U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Fuel Cell Technologies Program

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

Arlington VA

Project ID # PD016

June 17, 2104

Oil-Free Centrifugal Hydrogen Compression Technology Demonstration

PI: Hooshang Heshmat, PhD

Mohawk Innovative Technology, Inc.

Albany, NY

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Overview

Timeline

- Start Sept 1, 2008
- Funding Authorized 2/28/09
- Extended May 31, 2014
- 100% Complete

Budget

- Total Project Funding
  - $2,992,407 DOE
  - $748,437 Cost Share
- Fully Funded in FY12

Barriers

- Hydrogen Delivery Compressor
  - Reliability
  - Capital Cost
  - Compression Efficiency & Performance

Targets

CATEGORY	FY2017
Maximum Pressure (PSIG)	1500
Flow (Thousands of kg-H2/Day)	200+
Isentropic Efficiency	>88%
Capital Investment (based on 200,000 kg of H2/day)	$9M
Maintenance (% of Total Capital Investment)	3%
Reliability	HIGH
Contamination	NONE

Partners

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

Overall Project Objective

Design a reliable and cost effective centrifugal compressor for gaseous 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***

Objective This Reporting Period

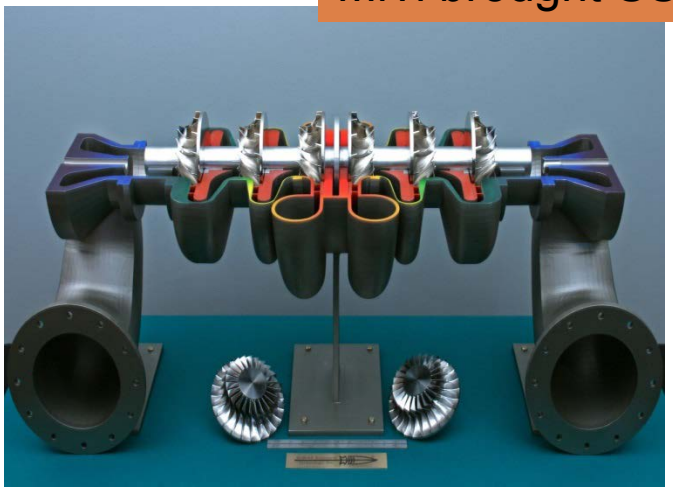
- ❑ Demonstrate Viability of H2 Centrifugal Compressor
  - Complete Test Facility
  - Assemble Single Stage Test
  - Conduct Performance ASME PTC-10 Test in Helium

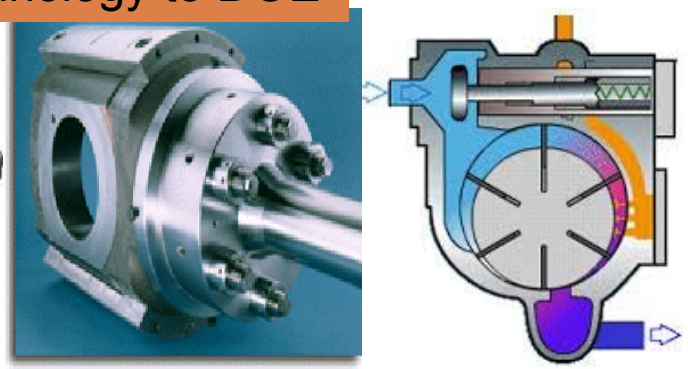
Barriers Addressed

- ❑ Centrifugal Compressor
  - Pressure Rise/Stage
  - System Efficiency
  - Capital & Operating Costs
- ❑ Contamination Free Operation
- ❑ Reliability

High Flow Compressor Technologies Assessed

MiTi brought SSME space age technology to DOE

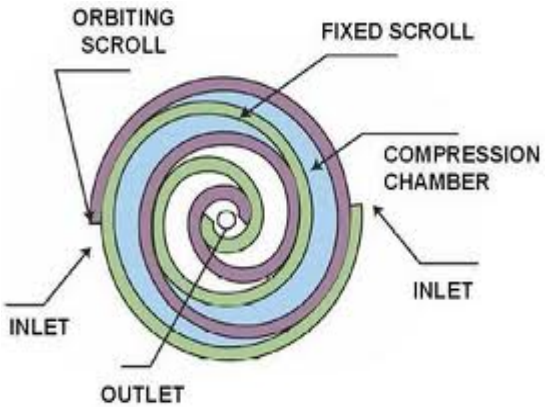


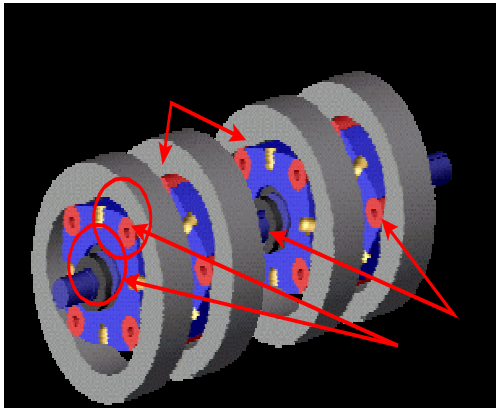


Contacting Surfaces, Numerous Parts, Lubrication

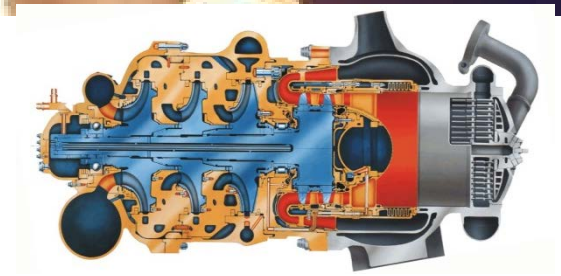
MiTi Centrifugal Compressor

- One Moving Part
- High Reliability
- Oil-Free
- No Contaminants
- Minimal Contact/Sliding
- High Efficiency
- High Flow



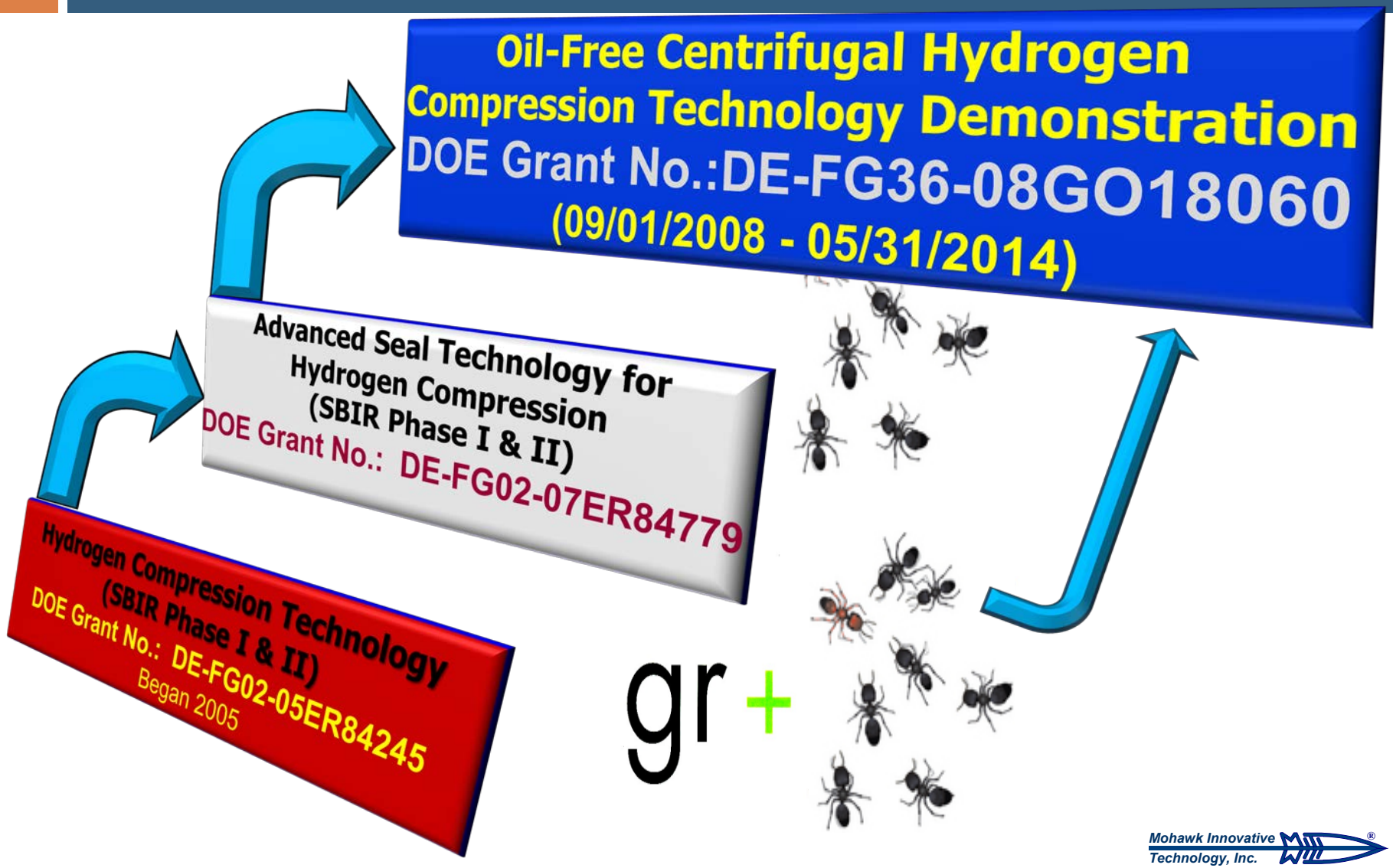


Space Age Technology Brought To Bear on Hydrogen Infrastructure



- Totally Oil-Free Compliant Foil Bearings and Seals
- Non-Contact Operation
- High-Speed Centrifugal Compressor Impellers
- Advanced Materials
- High-Speed Drive

SBIR Programs Leading to Technology Development



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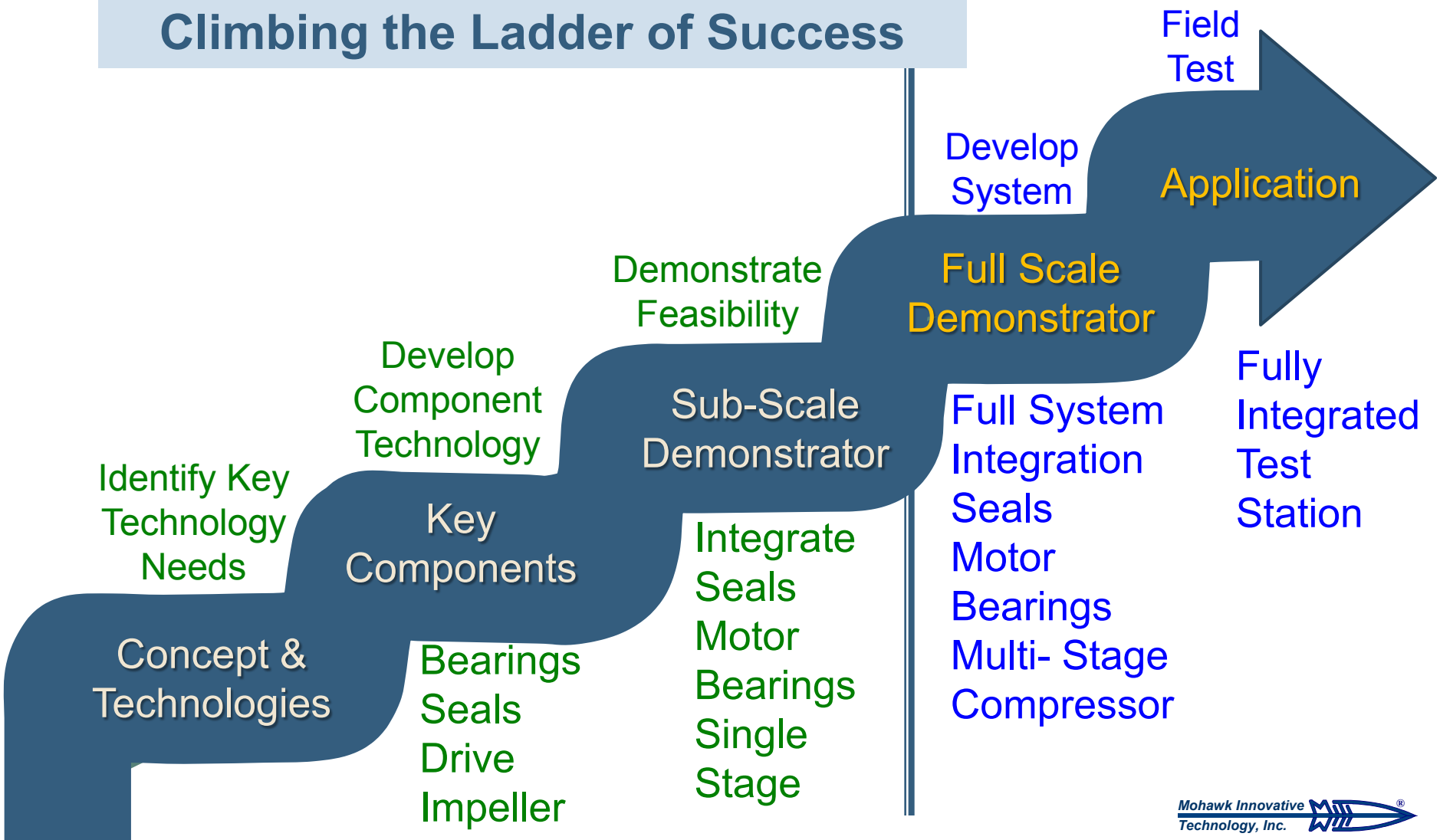
Development Plan

Climbing the Ladder of Success



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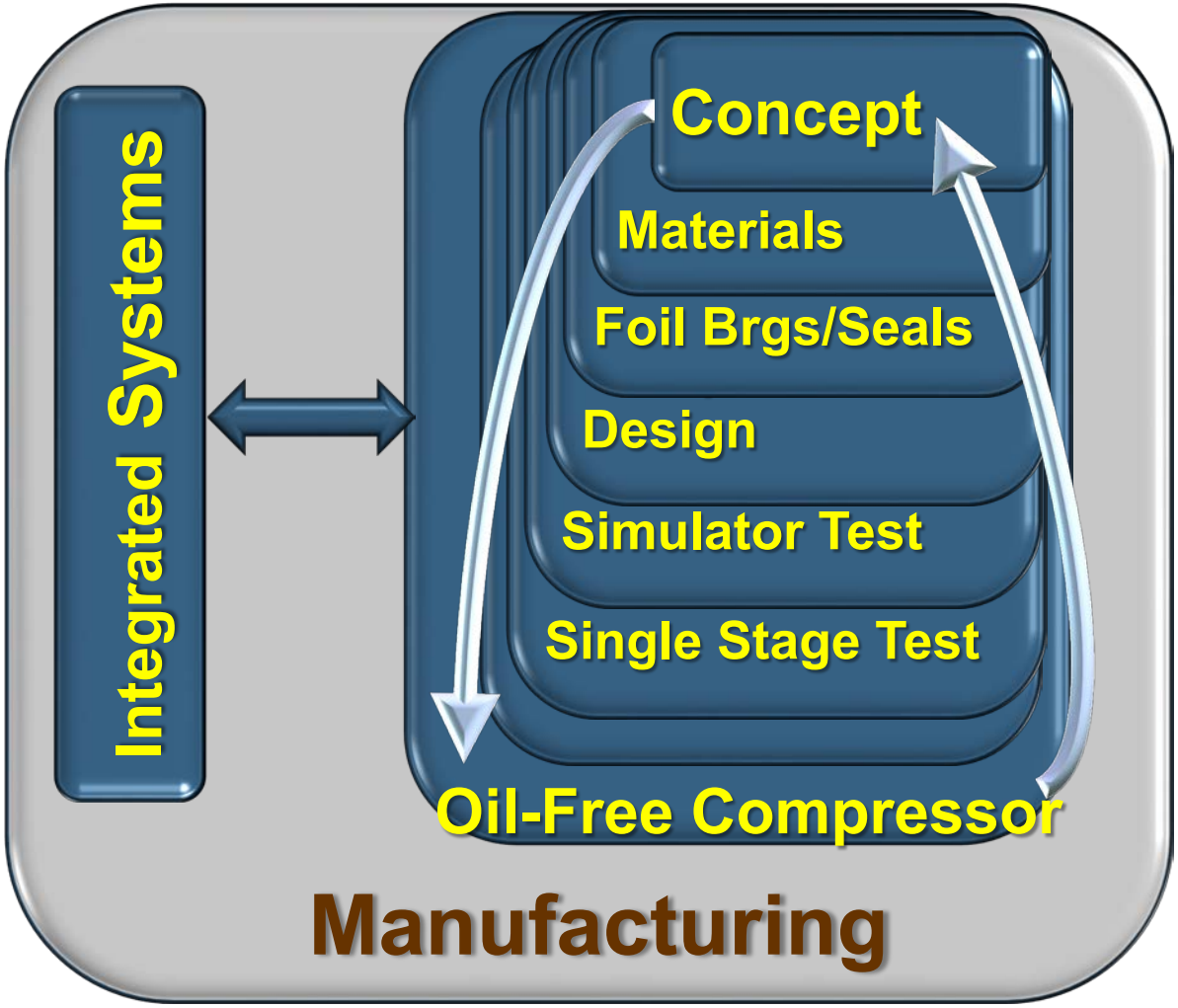
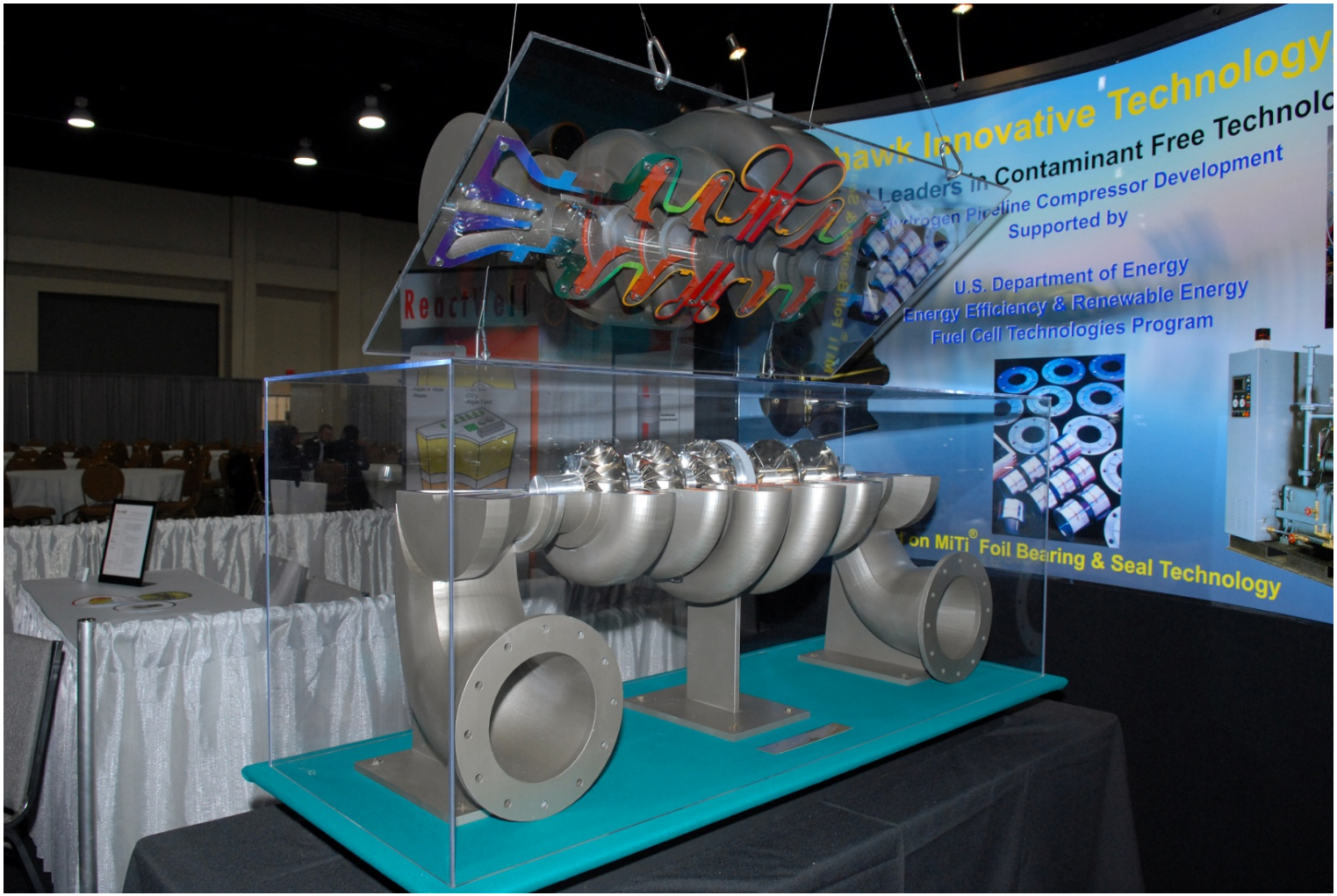
Design Methodology

Technologies Needed

- Non-Contacting Foil Bearings and Seals
- Advanced, High-Speed Centrifugal Compressor Impellers
- System Integration Rotor-Bearing-Compressor
- Hydrogen Compatible Materials



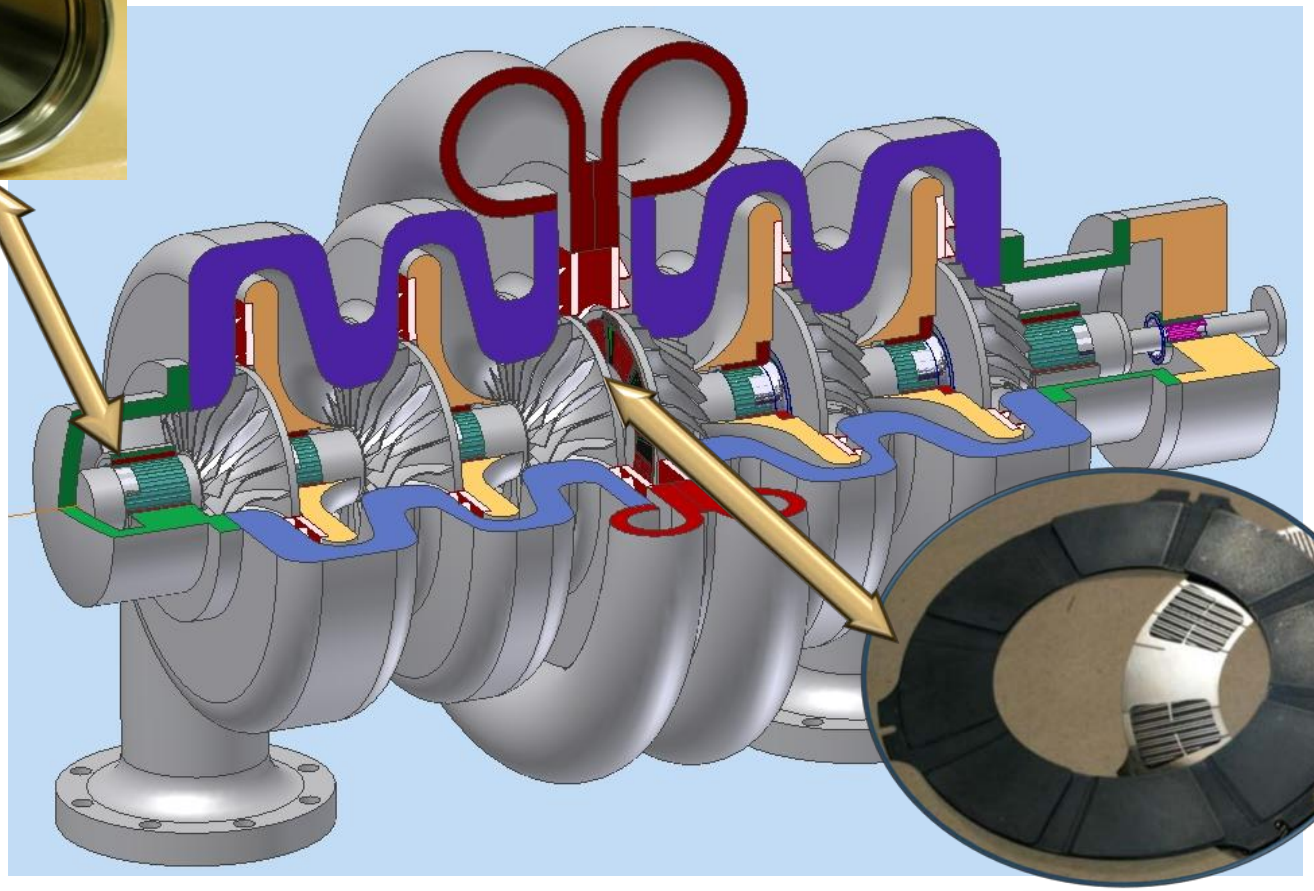
Full-Scale Hydrogen Compressor



CONCEPT: 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

Program Accomplishments

Compressor Design Analysis

- ✓ Mean Line Analysis, CFD, FEA

Sub-Component Design

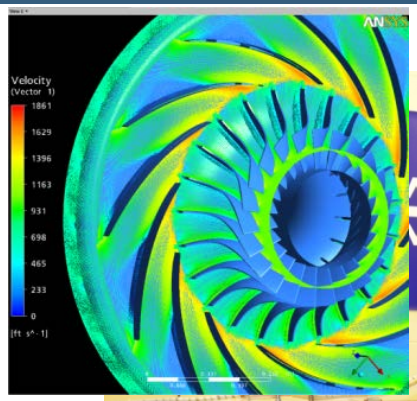
- ✓ Foil Bearings & Seals / Coatings
- ✓ Supercritical Rotordynamic Operation

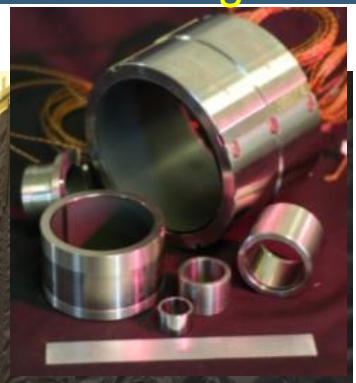
Design Single-Stage Compressor

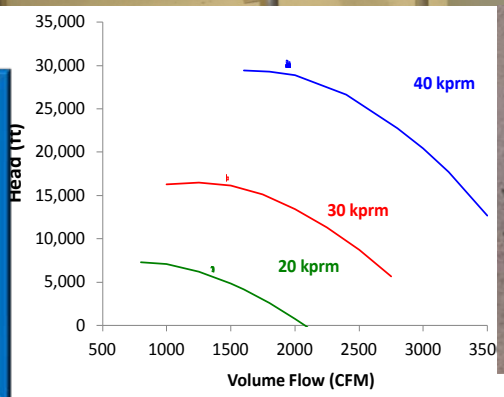
- ✓ Impeller, Diffuser and Others
- ✓ Drive System & Test Loop

Scale System Design

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







Single-Stage Performance Testing

- ✓ Fabricate Single Stage Test Facility
- ✓ Characterize Pressure & Flow
- ✓ Validate Design & Analysis

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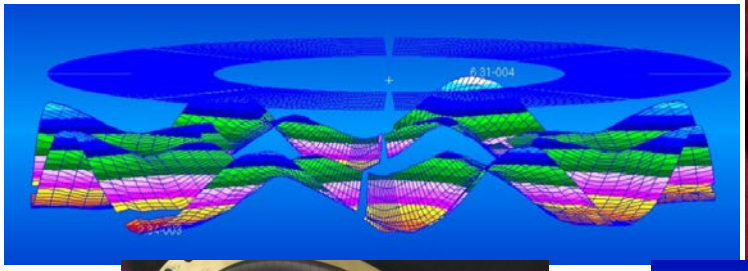
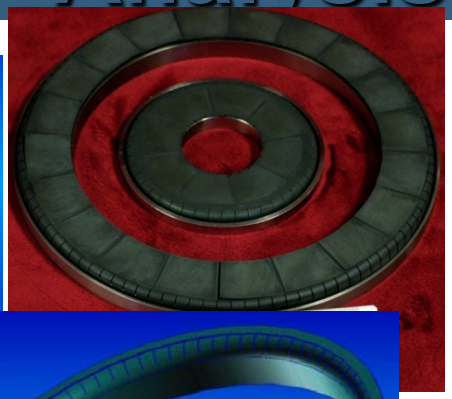
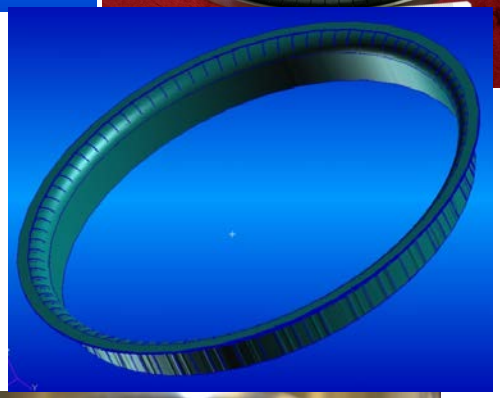
Foil Bearings and Seals: Coupled Elasto-Hydrodynamic Analysis

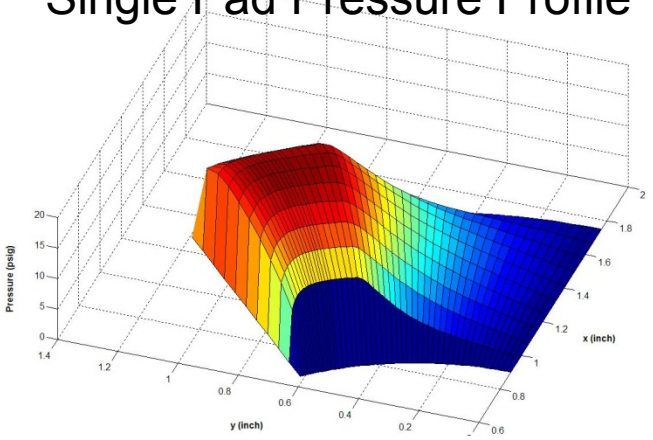
Approach

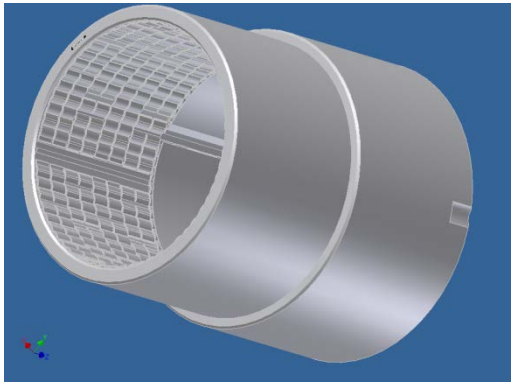


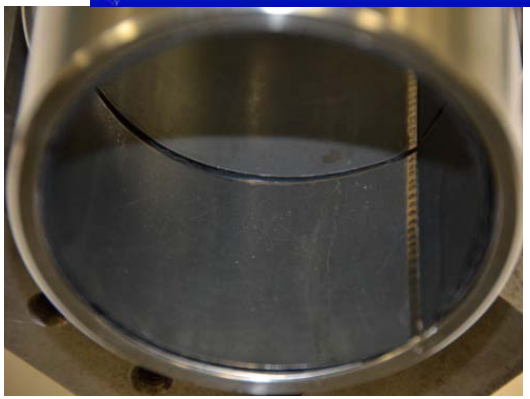


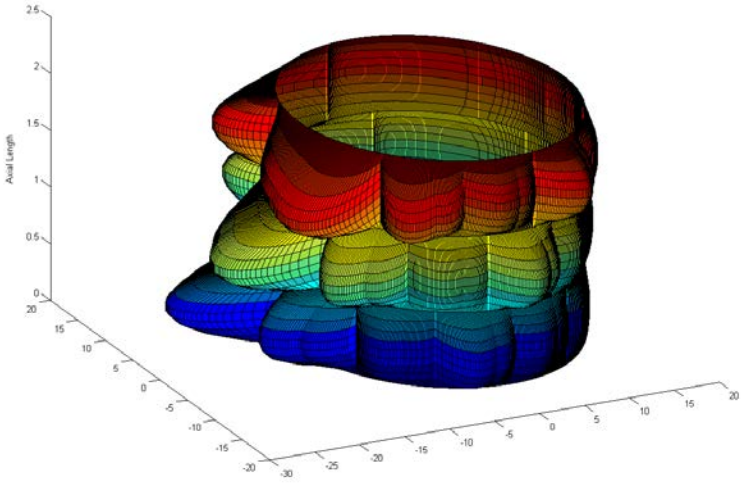


Single Pad Pressure Profile









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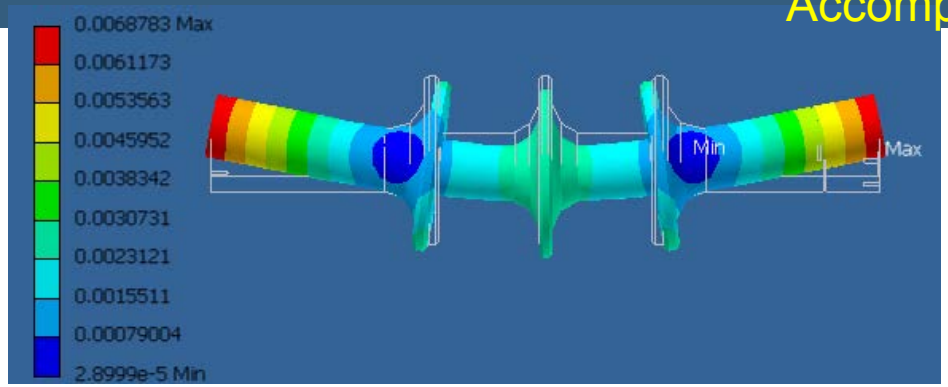
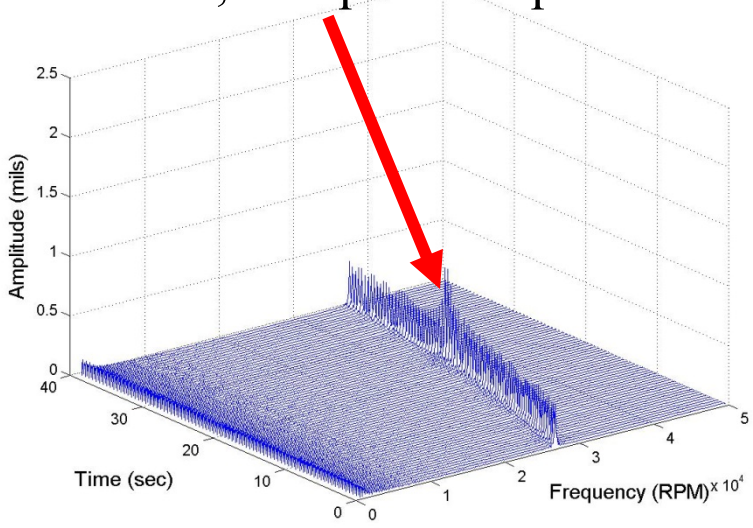
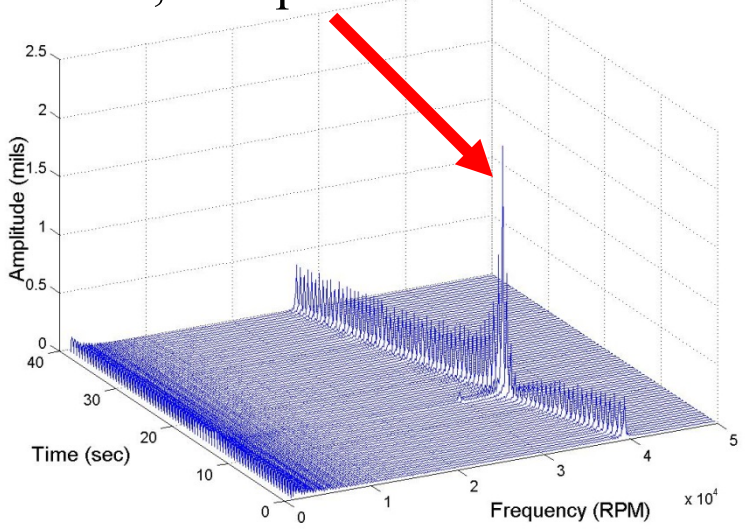
Supercritical Operation



34,400 rpm run up



34,300 rpm coast down



- Stable System With Excellent Correlation

Speed Limitation of Test Simulator Rotor; Rotor Fracture as Result of High Speed Operation

"Foil Bearing Speed Limitation Has Yet TBD"

Shaft Ultimate Centrifugal Stress Limit Is What Limits Foil Bearing Speed Capability

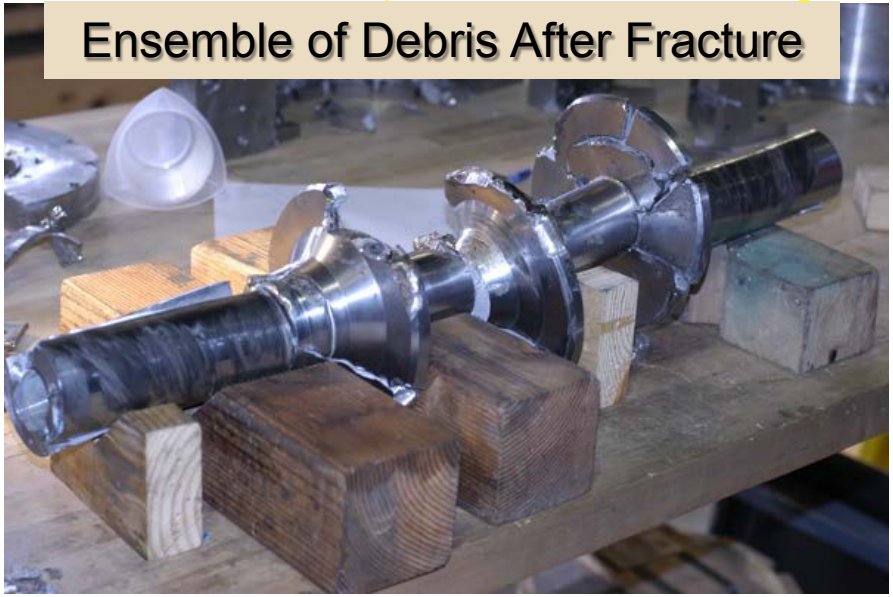
Rotor Prior to Max. Speed Test; Rotor Weight~25 Kg

Sudden And Irreparable Fracture Of The Test Rotor as Result Of "Ultimate Centrifugal Stress"

Material Integrity and Internal Flaws Are What Sets the Speed Limit of Rotors

Rotor prior to assembly and testing

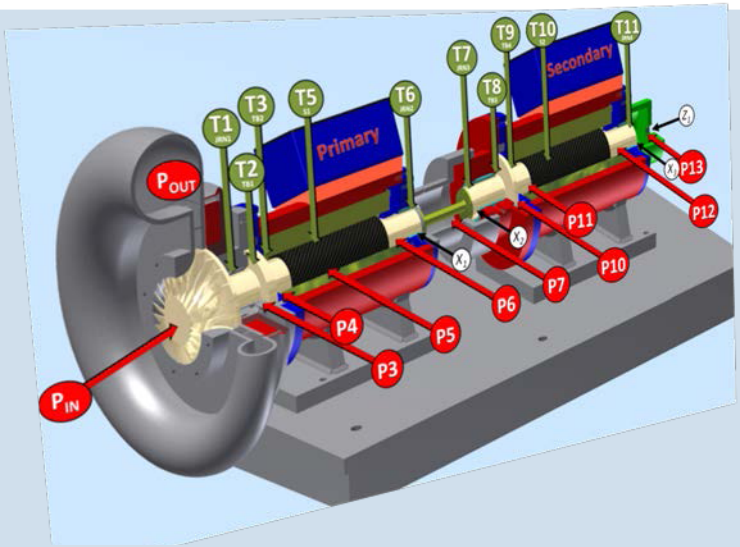
Ensemble of Debris After Fracture



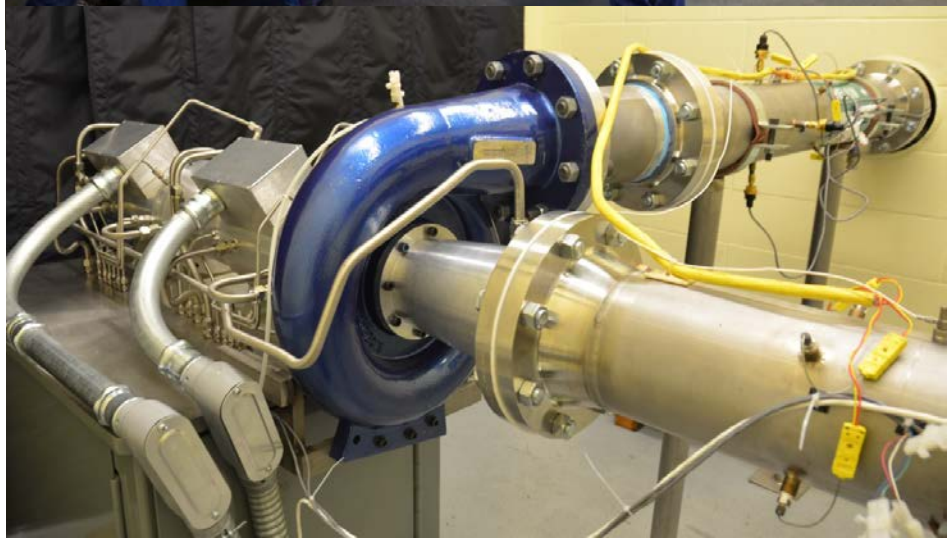
The fractured disk and shaft pieces showing the fracture mirror in the central region of the disk.

Compressor Test Cell

Closed Loop Helium Compressor Test Facility



- Oil-Free Centrifugal Compressor
- Ultra-High Operating Speed
- Gen. IV Foil Bearings & Seals
- Single Stage Testing in Helium
- 1300 to 1500 psi Pressure Rise In 8-Stages
- ½ x10^{+9} H2 gr-/day & 9 MW Drive



FY 14 Accomplishments

Simulated Hydrogen Compressor Testing

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

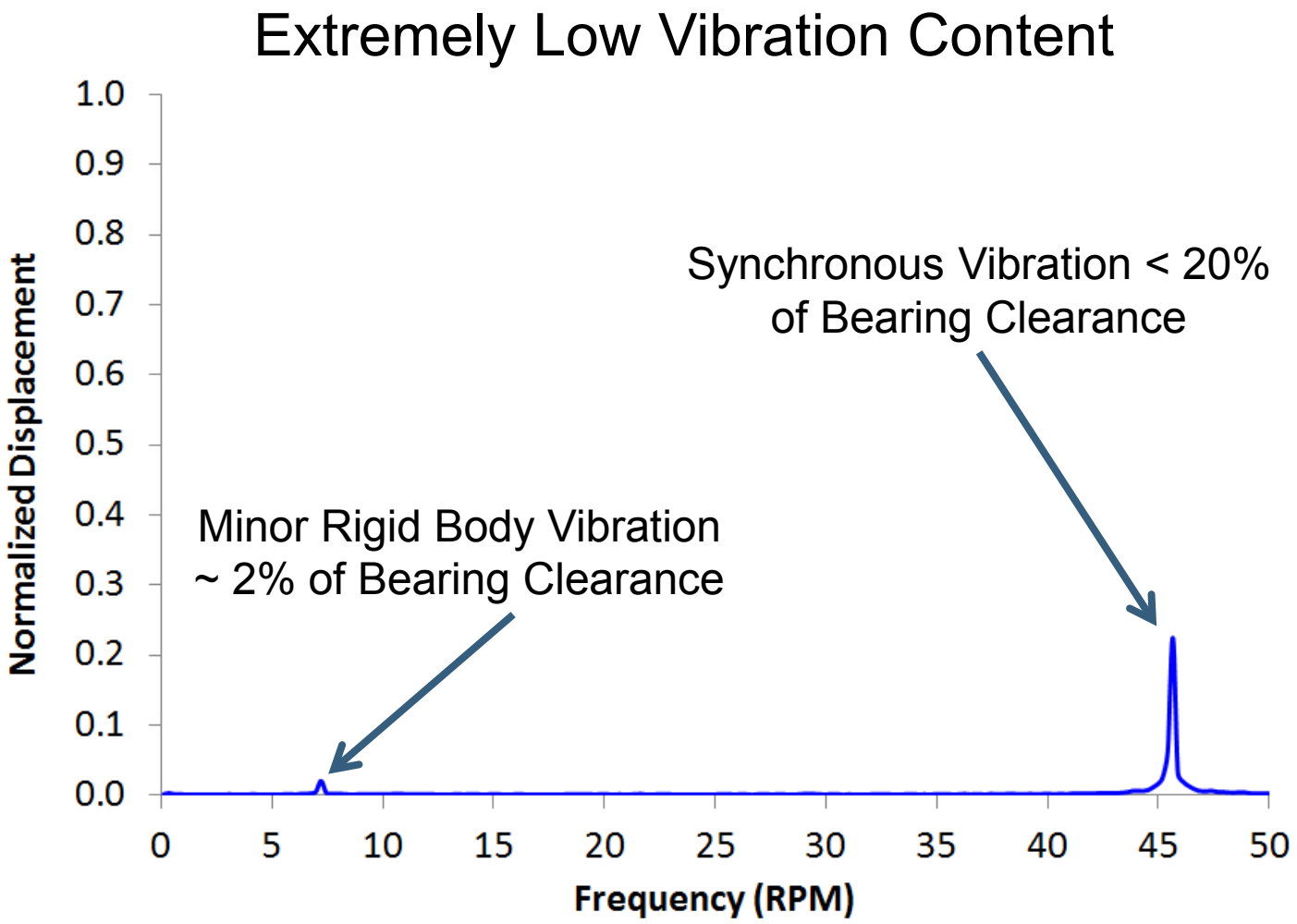
Hydrogen Compatibility Evaluation

- Evaluated H_2 compatibility of Ti Alloy Materials

Design Refinement

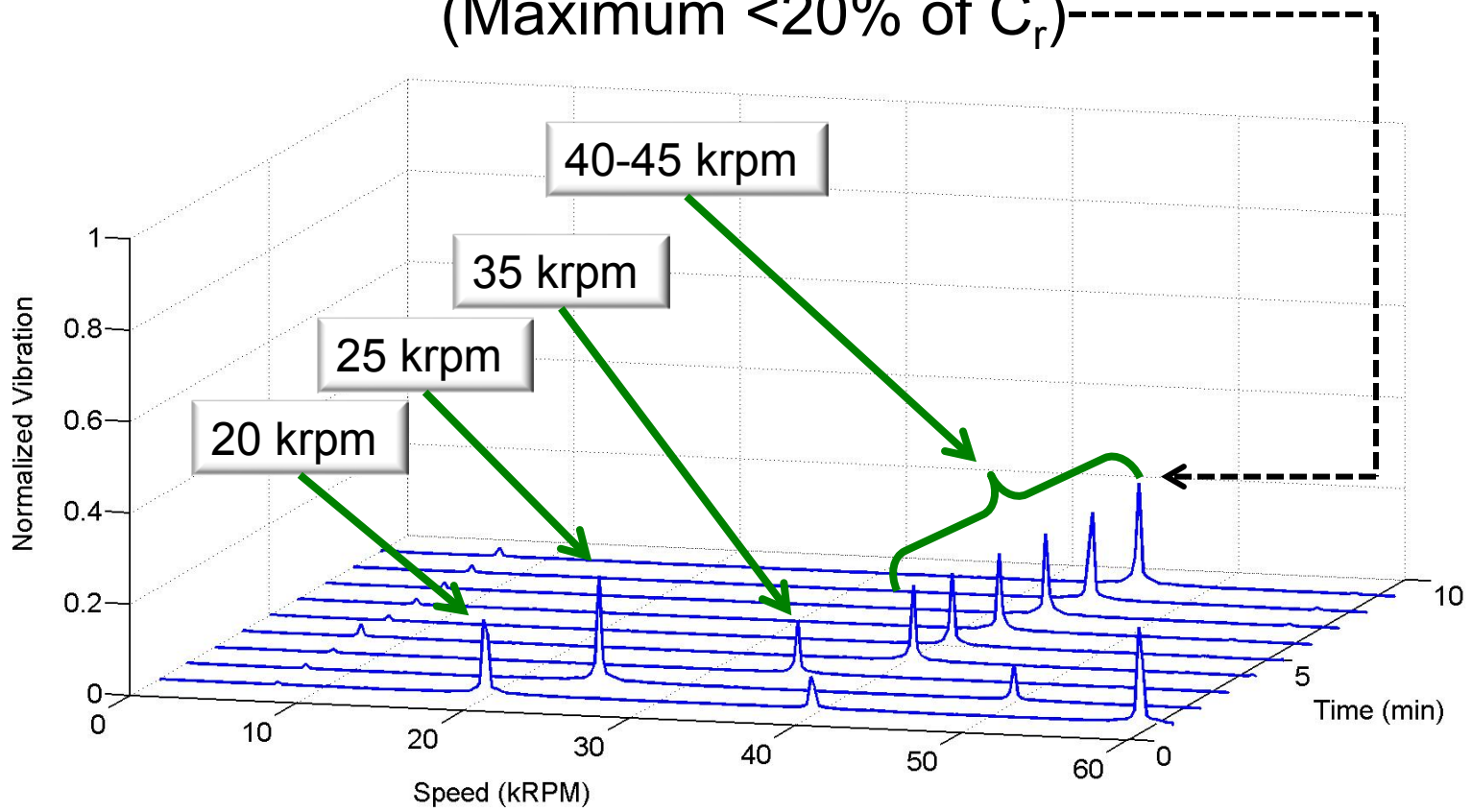
- Estimated Multi-Frame Compressor System Performance, Total Intercooler Heat Load and Total Driving Power Required per Frame, Based on Single Stage Test Data
- Refined Estimates of Capital Costs and Compare to DOE Targets

Vibration of Compressor at 45,000 rpm



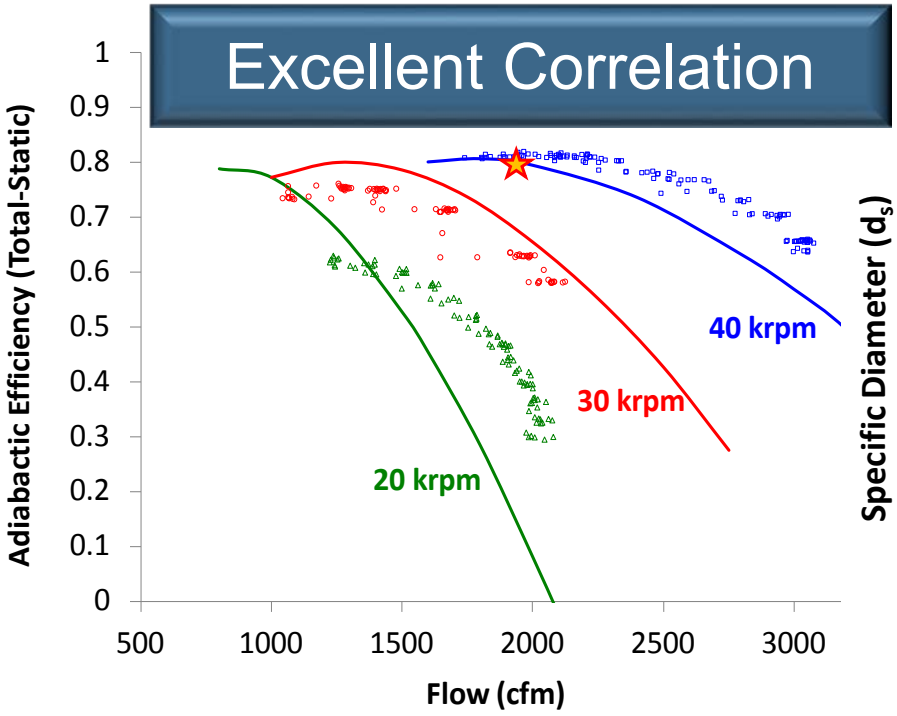
Compressor Operation to 45 krpm

Synchronous Vibration Normalized to Bearing Clearance (Maximum <20% of C_r)

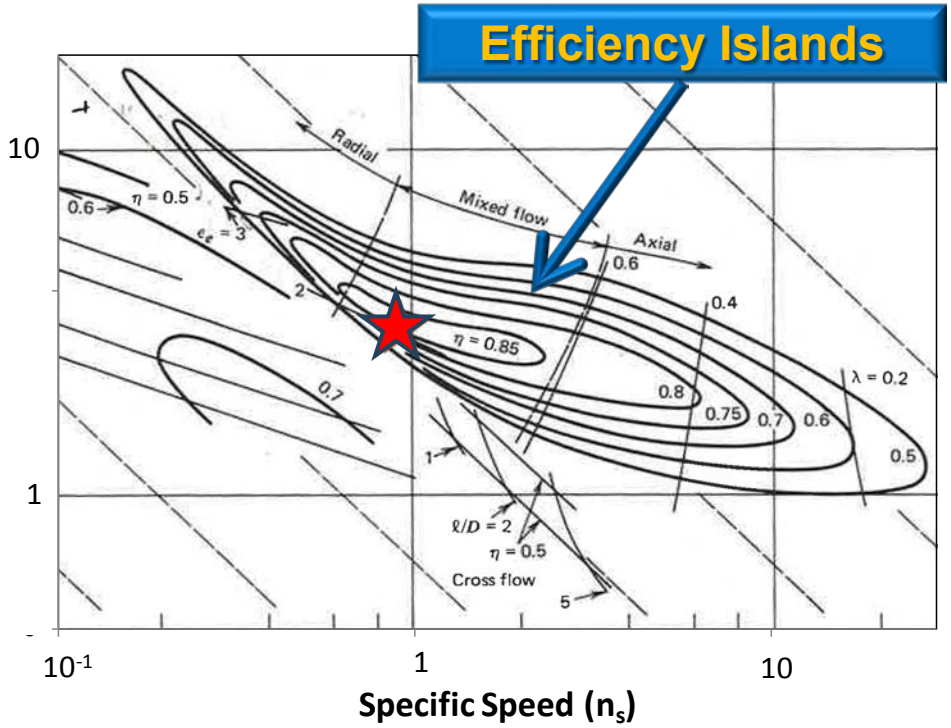


Experimental Validation of Achieved Optimal Efficiency

Excellent Correlation

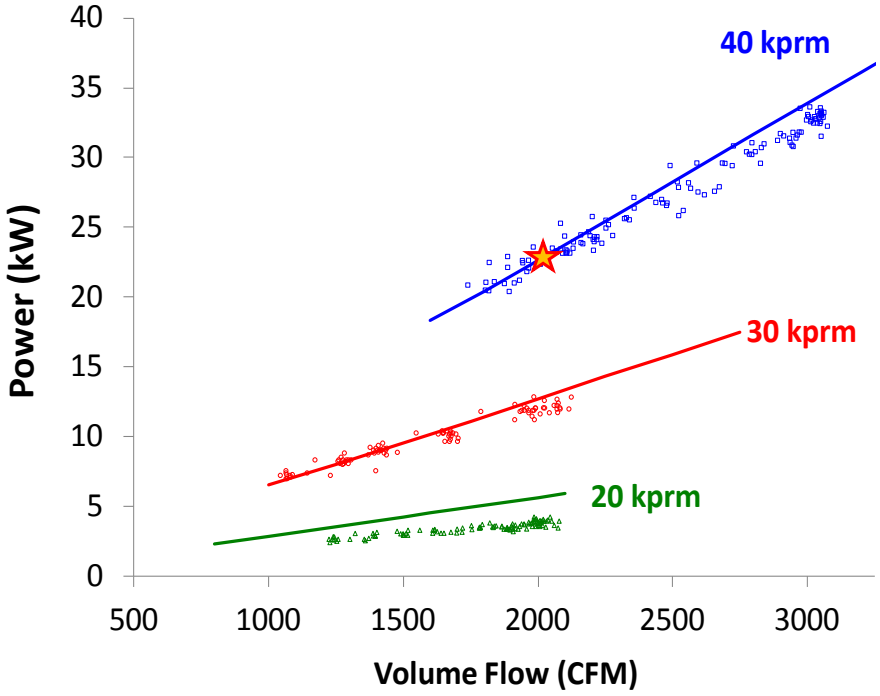


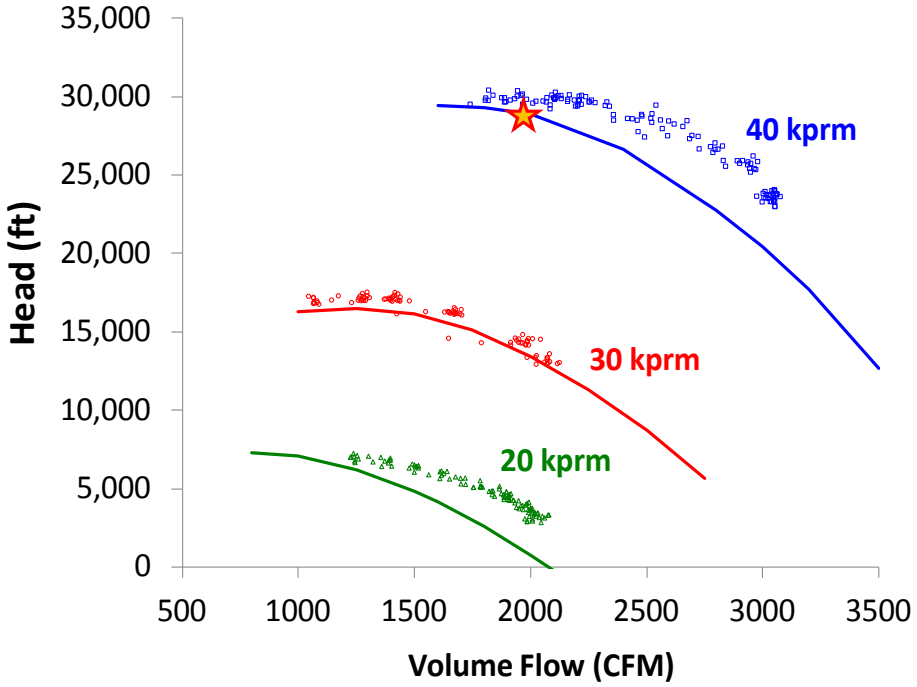
Efficiency Islands



Performance Verified In The World's Only High-Speed Contamination-Free, Oil-Free Compressor

Compressor Performance Verified in Helium





Performance Verified In The World's Only High-Speed Contamination-Free, Oil-free Compressor

Novel Technologies Developed by MiTi

Technologies Developed and Demonstrated Under This Program

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

Program Summary

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 (FY12-14)

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

Successfully Demonstrated That MiTi's Oil-Free, Very High-Speed Centrifugal Compressor Concept For Hydrogen Meets The Compressed Hydrogen Delivery Needs

Acknowledgements

MiTi is grateful for the support from the DOE Hydrogen and Fuel Cells Office for its sustained interest in our technology.

MiTi Team
Jose Cordova
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MHI Team
Satoshi Hata
Daisuke Hirata
Masayuki Kita

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

Thank you for your attention

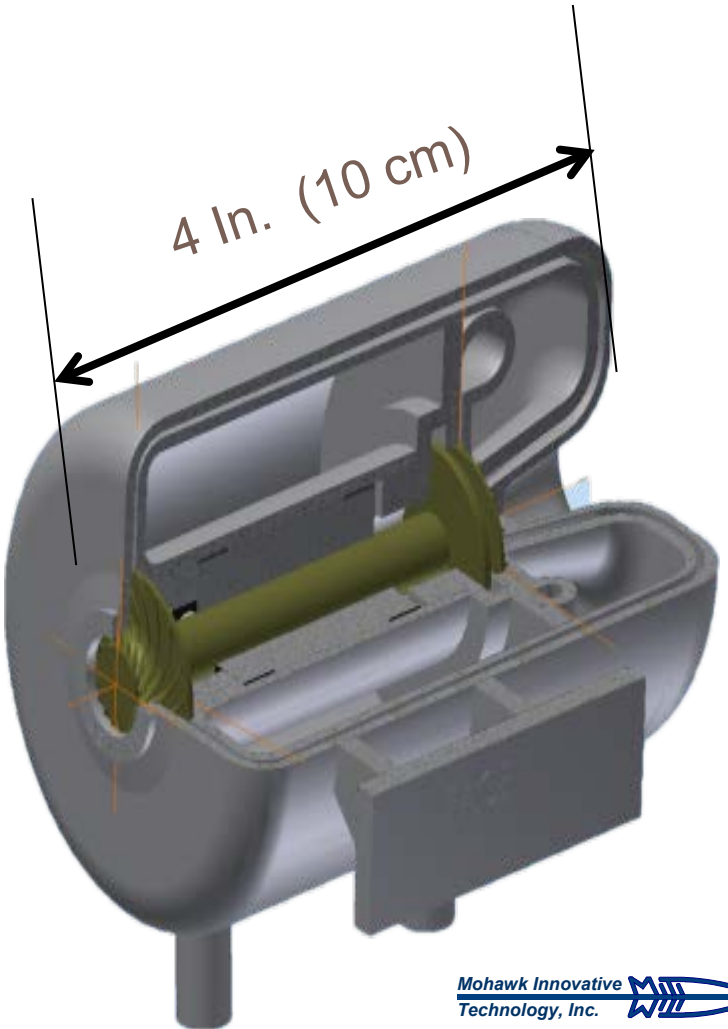
Mohawk Innovative Technology, Inc. is grateful to the DOE for its support of our small company and the advancement of centrifugal compressor technology.

Backup Slides

Design Rule for Miniaturization, M ~ ∫ (t x P)

Miniaturization Factor < 0.12

N ~ 0.5 x 10^6 rpm, P ~ 1 kW



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
  - Automotive and Aerospace Fuel Cell Applications

Issues to be Resolved for High Volume

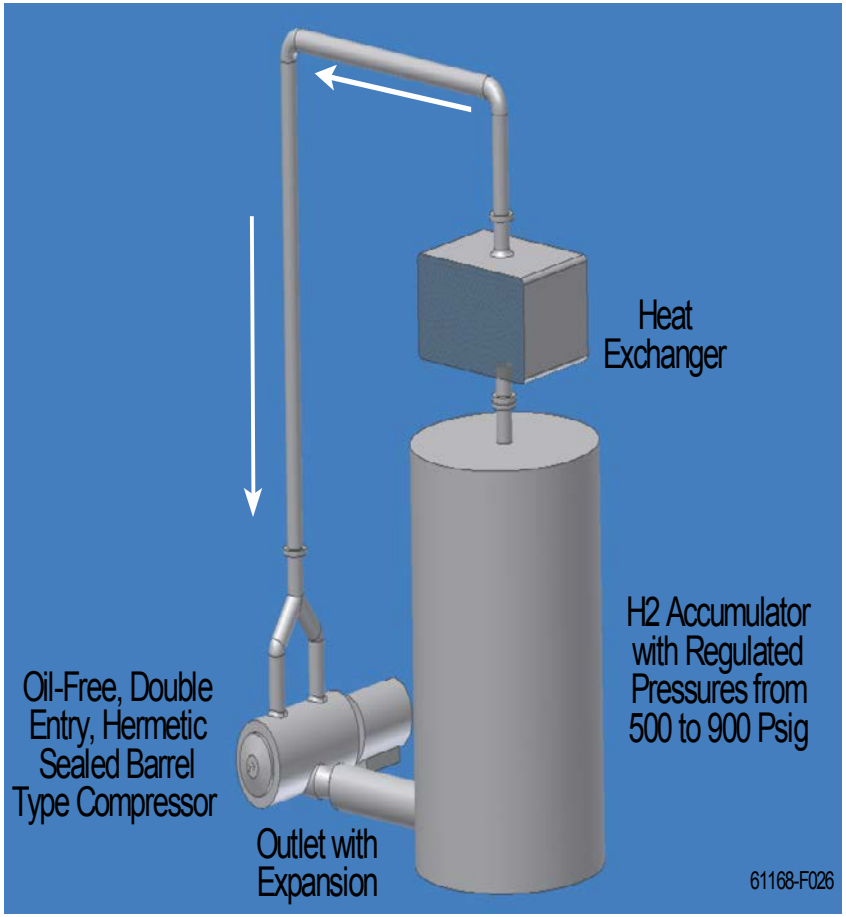
Future Work

Oil-Free High Power & Speed Drives

System Level Performance Validate Facility
- Multi-Stage Compressor Train
- High-Speed & Power Transmission Coupling
- Static & Dynamic Sealing
- Validate Life/Reliability/Maintenance

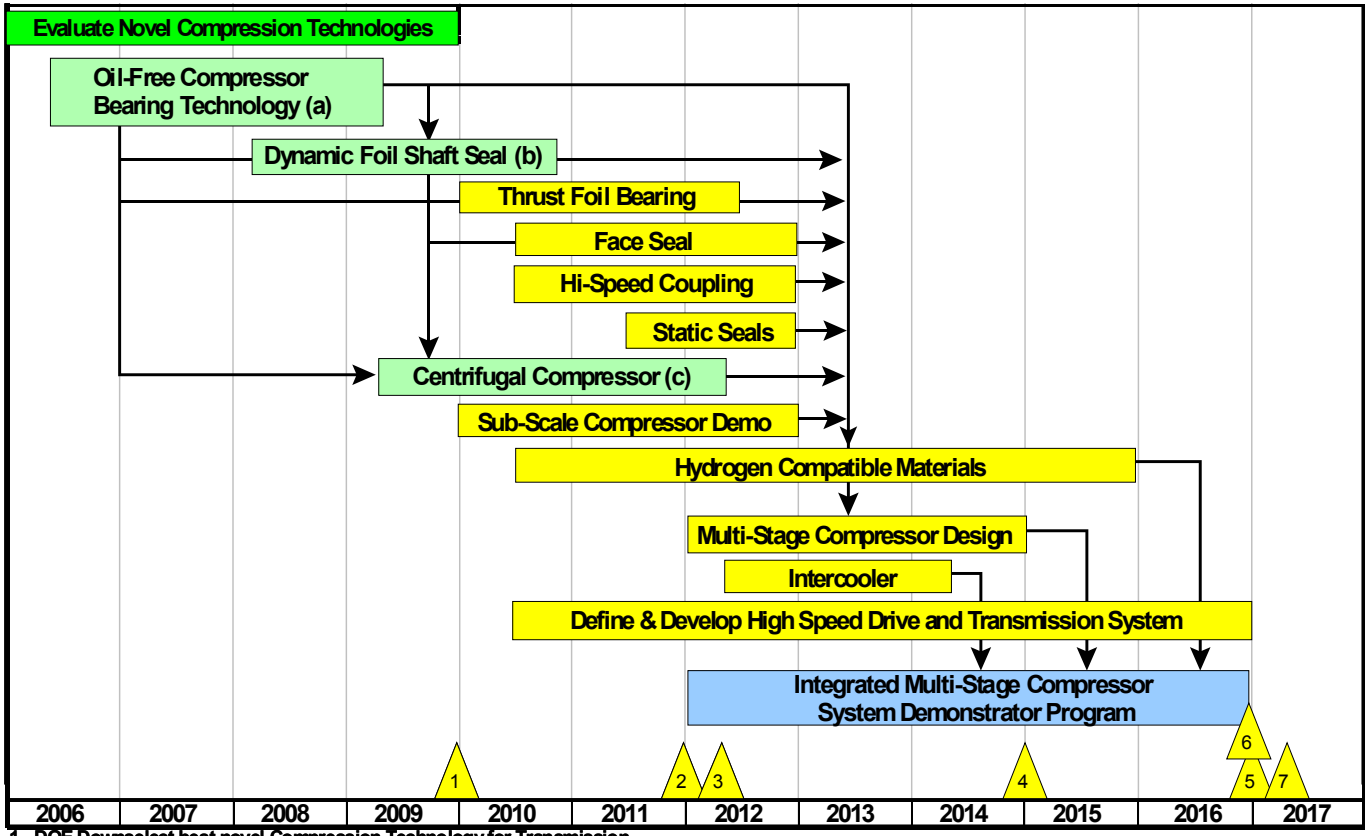
Materials
- Validation in High Pressure H2
- Foil Bearing/Seals Performance in H2

Economics & Manufacturing



Overall Technology Roadmap

Hydrogen Transportation & Delivery Development



1 - DOE Downselect best novel Compression Technology for Transmission
2 - Reduce cost of H2 transport from production facilities to refueling gates to <$0.90/gge
3 - $12M total capital investment for 200,000 kg/day compressor
4 - Reduce Cost of Compression < $0.40/gge indepedent of transport
5 - Energy Efficiency >98%
6 - Reduce cost of H2 Delivery from production to point of use < $1.00/gge
7 - $9M total capital investment for 200,000 kg/day compressor

(a) MiTi DOE SBIR Phase II Program Foil Journal Bearings
(b) MiTi DOE SBIR Phase II Program - Interstage Seal
(c) Grant Single Stage Centrifugal Performance Test

Existing Programs | Crucial Technology Programs | Objective Integrated Technology Demonstation

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Compressor Design Meets DOE 2020Target

2007 and 2012 Revised Technical Plan

Backup

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

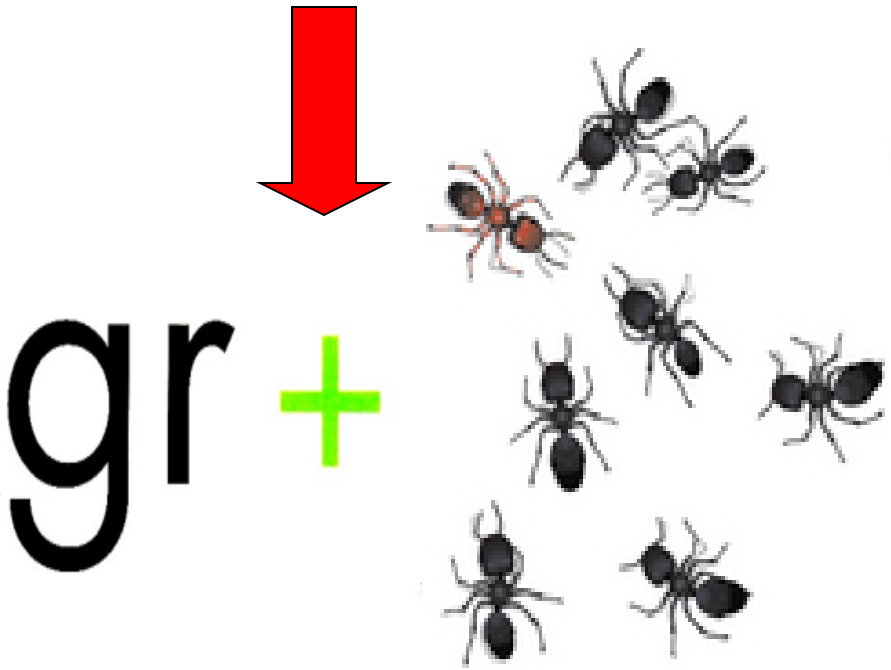
Capital and Maintenance Cost estimates based on data from MHI for comparably sized NG compressor systems, published oil and gas industry data and from quotes for fabrication of major components of MiTi's compressor design.

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

Establish Creative Design & Design Rules

SBIR Little



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Huge Potential Impact