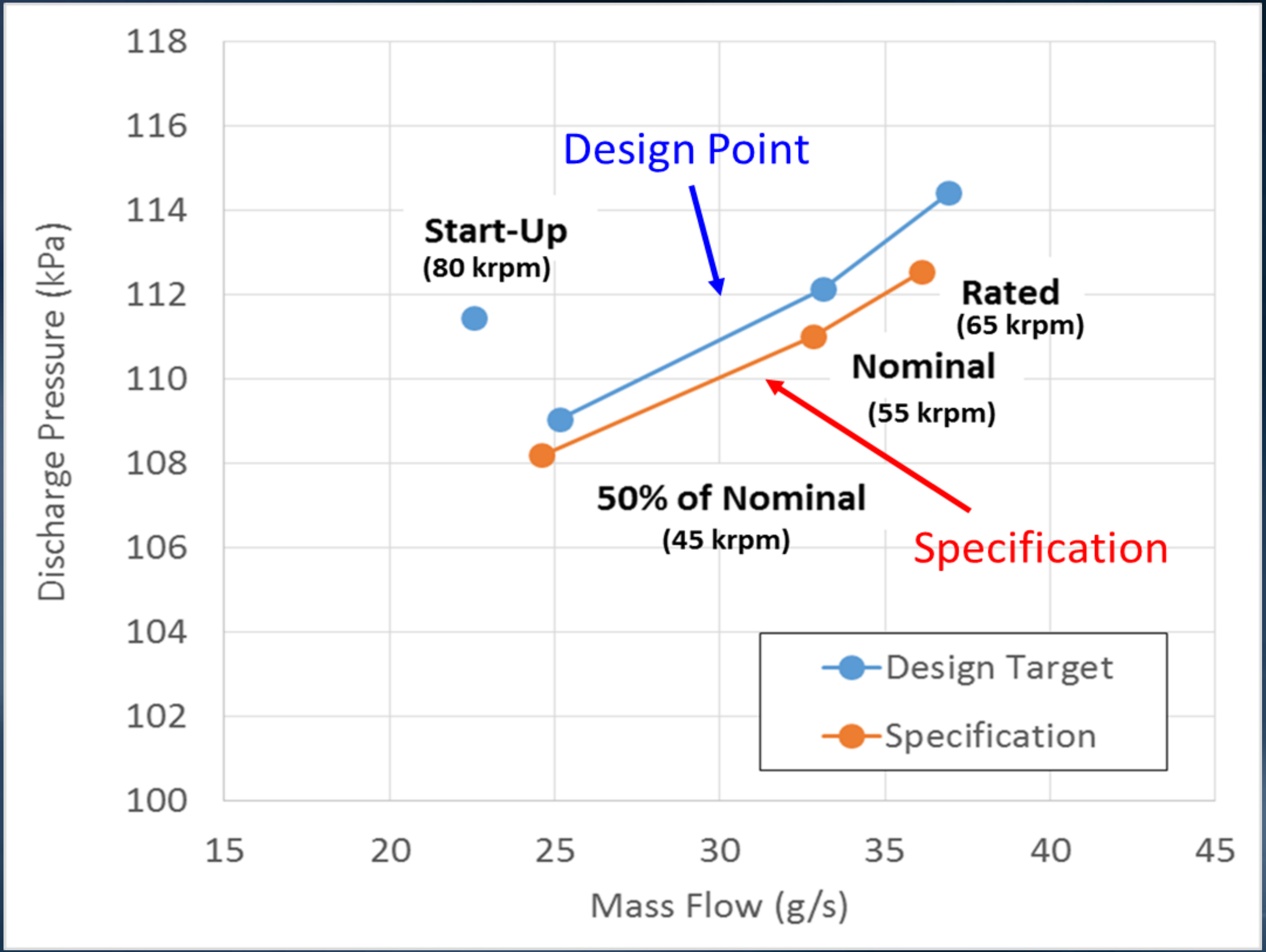
Task 3: Aerodynamic Design Summary

Preliminary Sizing Results

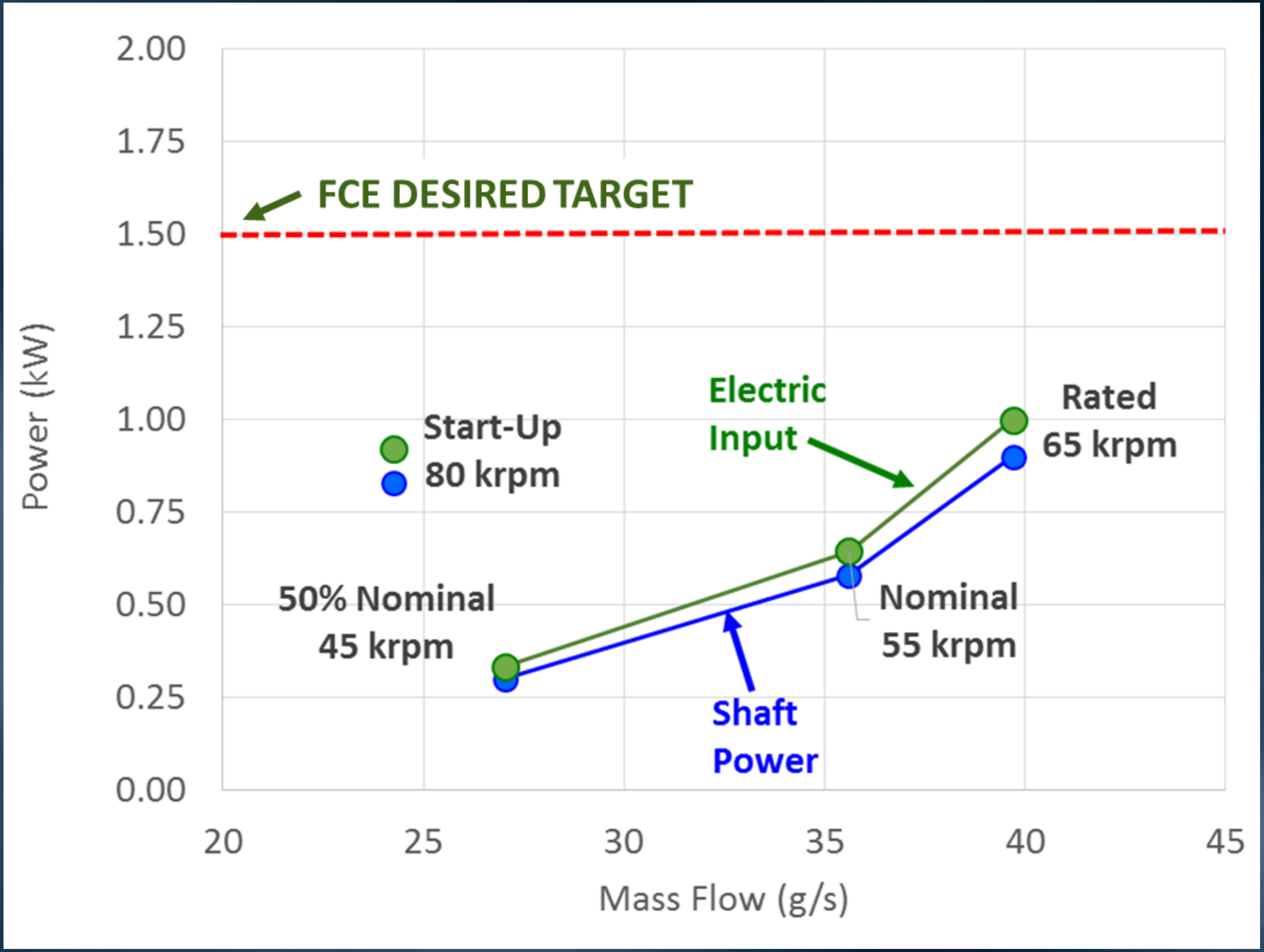
- Type = Centrifugal
- Diameter = 50 mm
- Operating Speed Range
  - 55 krpm < N < 80 krpm
- Efficiency > 85%
- Material Selection
  - Stainless Steel



Task 3: Aerodynamic Design Performance



Task 3: Aerodynamic Power Performance



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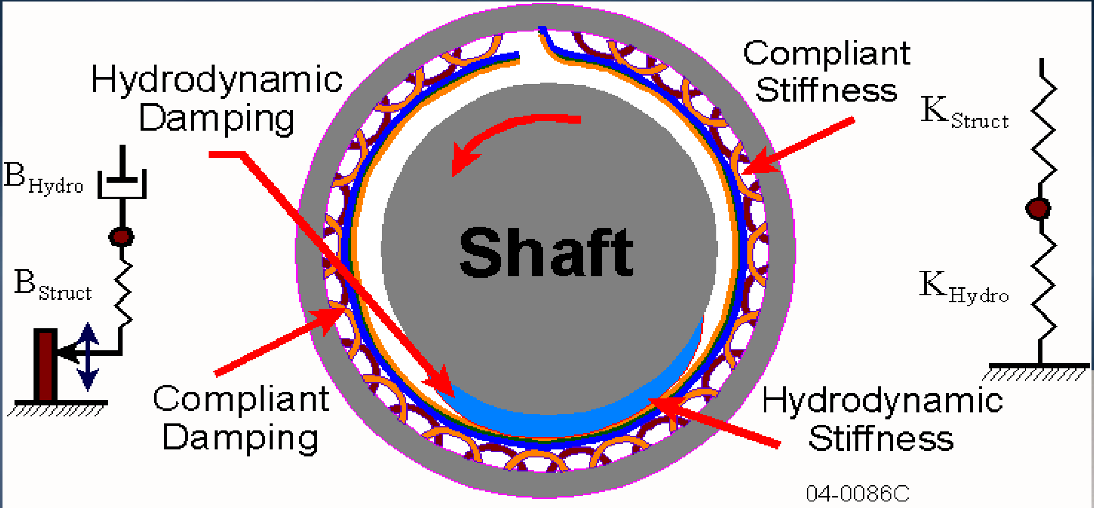
Task 3: Design – Motor Selection

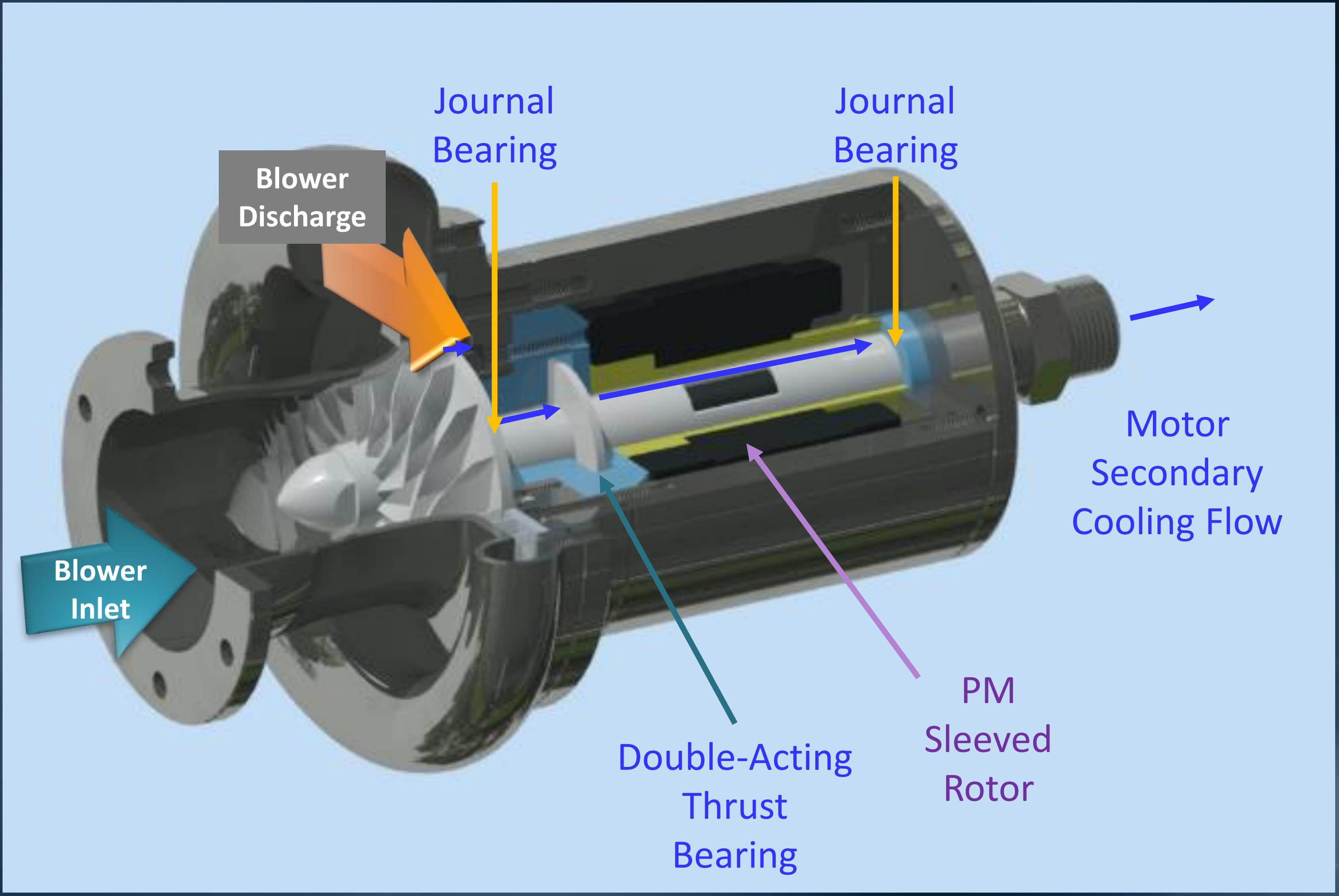
- Candidate Motor Types
  - Laminated Induction
    - Lower cost
    - Requires Smaller Air Gap
    - Requires Special Sealing
  - Permanent Magnet
    - No Special Seal Required
    - Permits Larger Air Gap
    - Higher Efficiency

Task 3: Oil-Free Foil Bearing Fundamentals

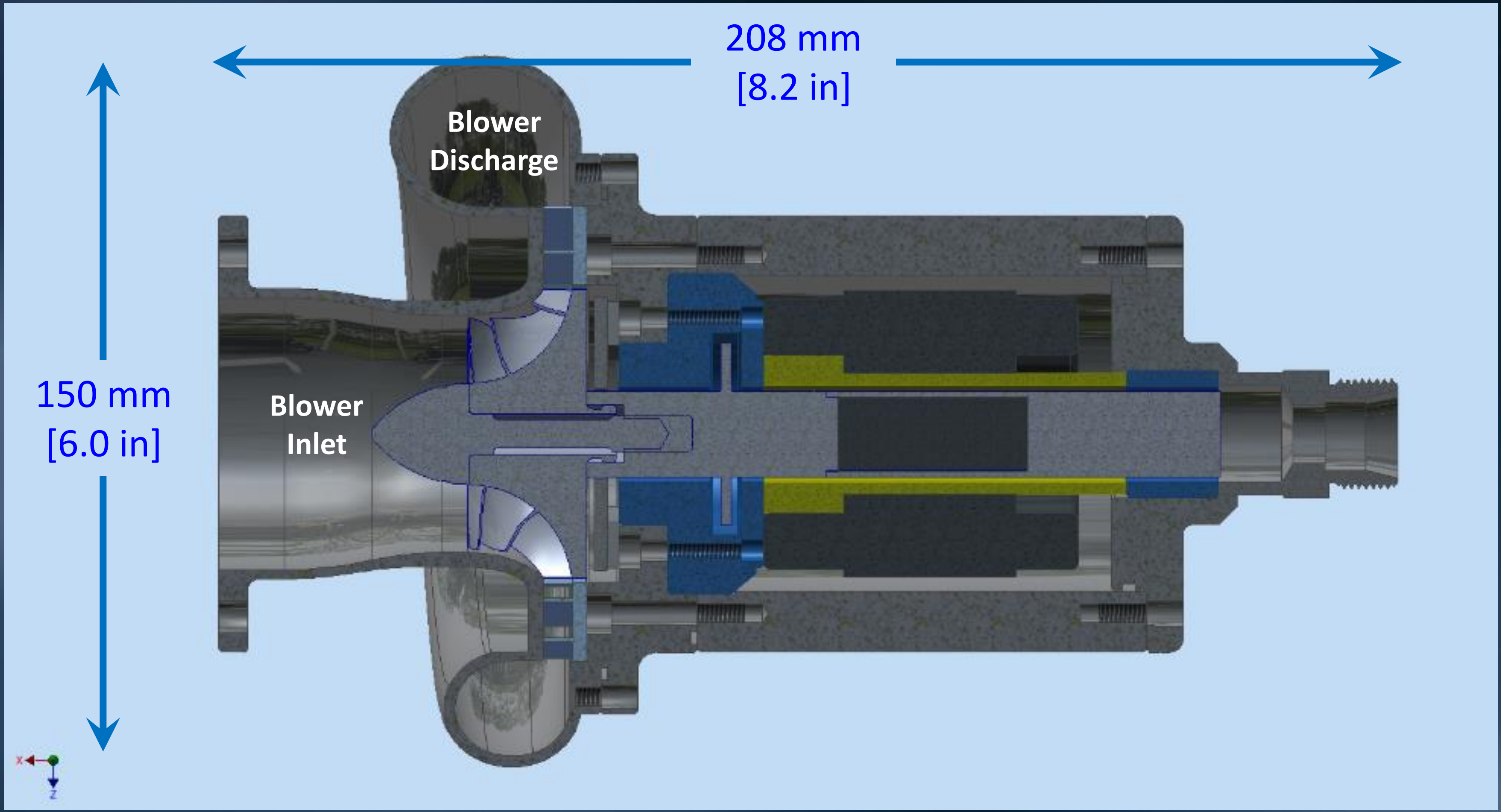
- Class of Hydrodynamic Self-Acting Gas Bearings
- Large Load Capacity and Damping/Stiffness Characteristic



Task 3: Blower Layout

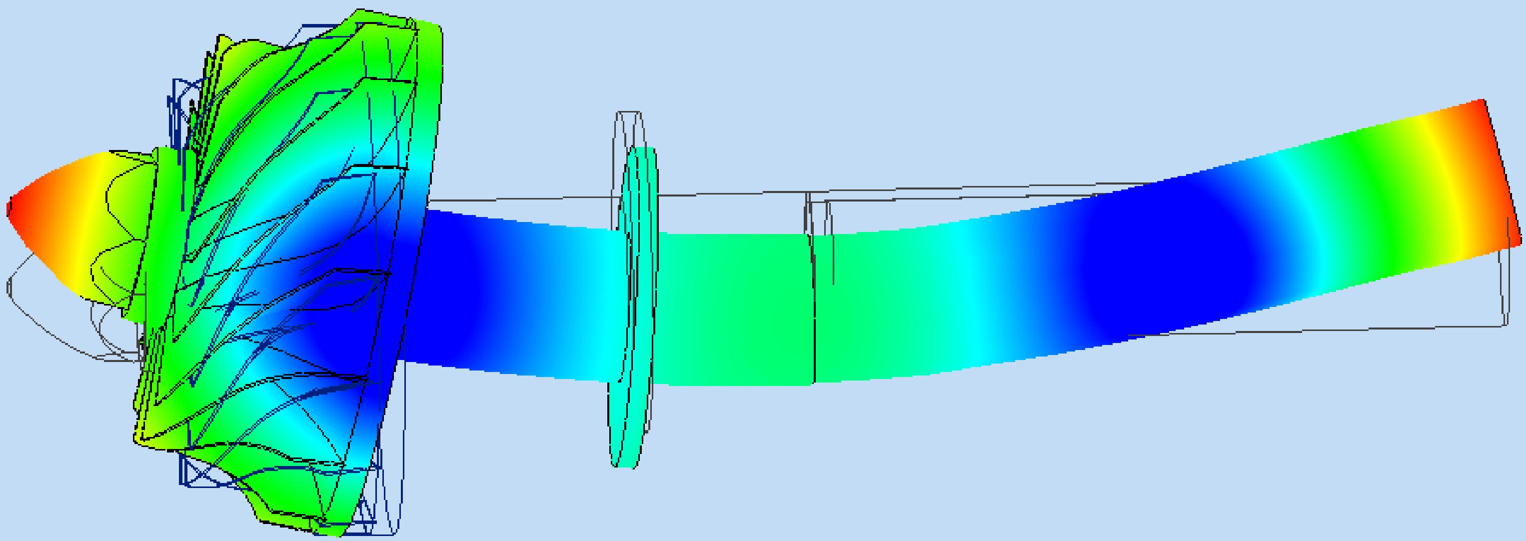


Task 3: Blower Cross Section



Task 3: Rotordynamics

1st Bending Critical Speed @ 157 krpm



2x Margin Relative to Max Operating Speed

Task 3: Work In Progress

- Complete Preliminary Layout
- Detailed Design
  - Rotating Components
  - Housing
  - Bearings
  - Thermal Management
- System Integration
- Manufacturing & Assembly Drawings

Task 4: Hardware Fabrication and Integration

- Fabricate and Instrument Prototype
  - Vibration/Displacement Probes
  - Thermocouples/Pressure Transducers
- Preliminary and Checkout Tests
  - Validate Instrumentation Operation
  - Verify Motor/Controller Operation
  - Confirm Rotor Lift-Off Speed
  - Demonstrate Low Speed Operation with Similitude Gas

Task 5: Test and Evaluate

- Demonstrate ability to achieve full design speed
- Measure flow rate and pressure/temperature rise with similitude gas and map performance characteristics
- Compare measured and design performance

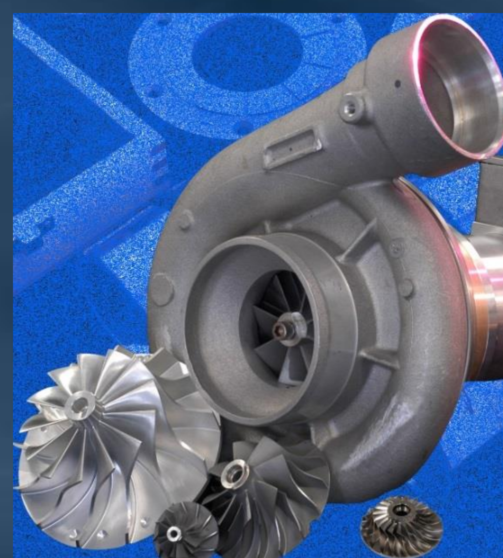
- ***Phase II*** – Test at FCE in a relevant environment

Task 6: Assessment and Plan Forward

- Compare mapped performance to design predictions
  - Identify potential design modifications to improve performance
- Use performance and cost data to identify paths for production cost reduction
- Assess scalability for higher capacity SOFC applications

Task 6: Oil-Free Blower Scalability

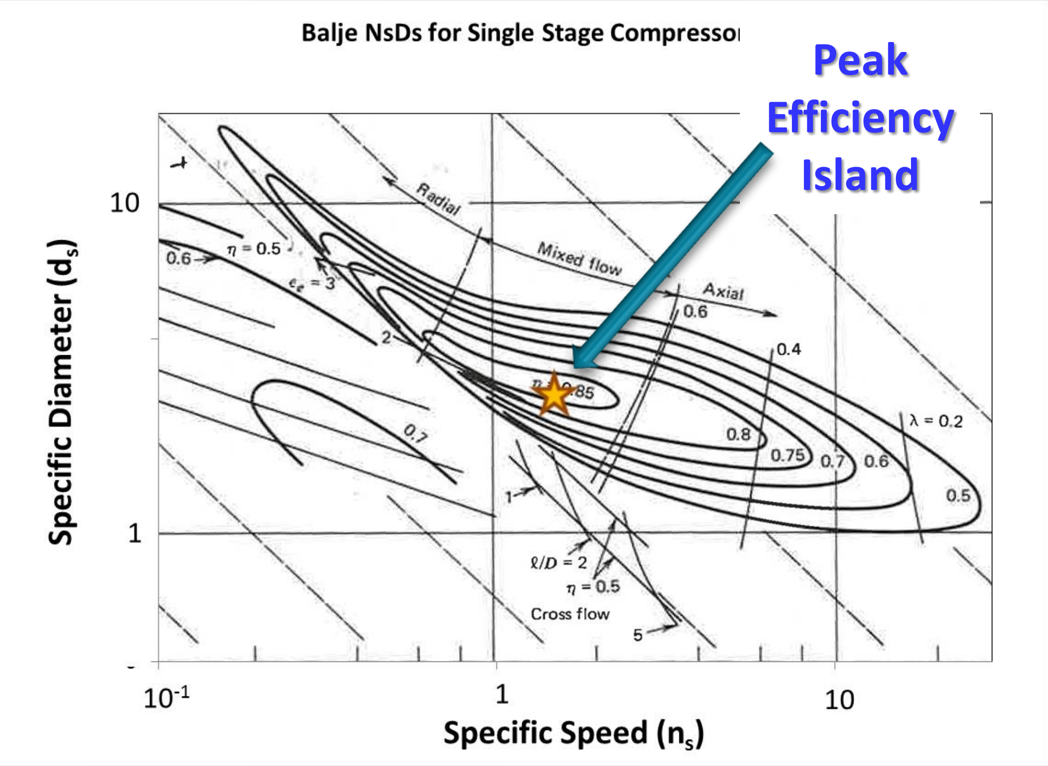
- MiTi Designs Capable of Supporting 100 kW to Multi-Megawatt SOFC
- MiTi has Demonstrated Oil-Free Blowers from 1 to 200 kW



Task 6: 50 kW Blower for 10 MW SOFC Scalability (Cont.)

High Efficiency Centrifugal Impeller Design

- Dia. = 125 mm
- $\dot{m}$ = 3.5 kg/s
- CDP = 18 psia
- Speed 50 kRPM
- Efficiency > 87%



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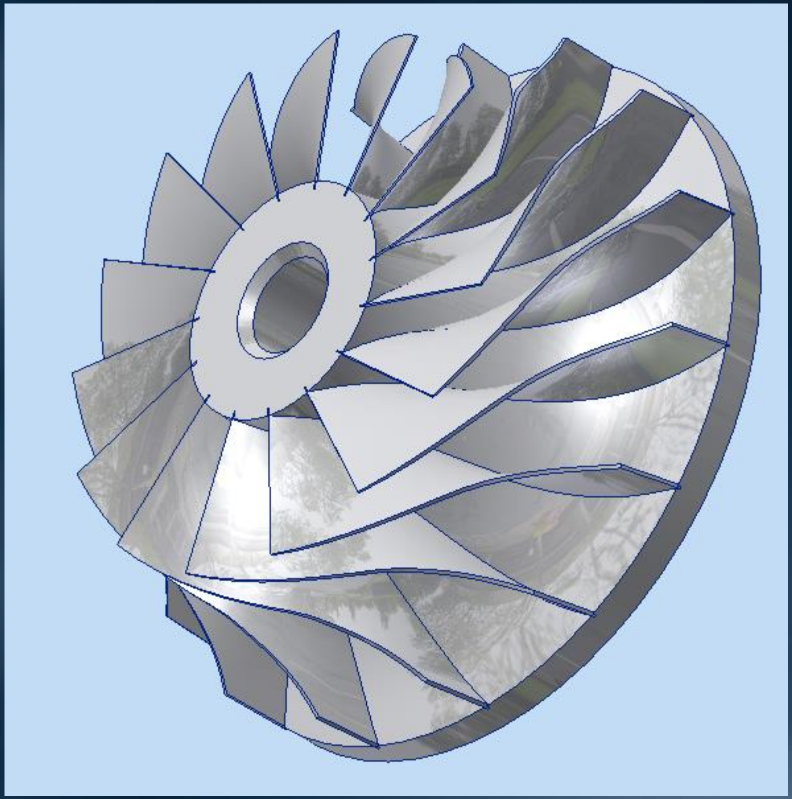
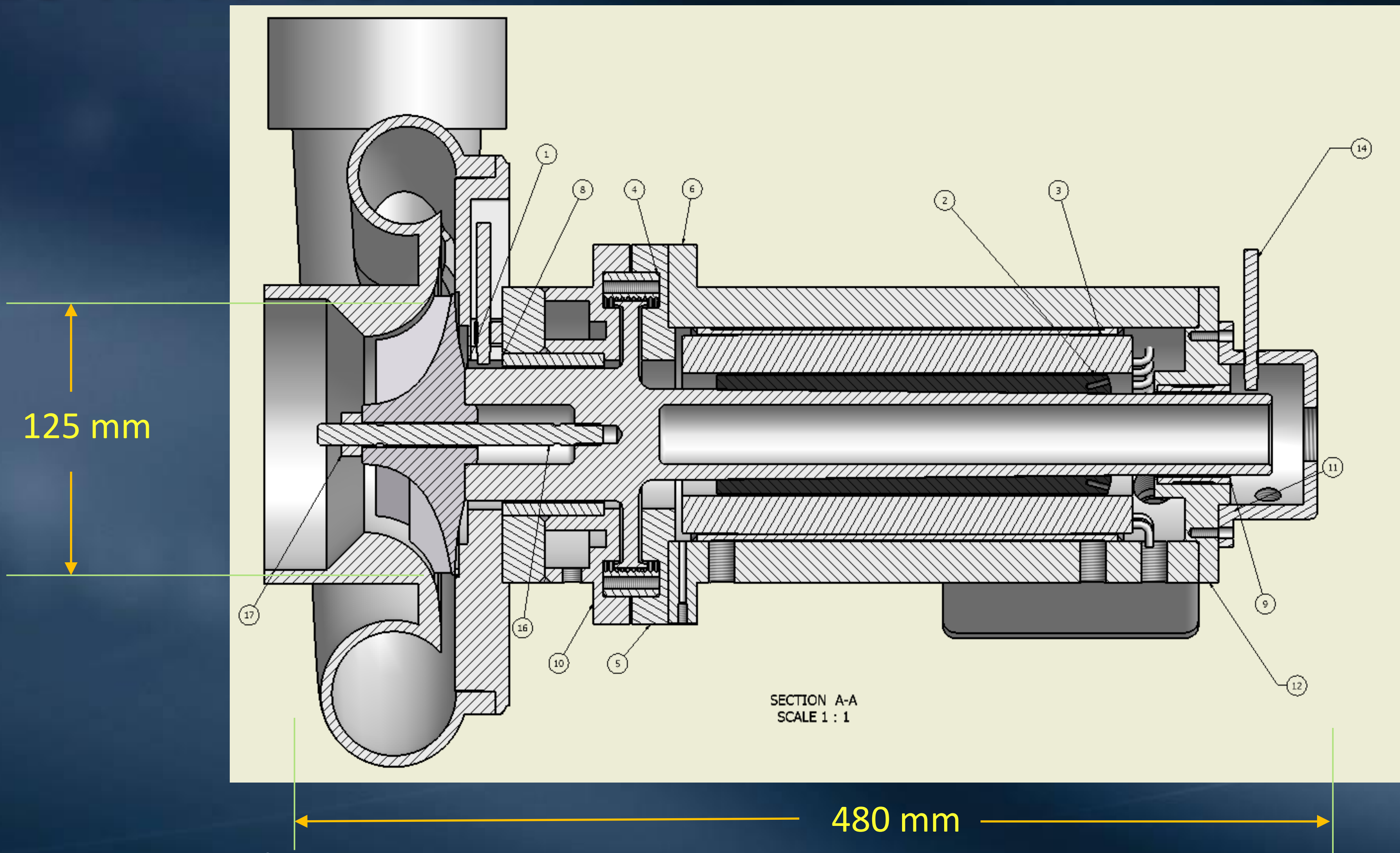
Task 6: Aerodynamic Design for 10 MW SOFC

Preliminary Sizing Results

- Type = Centrifugal
- Diameter = 125 mm
- Power = 50 kW
- Efficiency > 87%



Task 6: Notional 50 kW Blower for 10 MW SOFC



Task 6: Cost Considerations and Scalability for Commercialization

- **Projected Cost After Product Development**
- Estimated Cost for First 10 Units
  - 1.5 kW: $10k - $15k / unit
  - 50 kW: $40k - $60k / unit

Project Budget

- Total Estimated Cost: $ 758,855.00
  - Government Share: $ 598,855.00
  - Recipient Share: $ 160,000.00

Risk Management

- Main Risks (R) and Planned Mitigation Strategies (M):
  - R: Thermal management: Goal for natural air cooling may result in insufficient motor cooling at startup operating condition
    - *M: Design with provision for fitting optional oversized housing fins for enhanced natural cooling*
    - *M: Prepare design with provisions for housing modification to use previously proven forced cooling with a closed water/glycol and radiator loop*

Risk Management (Continued)

- Main Risk (R) and Planned Mitigation Strategies (M):
  - R: Schedule of long lead items: Motor Magnet procurement may cause prototype fabrication delay
  - *M: Handle motor set component procurement as a critical path step.*
  - *M: Secure quotes from multiple vendors*

Risk Management (Continued)

- Main Risks (R) and Planned Mitigation Strategies (M):
  - R: Prototype Fabrication Cost: Proof of concept fabrication methods may be too expensive for eventual production
  - *M: Minimize part count during detailed design*
  - *M: Plan for implementation of reduced cost fabrication methods for production, e.g.: castings*

Technology Readiness Level

- TRL Definitions
  - TRL 5 - System/subsystem/component validation in relevant environment:
  - TRL 6 - System/subsystem model or prototyping demonstration in a relevant end-to-end environment
- Prototype will be a high TRL 5 at end of Phase I
- Will achieve TRL 6 at end of Phase II

Summary

- Design Requirement Reviewed
- Preliminary Design and Layout Underway
- Manufacturing to Begin 2017
- Technology is Scalable to meet Multi-Megawatt SOFC Applications