Oil-Free Centrifugal Hydrogen Compression Technology Demonstration

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Project ID # PD016

Overview

Timeline

- Start Sept 1, 2008
- Funding Authorized 2/28/09
- End Aug 31, 2011
- 30 % Complete

Barriers

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

Budget

- Total project funding
  - $2,992,416 DOE
  - $1,149,253 MiTi/MHI Cost Share
- $1,496,208 FY08/09 Funding
- $1,496,208 FY10/11 Funding

Partners

- Lead: Mohawk Innovative Technology, Inc. (MiTi®)
- Mitsubishi Heavy Industries

Relevance

Objective:

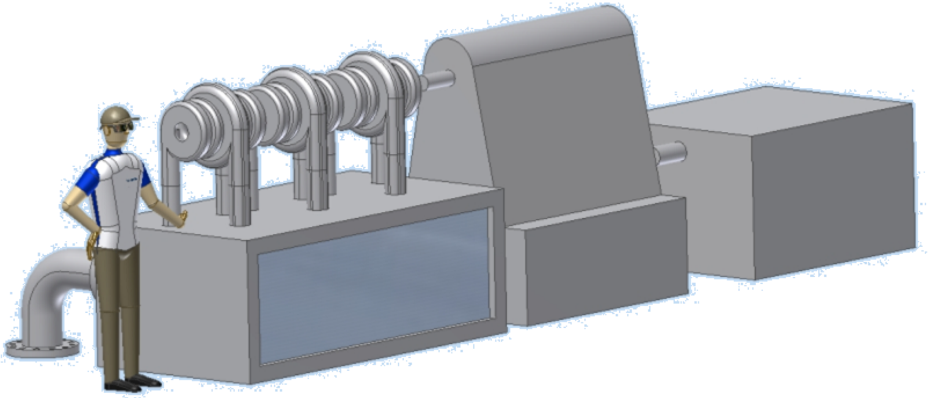
- Demonstrate key technologies needed to develop reliable and cost effective centrifugal compressors for hydrogen transport & delivery
  - Flow 500,000 to 1,000,000 kg/day
  - Pressure rise to 300-500 psig up to 1,200-1,500 psig
  - Contaminant-Free/Oil-Free Hydrogen

Category	2005 Status	Project Target FY2012	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
October 2007

Approach/Project Plan

- Compressor Design Analysis
  - Mean Line Analysis
  - Computational Fluid Dynamics
  - Finite Element Structural Analysi
- Design Bearings and Seals
  - Foil Bearings
  - Foil Seals
  - Low Friction Coating
- Select Single Compressor Stage
  - Inlet & Impeller
  - Diffuser & Return
  - Vane and Exhaust
- Fabricate Single Stage and Test to Characterize Pressure & Flow



- Scale System Design
  - Update Multi-Stage, Multi-Frame Compressor System Design
  - Predict Full Compressor System Performance
  - Economic Analysis

Demonstrate feasibility of very high speed hydrogen centrifugal compressor

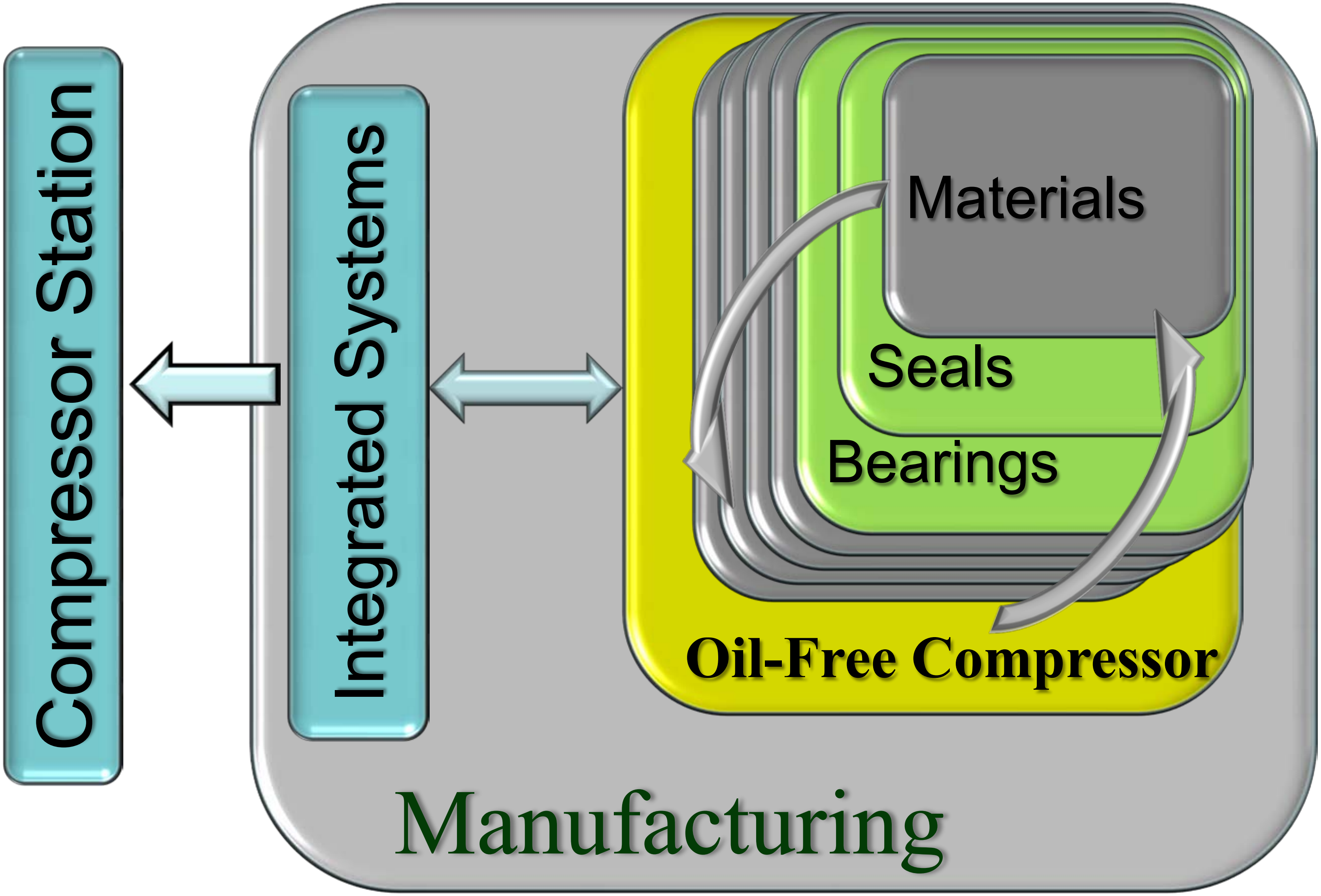
Project Milestones

Month/Year	Milestone or Go/No-Go Decision
July-09	**Project Milestone:** Complete preliminary modular centrifugal compressor frame design to achieve pressure and flow. Select stage for detailed design, fabrication and test.
April-10	**Project Milestone:** Complete single stage compressor design including inlet, impeller, diffuser, return channel. Complete oil-free bearing and seal mechanical component system designs

FY10 DOE Milestone: Down select novel compression technology for hydrogen delivery.

DOE Challenge: Increase the Reliability, Reduce the Cost, and Improve the Energy Efficiency of Gaseous Hydrogen Compression for Transportation and Delivery

Compressor Design Methodology

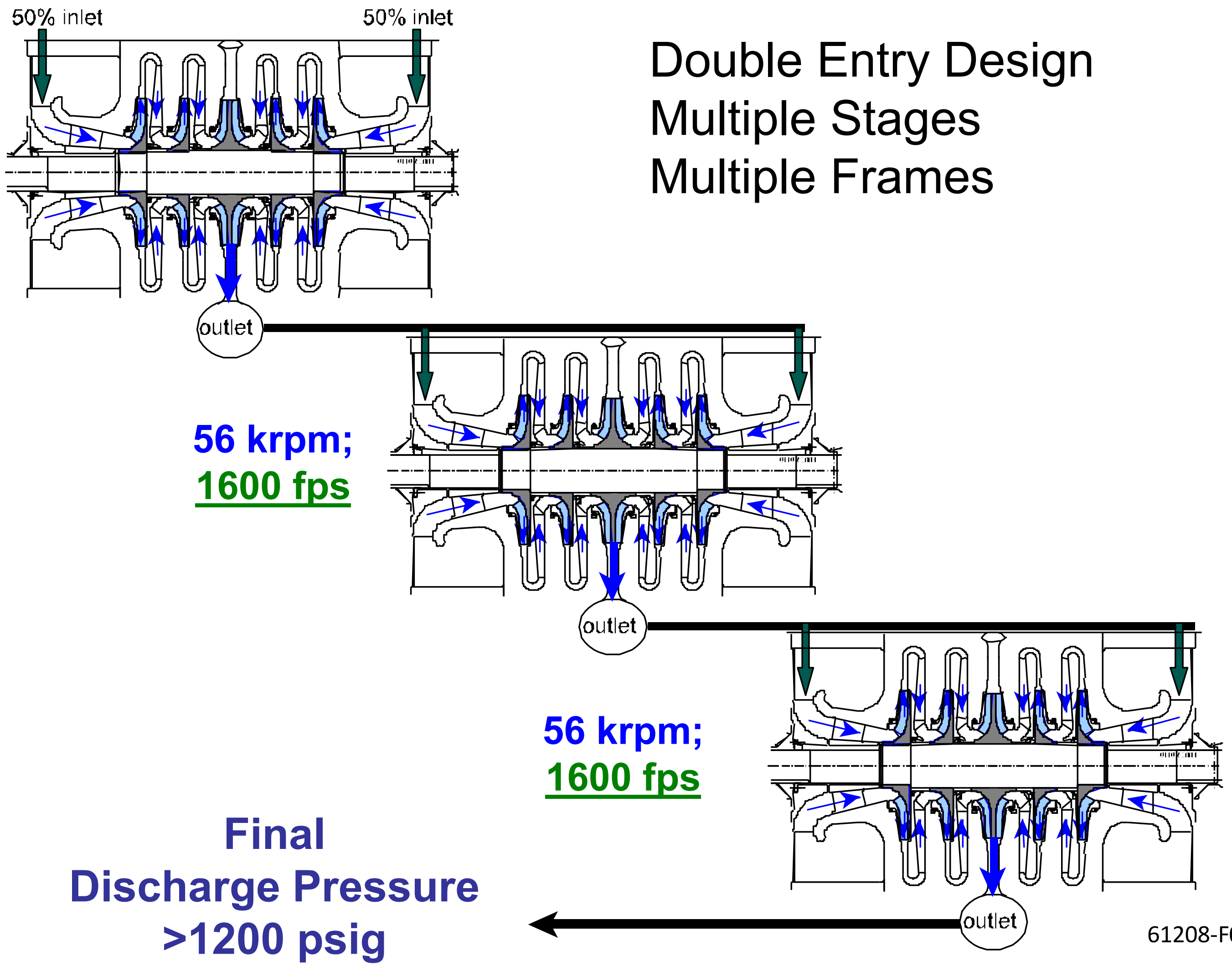


Modular Centrifugal Compressor System

56 krpm
1600 fps

Double Entry Design
Multiple Stages
Multiple Frames

Inlet:
350 to 500 psig
240,000 to
500,000 kg/day



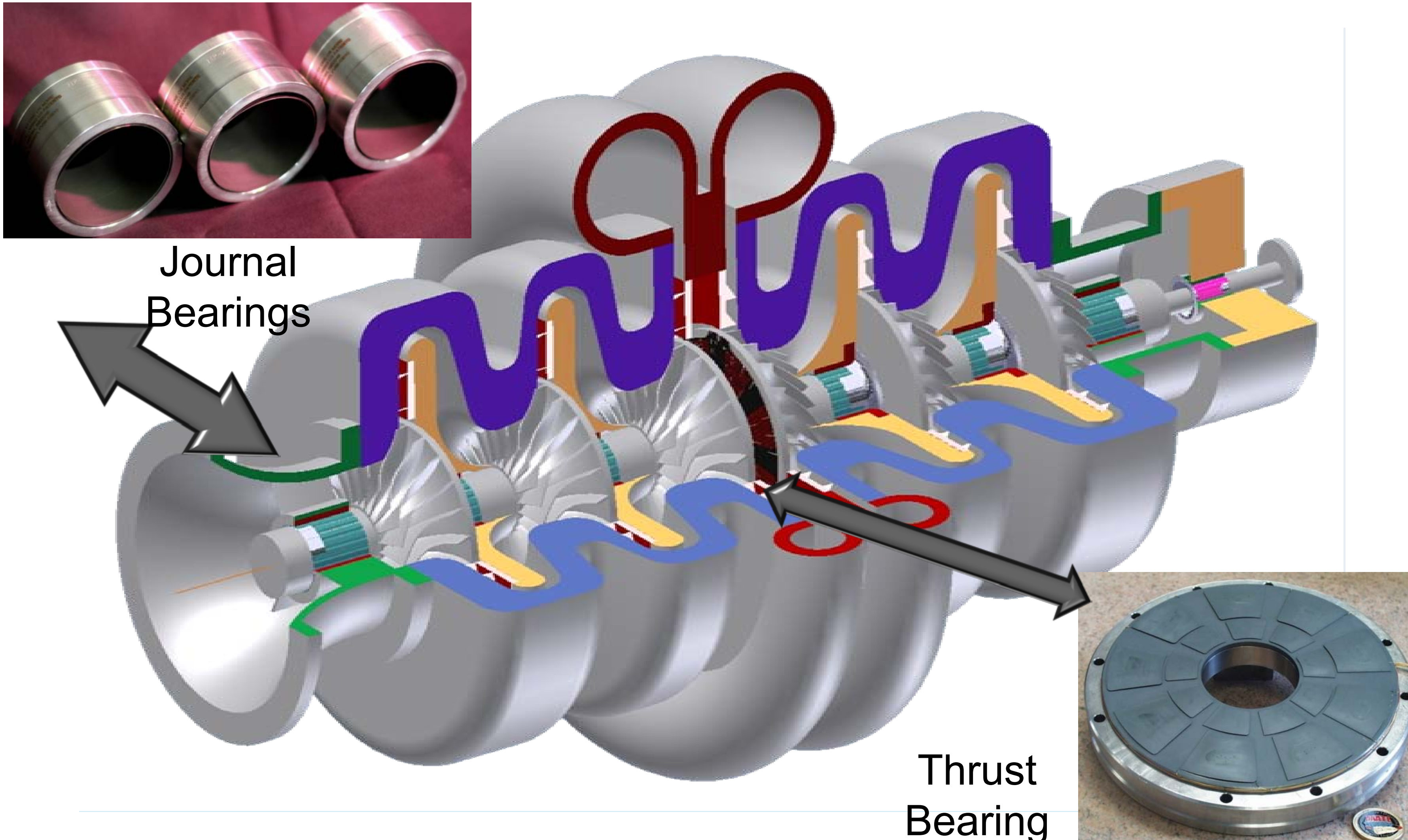
56 krpm;
1600 fps

56 krpm;
1600 fps

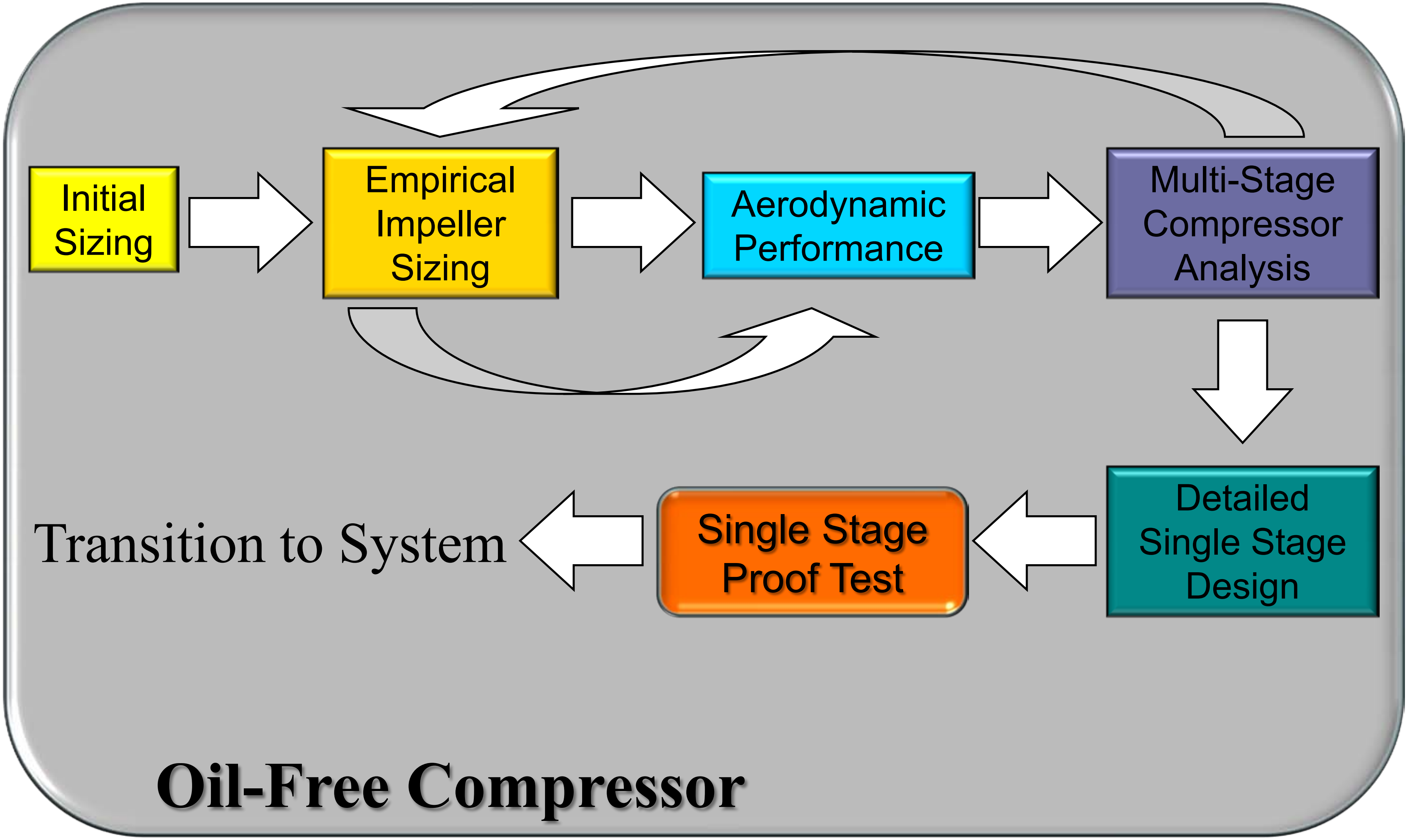
Final
Discharge Pressure
>1200 psig

61208-F001

Modular Double Entry Centrifugal Compressor System



Compressor Design Process

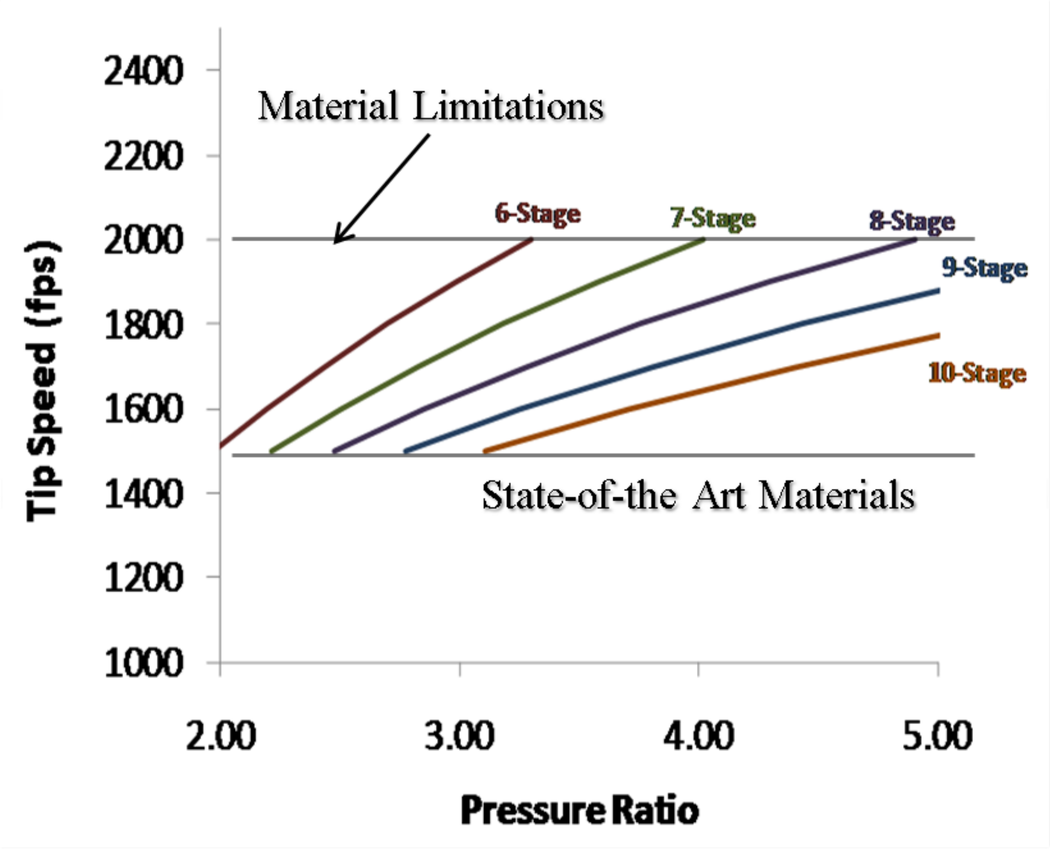


Aerodynamic Design

- **Design Criteria**
  - Pure Hydrogen
  - Inlet Pressure 350 & 500 psi
  - Discharge Pressure **>**1,200 psi
  - Mass Flow 240,000 kg/day & 500,000 kg/day
- **Produce Aerodynamically Stable Compressor Stages**
- **Key Design Variables:**
  - Tip Speed
  - Diffuser Design
  - Impeller Design Optimization
- **Analyze Multi-Stage Stability**

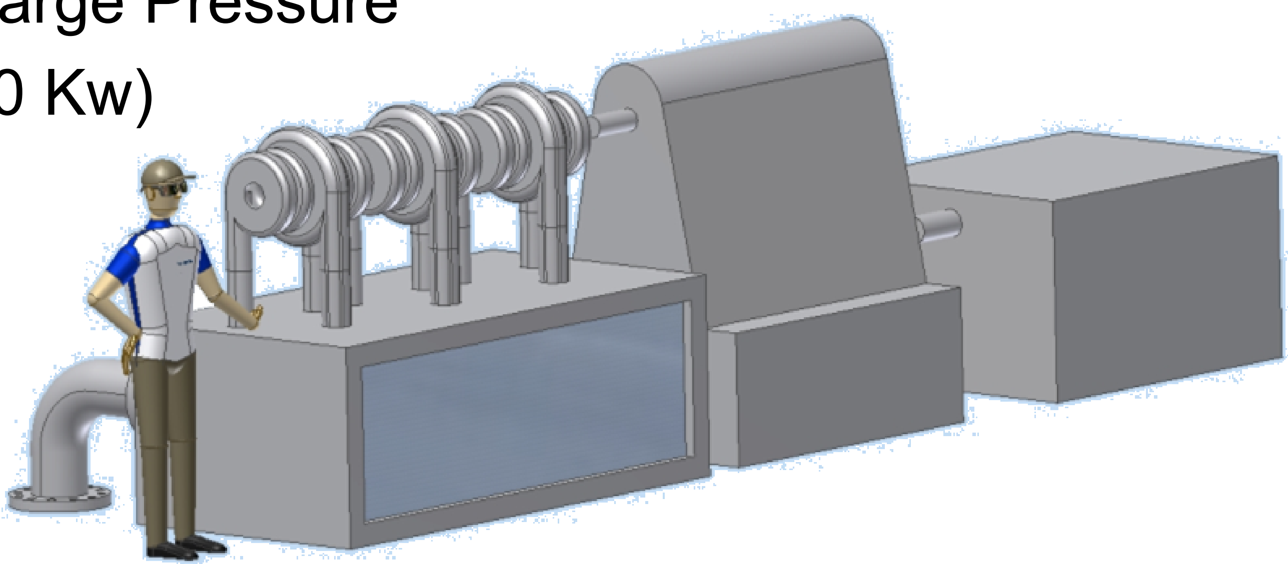
Parametric Study Results: Selecting Number of Stages

- Results Obtained Using Mean-line Analysis
- Number of Stages Function of Tip Speed
- Tip Speeds > 2,000 ft/s Could be Considered High Risk for H_2 Environment

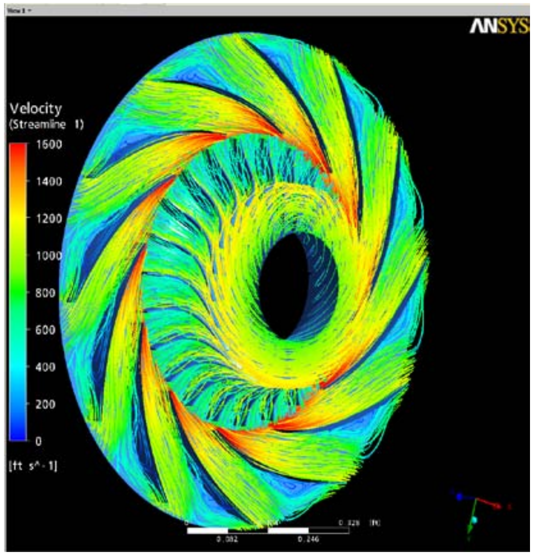


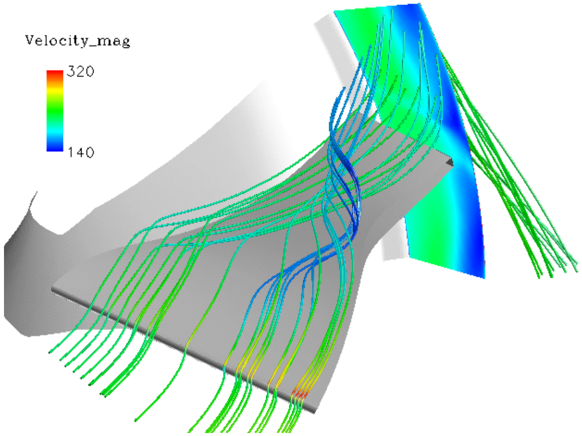
Aerodynamic Design Results

- Advanced Low-Risk, High-Range Modular Approach Provides Flexibility
  - Backup In Case of Reduced Performance
  - Accounts For Changes To Inlet Conditions
  - Accommodates Material Limitations
- 9 - Stage (3 Frames)
- 1,211 psi Discharge Pressure
- 7,835 HP (5,840 Kw)
- 1,800 ft/s
- 240,000 kg/day



Computational Fluid Dynamics Analysis

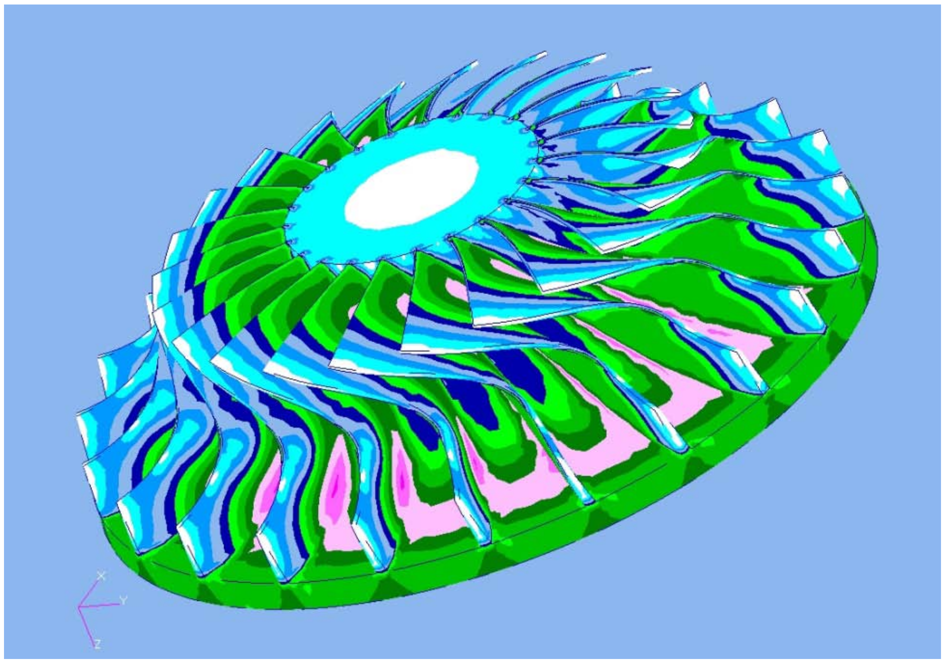




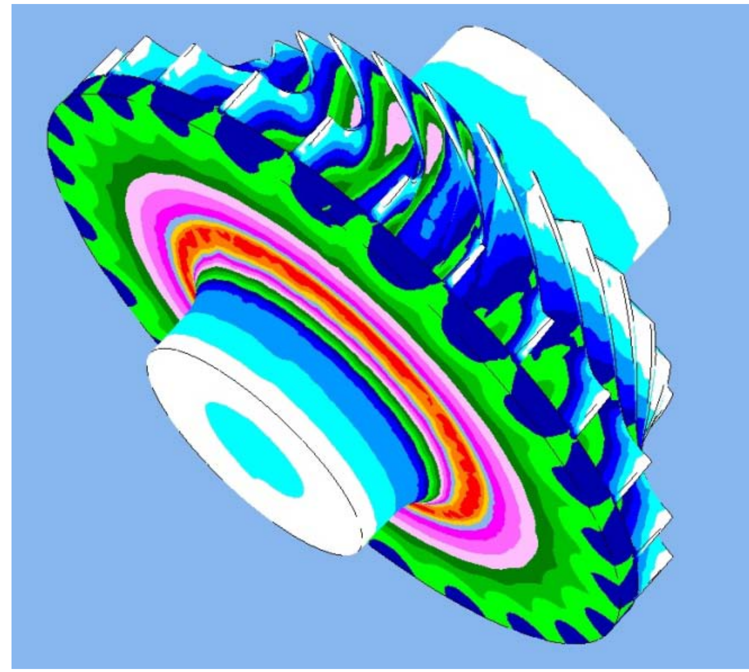
- Converged Solution of Complete Single Stage Obtained
- Excellent Correlation with Mean-Line Analysis Predictions
- Performance Analyzed from 70-120% of design flow
- No Turbulence or Flow Separation Identified in Flow path

Impeller Finite Element Structural Analysis

Maximum Blade Stresses



Maximum Disk Stresses



- Maximum Compressor Impeller and Blade Stresses at 1600 ft/s for HS Steel
- Backface of Impeller = 110 ksi (2.6 Stress Factor of Safety)
- Blade Stresses = 73.5 ksi (2.3 Fatigue Factor of Safety)

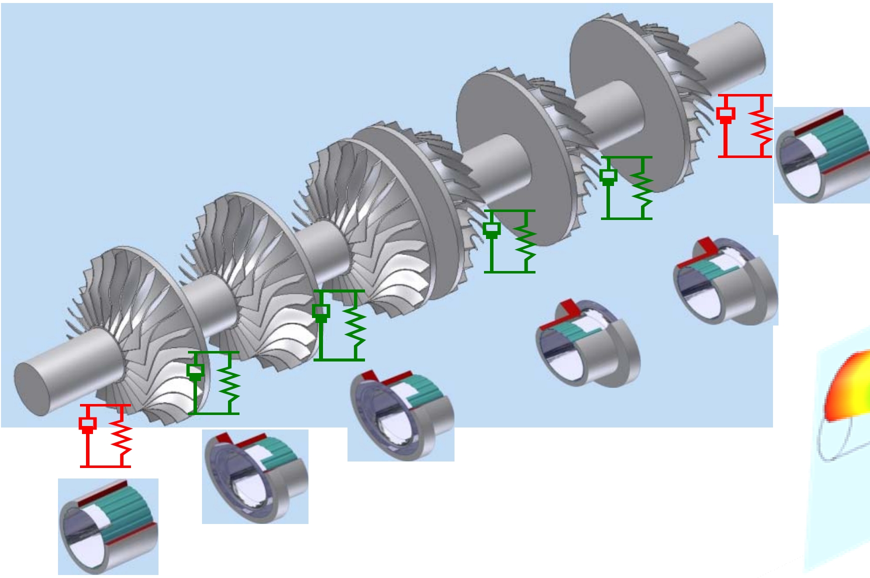
Strength and Fatigue Requirements

Materials	Al Alloy	Ti Alloy	HS Steel
Density (lb/in^3)	0.1	0.162	0.28
Modulus of Elasticity (10^3 ksi)	10.6	16	31
Yield Strength (ksi)	61	160	
Ultimate Strength (ksi)	84	170	290
Max von Mises Stress at 1600 fps (ksi)	39.5	64	110
Stress Safety Factor at 1600 fps	**2.1**	**2.7**	**2.6**
Fatigue Strength (ksi)	8.4	101	166
Max Blade Stress at 1600 fps (ksi)	26.4	38.6	73.5
Fatigue Safety Factor at 1600 fps	**0.3**	**2.6**	**2.3**
Max Disp Magnitude at 1600 fps (mil)	17.8	19.1	16.8
Max Axial Disp at 1600 fps (mil)	12.8	13.8	12.0

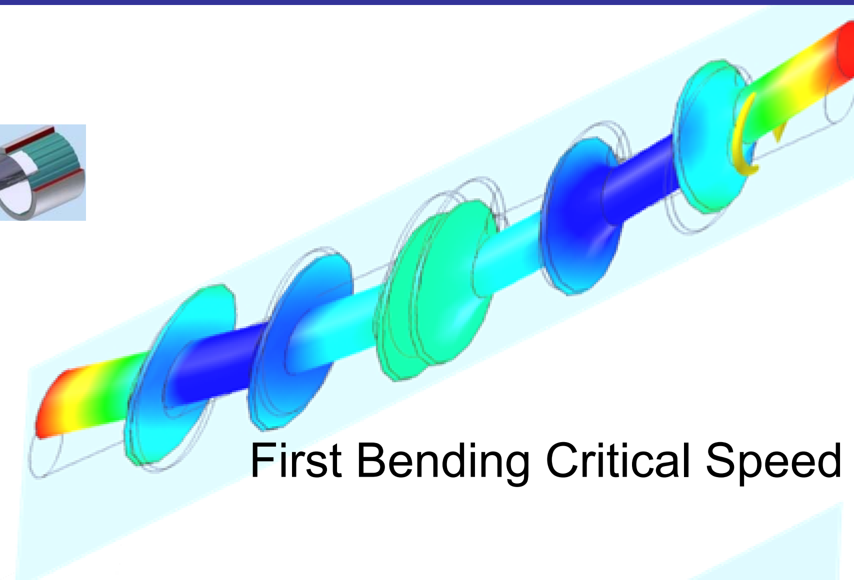
Materials Issues/Needs

- **Structural Materials (Housing)**
  - Durability under high internal pressures
- **Shafting Materials**
  - High strength, fatigue endurance, high toughness
- **Bearings and Seals**
  - High elastic modulus, fatigue resistance,
  - Material Characterization in H_2 and in thin film form
- **Tribological Coatings**
  - Low friction, wear resistant, electrical/thermal properties
- **Hydrogen Barrier Coating**
  - Reduce hydrogen permeability

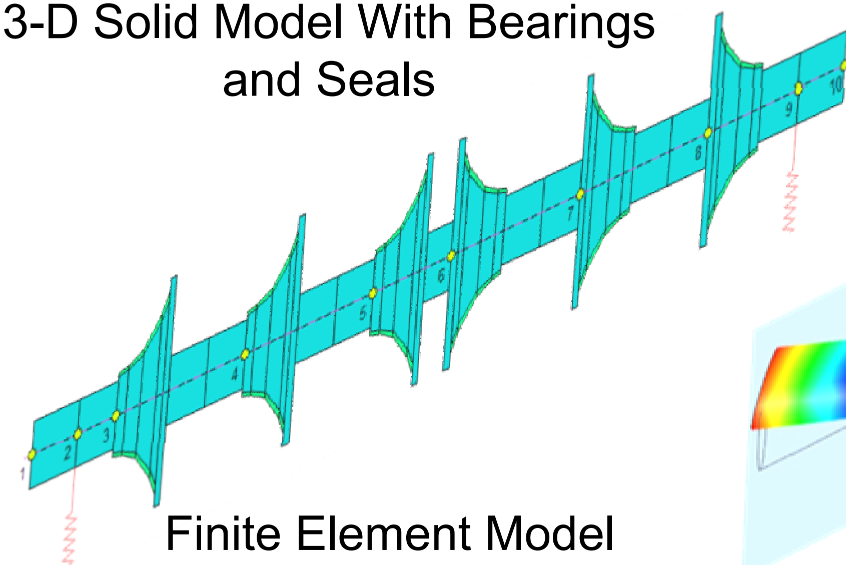
Rotor-Bearing Foundation



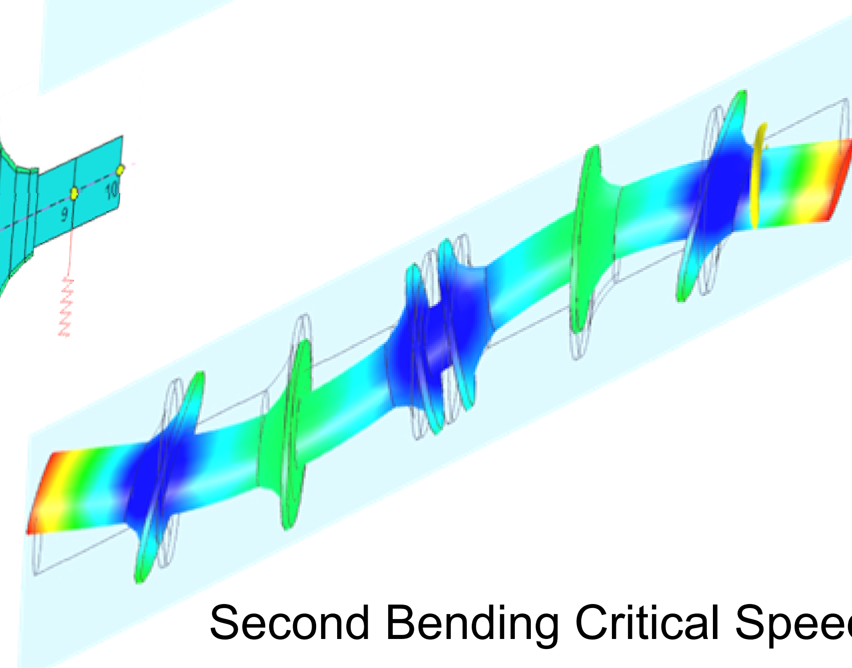
3-D Solid Model With Bearings and Seals



First Bending Critical Speed

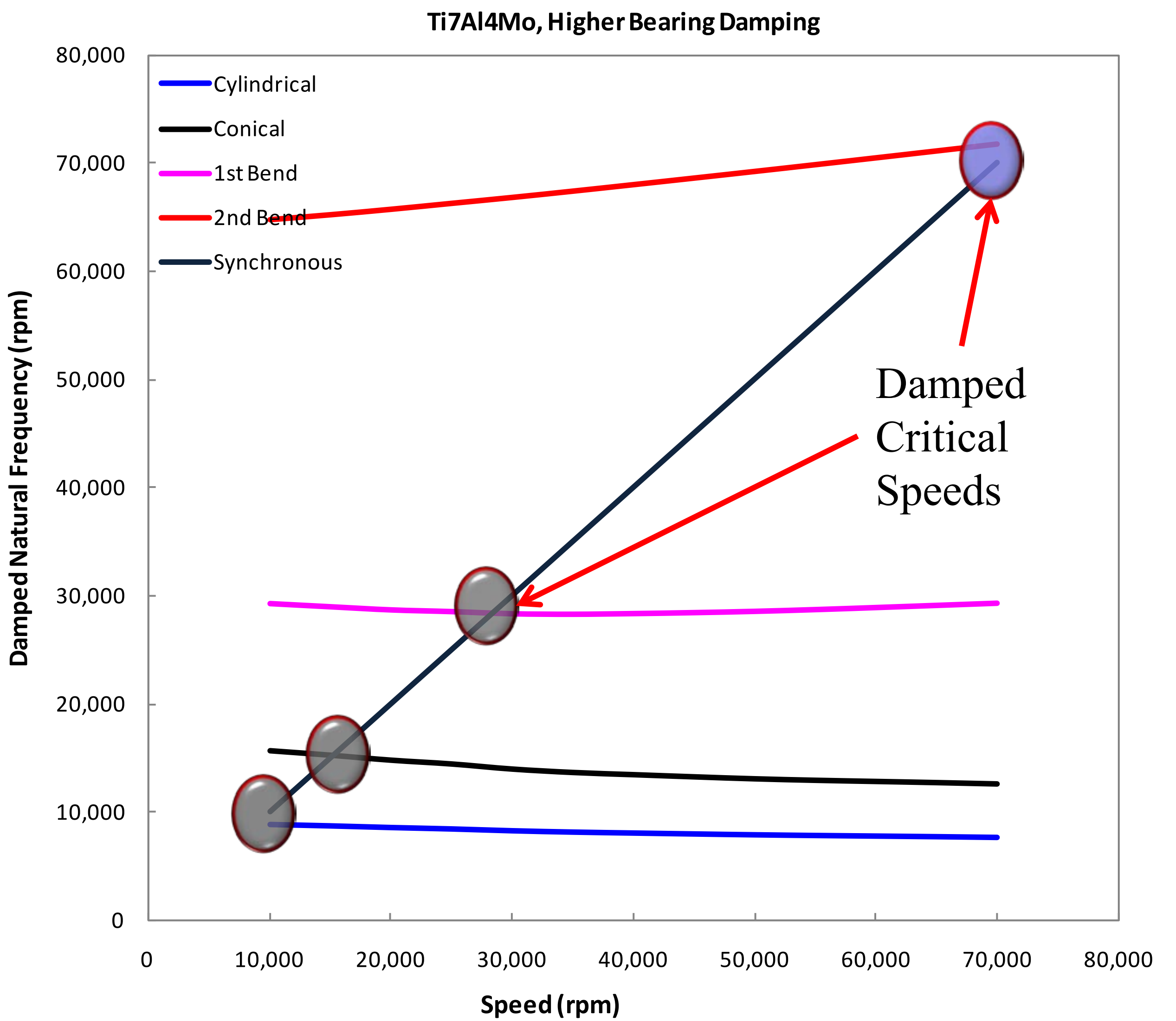


Finite Element Model

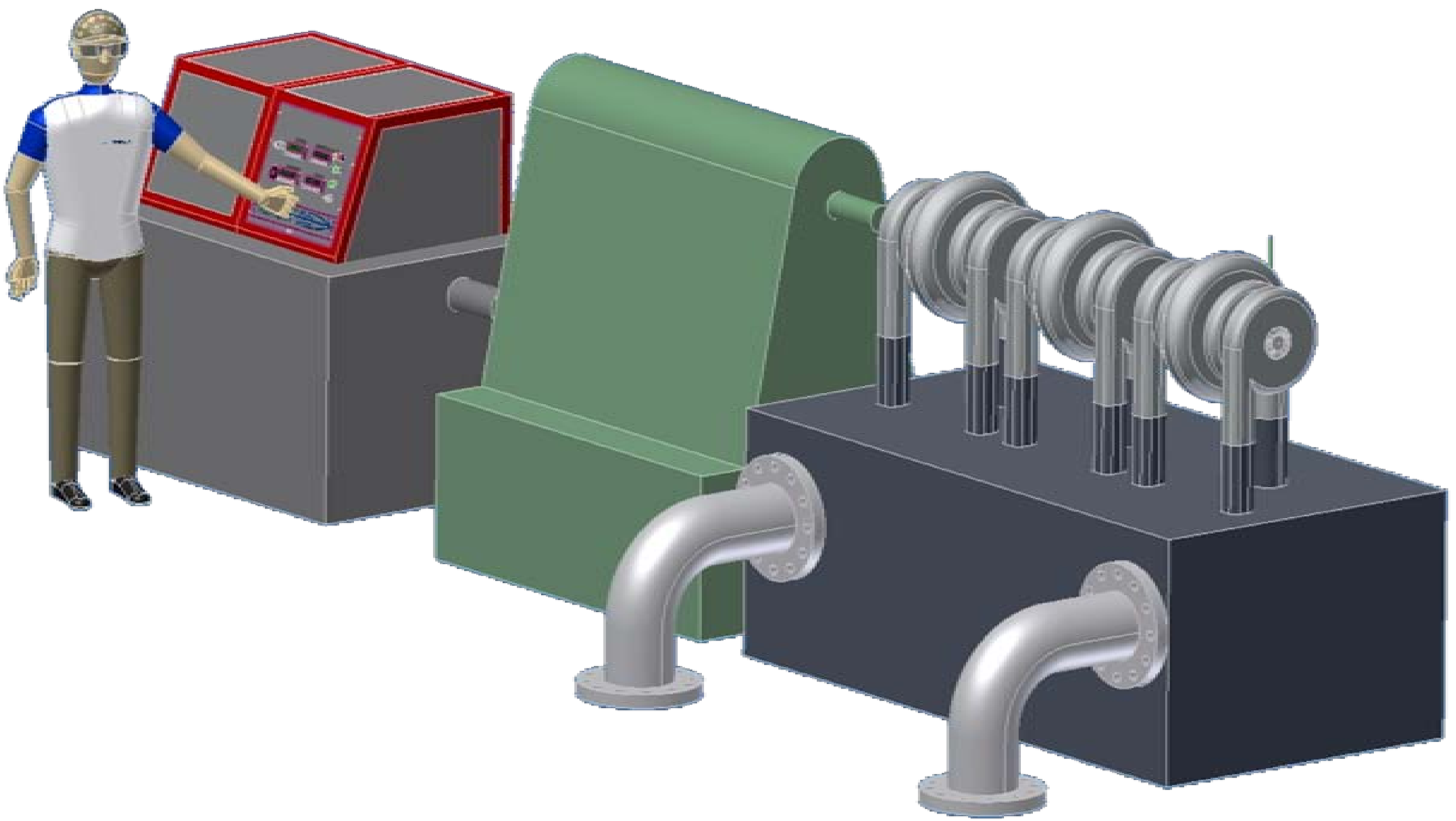


Second Bending Critical Speed

Whirl Map Stability Analysis



Compressor System Layout



Future Work for FY10-FY11

- Complete Single Stage Test Rig Design and Hardware Fabrication
- Conduct Single Stage Performance Testing at MiTi and MHI
- Validate Performance of Foil Bearings, Foil Seals, Aerodynamics, Rotordynamics
- Review Lessons Learned and Modify Compressor Design Accordingly
- Update Economic Estimates

Modular Designs

Design Strategy	Design Point A 350-1200 psig 240,000 kg/day	Design Point B 500-1200 psig 500,000 kg/day
High Margin Design Approach	9-Stages 1800 fps 6.5” diameter 7,835 Hp	9-Stages 1500 fps 6.5” diameter 12,250 Hp
High Performance/Risk Design Approach	6-Stages 2000 fps 6.5” diameter 8,036 Hp	6-stages 1800 fps 6.5” diameter 13,432 Hp

Energy Consumption Metrics

Design Strategy	Design Point A 350-1200 psig 240,000 kg/day	Design Point B 500-1200 psig 500,000 kg/day
State of The Art Design Approach	9-Stages 7,835 HP 0.584 kW-hr/kg	9-Stages 12,250 HP 0.439 kW-hr/kg
Advanced High Performance Design Approach	6-Stages 8,036 HP 0.599 kW-hr/kg	6-stages 13,432 HP 0.481 kW-hr/kg

Compressor Meets DOE Targets

Characteristics	Natural Gas Pipelines	DOE Target	MiTi Projection	MiTi Projection
Efficiency (%)		98%	98%	98%
Hydrogen Capacity Range (kg/day)		100,000 to 1,000,000		
Hydrogen Capacity Target (kg/day)		200,000	240,000	500,000
Hydrogen Leakage		<0.5	0.2	0.2
Hydrogen Purity		99.99	99.99	99.99
Inlet Pressure (psig)	300-700	300-700	350	500
Discharge Pressure (psig)	1,000-1,200	1,000-1,200	1,285	1,226
Compressor Component Cost ($Million)	$9.2[1]	$9.0	$4.1	$6.1
Compressor Drive $400/HP ($Million)	$6.4		$3.2	$6.4
Total Compressor Package (2005 $Million)	$15.6		$7.3	$12.5
Maintenance Cost (% total Capital Investment)	9.3%[2]	10%...7%...3%	<3%	<3%
Maintenance Cost ($/kW-hr)	$0.0157 [3]	$0.007	<$0.005	<$0.005
Package Size (sq-ft)	~1,000	300-350	145	160
Reliability (# Systems Required)		High - Eliminate Redundant Systems	Very High – Oil-Free Modular System	

1 Oil & Gas Journal, Vol. 107.Issue_34,2010, Transportation. Special Report: Pipeline Profits Capacity Expansion Plans Grow Despite Increased Costs

2 DOT/PRCI Pipeline R&D Forum December 11-12, 2003, Washington, DC; 3 Oil & Gas Pipeline Sept 14, 2009, pp77-79

Collaborations

Partners/Subcontractors

- Mitsubishi Heavy Industries
  - Centrifugal Compressor Stage Design
    - CFD
    - FEA
  - Single Stage Compressor Test
- Compressor Design Consulting Specialist
- CFD Consulting With Compressor Experience

Project Summary

- Demonstrated that Advanced and Very High-Speed, Oil-Free Centrifugal Compressors Can Meet Hydrogen Delivery Needs
- Refined Multi-Stage/Multi-Frame Compressor Concept
  - Established Stage Pressure Ratios and Flows
  - Defined and Selected Optimum Operating Speeds
  - Selected One Stage for Detailed Design and Test
- Conducted Detailed Design
  - Established Flow Path Including Inlet, Impeller, Diffuser and Return Channel Designs Using Established Design Analysis and Computational Fluid Dynamics for Several Flow and Pressure Conditions
  - Designed Foil Bearings and Seals Using Coupled Elasto-Hydrodynamic Analysis
  - Designed Test Shafting Using FEM Rotor-Bearing System Analyses
- Completed Layout of Single-Stage Test Rig

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