Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meeting

Arlington VA

Project ID # PD016

May 17, 2012

Oil-Free Centrifugal Hydrogen Compression Technology Demonstration

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Mohawk Innovative Technology, Inc.

Albany, NY

Overview

Timeline

- Start Sept 1, 2008
- Funding Authorized 2/28/09
- Extended End May 30, 2013
- 80 % Complete

Barriers

- Hydrogen Delivery Compressor
  - Reliability
  - System Cost
  - Efficiency of H_2 Gas Compression

Budget

- Total Project Funding
  - $2,992,407 DOE
  - $748,437 Cost Share
- FY11 Funding: $620k
- Planned FY12 Funding: $600k

Partners

- Lead: Mohawk Innovative Technology, Inc.
  MiTi - Albany, NY
- Mitsubishi Heavy Industries
  MHI - Hiroshima, Japan

Project Objectives

Design a reliable and cost effective centrifugal compressor for hydrogen pipeline transport

- Flow 240,000 to 500,000 kg/day
- Pressure Rise to 300-500 psig up to 1,200-1,500 psig
- Contaminant-Free/Oil-Free Hydrogen

Category	2005 Status	FY2012 (Project Target)	FY2017
Reliability	Low	Improved	High
Energy Efficiency	98%	98%	>98%
Capital Investment ($M) (based on 200,000 kg of H2/day)	$15	$12	$9
Maintenance (% of Total Capital Investment)	10%	7%	3%
Contamination	Varies by Design		None

Hydrogen, Fuel Cells & Infrastructure Technologies Program [DOE Publication]

Commercial Potential

- **Partner Mitsubishi Heavy Industries - Compressor Corporation (MHI) - Business Areas**
  - Energy Field
    - Pipeline Compressors
    - LNG
    - Gas Injection/Processing
  - Petrochemical Industries
- **Interim Outlet For Advanced Centrifugal Compressor Technologies In Meaningful Natural Gas And Other Industrial Uses**

MiTi & MHI Using Two-Tier H_2 Compressor Design Approach

- Single-Entry versus Dual Entry Centrifugal Compressor Designs
- Computational Fluid Dynamics (CFD)
- Finite Element Analysis (FEA)

Material Measurement Laboratory

- Compatibility of Foil Bearing and Foil Seal Materials in H_2 Environment

International Institute for Carbon-Neutral, Energy Research

- Consultation on Materials Selection

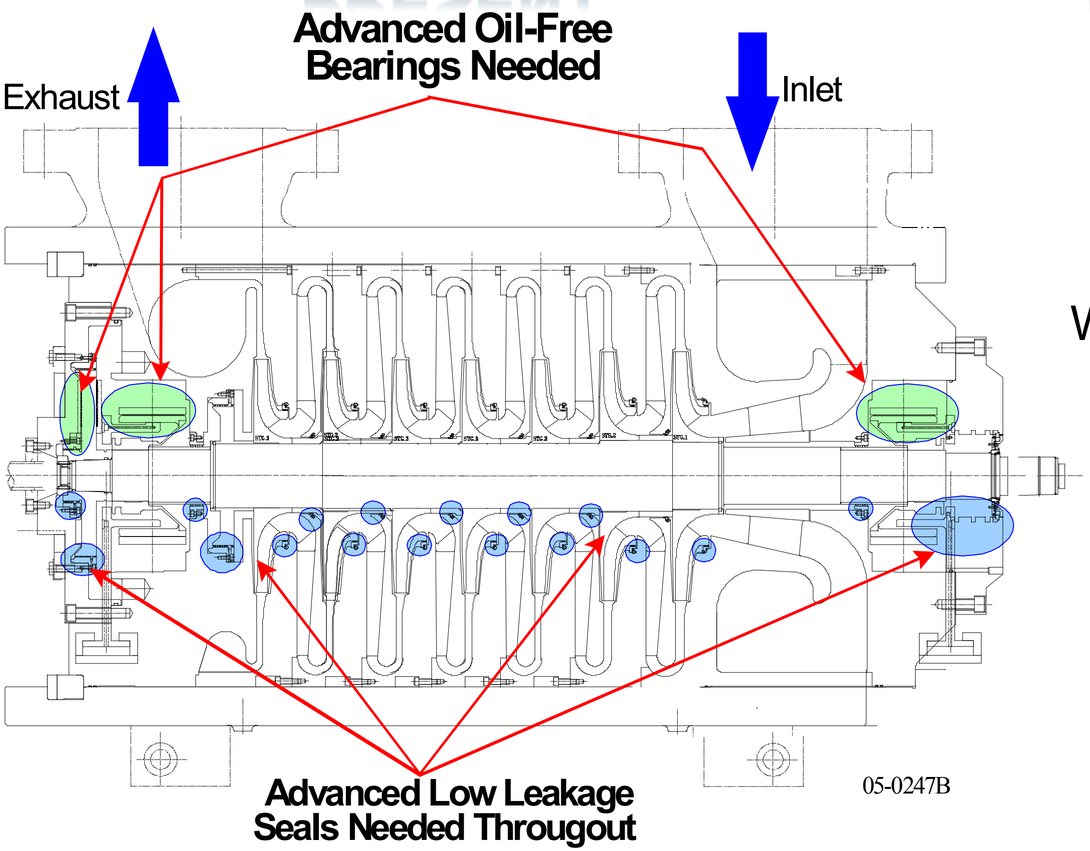
Sandia National Laboratory

- Consultation on Materials Selection

- **Recognized Compressor Design Consultant**
- **CFD Consulting Group With Compressor Expertise**

Comparative View of Present & Future In Gas Compression Technology

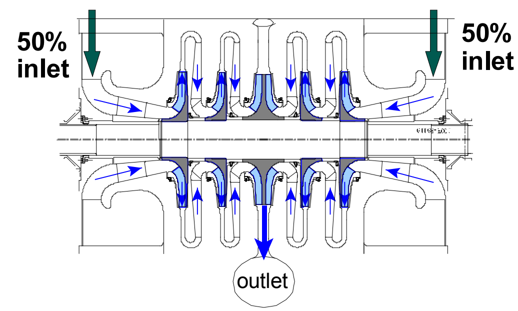
PRESENT



12,000 rpm

DEVELOPMENTS FOR FUTURE

Four Times Smaller In Size And Weight And Twice As Efficient SOA



60,000 rpm

Compressor Design Methodology

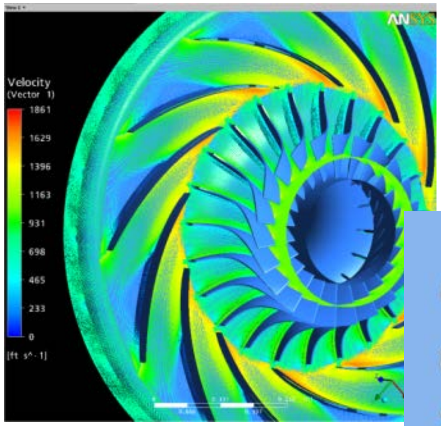
✓ **Compressor Design Analysis**
- Mean Line Analysis, CFD, FEA

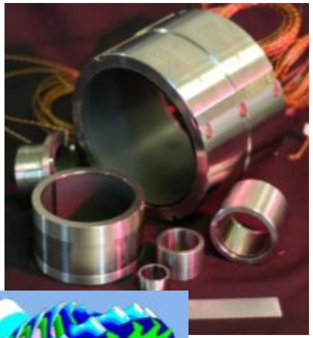
✓ **Sub-Component Design**
- Foil Bearings & Seals
- Coatings

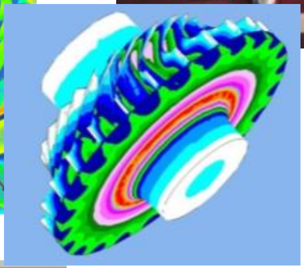
✓ **Design Single-Stage Compressor**
- Impeller, Diffuser and Others
- Drive System & Test Loop

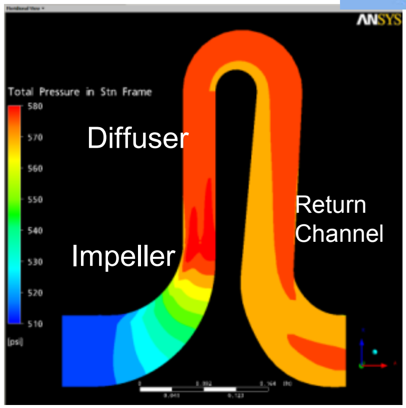
▸ **Single-Stage Proof Testing**
- Fabricate & Characterize Pressure & Flow

❑ **Scale System Design**
- Predict Complete System Performance
- Update Multi-Stage, Multi-Frame Design
- Economic Analysis



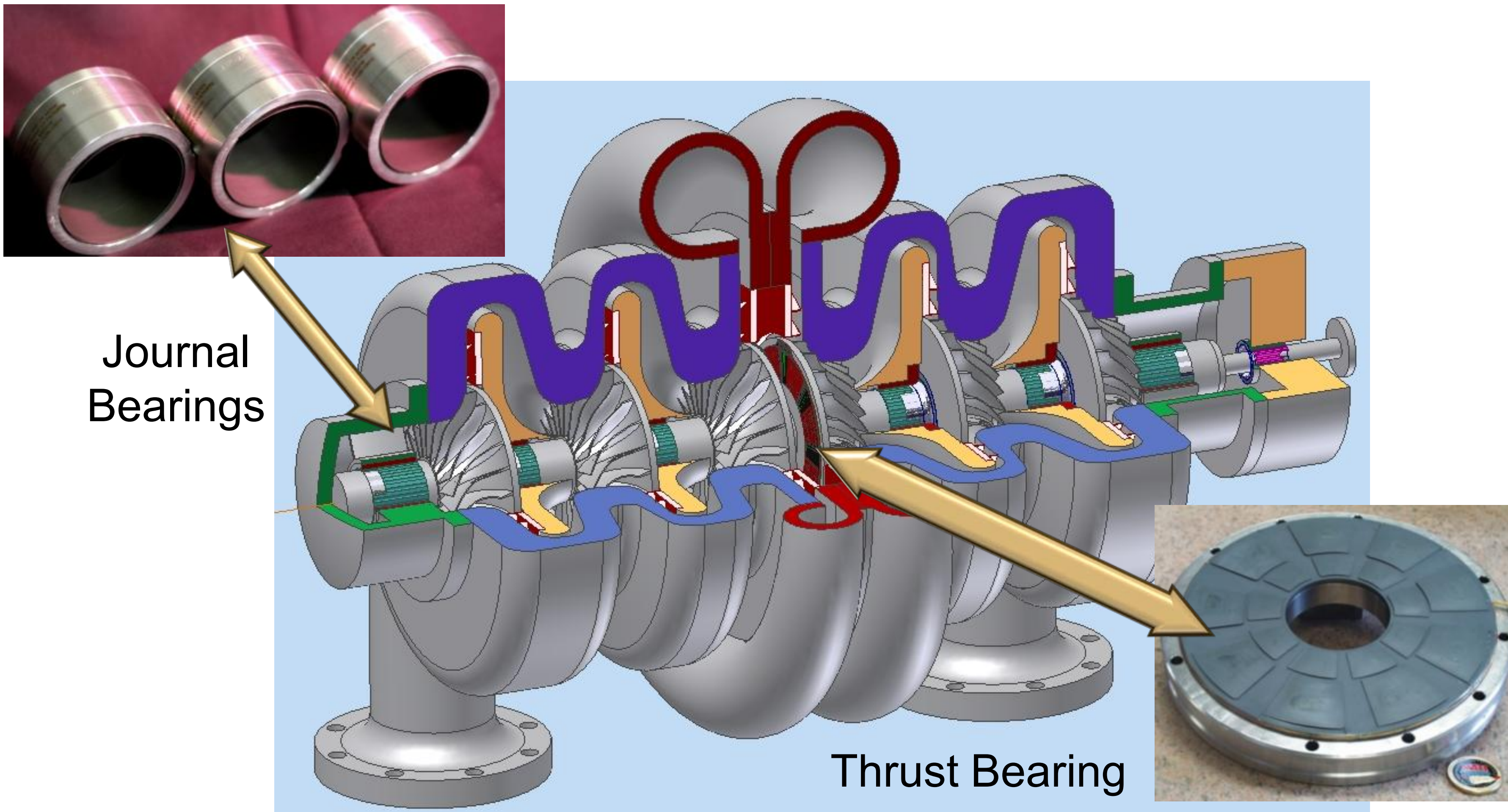






Demonstrate feasibility of very high speed hydrogen centrifugal compressor

Modular Double Entry Centrifugal Compressor



Compressor Design Meets DOE Target

Characteristics	DOE Target	MiTi Estimates
Efficiency (%)	98%	98%
Hydrogen Capacity Target (kg/day)	200,000	240,000 – 500,000
Hydrogen Leakage (%)	<0.5	0.2
Hydrogen Purity (%)	99.99	99.99
Inlet Pressure (psig)	300-700	350-500
Discharge Pressure (psig)	1,000-1,200	1,226 - 1,285
Total Compressor Package ($Million)	$15.6	$7.3-$12.5*
Maintenance Cost (% total Capital Investment)	3%	<3%
Annual Maintenance Cost ($/kW-hr)	$0.007	<$0.005
Package Size (sq-ft)	300-350	145 - 160
Reliability (# of Systems Required)	High - Eliminate Redundant Systems	Very High – Oil-Free Foil Bearings Eliminates Need for Redundant Systems

* Capital and Maintenance Cost estimates based on data from (1) MHI for comparably sized NG compressor systems, (2) published oil and gas industry data and (3) from quotes for fabrication of major components of MiTi's compressor design, including H2 compatible materials. Eliminates Redundancies required for Positive Displacement Compressors Due to Higher Reliability, And Reduced Maintenance Costs of Centrifugal Compressor Design. Estimates for Compressor Efficiency, Flows, Pressures and package size based on stage and system design analysis as performed by MiTi, TurboSolutions and MHI. Estimated hydrogen leakage based on industry and MHI experience with Natural gas and H2 compressors adjusted for hermetic sealing approach of MiTi Compressor Design and number of required seals/joints in the overall system.

Full-Scale Hydrogen Compressor

MiTi Compressor Full Scale Mockup Presented at 2012 ARPA-E Energy Summit

Materials Issues/Needs

- **Structural Materials (Housing)**
  - Durability under high internal hydrogen pressures (316L SS)
- **Shafting/Rotor Materials**
  - High strength, fatigue endurance, high toughness (Beta Ti 10-2-3)
- **Bearings and Seals**
  - High elastic modulus, fatigue resistance,
  - Material Characterization in H_2 and in thin film form (Beta Ti 15-3)
- **Tribological Coatings**
  - Low friction, wear resistant, electrical/thermal properties (Korolon)
- **Hydrogen Barrier Coating**
  - Reduce hydrogen permeability (TiN/CrN)

Preliminary material selection based on extensive literature search and consultation with hydrogen embrittlement experts at National Laboratories, NIST, Univ. of IL, and Others

Single-Stage Manufacturing Progress

All components fabricated or acquired

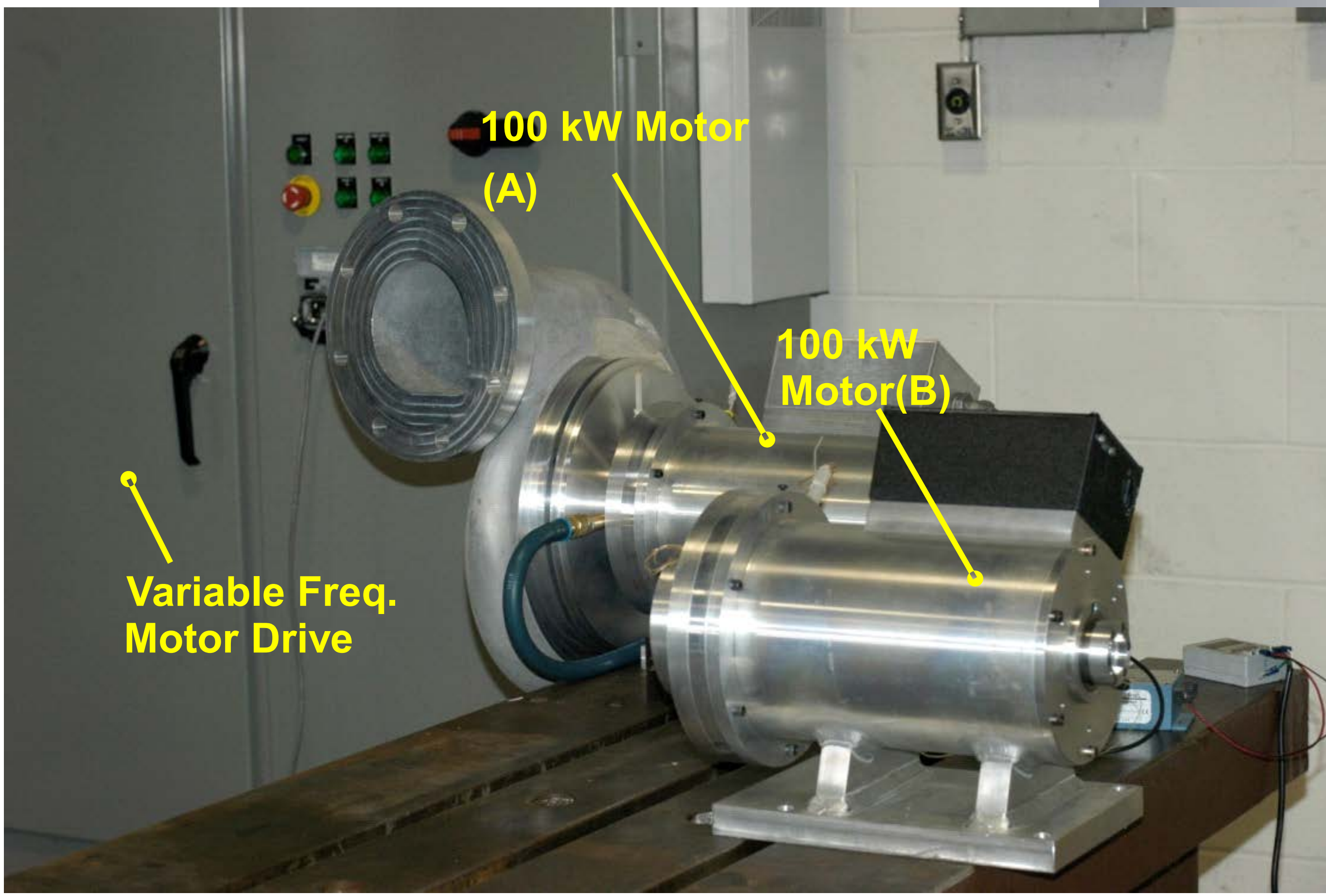
PM Motor Rotor/Stator Pairs

Foil Bearings

Final Machining of Housings

Machined Titanium Alloy Impellers

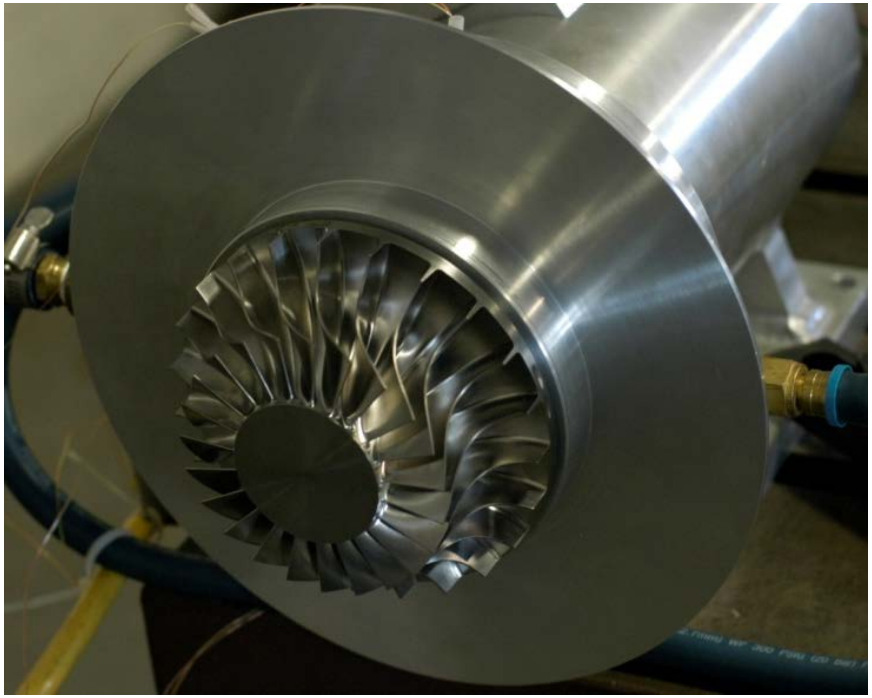
MiTi Compressor Simulator Assembly Progress



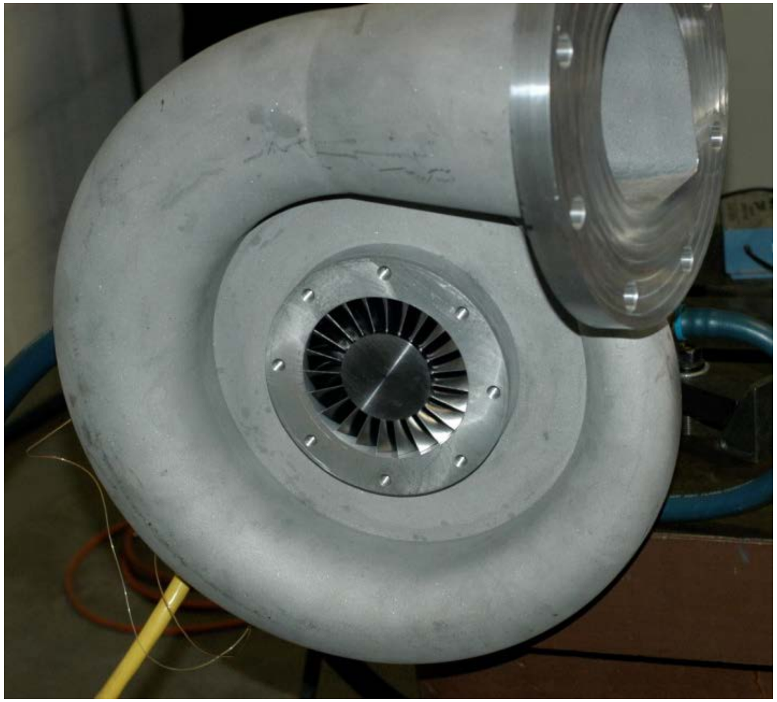
Two 100 kW motors, Compressor wheel and volute assembled and checked out

Compressor Test Facility at MiTi

Partial Assembly

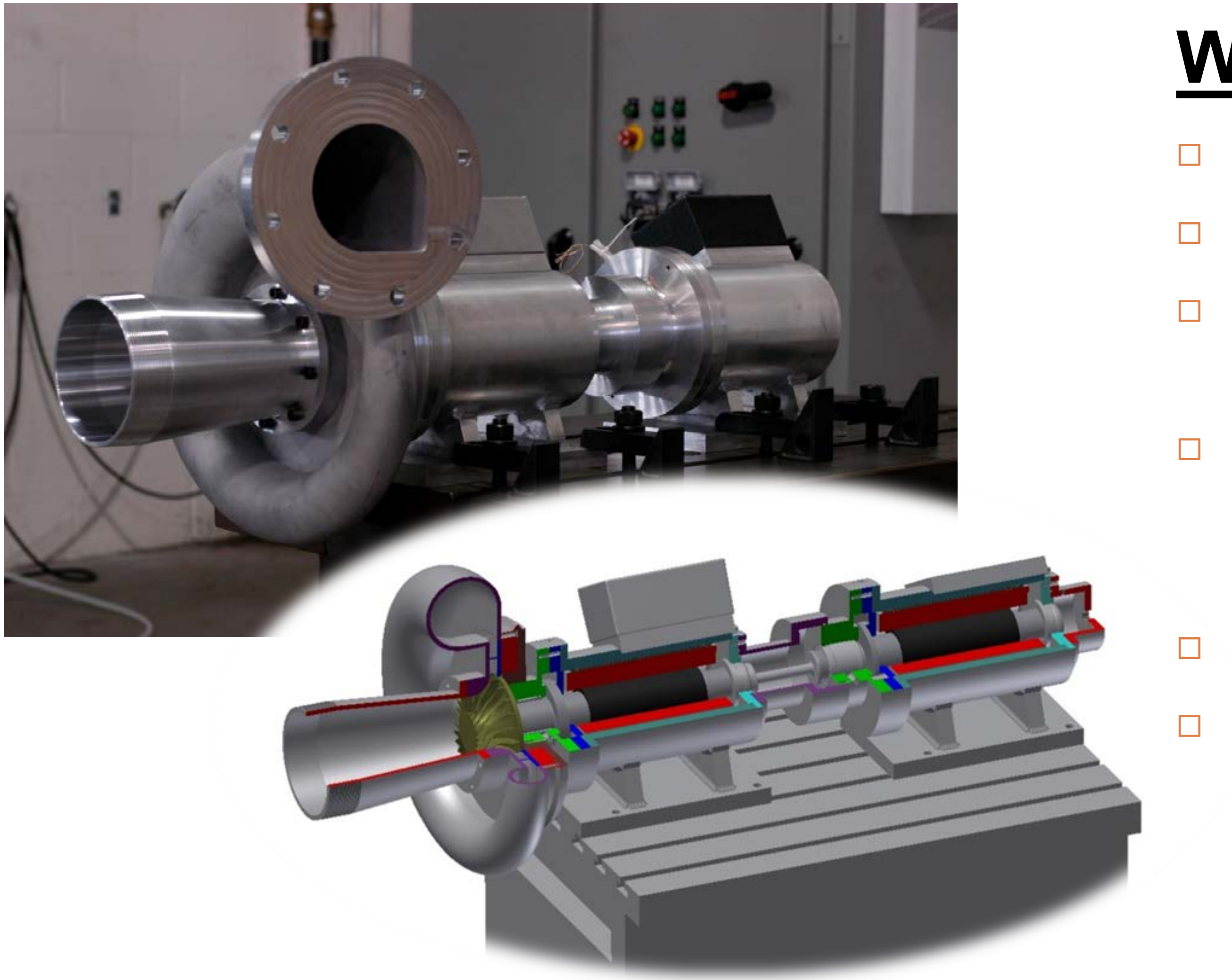


Cast Volute Final Assembly



Single Stage Compressor Has Been fully Assembled.
Testing At Full Speed Awaits Completion of Dedicated Test Cell With Appropriate Safety Measures

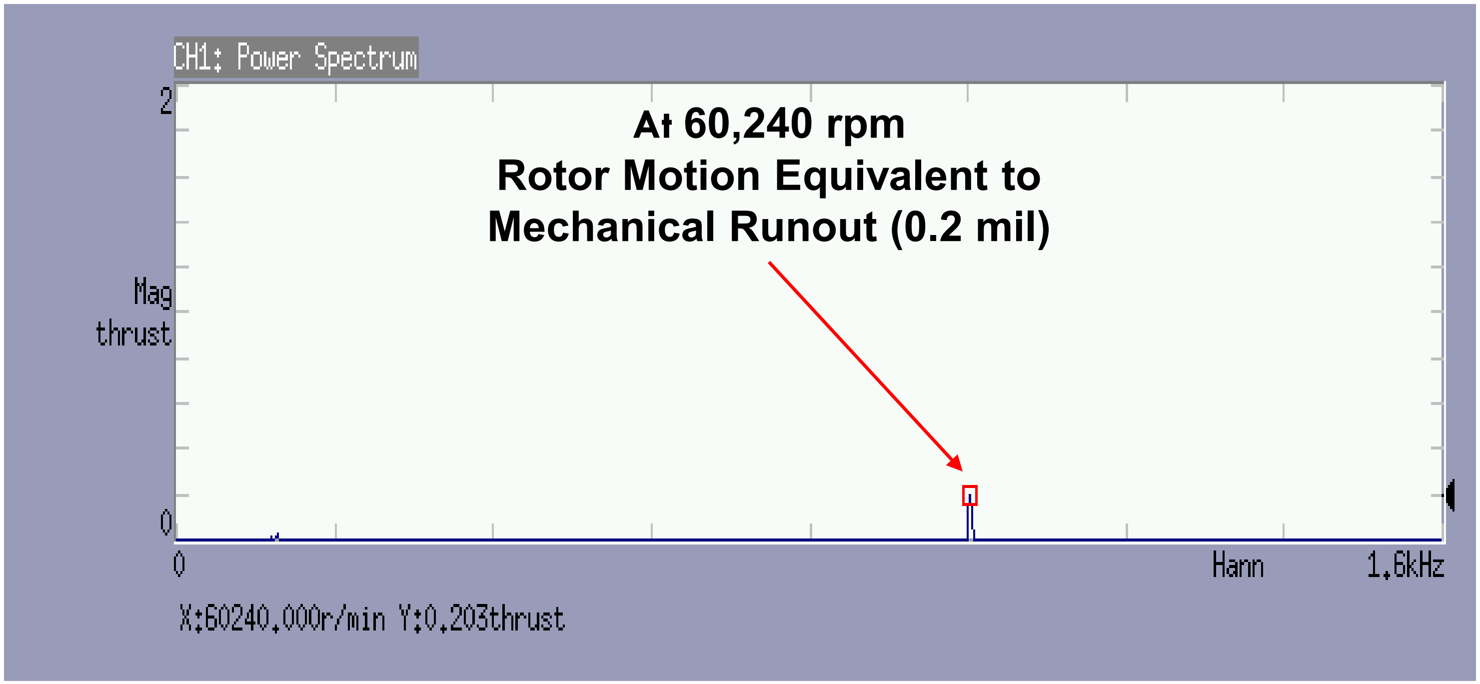
200 kW Gearless H2 Compressor



World's First

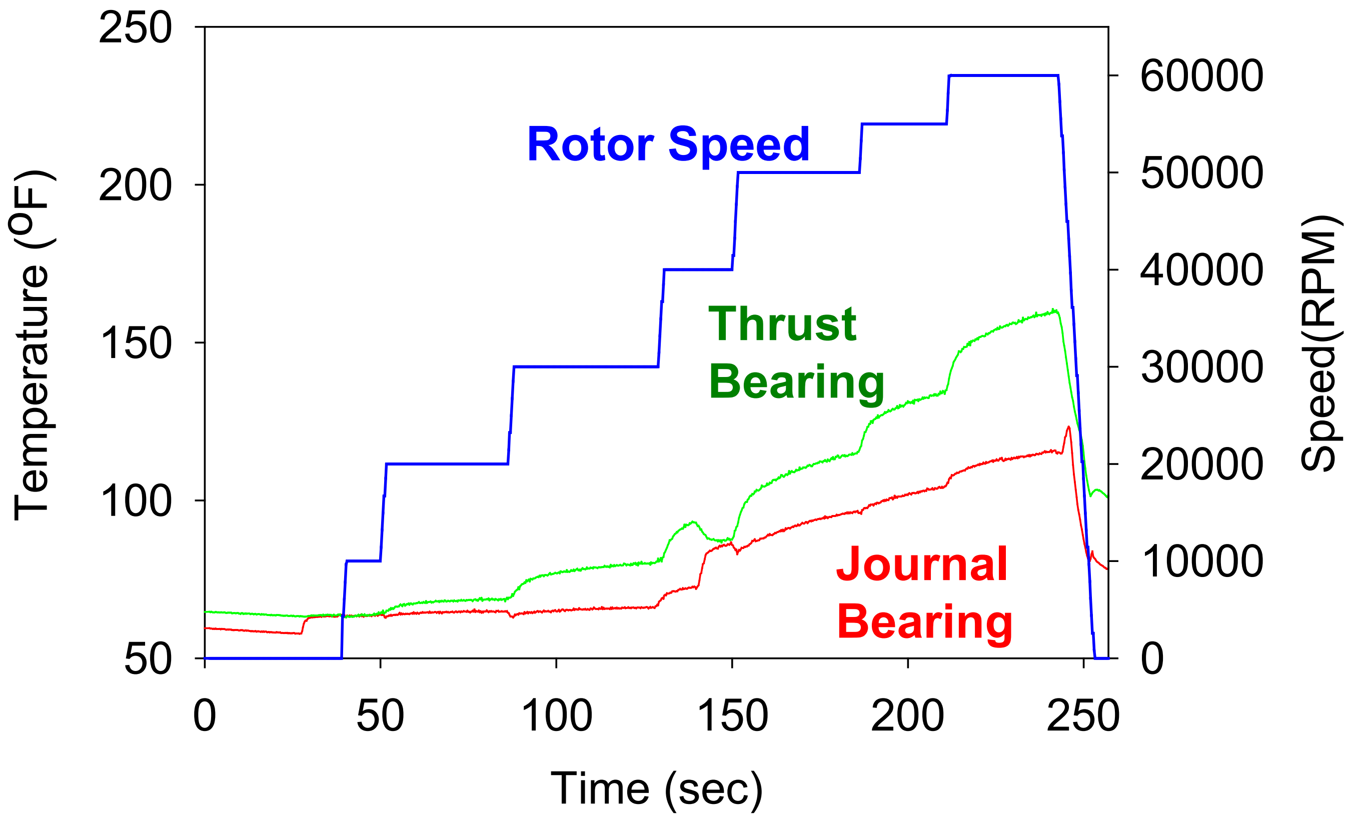
- Oil-free
- 200 Kw PM Motor
- Internally Gas Cooled Motor
- Direct-drive -- No Transmission Or Gearbox
- 60,000 Rpm
- Made In USA

Motor Dynamic Verification Testing To Over Speed



- Initial Motor Spin Testing Performed
- Testing up to 60,000+ rpm Completed for Each Motor
- Extremely Low Vibrations, Single Peak Only Due to Rotational Speed

Compressor Simulator Speed & Bearing Temps

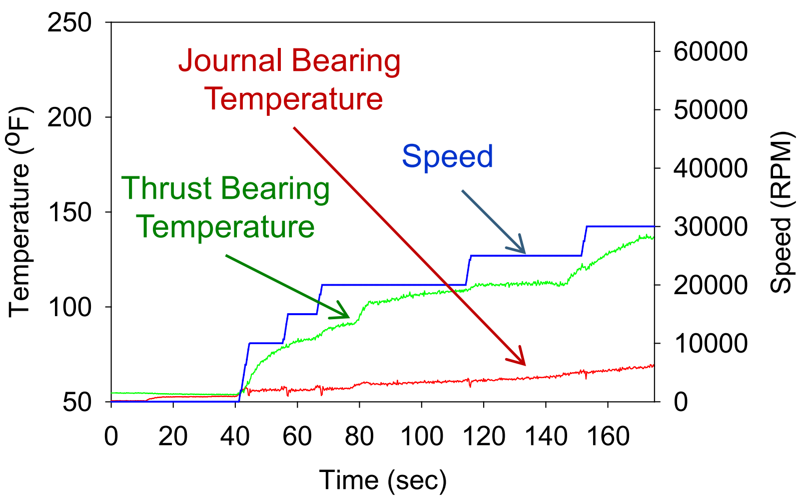


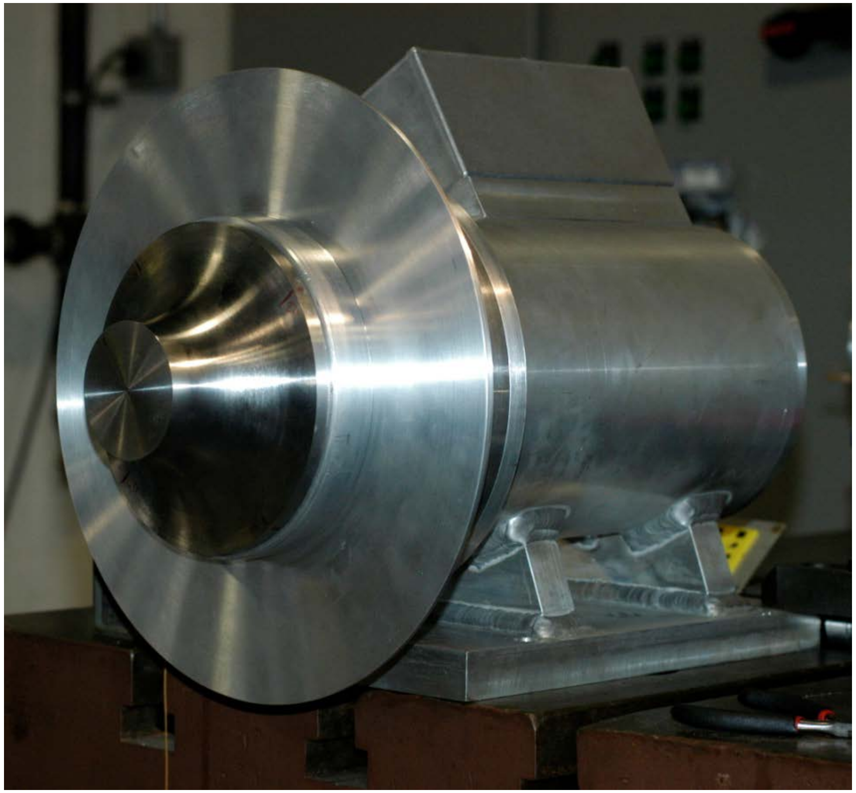
Thermally Stable - Maximum Bearing Temperature < 66 C

Internally Air Cooled @ 9 gm/sec (0.1% of Total Compressor Output)

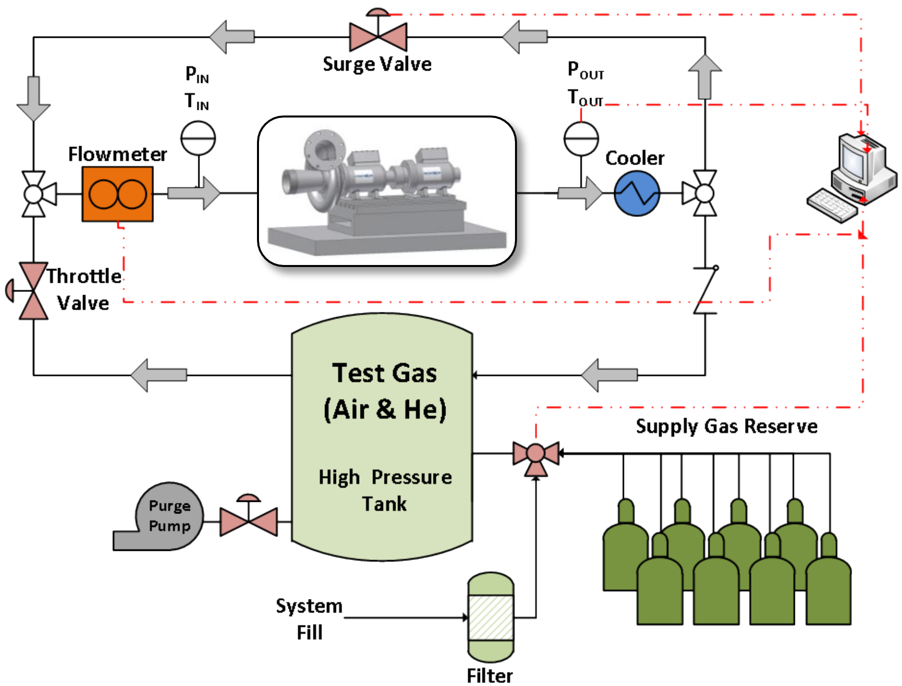
Compressor Dynamic Verification Simulator

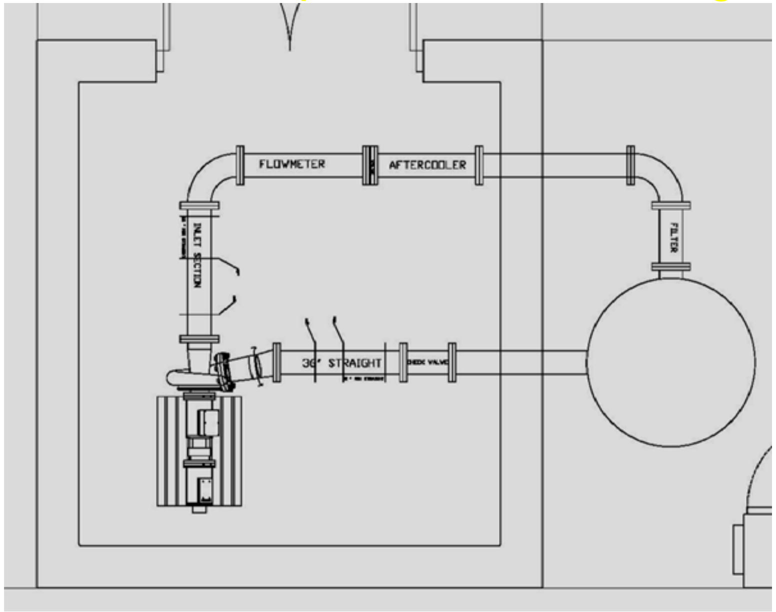
- Demonstrated Stable Motor Operation With Oil Free Foil Bearing & Bladeless Ti Wheel
- Testing Successfully Completed for Several 3-Minute Cycles Up To 30,000 rpm
- **Testing To Full Speed (60 Krpm) Requires Dedicated Test Cell**





Closed-Loop Test Facility Design





- Compressor System Testing Underway in Air
- Closed Loop Helium Testing Per PTC-10 Being Prepared For Summer 2012

- Safety Measures For Full Speed Testing Requires
  - Dedicated Facility Required
  - Reinforced Enclosure
  - Fully-remote Operation Capabilities And Data Acquisition

Future Work

- **Simulated Hydrogen Compressor Testing**
  - All Testing to be Conducted in Accordance with Industry Standard ASME PTC-10 with Air and He
  - Testing to be Conducted at MiTi
    - Validate Compressor with Foil Bearings and Seals
    - Demonstrate Oil-Free Coupling Technology with Foil Bearings
  - MHI Design To Be Tested at MHI
    - Fabricate and Validate MHI Compressor Stage
- **Critical Comparison of the Two Designs (MiTi/MHI)**
- **Hydrogen Compatibility Evaluation of Foil Bearing and Foil Seal Materials at SNL/NIST**

Future Work (Continued)

Design Refinement & System Selection

- Based Upon The Single Stage Data, Hydrogen Centrifugal Compressor Design Will Be Refined To Account For The Differences Between Test Data And Analyses
- Select Double (MiTi) Or Single Entry (MHI) System Design Approach And Integrate Best Features Of Both Into The Selected System
- Use The Stage Design As Reference For Subsequent Scaling And Streamline Trimming As Needed To Configure The Full Multi-Frame, Multi-Stage Modular Compressor System Concept
- Using Empirical Data, Estimate Multi-Frame Compressor System Performance, Total Intercooler Heat Load And Total Driving Power Required Per Frame
- Refine Estimates Of Capital Costs And Compare To The Established 2017 DOE Target For 200,000 Kg/Day System

Summary

- **Refined Multi-Stage/Multi-Frame Compressor Concept (FY09)**
  - Established Stage Pressure Ratios and Flows
  - Defined and Selected Optimum Operating Speeds
  - Selected One Stage for Detailed Design and Verification Test
- **Conducted Detailed Compressor Design (FY10-11)**
  - Established Detailed Flow Paths Including Inlet, Impeller, Diffuser and Return Channel Using Computational Fluid Dynamics at Several Operating Points
  - Designed Foil Bearings and Seals Using Coupled Elasto-Hydrodynamic Analysis
  - System Designed Using FEM Dynamic and Stress Analyses with Titanium Alloys
- **Completed Fabrication and Initial Verification Testing of MiTi® Hydrogen Compressor Stage – Additional Testing is Underway (FY12)**

MiTi's Advanced and Very High-Speed, Oil-Free Centrifugal Compressors Can Meet Hydrogen Delivery Needs

Backup Slides

- Next Slide, Please.

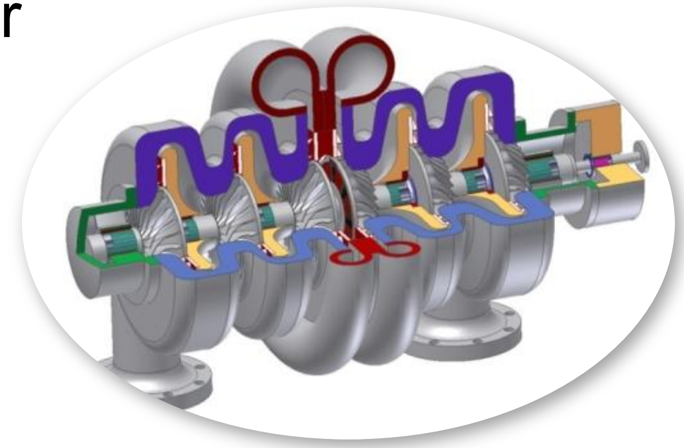
Assessed Pros and Cons for MiTi and MHI Hydrogen Compressor Designs

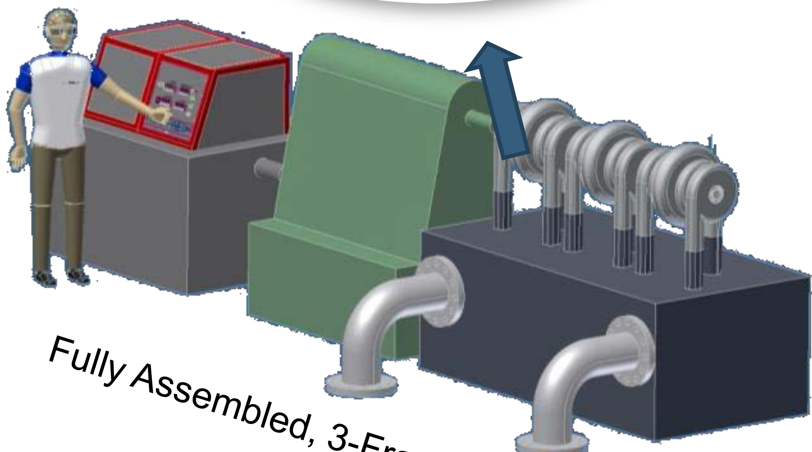
	Pros	Cons
MiTi Design *Double Entry*	Inherently Internally Balanced Thrust Forces	Higher Parts Count
	All Stages Derived from Common Wheel Design – Economies of Scale	Control of Axial Clearance Requires Close Attention
	Modest Tip Velocities for Hydrogen Environment (25% Lower than MHI)	Careful Design of Double Inlet/Discharge Piping Required
	High Stress Safety Margin	
MHI Design *Single Entry*	Fewer Parts	Unique Impellers used in each Frame
	Close Control of Axial Clearance	High Tip Speeds Required
	Uses Balance Piston For Thrust Loads	Larger Diameter Wheels Used
	Simple Inlet Piping	Reduced Stress Safety Margin
		Very High Thrust Loads Requires Balance Piston Plus Thrust Bearing

MiTi Compressor Design Analysis

- Double-Entry Multi-Frame Compressor
  - 6 and 9 Stages (2 and 3 Frames)
- Exit Pressure > 1,200 psi
- Power: 7,800 – 12,000 HP
- Tip Speed: 1,500 – 2,000 ft/s
- Mass Flow: 240K – 500K kg/day
- Max Bearing/Seal Temp: 180-200^{c}
- Specific Energy: 0.48-0.59 ($\frac{\text{kW-HR}}{\text{Kg}}$)

Single Frame



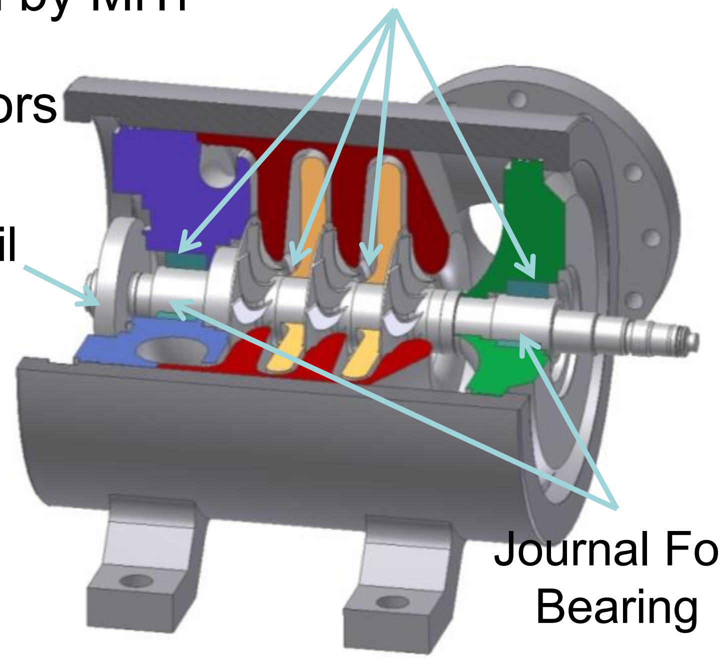


Fully Assembled, 3-Frame System

Mohawk Innovative Technology, Inc.®

Mitsubishi Compressor Design Analysis

- Single-Entry Multi-Frame Compressor
  7 and 9 Stages (2 and 3 Frames)
- Design Developed by MHI with Input from MiTi
- Bearing/Rotor Design Analysis Performed by MiTi
- Design Based on NG Pipeline Compressors
- Exit Pressure: > 1,200 psi
- Power: 8,300 - 12,000 HP
- Tip Speed: > 2,000 ft/s
- Mass Flow: 240K – 500K kg/day
- Specific Energy: 0.44-0.65 ($\frac{\text{kW-HR}}{\text{Kg}}$)

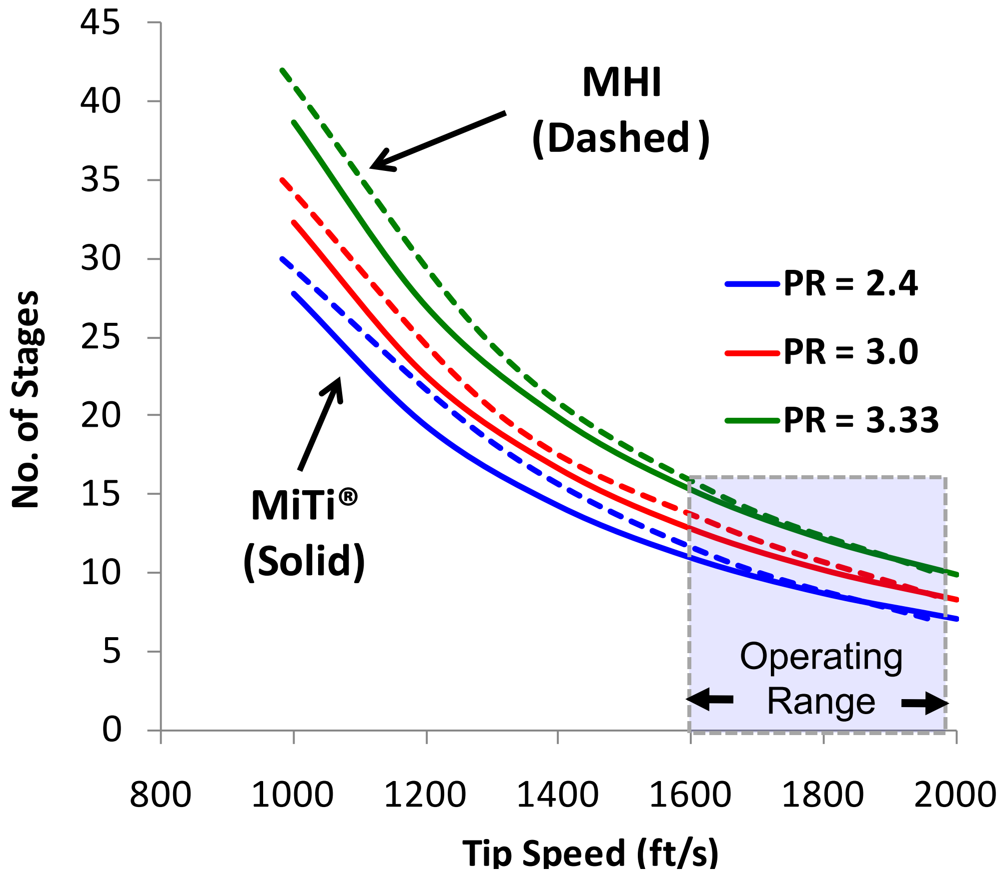


Single Frame

Multi-Stage Compressor Design

- MiTi - Double-Entry
- MHI - Single-Entry
- Excellent Correlation Between the Two Designs Within the Operating Range

Design Comparison: No. Stages vs. Tip Speed for Three Different Pressure Ratios



Beta Ti Alloys for Rotating Group & Foil Bearings

Beta TI Alloy	Ultimate Tensile ksi	0.2% Yield ksi	% Elongation	Fatigue Threshold $ksi.in^{1/2}$	Comments
Ti-10-2-3	174 →116	165 → 90	8 → 20	2.7 → 5.5	Ductility Gain
Ti Beta C	145 →160	128 →162	37 → 3	4.5 → 1.8	Ductility Loss

Mechanical properties change as a result of hydrogen charging for solution annealed alloys (Christ et al 2003) .Mechanical Properties of Beta Titanium alloys in air: properties depend on heat treatment (International Titanium Association).

Material	UTS ksi	Hydrogen Embrittlement	Modulus $ksix10^3$	Fatigue Limit ksi	Thermal Expansion µin/in F	Electrical Resistivity µohm in
X-750 Ni	192	YES	31	80	7.8	48
316L SS	70	NO	28	37	8.6	30
Ti-15-3	200	NO	14.5	87	4.7	55
Ti Beta 21S	190	Yes	15	?	5.3	53

Typical properties of several alloys in air as candidates for foil bearing fabrication