2009 DOE Hydrogen Program Merit Review

Development of a Centrifugal Hydrogen Pipeline Gas Compressor

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Concepts NREC (CN)

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This presentation was prepared with support of the U.S. Department of Energy.

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Project Overview

Timeline

- Project Start: June, 1, 2008
- Project End: June 1, 2011
- Percent Complete: 30%

Budget

- Total Project Funding
  - DOE Share: $4,202,562
  - Contractor Share: $850,055
- Funding Received in FY08
  - $955,000
- Funding for FY09
  - $1,162,502

Barriers

- Improve Pipeline Compression effectiveness to deliver pure (99.99%) hydrogen at <$1/GGE with 98% hydrogen efficiency
- Reduce Initial Capital Equipment (<$5.4 M) and Operation & Maintenance Cost (<$0.01/kWhr)
- Reduce Compressor Module Footprint

Project Lead

- Concepts NREC

Project Partners

- Praxair (Industrial User/Engineering Assistance)
- Texas A&M University (Materials Testing)
- HyGen Industries (Hydrogen Industry Consultant)

Technical Collaboration

- Sandia National Lab, Argonne National Lab, Savannah River National Lab
- GE, Cotta Transmission, ABB, KMC, Flowserve, Tranter, Heatric, Lufkin, Artec Machine Sys.s

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Project Objectives - Relevance

- Demonstrate Advanced Centrifugal Compressor System for High-Pressure Hydrogen Pipeline Transport to Support DOE's Strategic Hydrogen Economy Infrastructure Plan
  - Deliver 1,200 psig and 100,000 to 1,000,000 kg/day of pure hydrogen to forecourt station at < $1/GGE
    - Actual design specifications of 1,200 psig and 240,000 kg/day.
  - Reduce initial installed system equipment cost to less than $5.4 million uninstalled based on DOE's HDSAM 2.0 Economics Model
    - Current projected cost at 25% less than DOE's target cost
  - Reduce Operating & Maintenance Costs via improved reliability
    - DOE's HDSAM 2.0 Economics Model indicates 4% of installed cost per year or $0.01/kWhr
    - Improved reliability eliminates the need for system redundancies
  - Reduce System Footprint
    - Small footprint of 175 ft^2, 1/3 of conventional machines

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Three-phase Program Approach

Phase 1. Initial Design (06/2008 to 07/2009)	Phase 2. Detailed Design (08/2009 to 04/2010)	Phase 3.System Validation Testing (05/2010 to 06/2011)
• Initial design criteria and performance specifications • Subsystems Modeling: aerodynamic and structural analysis of compressor • Initial integrated systems analysis • Initial design and cost analysis • Final design specifications • Materials and/or coatings investigated for use in high-pressure hydrogen environment • Revised Phase II Program Plan	• Detailed subsystems modeling • Detailed integrated systems analysis • Critical components design, testing, and development • Detailed integrated design of full-scale and laboratory validation systems • Detailed cost analysis of full-scale system	• Component Procurement • Two-stage centrifugal compressor system assembly • Performance evaluation test plan • Lab testing and system maturation • Final design of full-scale system completed • Field demonstration program plan prepared

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Project Milestones

- July 2009– Go/No-Go Decision – Alternative system designs reviewed and selection made of preferred approach. Materials and components testing will be completed and a material selected for the compressor rotor.

- May 2010 - Go/No-Go Decision – Detailed design and cost analysis of full-scale pipeline system completed. Design of Laboratory Validation System finalized.

- June 2011 – Go/No-Go Decision – Fabrication and testing of two-stage Laboratory Validation System completed. Revised design and updated manufacturing cost analysis completed.

Project Engineering Approach - 1
Innovative Compressor Design

- Technical Approach
  - Utilize state-of-the-art aerodynamic/structural analyses to develop a high-performance centrifugal compressor system, able to provide high pressure ratios under acceptable material stresses.
  - Utilize proven bearings and seal technology to reduce developmental risk and increase system reliability at a competitive cost.
  - With project and industrial collaborators, prepare an implementation plan that can provide for near-term industrial pipeline applications.
- Methodology
  - Investigate and prioritize alternative system configurations using operating conditions that meet initial capital and operational costs to meet near-term applications.
  - Identify critical engineering constraints of commercially available components and operational limitations of state-of-the-art materials, compatible with hydrogen to increase the range of safe compressor operating speeds.
  - Design and test critical rotor aerodynamics and material components under design conditions and demonstrate full-scale components in an integrated compressor system.

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Project Engineering Approach – 2
Primary Engineering Challenge

The Engineering Challenge

- Design centrifugal compressor with highest acceptable pressure ratio and thermodynamic efficiency per stage to minimize system size, complexity, cost, and maximize system performance and reliability.

Solution

- Maximize centrifugal compressor tip speed within stress limitations of material.
  - Pressure ratio is proportional to rpm^2 x $radius^2$, so small increase in tip speed results in significant increases in pressure.
  - Maximum thermodynamic efficiency is typically achieved at high operating tip speeds.
- Utilize advanced diffuser systems to maximize recovery of dynamic head into static pressure.

Constraints

- High operating speeds increases impeller material stresses.
  - Stress is also proportional to rpm^2 x $radius^2$ x material density. Therefore, pressure rise is limited by maximum stress capability of impeller material.
- Need to select materials that are not significantly affected by hydrogen embrittlement.
- Limited number of materials that have high strength to material density ratio and resistant to hydrogen embrittlement.

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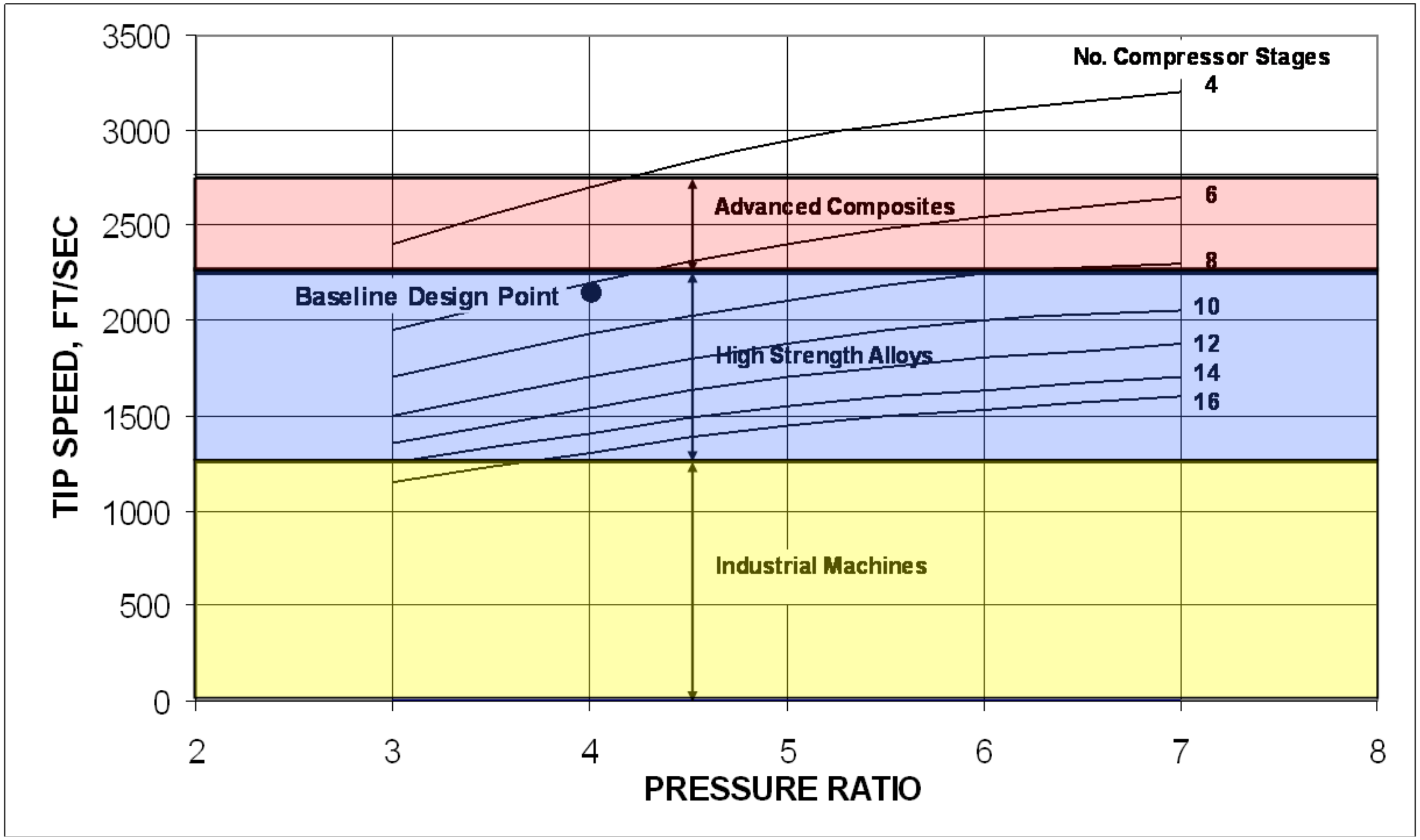
Project Engineering Approach - 3
Operational Design Envelope

Design Options for Alternative Operating Conditions



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Technical Accomplishments and Progress
Status of Phase 1. Initial Design Investigation

- Task 1. Initial System Design Criteria and Specifications – completed
- Task 2. Subsystems Modeling – 90% complete
- Task 3. Integrated Systems Analysis – 80% complete
- Task 4. Initial Design and Cost Analysis – 80% complete
- Task 5. Final Design Specifications – scheduled to be done at the end of Phase I
- Task 6. Bench Top-Scale Materials Selection (completed) & Testing (in progress)
- Task 7. Revised Phase II program Plan – scheduled to be done at the end of Phase I
- Task 8. Program Management – in progress

Technical Accomplishments and Progress
Summary- 1

- Compressor design conditions confirmed by project collaborators (P_{inlet}= 350 psig, P_{outlet}=1,200 psig; Flow rate= 240,000 kg/day)
- Compressor aerodynamic studies culminated in 6-stage, 60,000 rpm, 3.33 pressure ratio compressor.
- Integral gearbox pinions driving individual impellers
- Design of compressor's major mechanical elements completed and satisfied by two manufacturers per component:
  - Titling pad radial and thrust bearings designs validated for use.
  - Face-seals with buffer gas have been validated for use.
- Heat exchanger specifications met by two manufacturers
  - Tranter Plate-type Heat Exchanger Design
  - Heatric Heat Exchanger (compact, plate-fin surface core)

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Technical Accomplishments and Progress
Summary - 2

- Over 30 alternative compressor-gearbox configurations, materials, and compressor drive options (including gas turbine drives with heat recovery for intercooler cooling) studied and evaluated using a Relative Risk and Relative Cost Optimization Program Developed for the project culminating in a “Best” choice:
  - Six independent, overhung, integrally driven rotor-shafts
  - A two-speed step gearbox with parallel bull gears
  - 8,400 hp (6,300 kWe), 1,800 rpm, synchronous motor prime mover
  - External intercoolers to cool hydrogen gas to 100°F between stages
  - Intercoolers packaged within base frame

- Compressor Station Performance and Cost Model Developed
  - Suitable as a Macro for DOE “HDSAM v2.0” Economics Model
    - Identifies hydrogen compressor package performance (power, efficiency, component sizes)
    - Estimates compressor station cost
    - Estimates O&M costs

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Technical Accomplishments and Progress

Compressor Package Performance and Cost Model

- Compressor Package Performance provides a single point summary of each of the components within the package:
  - Compressor rotor aerodynamics (pressure ratio, power, speed vs. flow rate and intercooler pressure drop)
  - Intercooler size vs. effectiveness (i.e., desired outlet temperature)
  - Electric motor power
  - Overall hydrogen efficiency based on compressor power, component efficiencies
  - Compressor shaft diameter sizing based on fatigue loading
  - Impeller radial and axial loadings calculated
- Cost Model uses algorithms to determine the relative cost effects of changes in design specifications such as:
  - Number of compressor stages, single or back-to-back
  - Number of volute housings (1 or more stages per housing)
  - Rotor rpm
  - Compressor efficiency
  - Gearbox (1- or 2-speed step),
  - Driver speed and type
  - Choice of compressor materials
  - Rotor materials with or without coatings
  - Number of intercoolers

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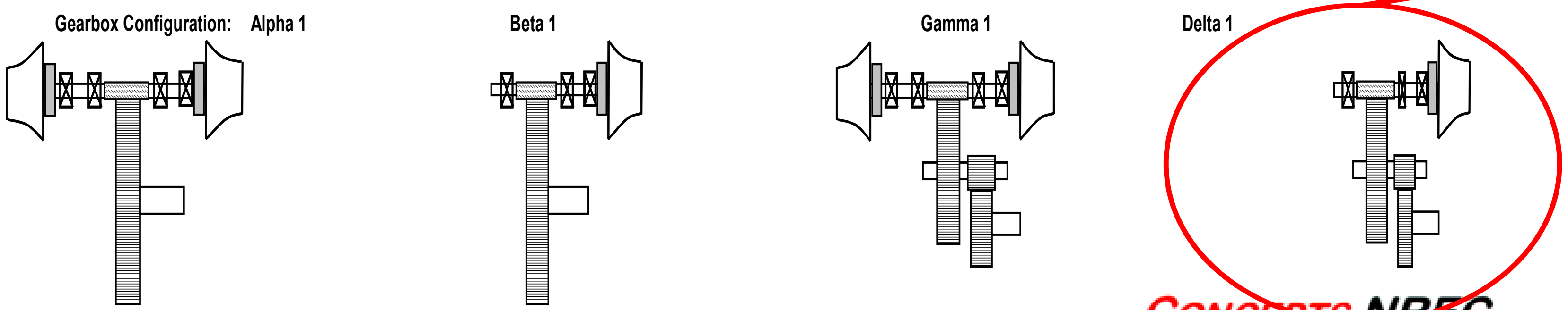
Technical Accomplishments and Progress

Compressor-Gearbox "Best Case" Selection Based on Relative O&M and Mechanical Risk Analysis

- Driver speed (1800, 3600, and 10,000 rpm)
- Number of stages (4, 6, and 7)
- Number of intercoolers (3 or 5) for impeller temp. < 140 F
- Pressure loss in intercooler and interconnect piping
- Number of drive shafts and number of impellers per shaft drive (1 or 2 impellers per drive shaft)
- Compressor aerodynamics and geometry
  - Hydrogen flow rate
  - Compressor impeller speed (50k to 90krpm)
  - Stage pressure ratio
  - Effect of forward sweep to reduce tip speed for same stage pressure ratio
  - Inlet guide vanes
  - Use of compressor inlet swirl to increase pressure ratio

	Compressor Configurations "A" through "F"					
Configuration Designation:	A	B	C	D	E	F
Impeller Speeds (rpm):						
1st and 2nd	70,000	50,000	50,000	50,000	50,000	60,000
3rd and 4th	80,000	50,000	60,000	50,000	50,000	60,000
5th and 6th	90,000	50,000	70,000	50,000	50,000	60,000
Total Power, hp=	8,360	8,354	8,450	8,610	8,543	8,349
Max. Tip Speeds,ft/s=	2,236	2,178	2,194	2,194	2,101	2,094
Avg. Pres. ratio=	1.243	1.243	1.243	1.243	1.2541	1.247

BEST CHOICE



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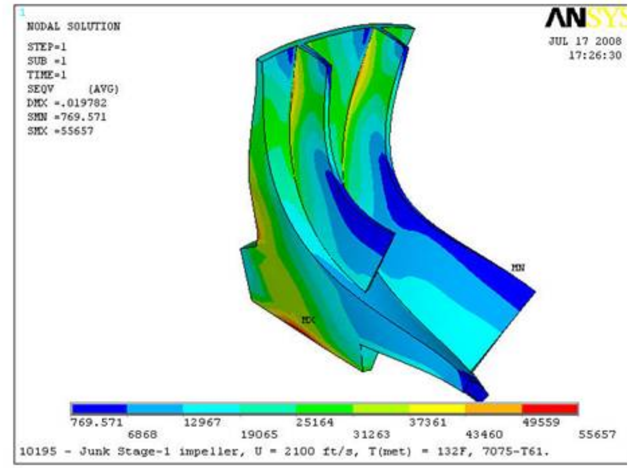
Technical Accomplishments and Progress
Compressor Design Specifications

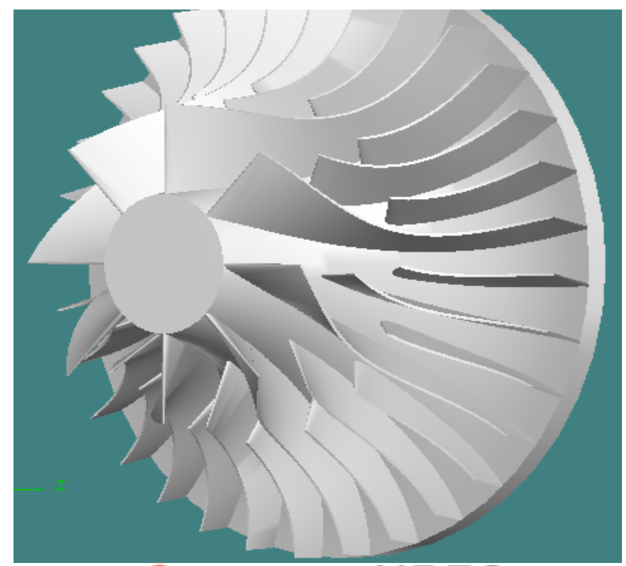
- **Compressor Design Details:**
  – Centrifugal Compressor overall efficiency = 80.3%
  – A nominal shaft speed of 60,000 rpm
  – Six-stages
  – Tip speed < 2,100 ft/s
  (corresponding to a hub stress of less than 60 kpsi)
  – Power of 1400 hp per wheel,
  – Suction pressure 350 psig, discharge pressure 1200 psig for an overall pressure ratio of 3.33
  – 240,000 kg/day hydrogen flow rate
  (ranging from 200,000 to 250,000 kg/day)

- **Geometry Advances**
  - Open passages with two splitter vanes
  - Forward sweep at vanes exit (not shown)
  - IGV causing negative swirl

- **Boreless Hub Design**
  -Decreases rotor hub stress

- **Multiple Patents Pending**





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Technical Accomplishments and Progress
Materials Selection and Testing Summary- 1

- A wide-ranging literature search and personal discussions with materials researchers (Sandia, Savannah River, Argonne National Laboratories, Failure Analysis Associates) have been conducted (and continue)
  - Most hydrogen embrittlement material studies have focused on steels and titanium alloys
  - There is agreement that aluminum alloy is protected from hydrogen embrittlement by its quickly formed oxide layer and the extremely slow diffusion of hydrogen into the metal
- From a turbomachinery design focus:
  - Aluminum (alloys: 2618-T6, 2918-T81 and 7075) is light but strong (as evidenced by its relatively high specific strength), comparable to titanium and thus very suitable for centrifugal compressor applications
  - However, titanium is recognized by most (all?) researchers as affected by hydrogen embrittlement
- Collaboration with Texas A&M (Dr. Hong Liang) and coordinating their tests with two National Labs is in progress to conduct relevant tests with aluminum per a Test Protocol derived from discussions with researchers, including:
  - Sandia National Labs (Fracture mechanics testing; Dr. Chris San Marchi)
  - Savannah River National Labs (Specimen "Charging" with Hydrogen plus Tensile testing with H_2; Dr. Andrew Duncan)
  - Argonne National Labs (Dr. George Fenske)

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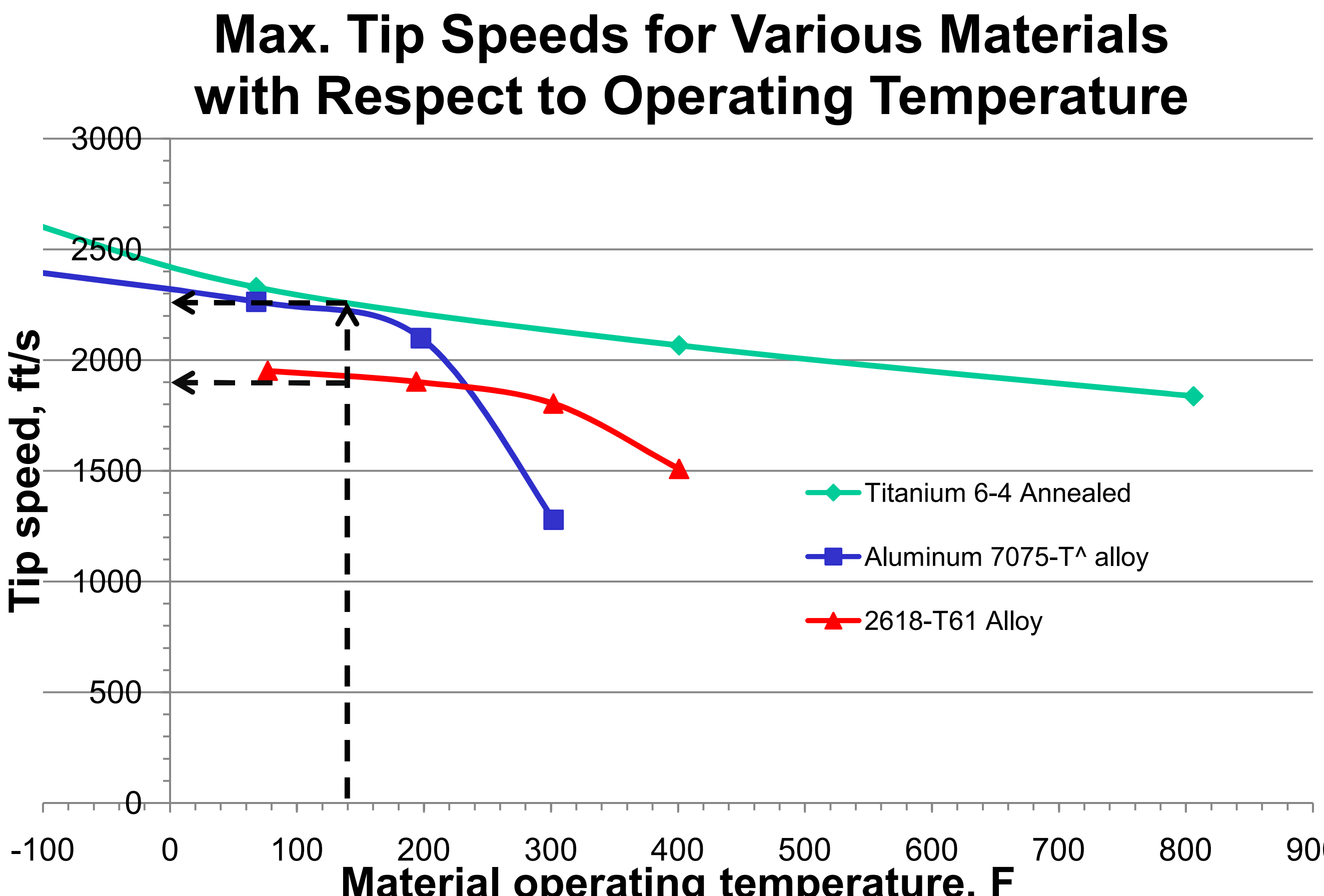
Design Experience Associating Material Properties with Tip Speed of 2,200 ft/s with Aluminum Alloy - 2

Literature Survey (Rocketdyne Lab Tests for NASA) and reviews with materials researchers at national labs and private consultants indicate Aluminum Alloy shows no effect from hydrogen …. AND aluminum is an excellent structural material for high speed impellers based on specific strength (ultimate strength/density)



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Technical Accomplishments and Progress
Material Coatings to Inhibit Hydrogen Embrittlement - 3

- Paraphrasing comments made during many interviews with researchers, the quick answer is: **"…no known coating materials exist to prevent hydrogen diffusion and hence the embrittlement of the base material"**
- Texas A&M conducts coating experiments with coatings recommended by CN and others
  - Proposed coatings are all aluminum oxide-based (although DLC-Diamond Like Coating, has also been considered, but discouraged by Texas A&M and others)
    - Accuratus (APS Company)
    - Alodine EC2 ElectroCeramic (Henkel Corp)
    - Sermalon (Sermatech International)
- Some structural concerns:
  - Can the coating be applied without affecting compressor material or vane design?
  - Will it compromise the base material by exposing even a small activation site on the base material if coating is chipped, cracked, or otherwise broken?
  - Will it contaminate the hydrogen during long-term use?

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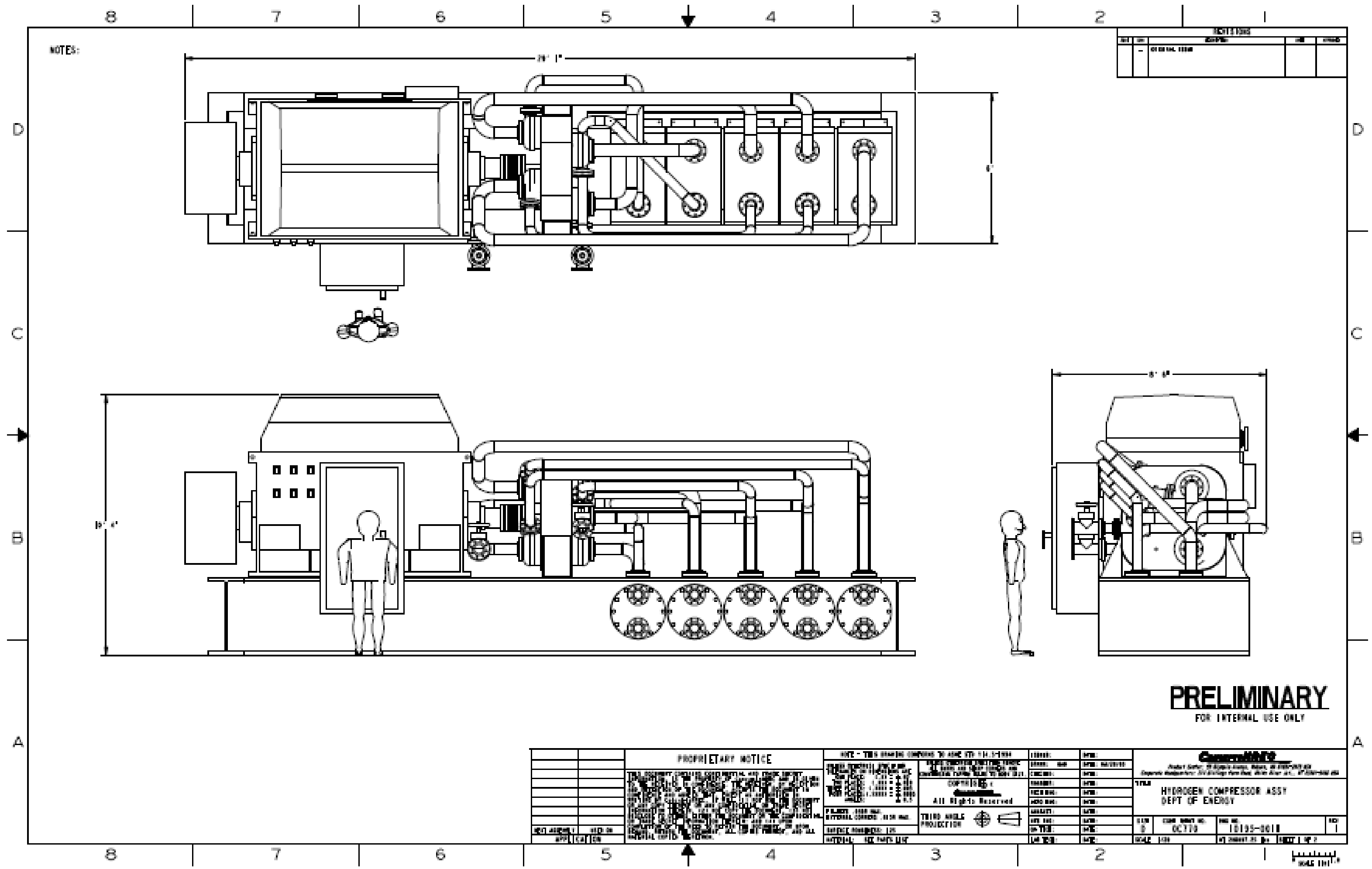
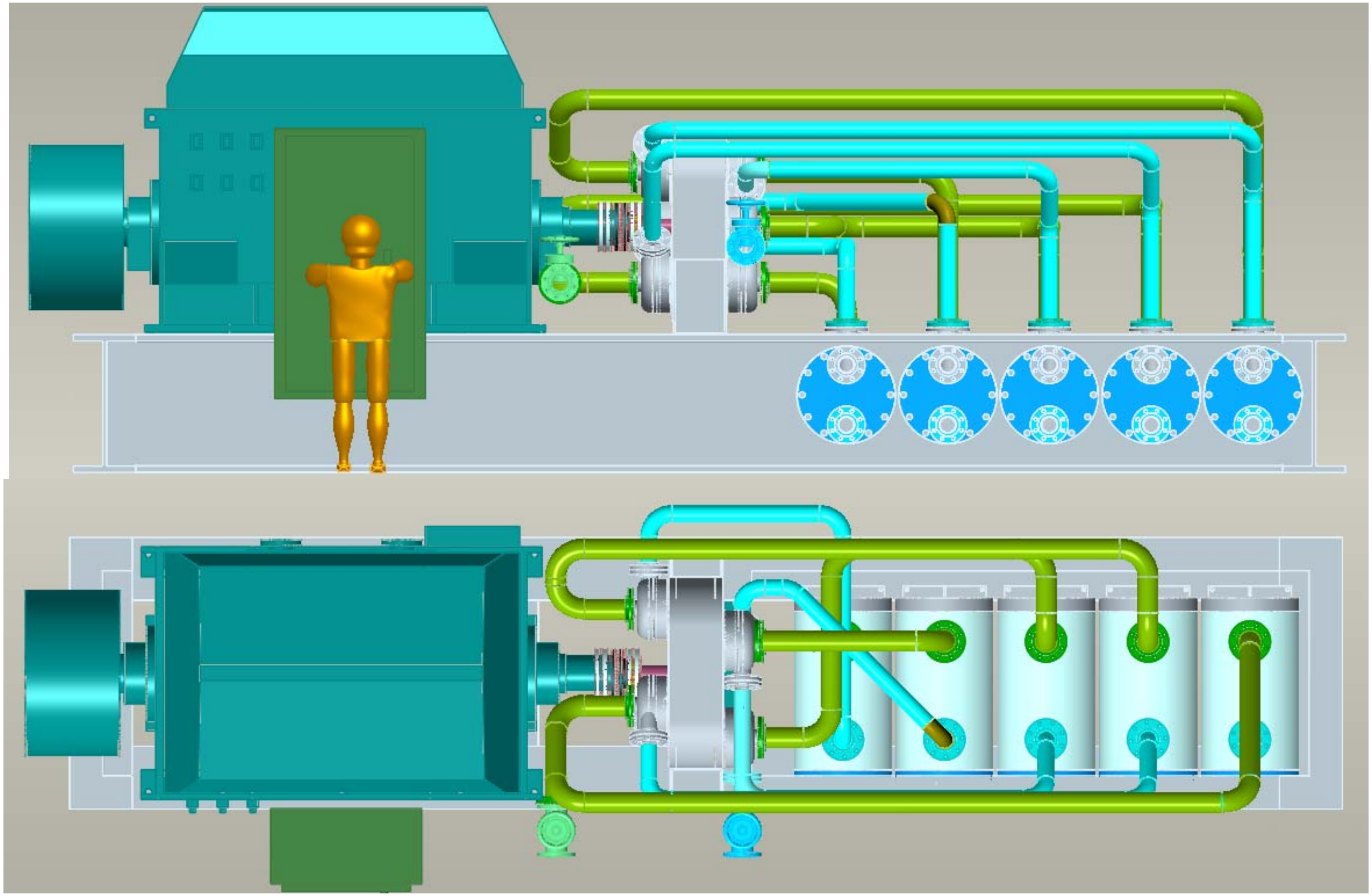
Overall Layout Drawing of System



Pipeline Compressor System Module



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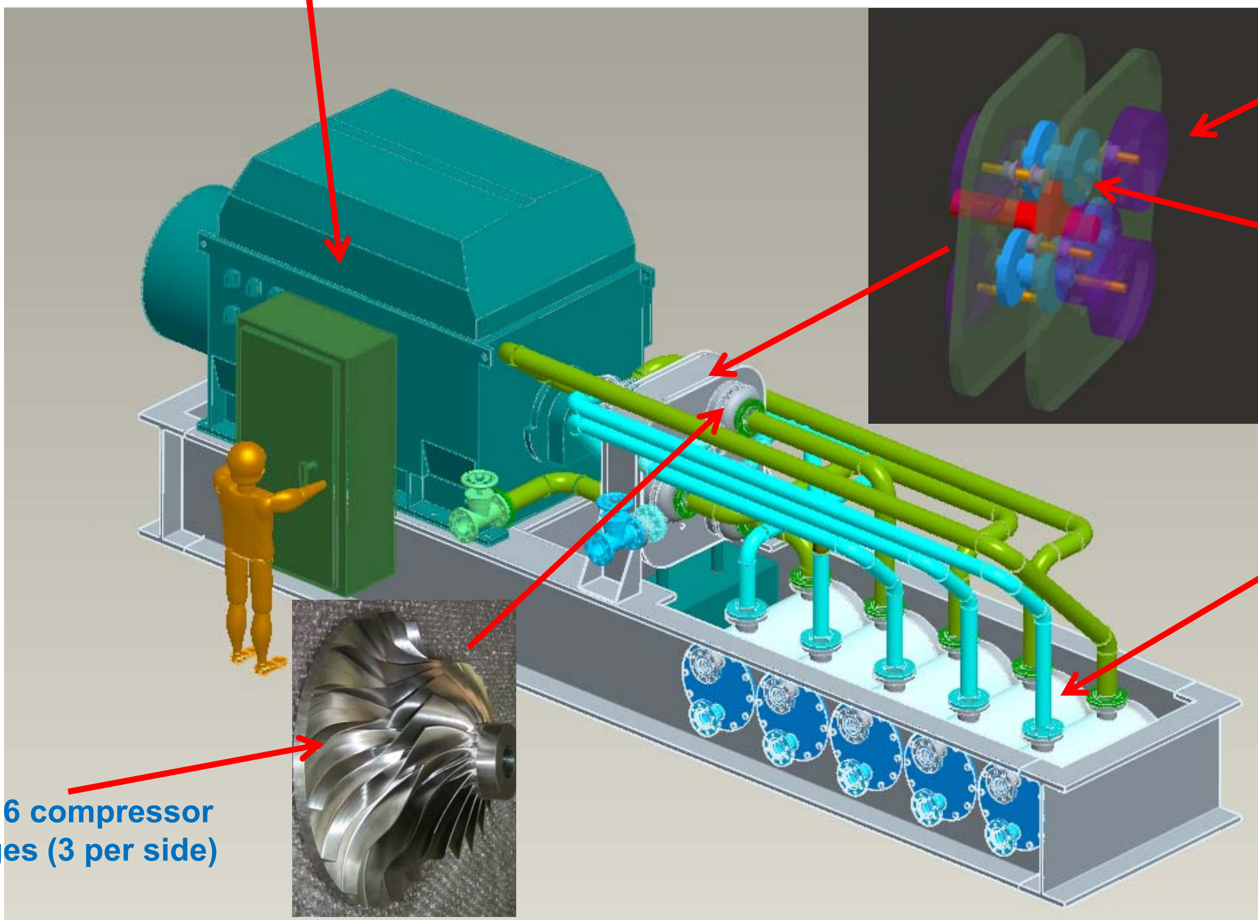
Hydrogen Compressor Package Assembly
Compressor Module Rating: 240,000 kg/day; 6,300 kWe



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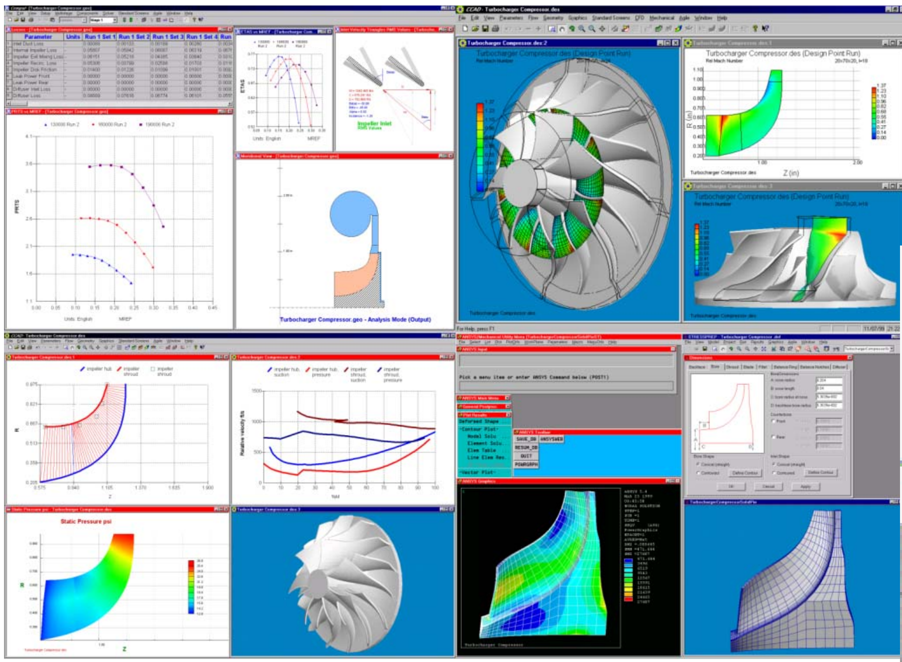
Project Collaborations-
Principal Investigator- Concepts NREC:
Capabilities from Aero Design to Manufacturing



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Project Collaborations:
Strengths & Responsibilities of Partners

- Praxair
  - Provides industrial user experience, gas industry specification data, and "hands-on" experience with compressor systems, including hydrogen compression, for industrial gas industry
  - Future industrial customer
- Texas A&M University
  - Provides material science expertise and coordination of materials testing with Sandia and Savannah River National labs
- HyGen Industries
  - Provides experience in hydrogen fueling infrastructure: pipeline and refueling station systems, has a database of customer-user engineering specifications. Assists in developing implementation plan for pipeline applications for hydrogen compressors

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Future Project Work

- Complete Current Phase 1 Effort
  - Continue to update compressor station Performance and Cost Module:
    - Including Operation & Maintenance Costs ($\$_{O\&M}$/kg/day)for centrifugal compressors working with hydrogen
    - Sizing and pricing of the compressor station module subsystems: intercoolers, prime mover, gearbox design, couplings, controls, safety systems, and base frame
  - Complete mechanical design of integral compressor rotor-shaft with gearbox pinion design
  - FMEA for compressor-gearbox and station
  - Outline compressor start-up and shut-down strategy
  - Review present Hydrogen Safety Standards and Commercial Systems and future requirements
  - Complete materials testing with Texas A&M
  - Go/No Go decision (July, 2009)
- Phase 2. Detailed Design (08/2009 to 04/2010)
  - Detailed subsystems modeling
  - Detailed integrated systems analysis
  - Critical components design, testing and development
- Phase 3. System Validation Testing (May 2010 to June 2011)
  - Component Procurement
  - Two-stage centrifugal compressor system assembly

Project Summary

- **Relevance:** An advanced pipeline compressor system has been designed that meets DOE's performance goals for a reliable 98% hydrogen efficiency compressor system with a footprint one-third the size of existing industrial systems and at a projected less than 75% of DOE's target.
- **Approach:** Utilize state-of-the-art aerodynamic/structural analyses to develop a high-performance centrifugal compressor system able to provide high pressure ratios under acceptable material stresses. Utilize proven bearings and seal technology to reduce developmental risk and increase system reliability at a competitive cost.
- **Tech. Accomplishments & Progress:** Aerodynamic analysis and design of a high volume, cost effective, six-stage centrifugal compressor has been completed to compress 240,000 kg/day from 350 to 1,200 psig and will be the largest hydrogen centrifugal compressor available for pipeline-grade service.
- **Technology Transfer/Collaboration:** The collaborative team consists of an industrial user with engineering experience in pipeline compressors (Praxair), a materials researcher (Texas A&M) and a hydrogen refueling industry consultant (HyGen) who are all committed to producing the first commercially reliable hydrogen compressor for hydrogen pipeline delivery.
- **Proposed Future Research:** Complete materials testing to verify materials yield stress; continue with detail design of compressor in Phase 2 culminating in the fabrication and laboratory testing of prototype compressor-gearbox in Phase 3. Complete the compressor module Cost and Performance Model that may be suitable for use as a "Macro" to DOE's HDSAM v.2 economics model.