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

Arlington VA

Project ID # PD016

May 15, 2013

Oil-Free Centrifugal Hydrogen Compression Technology Demonstration

PI: Hooshang Heshmat, PhD
Mohawk Innovative Technology, Inc.
Albany, NY

Overview

Timeline

- Start Sept 1, 2008
- Funding Authorized 2/28/09
- Extended Nov 30, 2013
- 90 % 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
- Fully Funded in FY12

Partners

- Lead: Mohawk Innovative Technology, Inc. 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***

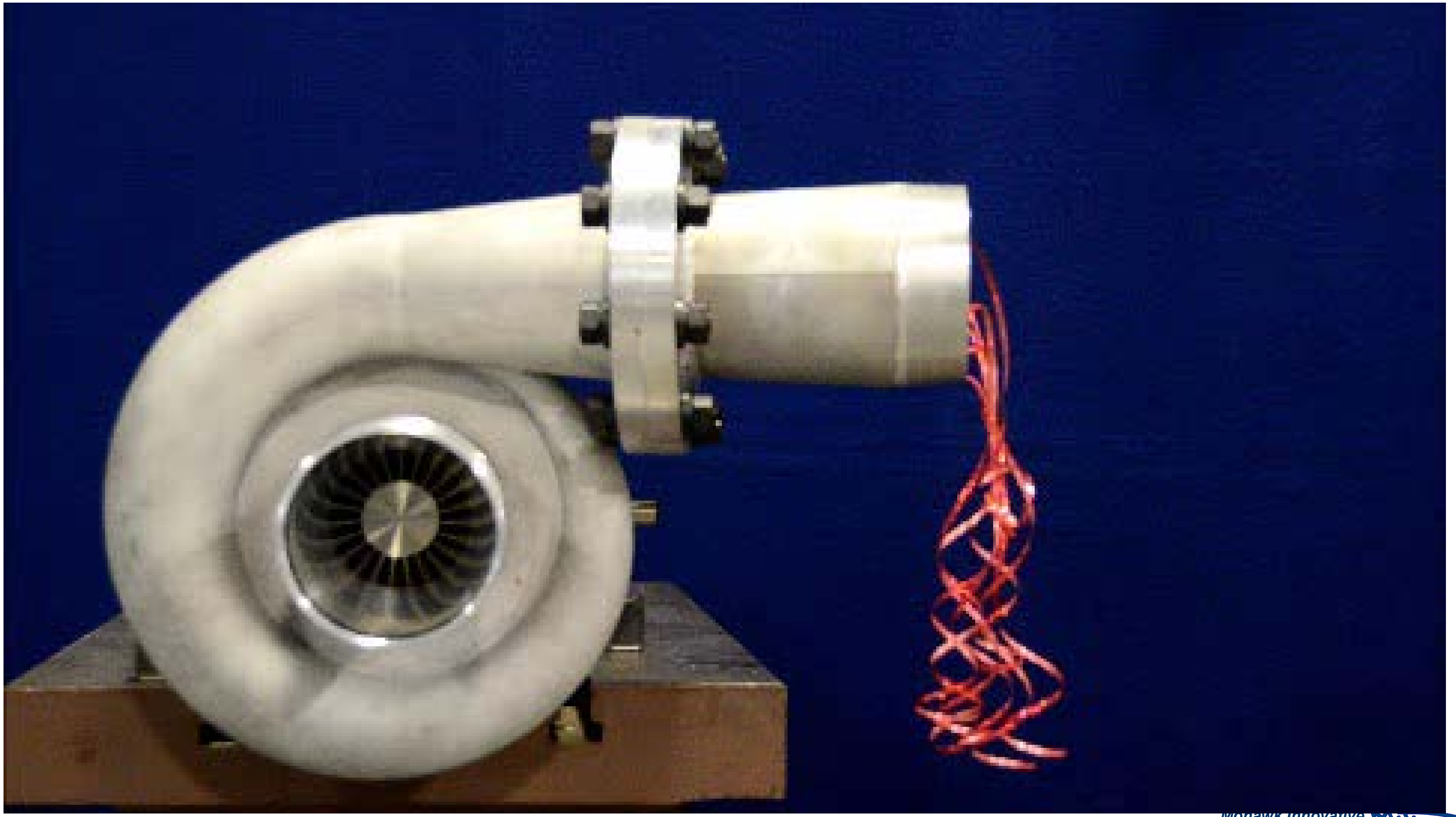
Category	2005 Status	FY2012	FY2017 (Project Target)
Reliability	Low	Improved	High
Isentropic Efficiency	NA	NA	>88%
Capital Investment ($M) (based on 200,000 kg of H2/day)	$15	$12	$9
Maintenance (% of Total Capital Investment)	10%	7%	3%
Contamination	Varies by Design		None

Hydrogen, Fuel Cells & Infrastructure Technologies Program [DOE Publication 2007 & 2012]

Single Stage Centrifugal Compressor

Preliminary Compressor Testing in Air

(Click on Picture to view the video)



Commercial Potential for Advanced Oil-Free Centrifugal Compressors

- Pipeline Compressors (Hydrogen and other Gases)
- Petrochemical Industries
- Natural Gas Compression
- CO_2 Sequestration
- Other Industrial Uses
  - Waste Water Treatment
  - Fuel Cell Anode H2 Gas Recycle
  - Waste Heat Recovery Turbogenerator

Team/Collaboration

MHI – Mitsubishi Heavy Industries – Compressor Company

Single-Entry Centrifugal Compressor Design

Boeing

Materials Recommendation for Hydrogen Environment

NIST Material Measurement Laboratory

Compatibility of Materials in Hydrogen Environment

International Institute for Carbon-Neutral, Energy Research

Consultation on Materials Selection

Sandia National Laboratory

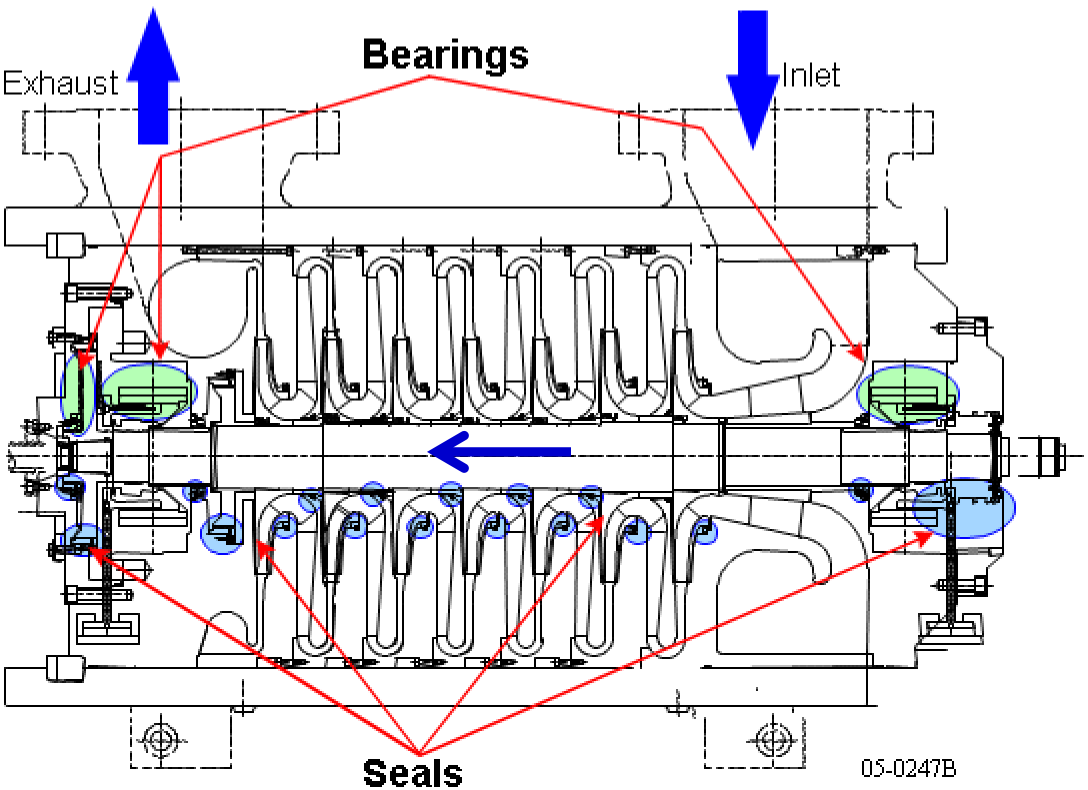
Testing and Consultation on Materials Selection

External Expert Consultants

Compressor Design, CFD, Compressor Testing

Comparative View of Present & Future In Gas Compression Technology

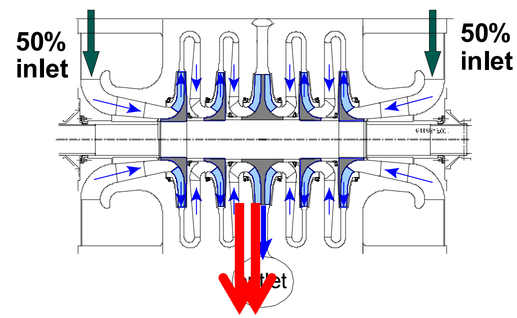
PRESENT



Single Entry Design
12,000 rpm

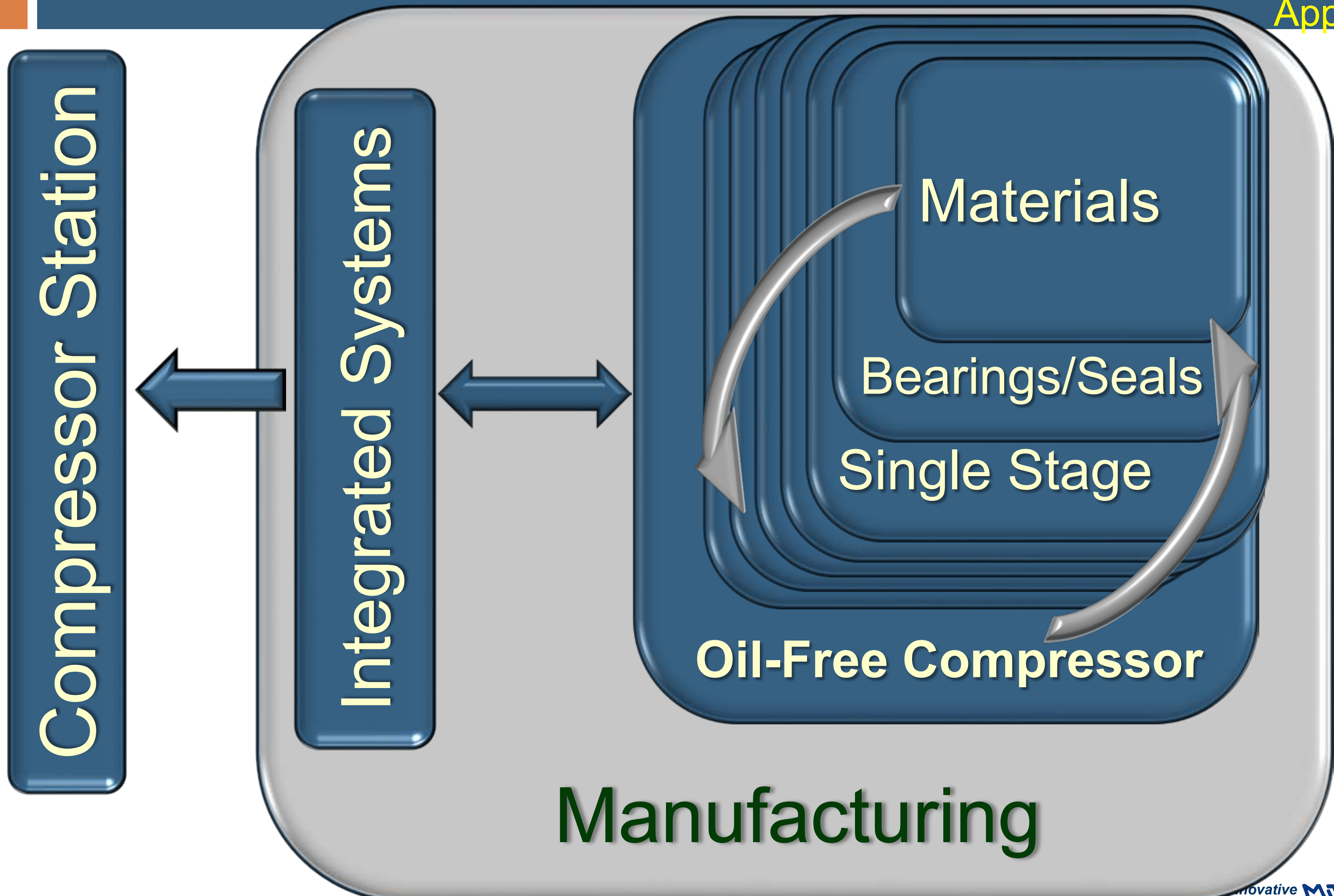
DEVELOPMENTS FOR FUTURE

Four Times Smaller
Twice The Efficiency



Dual Entry Design
60,000 rpm

Compressor Design Methodology



Program Tasks

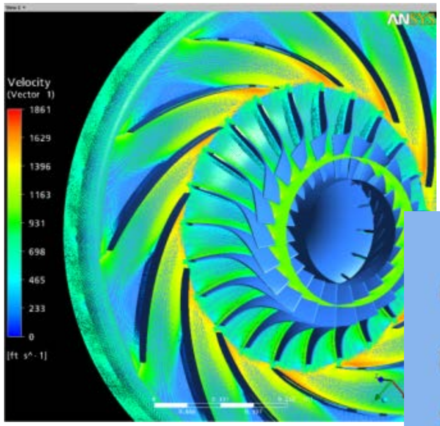
Compressor Design Analysis
- ✓ Mean Line Analysis, CFD, FEA

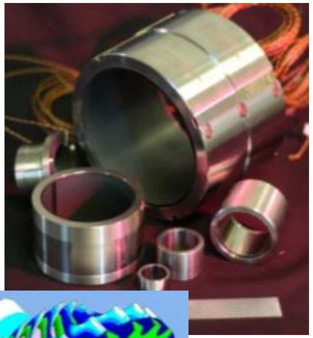
Sub-Component Design
- ✓ Foil Bearings & Seals / Coatings

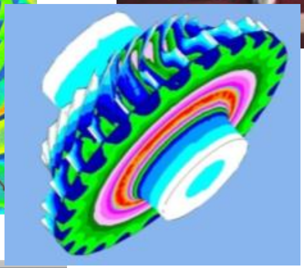
Design Single-Stage Compressor
- ✓ Impeller, Diffuser and Others
- ✓ Drive System & Test Loop

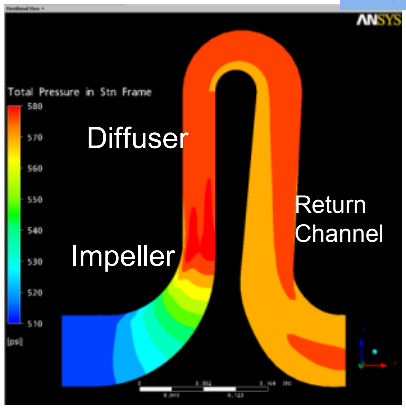
Single-Stage Proof Testing
- ✓ Fabricate
- ➡ Characterize Pressure & Flow

Scale System Design
- ✓ Predict Complete System Performance
- ➡ Update Multi-Stage, Multi-Frame Design
- ✓ Economic Analysis









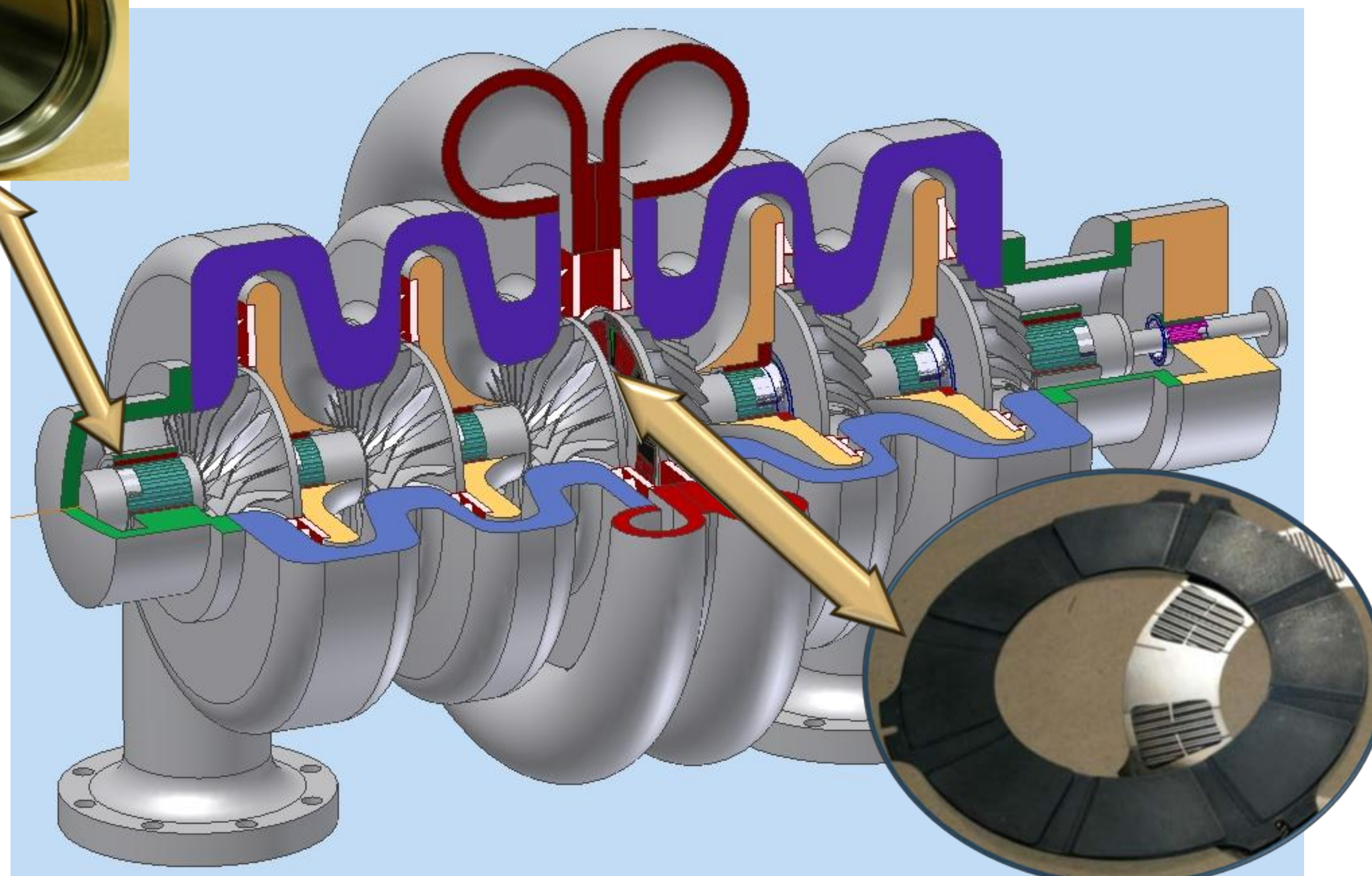
Demonstrate Feasibility of Very High Speed Hydrogen Centrifugal Compressor

Modular Double Entry, Oil-Free, Centrifugal Compressor

Journal Bearing

Advanced MiTi® Foil Bearings and Seals

Hydrogen Lubrication Enables Contaminant-Free High-Speed Compression

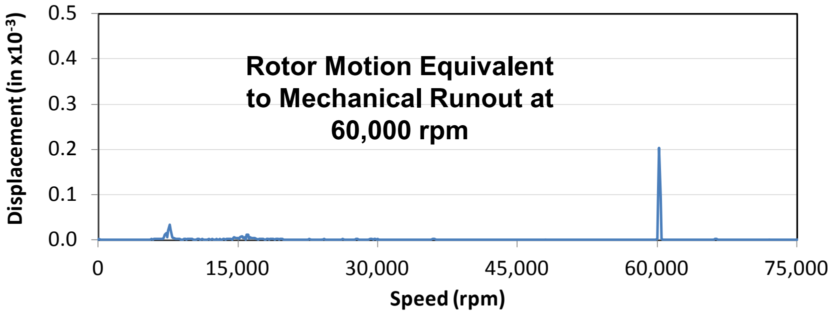


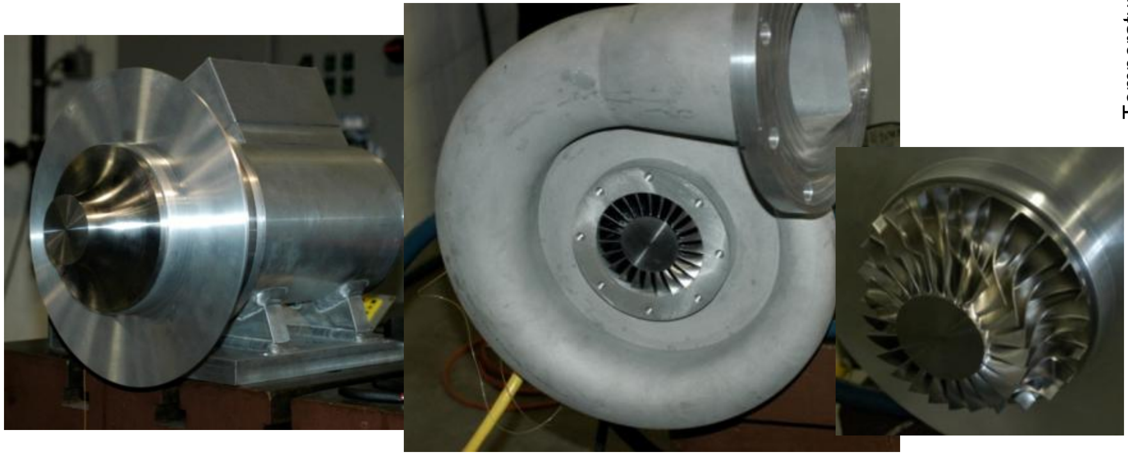
Thrust Bearing

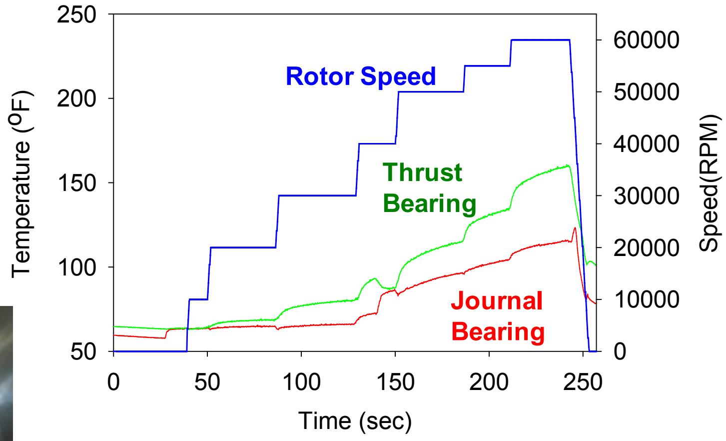
Mohawk Innovative Technology, Inc.®

Component/Subsystem Verification Testing

- Motor Spin Testing Completed
- Smooth Operation Demonstrated
- Low Bearing Temperatures Achieved
- Stable Operation with a Bladeless Impeller Demonstrated
- Compressor Wheel Spin Testing in Air Successfully Completed
- Dynamic Performance Verified







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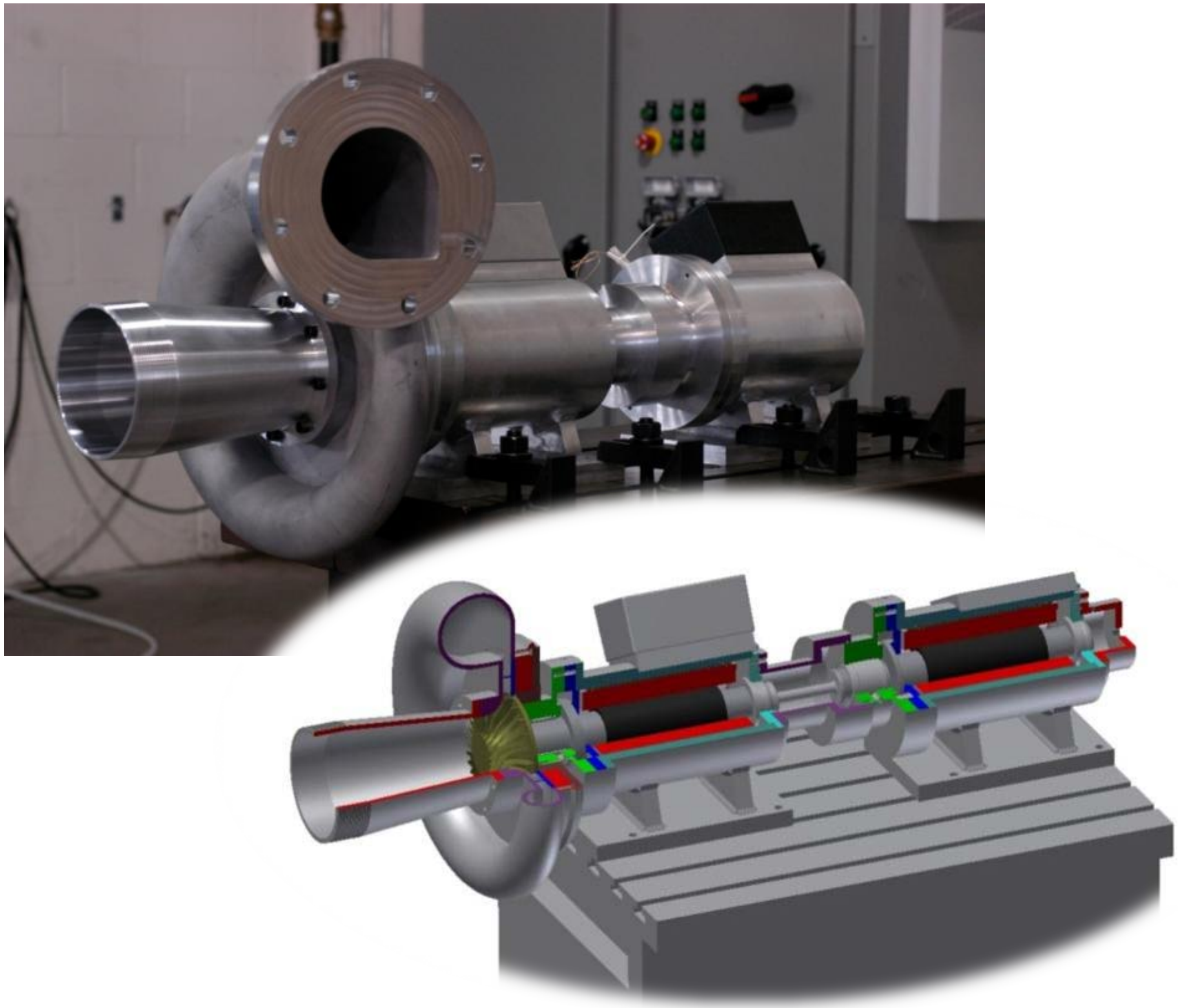
Gearless Single-Stage H_2 Compressor

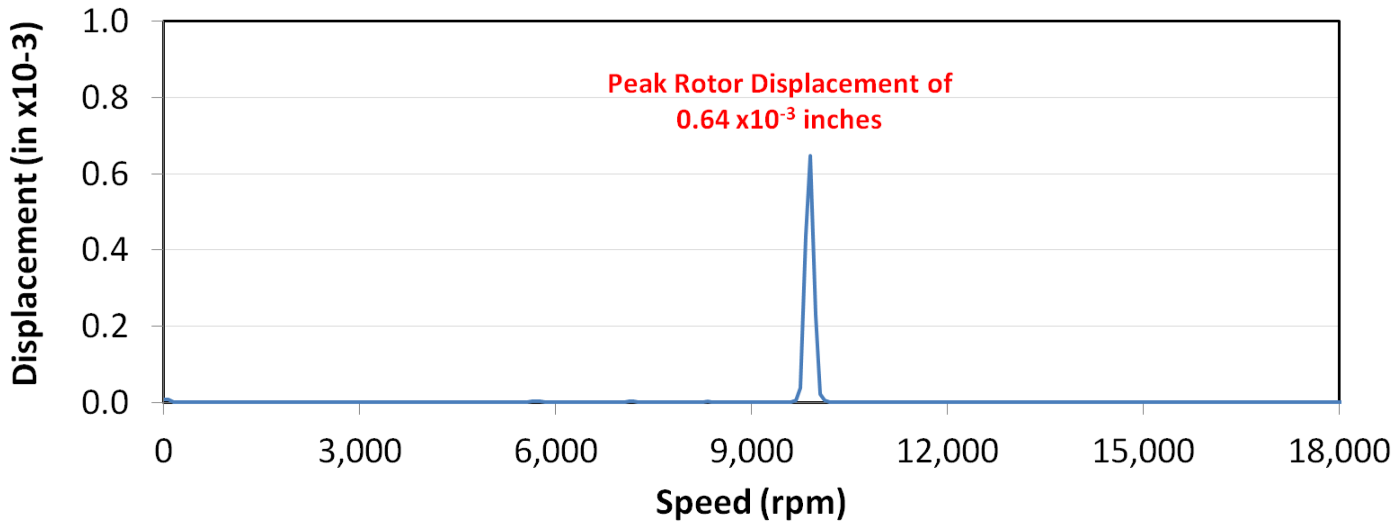


World's First

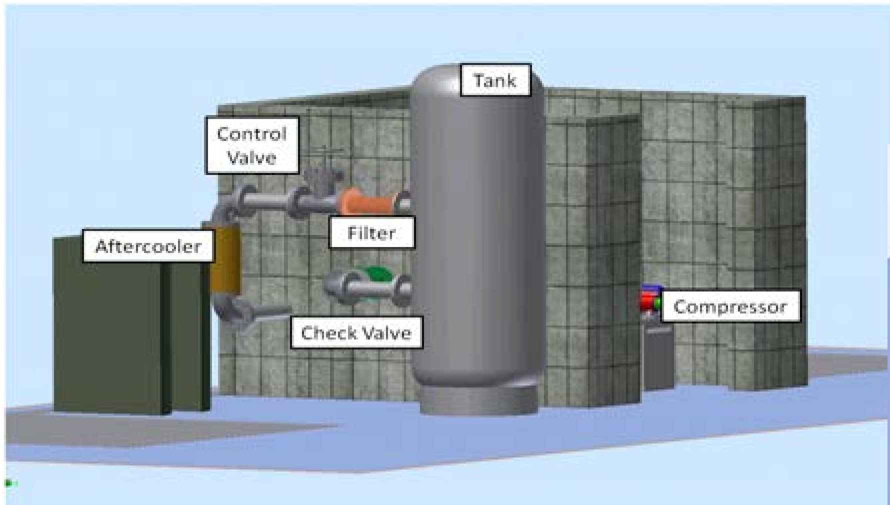
- Oil-Free
- 200 KW PM Motor
- Internally Gas Cooled
- Direct-drive
- No Transmission or Gearbox
- 60,000 rpm
- Made In USA

Development of 200 kW High-Speed Coupled Motors

- Two 100 kW motor drives mechanically coupled
- MiTi® Coupling Technology verified
- Dual drive system operation verified
- FFT data shows no sign of sub-synchronous vibrations
- Represents a novel achievement

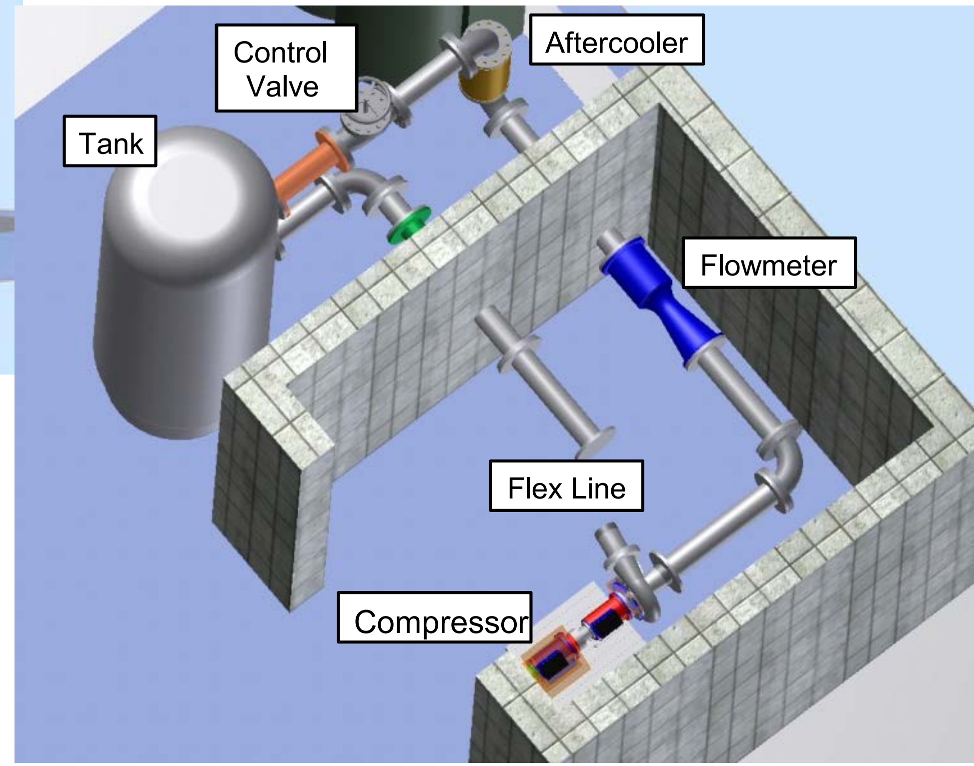


Closed-Loop Test Facility Design Completed



- Dedicated Test Facility
- Reinforced Enclosure
- Fully-Remote Operation
- Remote Data Acquisition

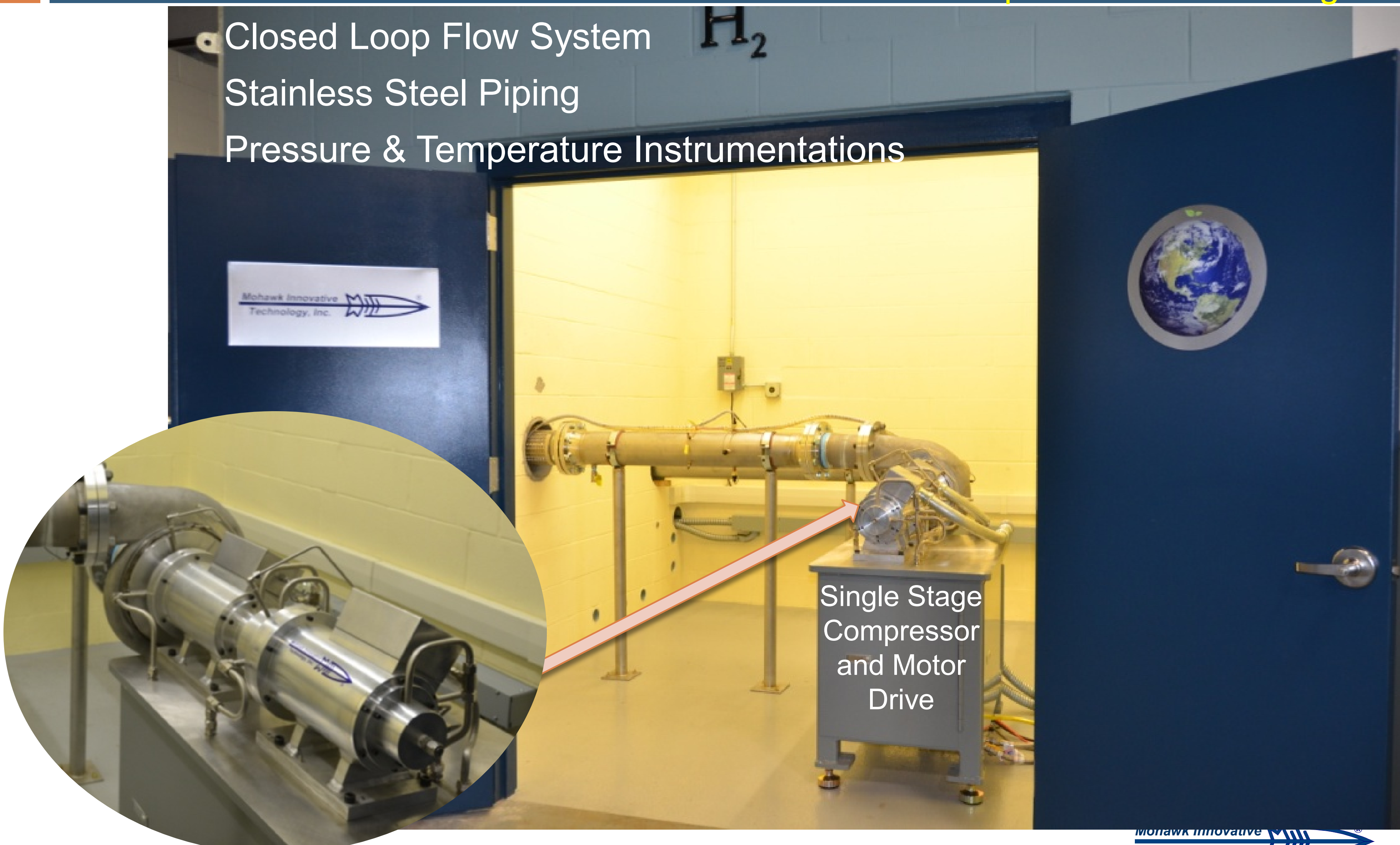
Safety Measures For Full Speed Testing



Dedicated Hydrogen Compressor Test Cell

Test Cell Construction for Full Speed Testing in Closed Safe Environment

Closed Loop Piping System



Closed Loop Piping System

Motor Control System



- Facility Upgraded
- 800 Amps @ 480 V Service Line
- Dual High Frequency Drives 200 Amps Each

Closed Loop Piping System

MiTi® Closed-Loop Compressor Test Facility

Sensors
- Pressure
- Temperature
- Displacement

Video Camera
- Remote Monitoring

Command Console
- Control Motor Speed
- Monitor Sensors
- Data Acquisition
- FFT Analyzer

Remote Control and Operation

Gas Choices For Compressor Testing

Hydrogen

- Safety Issues & Facility Requirements Beyond Present Scope

Air

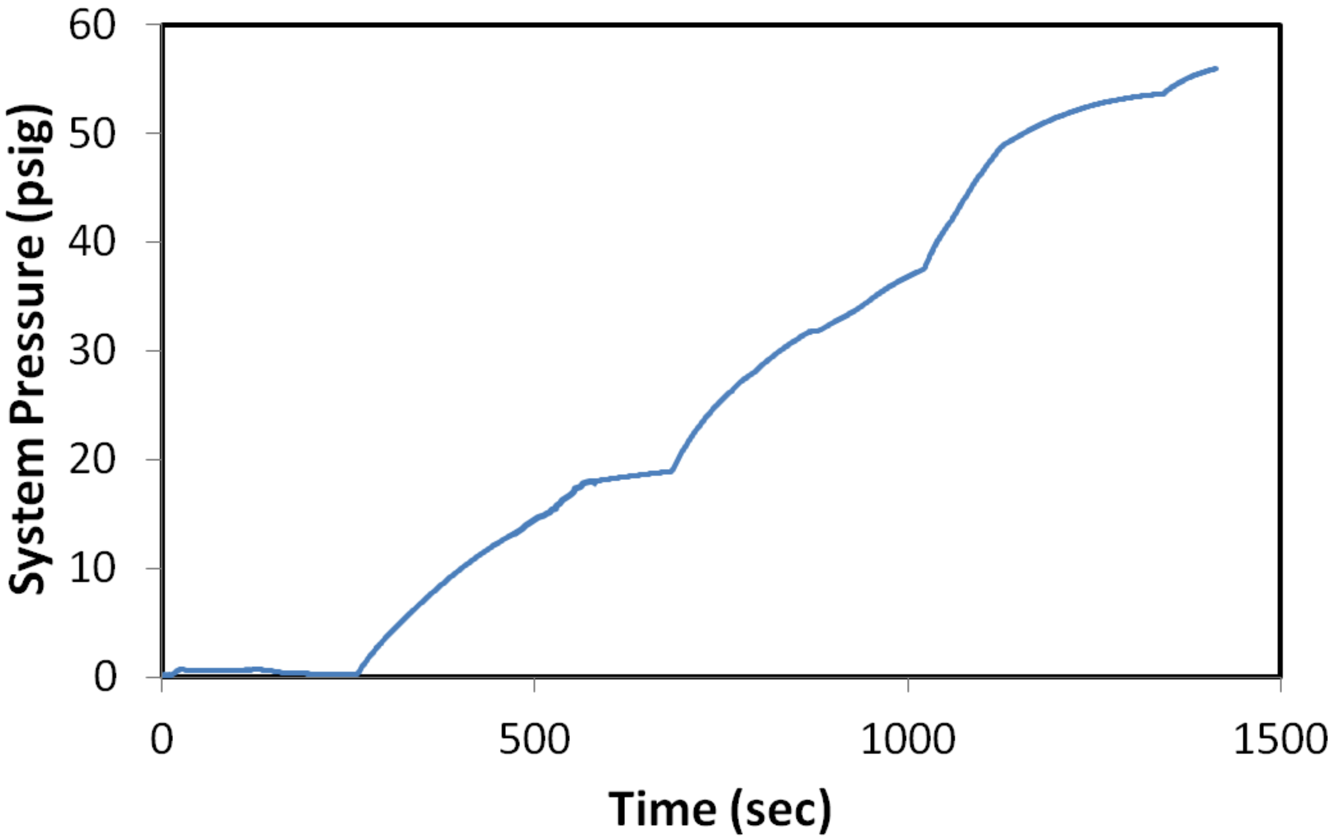
- Readily Available, But Drastic Density Variance
- Preliminary Checkout – Below Full Speed
  - System Operation
  - Instrumentation
  - Stress/Loading

Helium

- Affordable Similitude Gas
- Full Speed Aerodynamic Validation
- Qualifies for ASME PTC-10 Type 2 Test

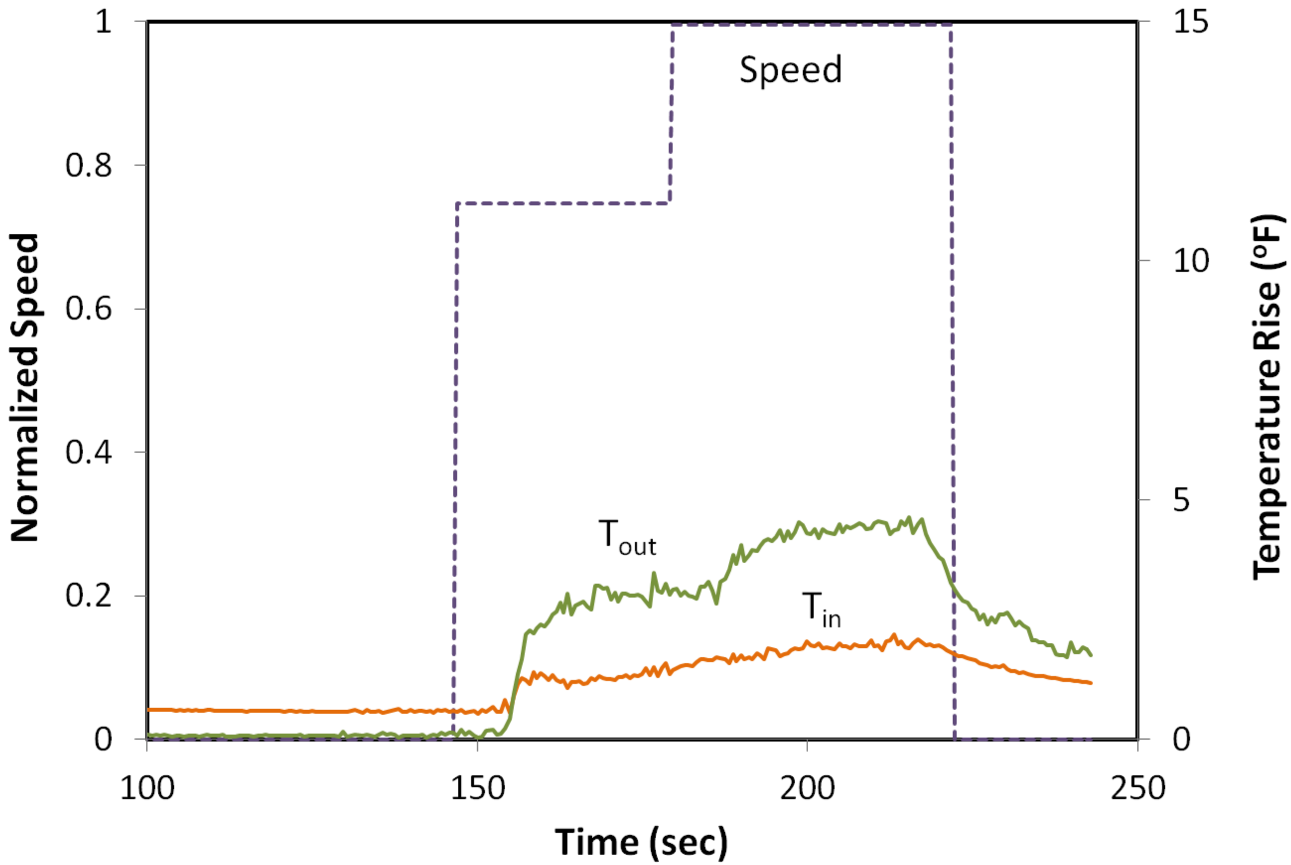
System Pressurization Checkout With Helium

Closed Loop System Filled and Pressurized with He



Preliminary Compressor Testing in Helium

Stable Compressor Performance Showing Inlet and Outlet Temperatures



Future Work (FY 13)

Simulated Hydrogen Compressor Testing

- Complete Testing in Accordance with Industry Standard ASME PTC-10 with He
- Validate Oil-Free Compressor with Foil Bearings and Seals

Hydrogen Compatibility Evaluation

- Evaluate H_2 compatibility of Ti Alloy and Foil Bearing/Seal Materials

Design Refinement

- Estimate Multi-Frame Compressor System Performance, Total Intercooler Heat Load and Total Driving Power Required per Frame, Based on Single Stage Test Data
- Refine Estimates of Capital Costs and Compare to DOE Targets

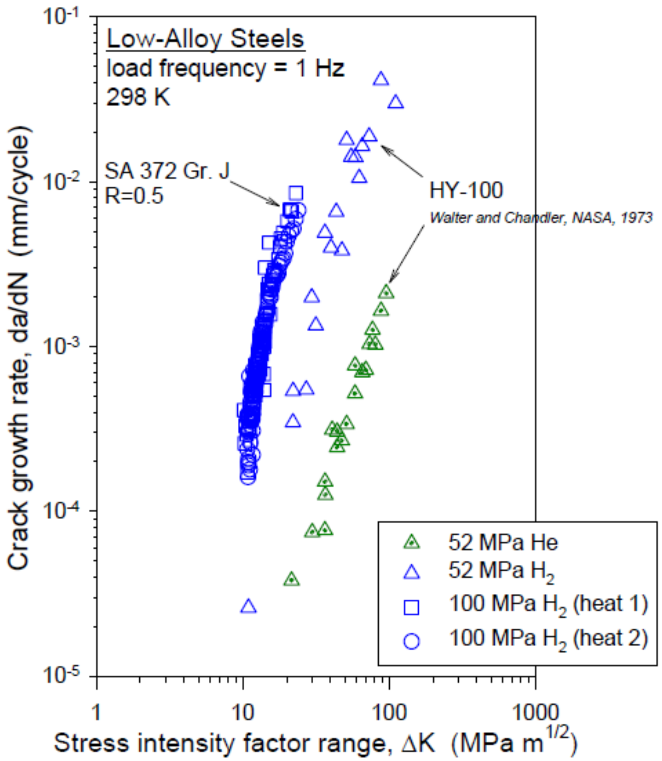
ASME PTC10- Single Stage Testing, Helium

Quantity	Symbol	Compressor Performance	PTC-10 Test Parameters
Specific Volume Ratio	v_i/v_d	**1.052**	1.018 – 1.126
Flow Coefficient	Φ	**0.1253**	0.120 - 0.130
Machine Mach No.	Mn	**0.3266**	0.141 - 0.532
Machine Reynolds No.	Re_m	**3.33e5**	1.55e5 – 1.55e7

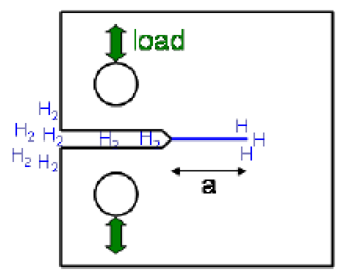
- **Type 2 Testing**
  - Speed 39,323 rpm (70% of design)
  - Inlet Pressure 100 psig
  - Inlet Temperature 100°F
  - Input Power 137 Hp
- **Full Speed Testing**
  - Speed 56,414 rpm
  - Inlet Pressure 50 psig
  - Inlet Temperature 100°F
  - Input Power 260 Hp

Crack Growth Testing in Hydrogen at SNL

Sample Data for Steel



Testing planned at SNL on Beta Ti Alloy Compact Tension Specimens

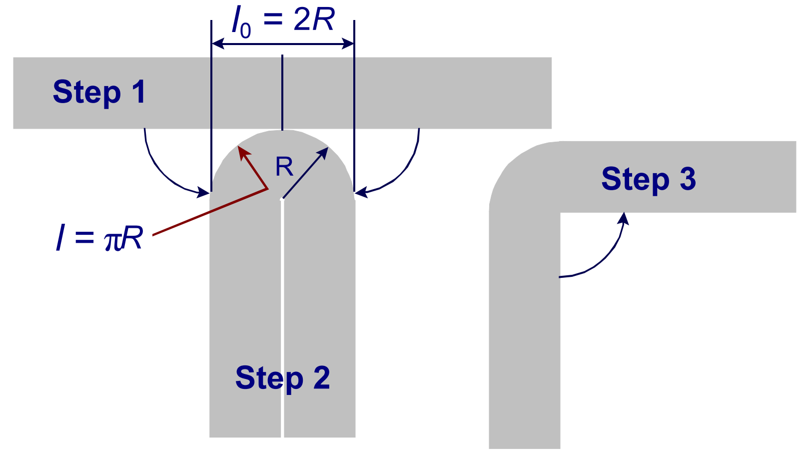


Data Courtesy of Brian Somerday

Mohawk Innovative Technology, Inc.

Testing of Korolon® Coatings in Hydrogen

- Evaluate coating stability in Hydrogen
- Bend Testing of coated samples after Hydrogen charging
- Examine coating integrity after bending
- Established ASTM Test Method
- Testing at NIST or SNL

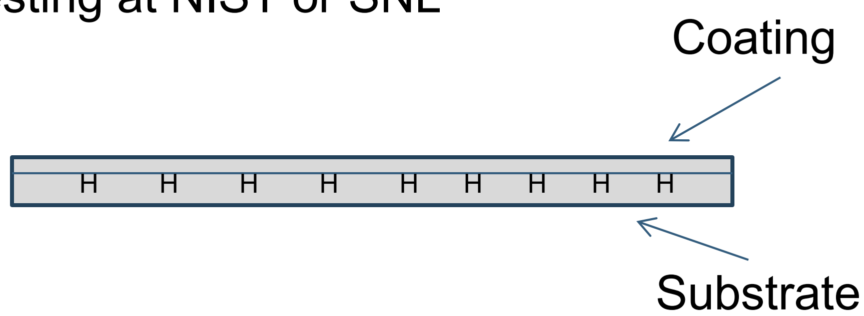


% Elongation = $100^*(l - l_0) / l_0 = (\pi-2)/2 = 57\ \%$

03-0138

Example of good coating after bend test

www.Korolon.com



Compressor Design Meets DOE 2020Target

2007 and 2012 Revised Technical Plan

Characteristics	DOE Target	MiTi Estimates
Isentropic Efficiency (%)	88%	83%
Hydrogen Capacity Target (kg/day)	200,000	240,000 – 500,000
Hydrogen Leakage (%)	<0.5	0.2
Hydrogen Contamination	None	None
Inlet Pressure (psig)	300-700	350-500
Discharge Pressure (psig)	1,000-1,200	1,226 - 1,285
Uninstalled Capital Cost ($Million) **(Based on 9,000 kW motor rating)**	$5.7	$4.1-$6.1
Maintenance Cost (% total Capital Investment)	2%	2%-3%
Annual Maintenance Cost ($/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

Additional 3-4% in efficiency can be gained by thermal management

Capital and Maintenance Cost estimates based on data from MHI for comparably sized NG compressor systems, published oil and gas industry data and from quotes for fabrication of major components of MiTi's compressor design.

Estimates for Compressor Efficiency, Flows, Pressures and package size based on stage and system design analysis 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

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 Verification Testing of MiTi® Hydrogen Compressor Stage (FY12-13)

- Completed Testing in Air and Preliminary Testing in He
- Selected Double-Entry design over Single Entry Design

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

Novel Technologies Developed by MiTi

Technologies Developed and Demonstrated Under This Program

- Advanced Foil Bearings and Seals
- 200 kW Oil-Free High-Speed Motor
- Motor Coupling Technology
- Oil-Free High-Speed Gearless Compressor
- Closed Loop Testing Facility

Partial List – Publications and Presentations

1. Heshmat H., Walton JF., “Oil-Free Modular System Designs for Industrial Compressors and Renewable Energy Turbine Generator Systems,” Clean Technology Conference and Expo, June 21, 2010, Anaheim, CA
2. Heshmat H., Hunsberger AZ., Ren Z., Jahanmir S., Walton JF., “On the Design of a Multi-Megawatt Oil-Free Centrifugal Compressor for Hydrogen Gas Transportation and Delivery – Operation Beyond Supercritical Speeds”, Proceedings of the ASME International Mechanical Engineering Congress and Expo, November 12-18, 2010, Vancouver, BC, Canada.
3. Heshmat H., *Invited Keynote*, “Tribological Requirements of High-Speed Oil-Free Rotating Machinery for Hydrogen Applications,” 2011 Hydrogenous Tribology Symposium, February 3, 2011, Fukuoka, Japan.
4. Heshmat H., “Design of a Multi-Megawatt Oil-Free Centrifugal Compressor for Hydrogen Gas Transportation and Delivery,” Fuel Cell and Hydrogen Energy Expo, February 15, 2011, National Harbor, Md.
5. Heshmat, H., Hunsberger, A., Ren, Z., Jahanmir, S., and Walton, J., *Invited Keynote,* “Oil-Free Bearings and Seals for Centrifugal Hydrogen Compressor,” International Tribology Conference, Hiroshima, Japan, December 5, 2011.
6. Walton, JF, “Design of a Multi-Megawatt Oil-Free Centrifugal Compressor for Hydrogen Gas Transportation and Delivery”, World Hydrogen Energy Conference, Toronto, Canada, June 6, 2012.
7. MiTi presents, “Operation of the single stage compressor”. Multimedia video can be viewed at the following site: (http://www.youtube.com/watch?v=dPn0uLIdtS8).
8. H. Heshmat, A. Hunsberger, Z. Ren, S. Jahanmir, and J. F. Walton, “Oil-Free Foil-Bearings for Centrifugal Hydrogen Compressor,” Tribology Online, January 2013.

Acknowledgements

MiTi is grateful for the support from the DOE Hydrogen and Fuel Cells Program and in particular, Sara Dillich, Erika Sutherland, Katie Randolph, Monterey Gardiner and Mark Paster for their sustained interest in our technology.

MiTi Team
Jose Cordova
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Said Jahanmir
Michael J. Tomaszewski
James F. Walton II

MHI Team
Satoshi Hata
Daisuke Hirata
Masayuki Kita

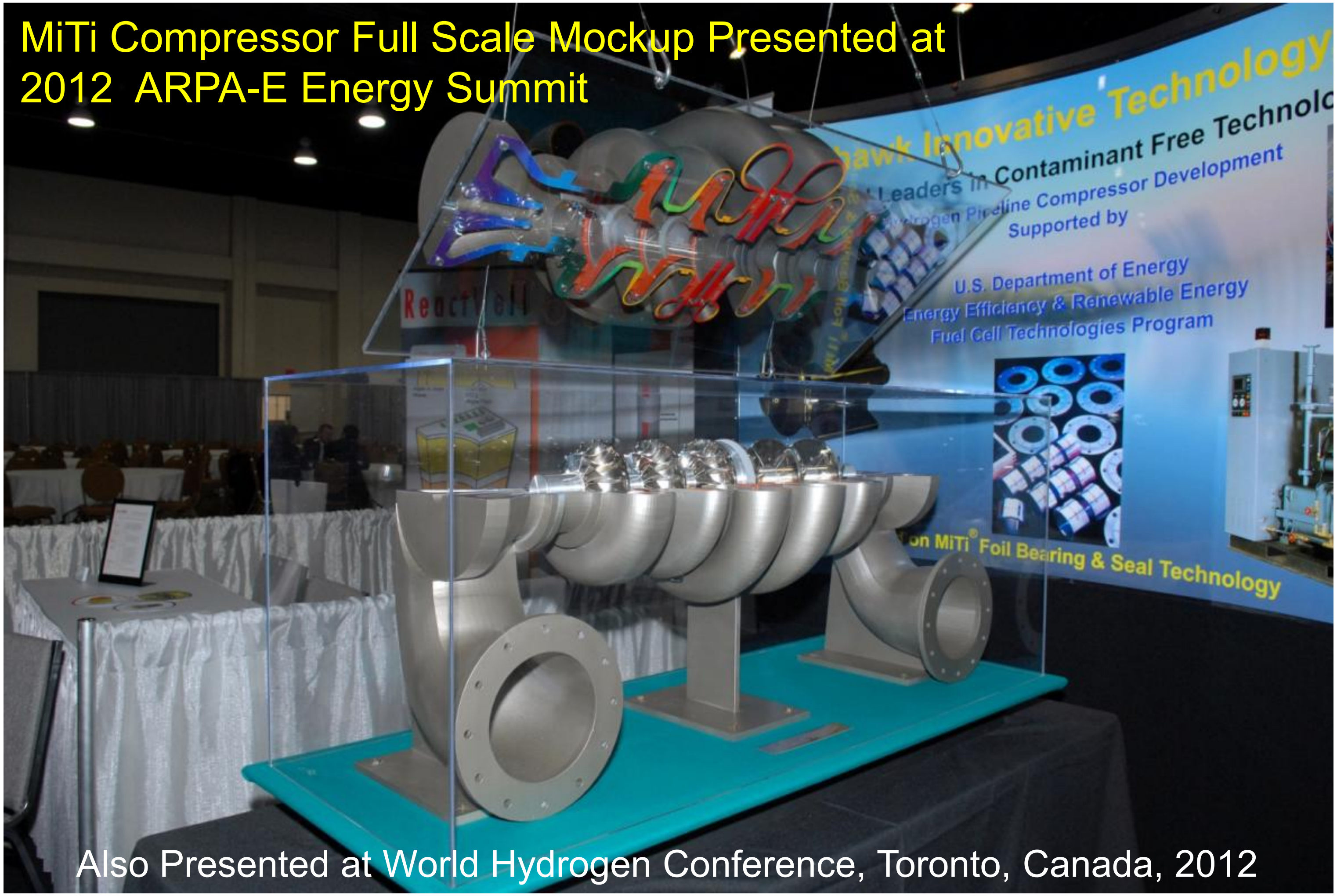
Other Collaborators
Petros Sofronis – U of Illinois
Brian Somerday – Sandia
Rick Ricker – NIST

Backup Slides

Full-Scale Hydrogen Compressor

Backup

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



Also Presented at World Hydrogen Conference, Toronto, Canada, 2012

Single Stage Compressor Testing – ASME PTC-10

- **Type 1 Test:** A test conducted with the specified gas at or very near the specified operating conditions.
- **Type 2 Test:** A Test Conducted Subject To The Permissible Deviations Listed In Table Below with Similitude Gas

Quantity	Symbol	Design Performance	PTC-10 Test Parameters
Specific Volume Ratio	v_i/v_d	1.072	1.018 – 1.126
Flow Coefficient	Φ	0.1253	0.120 - 0.130
Machine Mach No.	Mn	0.3266	0.141 - 0.532
Machine Reynolds No.	Re_m	1.55e6	1.55e5 – 1.55e7

Review of Closed-Loop Test Design

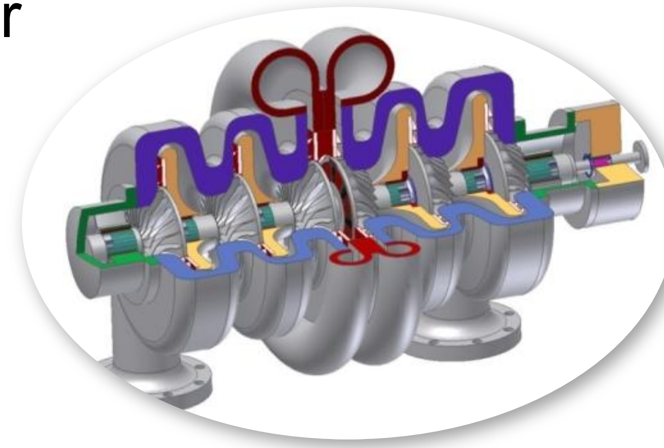
Backup

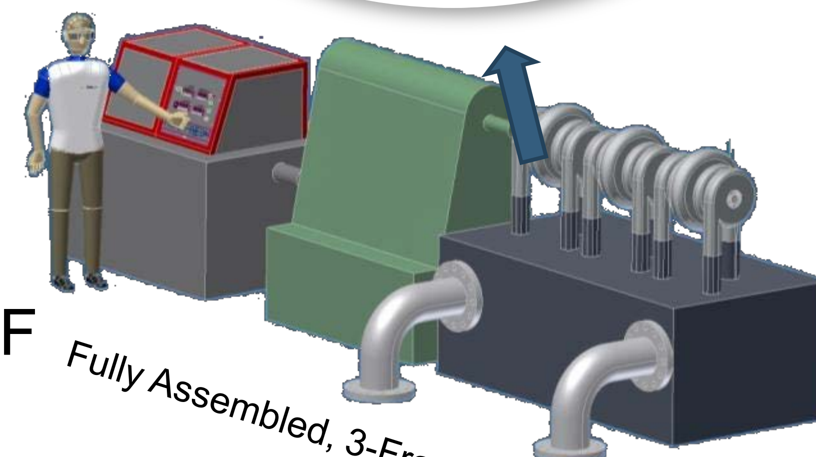
- Independent review of the designed test plan performed by McHale Associates.
- Review included test rig component sizing, loop configuration, valve sizing, surge prevention verification, and instrumentation and uncertainty estimation.
- ***McHale concluded that proposed test plan conforms with ASME PTC-10 and that the test loop components and configuration are appropriate.***
- Several helpful suggestions were made and recommendations regarding specific selection of critical components were given. Test plan has been accordingly revised to avoid unstable flow behavior that could result in surge.
- Give the promising results of the independent review by McHale, MiTi is moving forward with fabrication and assembly of the closed-loop system for testing the compressor with helium.

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^{o}F
- Specific Energy: 0.48-0.59 ($\frac{\text{kW-HR}}{\text{Kg}}$)

Single Frame



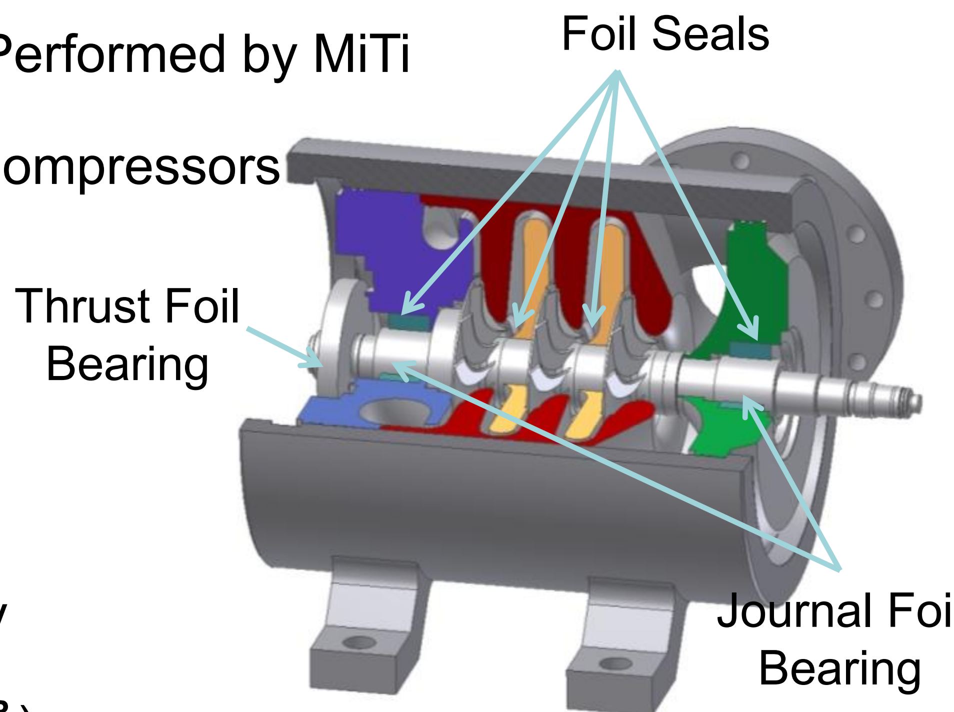


Fully Assembled, 3-Frame System

Mitsubishi Compressor Design Analysis

Backup

- 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 ($\frac{\text{kW-HR}}{\text{Kg}}$)



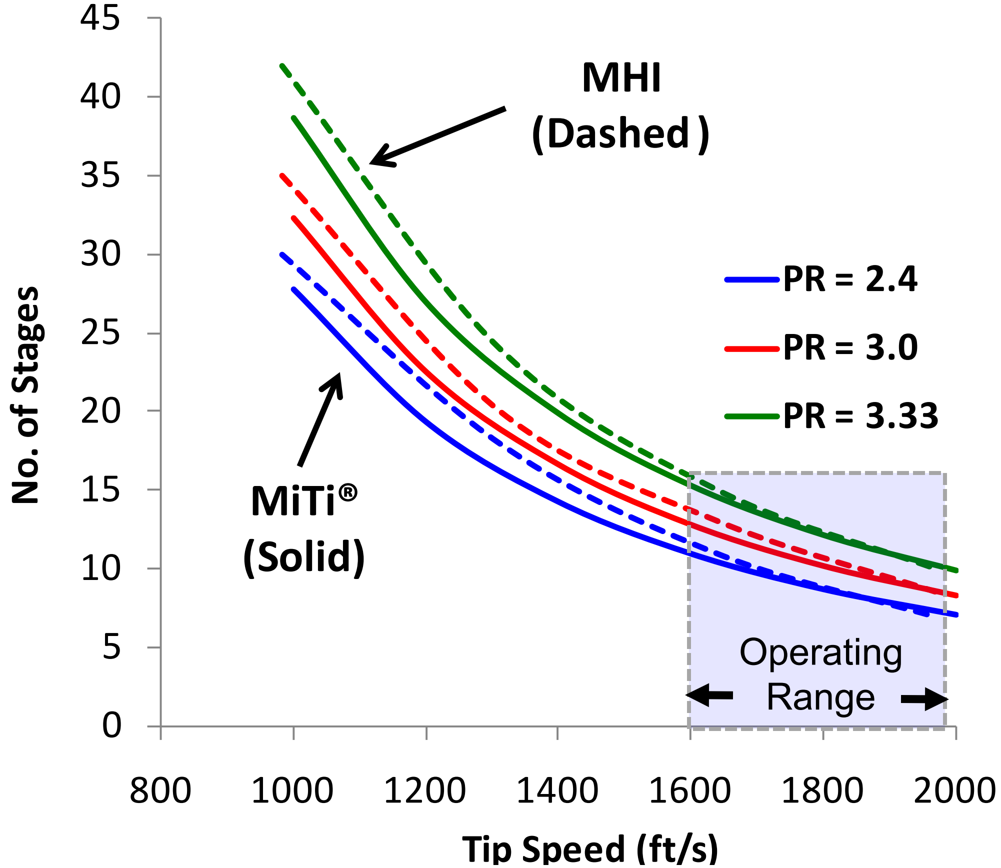
Single Frame

Multi-Stage Compressor Design

Backup

- 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



Multi-Frame Centrifugal Compressor Designs

Backup

Design Strategy	Mohawk Innovative Technology, Inc.	MHI
Compressor Type	Double-Entry	Single-Entry
Number of Stages	6 and 9	7 and 9
Number of Frames	2 and 3	2 and 3
Flow Capacity (Kg H_2/day)	240,000 – 500,000	
Total Pressure Ratio	2.4 - 3.33	
Total Power Input (HP)	7,800-12,000	8,300 – 12,000
Max Tip Speed (1000 ft/s)	1.6 – 1.8	1.8 - 2.0
Compressor Footprint (ft^2)	145 - 160	150 - 175

Mohawk Innovative Technology, Inc.

Assessed Pros and Cons for MiTi and MHI Hydrogen Compressor Designs

	Pros	Cons
MiTi Design *Double Entry*	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*	Balance Piston For Thrust Loads	High Thrust Loads Requires Balance Piston Plus Thrust Bearing
	Control of Axial Clearance	High Tip Speeds Required
	Fewer Parts	Larger Diameter Wheels Used
	Simple Inlet Piping	Unique Impellers in each Frame
		Reduced Stress Safety Margin

Comparative Analysis of Compressor Designs

Backup

- Detailed and careful comparisons between the Single Entry and Double Entry designs
- Concerns over the safety margin of MHI design
- **MHI Single Entry** design could be more costly and require more maintenance
- **MiTi Double Entry** design selected as the final configuration for hydrogen compressor

Materials Issues/Needs

Backup

- **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

Beta Ti Alloys for Rotating Group & Foil Bearings

Backup

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).

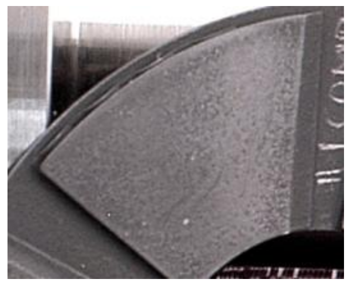
Material	UTS ksi	Hydrogen Embrittlement	Modulus ksix10^3	Fatigue Limit ksi	Thermal Expansion µin/in F	Electrical Resistivity µohm in
X-750 Ni	192	YES	31	80	7.8	48
316L SS	70	NO	28	37	8.6	30
Ti-15-3	200	NO	14.5	87	4.7	55
Ti Beta 21S	190	Yes	15	?	5.3	53

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

MiTi Korolon® Coatings

Successful Operation of Foil Bearings/Seals Require Solid Lubricant Coatings
Korolon® Coatings Have Been Specifically Designed for Foil Bearings/Seals

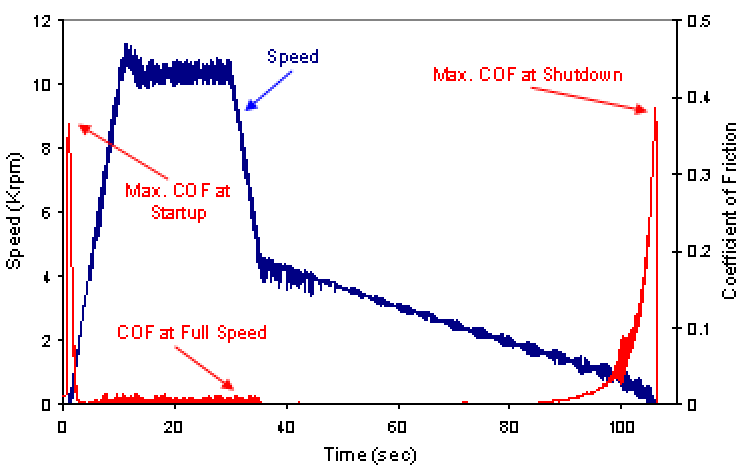
Flexible Ceramic Coating



New Foil Pad

	Korolon® 700	Korolon® 800 & 900	Korolon® 1350 A & B
Chemical Composition	Polymer based with solid lubricants	Tungsten Disulfide based with solid lubricants	Nickel-Chrome with solid lubricants
Max Service Temperature	700 °F	900 °F	1350°F

- Low Friction and Wear Rate
- Deposited with Spray Gun Process at Room Temp



Typical Friction/Speed Results Showing Hydrodynamic Lift

Recent research has shown that polyamide coatings and PTFE and also disulphide solid lubricants are compatible with H_2.

Publications from ANL (USA), BAM (Germany) and Kyushu University (Japan).

Mohawk Innovative Technology, Inc.