Development of a Centrifugal Hydrogen Pipeline Gas Compressor

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Concepts NREC (CN)
June 9, 2010

Project ID#: PD017

This presentation does not contain any proprietary, confidential, or otherwise restricted information
Project Overview

Timeline
- Project Start: June 1, 2008
- Project End: June 1, 2011
- Percent Complete: 50% (all Ph.I and Ph. II in Progress)

Budget
- Total Project Funding
  - DOE Share: $4,202,562
  - Contractor Share: $850,055
- Funding Received in FY08 (Phase I)
  - $1,055,000
- Funding for FY10 (Phase II)
  - $1,076,924

Barriers/Tech. Objectives
- Pipeline delivery of pure (99.99%) hydrogen at <$1/GGE with 98% hydrogen efficiency
- Reduce Initial Capital Equipment and O&M Cost
- Reduce Compressor Module Footprint & Increase Reliability of Hydrogen Piston Compressors

Project Lead
- Concepts NREC (Woburn, MA and Wilder, VT)

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

Technical Collaboration
- Sandia National Lab, Argonne National Lab, Savannah River National Lab
- ABB, Cotta Transmission, GE, KMC, Flowserve, Tranter, Heatric
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
  - Reduce initial installed system equipment cost to less than $5.4 million uninstalled based on DOE’s HDSAM 2.0 Economics Model
  - 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
### Three-phase Program Approach

<table>
<thead>
<tr>
<th>Phase I</th>
<th>Phase II Detailed Design</th>
<th>Phase III System Validation Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Design (COMPLETED) (06/2008 to 12/2009)</td>
<td>Detailed subsystems modeling</td>
<td>Component Procurement</td>
</tr>
<tr>
<td>Initial design criteria and performance specifications</td>
<td>Detailed integrated systems analysis</td>
<td>Two-stage centrifugal compressor system assembly</td>
</tr>
<tr>
<td>Subsystems Modeling: aerodynamic and structural analysis of compressor</td>
<td>Critical components design, testing, and development</td>
<td>Performance evaluation test plan</td>
</tr>
<tr>
<td>Initial integrated systems analysis</td>
<td>Detailed integrated design of full-scale and laboratory validation systems</td>
<td>Lab testing and system maturation</td>
</tr>
<tr>
<td>Initial design and cost analysis</td>
<td>Detailed cost analysis of full-scale system</td>
<td>Final design of full-scale system completed</td>
</tr>
<tr>
<td>Final design specifications</td>
<td></td>
<td>Field demonstration program plan prepared</td>
</tr>
<tr>
<td>Materials and/or coatings investigated for use in high-pressure hydrogen environment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Revised Phase II Program Plan</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Phase III System Validation Testing**

- (10/2010 to 06/2011)
Project Milestones

• May, 2008 - START 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.

• Dec., 2009 - Go/No-Go Decision – Detailed design and cost analysis of full-scale pipeline system completed. Design of Laboratory Validation System finalized.

• Oct., 2010 - 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.
  – Utilize acceptable practice for high-speed gear materials, tip speeds, and loadings.
  – 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.
The Engineering Challenge
• Design centrifugal compressor with highest acceptable pressure ratio and thermodynamic efficiency per stage to minimize system size, complexity, and cost, and to maximize system performance and reliability.

Solution
• Maximize centrifugal compressor tip speed within stress limitations of material.
  – Pressure ratio is proportional to \( \text{rpm}^2 \times \text{radius}^2 \), 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 increase impeller material stresses.
  – Stress is also proportional to \( \text{rpm}^2 \times \text{radius}^2 \times \text{material density} \). 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 are resistant to hydrogen embrittlement.
Design Options for Alternative Operating Conditions

- **Industrial Machines**
- **High Strength Alloys**
- **Advanced Composites**

- **No. Compressor Stages**
  - 4
  - 6
  - 8
  - 10
  - 12
  - 14
  - 16

- **Baseline Design Point**
- **Desired Pres. Range**
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).

![Graph showing max. tip speeds for various materials with respect to operating temperature.](image)
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
# Phase I Summary: DOE Target/Goals and Project Accomplishments

## Progress Towards Meeting Technical Targets for Delivery of Hydrogen via Centrifugal Pipeline Compression

(Note: Letters correspond to DOE's 2007 Technical Plan-Delivery Sec. 3.2 - page 16)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Units</th>
<th>DOE Target</th>
<th>Project Accomplishment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen Efficiency (f)</td>
<td>[btu/btu]</td>
<td>98%</td>
<td>98%</td>
</tr>
<tr>
<td>Hyd. Capacity (g)</td>
<td>kg/day</td>
<td>100,000 to 1,000,000</td>
<td>240,000 (per Flowserve Shaft Seal Spec)</td>
</tr>
<tr>
<td>Hyd. Leakage (d)</td>
<td>%</td>
<td>&lt; 0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>Hyd. Purity (h)</td>
<td>%</td>
<td>99.99</td>
<td>99.99 (per Flowserve Shaft Seal Spec)</td>
</tr>
<tr>
<td>Discharge Pressure (g)</td>
<td>psig</td>
<td>&gt;1000</td>
<td>1285</td>
</tr>
<tr>
<td>Comp. Package Cost (g)</td>
<td>$/M</td>
<td>6.2</td>
<td>4.5</td>
</tr>
<tr>
<td>Main. Cost (Table 3.2.2)</td>
<td>$/kWhr</td>
<td>0.007</td>
<td>0.005 (per CN Analysis Model)</td>
</tr>
<tr>
<td>Package Size (g)</td>
<td>sq. ft.</td>
<td>300 to 350</td>
<td>175 to 200 (per CN Design)</td>
</tr>
<tr>
<td>Reliability (e)</td>
<td># sys.s req'd</td>
<td>Eliminate redundant system</td>
<td>Modular sys.s with 240K kg/day with no redundancy req'd</td>
</tr>
</tbody>
</table>
DOE Stated Objectives:

- Develop and demonstrate an advanced centrifugal compressor system for high-pressure hydrogen pipeline transport to support DOE’s strategic hydrogen economy infrastructure plan
- Delivering 100,000 to 1,000,000 kg/day of 99.99% hydrogen gas from generation site(s) to forecourt stations
- Compressing from 350 psig to 1,000 psig or greater
- Reduce initial installed system equipment cost to less than $9M (Compressor Package of $5.4 M) for 200,000 kg/day system by FY 2017
- Reduce package footprint and improve packaging design
- Achieve transport delivery costs below $1/GGE
- Reduce maintenance cost to below 3% of Total Capital Investment by FY 2017
- Increase system reliability to thus avoid purchasing redundant systems
- Maintain hydrogen efficiency (as defined by DOE) to 98% or greater
- Reduce H2 leakage to less than 0.5% by FY 2017

Completed in Phase I

Project Objectives - Relevance to DOE Hydrogen Economy Planning
Hydrogen Compressor Phase I Feasibility Design

Results: 240,000 kg/day; 350 to 1,285 psig; 6,300 kWe

1,800 rpm Synchronous Motor and Controls

Compressor-Gearbox (10:1 and 3.33:1, parallel bull gear driving 6 pinions [3 per side])

Compressor drive connection

Intercoolers (cooling hydrogen at compressor inlet to 100°F)

Overall dimensions: 26 ft long x 6-8 ft wide x 10 ft high

Lube oil cooler and reservoir

1 of 6 compressor rotors - 3 per gearbox side

1 of 6 compressor stages (3 per side)
Hydrogen Pipeline Compressor Module
Design Specifications for Conservative Choice

- Compressor design conditions confirmed by project collaborator Praxair as necessary for industrial applications
  - $P_{\text{inlet}} = 350$ psig, $P_{\text{outlet}} = 1,285$ psig; Flow rate = 240,000 kg/day
- 6-stage, 60,000 rpm, 3.56 pressure ratio compressor
  - A more advanced, experimental compressor rotor design is still under aero research and may provide the same pressure ratio, but with one less stage
- Integral gearbox pinions driving individual, overhung impellers
  - Cotta Gearbox with two-step gearing operating at state-of-the-art gear tip speeds
- Design of compressor’s major mechanical elements completed and satisfied by two manufacturers per component:
  - KMC tilting-pad radial and thrust bearing designs confirmed for use
  - Flowserve gas face-seals have been confirmed to meet necessary specifications for hydrogen applications
- Heat exchanger specifications met by two manufacturers to cool hydrogen gas to 100°F between stages
  - Tranter Plate-type Heat Exchanger Design
  - Heatric Heat Exchanger (compact, plate-fin surface core)
Technical Accomplishments and Progress
Compressor Design Specifications

• **Compressor Design Details:**
  – Centrifugal Compressor overall efficiency = 80.3%
  – A nominal shaft speed of 60,000 rpm
  – 6 stages (aluminum rotor)
  – Tip speed ~ 2,100 ft/s (corresponding to a hub stress of less than 60 kpsi)
  – Power of 1,400 hp per wheel,
  – Suction pressure 350 psig, discharge pressure 1,250+ psig for an overall pressure ratio of 3.6
  – 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**
Phase II – Detailed Engineering Design

PHASE II OBJECTIVES:

• Critical components development and testing (rotor, shaft seal, bearings)
• Detailed design and cost analysis of a complete pipeline compressor system
• Go/No-Go decision regarding proceeding into Phase III: Fabrication of Complete Two-stage Hydrogen Compressor for Laboratory Testing

TASK DESCRIPTION:

Task 1 Detailed Subsystems Modeling
Task 2 Detailed Integrated Systems Analysis
Task 3 Components Design
Task 4 Critical Components Testing and Development
Task 5 Integrated System Design
Task 6 Detailed Cost Analysis
Task 7 Revised Phase III Program Plan (Go/No-Go Decision)
Task 8 Program Management and Reporting
Mechanical Detail of Compressor Stage
All Stages Have the Same Mechanical Design
Mechanical Design Detail of Compressor Stage Coupled to Gearbox
General Piping and Instrumentation Flow Diagram for Hydrogen Compressor System
Phase II Accomplishments In Progress

- FMEA Analysis
- Comparative Reliability Assessment
- Comparative O&M Assessment
- Algorithm for Anti-surge Valve Sizing for Emergency Shutdown
## FMEA Working Component List

### 1 Motor Subsystem
- 1.1 Motor Shaft
- 1.2 Motor Bearings
- 1.3 Motor Windings
- 1.4 Motor Cooling

### 2 Gearbox Subsystem
1. **Low Speed (Input) Stage**
   - 2.1.1 Input Coupling
   - 2.1.2 Input Shaft
   - 2.1.3 Input Shaft Bearings
   - 2.1.4 Input Shaft Seal
   - 2.1.5 Input Gear
2. **Intermediate Speed Stage**
   - 2.2.1 Int. Gear (in)
   - 2.2.2 Int. Shaft
   - 2.2.3 Int. Bearings
   - 2.2.4 Int. Gear (out)
3. **High Speed (Output) Stage (2X)**
   - 2.3.1 High Speed Gears
   - 2.3.2 High Speed Shaft
   - 2.3.3 High Speed Bearings
   - 2.3.4 Thrust Bearing
   - 2.3.5 High Speed Shaft Seals
4. **Lubrication Subsystem**
   - 2.4.1 Lubricant
   - 2.4.2 Pump
   - 2.4.3 Filter
   - 2.4.4 Lubrication Jets

### 3 Compressor Stages Subsystems
1. **Stage #1**
   - 3.1.1 Stage #1 Shaft
   - 3.1.2 Stage #1 Impeller
   - 3.1.3 Stage #1 Impeller Attachment
   - 3.1.4 Stage #1 Shaft Seal
   - 3.1.5 Stage #1 Housing
2. **Stage #2**
3. **Stage #3**
4. **Stage #4**
5. **Stage #5**
6. **Stage #6**

### 4 Piping and Intercooling Subsystem
1. **Piping**
   - 4.1.1 Flanges / Seals
   - 4.1.2 Pipe
2. **Intercoolers**
   - 4.2.1 Flange / Seal, Working Fluid
   - 4.2.2 Flange / Seal, Coolant
   - 4.2.3 Internal Piping
   - 4.2.4 Coolant

### 5 Hydrogen Containment Subsystem
1. **Containment Housing**
2. **HP Re-Introduction System**
3. **LP Ventilation System**

### 6 System Skid

### 7 Controls and Instrumentation
Example of Methodology for Comparing the Relative Maintenance Cost of a Piston and Centrifugal Hydrogen Compressor

<table>
<thead>
<tr>
<th>Component</th>
<th>fn</th>
<th>Nfail/s yr</th>
<th>$/comp</th>
<th>Dt x fn</th>
<th>$/comp repair</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gearbox</td>
<td>10</td>
<td>0.16</td>
<td>15000</td>
<td>640</td>
<td>12979</td>
</tr>
<tr>
<td>Gears</td>
<td>8</td>
<td>0.09</td>
<td>7500</td>
<td>480</td>
<td>3263</td>
</tr>
<tr>
<td>Spare</td>
<td>0</td>
<td>0.00</td>
<td>15000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Dynamic Seal</td>
<td>3.5</td>
<td>0.17</td>
<td>8000</td>
<td>280</td>
<td>6235</td>
</tr>
<tr>
<td>Sleeve bearing</td>
<td>6</td>
<td>0.52</td>
<td>7500</td>
<td>480</td>
<td>28821</td>
</tr>
<tr>
<td>Heat Exchangers</td>
<td>3</td>
<td>0.27</td>
<td>15000</td>
<td>240</td>
<td>10437</td>
</tr>
<tr>
<td>Highly Stressed Shaft</td>
<td>3</td>
<td>0.011</td>
<td>10000</td>
<td>240</td>
<td>357</td>
</tr>
<tr>
<td>Pinion Gear</td>
<td>4.5</td>
<td>0.26</td>
<td>7500</td>
<td>360</td>
<td>11432</td>
</tr>
<tr>
<td>Routine Maintenance</td>
<td>1</td>
<td>1</td>
<td>20000</td>
<td>80</td>
<td>28000</td>
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</tbody>
</table>

\[
$\text{maintenance/kWhr} = 0.00595
\]

\[
\text{Availability} = 0.51
\]

Centrifugal Compressor Maintenance Cost Analysis

<table>
<thead>
<tr>
<th>fn</th>
<th>Nfail/s yr</th>
<th>$/comp</th>
<th>Dt x fn</th>
<th>$/comp repair</th>
</tr>
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<tbody>
<tr>
<td>10</td>
<td>0.16</td>
<td>15000</td>
<td>640</td>
<td>12979</td>
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<td>8</td>
<td>0.09</td>
<td>7500</td>
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<tr>
<td>0</td>
<td>0.00</td>
<td>15000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3.5</td>
<td>0.17</td>
<td>8000</td>
<td>280</td>
<td>6235</td>
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<td>6</td>
<td>0.52</td>
<td>7500</td>
<td>480</td>
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<tr>
<td>1</td>
<td>1</td>
<td>20000</td>
<td>80</td>
<td>28000</td>
</tr>
</tbody>
</table>

\[
$\text{maintenance/kWhr} = 0.00354
\]

CONCEPTS NREC
Example of Relative Comparison of Centrifugal vs. Piston Compressor Reliability

Hazard failure Rates (λ x e^6): (ref.: Tables 9.2, 9.3, 9.4, 9.5 in B.S. Dhillon's text)

<table>
<thead>
<tr>
<th></th>
<th>Hazard Failure Rates (λ x e^6)</th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Gearbox 18.755</td>
<td>B</td>
<td>Gears 5</td>
</tr>
<tr>
<td>C</td>
<td>spare</td>
<td>D</td>
<td>Dynamic Seal 3.295</td>
</tr>
<tr>
<td>E</td>
<td>spare</td>
<td>F</td>
<td>Sleeve bearing 4.94</td>
</tr>
<tr>
<td>G</td>
<td>Heat Exchangers 6.11</td>
<td>H</td>
<td>Generic Compressor 200</td>
</tr>
<tr>
<td>I</td>
<td>Highly Stressed Shaft 0.2</td>
<td>J</td>
<td>Pinion Gear 5</td>
</tr>
<tr>
<td>K</td>
<td>spare</td>
<td>L</td>
<td>spare</td>
</tr>
<tr>
<td>M</td>
<td>spare</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Number of Impellers: 6
Time Period (yrs): 3

Individual Reliabilities (R):

<table>
<thead>
<tr>
<th></th>
<th>Increased Risk Multipl Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Gearbox 0.990 1</td>
</tr>
<tr>
<td>B</td>
<td>Gears 0.997 1</td>
</tr>
<tr>
<td>C</td>
<td>spare 1.000 1</td>
</tr>
<tr>
<td>D</td>
<td>Dynamic Seal 0.998 1</td>
</tr>
<tr>
<td>E</td>
<td>spare 1.000 1</td>
</tr>
<tr>
<td>F</td>
<td>Sleeve bearing 0.997 1</td>
</tr>
<tr>
<td>G</td>
<td>Heat Exchangers 0.997 1</td>
</tr>
<tr>
<td>H</td>
<td>Generic Compressor 0.900 1</td>
</tr>
<tr>
<td>I</td>
<td>Highly Stressed Shaft 1.000</td>
</tr>
<tr>
<td>J</td>
<td>Pinion Gear 0.997 1</td>
</tr>
<tr>
<td>K</td>
<td>spare 1.000 1</td>
</tr>
<tr>
<td>L</td>
<td>spare 1.000 1</td>
</tr>
<tr>
<td>M</td>
<td>spare 1.000 1</td>
</tr>
</tbody>
</table>

CALC.D SINGLE-STG CENTRIFUGAL COMPRESSOR RELIABILITY= 0.990 6
Calculated Gear Box Reliability= 0.985 1
Calculated Heat Exchanger Reliability= 0.984 5
BASIC COMPRESSOR V 0.943
Anti-surge Control Model Algorithm for Emergency Shutdown

- Enables the sizing of Anti-surge Control Valve and Downstream Piping

6-Stage, Hydrogen Compressor Performance Map with Surge Modeling at Emergency Shut-down
(Cv=42 cft/s/psig)

Pressure ratio & flow rate path of compressor as it almost exceeds surge control with valve Cv=42
Materials Testing Technical Accomplishments in Progress by Texas A&M University

- 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 will conduct 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 is 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?
Small Punch Test Apparatus by TAMU to Determine Effects of Hydrogen Exposure

The following figures have been reproduced from the three technical papers that have used the technique to test materials.

Sources:


Some Texas A&M Material Testing Results

Cross section of test sample (0.5-mm x 3-mm dia.) with puncture made by metal 1-mm diameter ball bearing

This figure compares the average force vs. extension curve for the aluminum 1100 and aluminum 3003 samples, showing the standard deviation for each.
Future Project Work

• **Phase II Detailed Design** *(12/2009 to 09/2010)*
  – Detailed subsystems modeling
  – Detailed integrated systems analysis
  – Critical components design, testing, and development
  – Detailed design of two-stage hydrogen compressor prototype
  – Continue materials testing at Texas A&M University with hydrogen-charged specimens and coatings

• **Phase III System Validation Testing** *(10/2010 to 06/2011)*
  – Component procurement for two-stage functional hydrogen compressor system
  – Two-stage centrifugal compressor system assembly
  – Testing at Praxair or National Laboratory hydrogen facility
Project Summary

• **Relevance:** An advanced pipeline compressor system has been designed that meets DOE's performance goals for:
  – High reliability with 350 to 1,200+ psig compression of 240,000 kg/day at 98% hydrogen efficiency
  – footprint one-third the size of existing industrial systems at projected cost of less than 75% of DOE’s target.

• **Approach:** Utilize state-of-the-art and acceptable engineering practices to reduce developmental risk for:
  – aerodynamic/structural analyses for acceptable material stresses,
  – Industrially proven bearings, seal technology, gearing, heat exchangers, lube system

• **Tech. Accomplishments & Progress:** Aerodynamic analysis and design of a cost-effective, six-stage centrifugal compressor has been completed - the largest hydrogen centrifugal compressor available for pipeline-grade service. Detailed design is underway.

• **Technology Transfer/Collaboration:** The collaborative team consists of an industrial user, Praxair, with engineering experience in pipeline compressors; a materials researcher, Texas A&M; a hydrogen refueling industry consultant, HyGen; and the coordinated technical support of several National Labs.

• **Proposed Future Research:** Complete materials testing with TAMU of specimens and actual rotor forensics after high-speed testing and coatings; continue with detailed design of compressor in Phase II, culminating in the fabrication and laboratory testing of prototype compressor-gearbox in Phase III; update cost of system.
Additional Supportive Data

- The following slides are included here to provide additional support during the question and answer period for the salient summary that has been offered during the formal presentation describing the extensive work that has been performed during the last 10 months.
Project Collaborations-
Principal Investigator - Concepts NREC:
Capabilities from Aero Design to Manufacturing
## FMEA Document Risk Ranking Used with Compressor Subsystems Shown

### Risk Matrix:

<table>
<thead>
<tr>
<th>Risk Level</th>
<th>Description</th>
<th>Probability Classes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Tolerable, no action required</td>
<td>1</td>
</tr>
<tr>
<td>Medium</td>
<td>Mitigation and improvement required to reduce risk to low</td>
<td>2</td>
</tr>
<tr>
<td>High</td>
<td>Not acceptable, mitigation and improvement required to reduce risk to low</td>
<td>3</td>
</tr>
</tbody>
</table>

### Failure Mode Identification and Risk Ranking

**Project title:** 10195 DOE Hydrogen Compressor - Preliminary Design  
**Author:** ARP  
**Date:**

#### Probability Classes:

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Description</th>
<th>Indicative Annual Failure Rate (up to)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very Low</td>
<td>Negligible event frequency</td>
<td>1.0E-04</td>
</tr>
<tr>
<td>2</td>
<td>Low</td>
<td>Event unlikely to occur</td>
<td>1.0E-03</td>
</tr>
<tr>
<td>3</td>
<td>Medium</td>
<td>Event rarely expected to occur</td>
<td>1.0E-02</td>
</tr>
<tr>
<td>4</td>
<td>High</td>
<td>One or several events expected to occur during the lifetime</td>
<td>1.0E-01</td>
</tr>
<tr>
<td>5</td>
<td>Very high</td>
<td>One or several events expected to occur each year</td>
<td>1.0E+00</td>
</tr>
</tbody>
</table>

#### Consequence Classes:

<table>
<thead>
<tr>
<th>Class</th>
<th>Function</th>
<th>Safety</th>
<th>Environment</th>
<th>Operation</th>
<th>Assets</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Minimal effect, easily repairable or redundant system</td>
<td>Negligible injury, effect on health</td>
<td>Negligible pollution or no effect on environment</td>
<td>Negligible effect on production (hours)</td>
<td>Negligible</td>
</tr>
<tr>
<td>2</td>
<td>Loss of redundant function, reduced capacity</td>
<td>Minor injuries, health effects</td>
<td>Minor pollution / slight effect on environment</td>
<td>Some small loss of production, less than a month</td>
<td>Significant, but repairable</td>
</tr>
<tr>
<td>3</td>
<td>Loss of parts of main function, with significant repairs required</td>
<td>Significant injuries and/or health effects</td>
<td>Limited levels of pollution, manageable / moderate effect on environment</td>
<td>Production loss of 1 month. Light intervention required to replace equipment</td>
<td>Localised damage, repairable on site</td>
</tr>
<tr>
<td>4</td>
<td>Shutdown of system</td>
<td>A fatality, moderate injuries</td>
<td>Moderate pollution, with some clean-up costs / Serious effect on environment</td>
<td>Significant loss of production of 1 to 3 months</td>
<td>Loss of main function, major repair needed by removal of part of device</td>
</tr>
<tr>
<td>5</td>
<td>Complete failure</td>
<td>Several fatalities, serious injuries</td>
<td>Major pollution event, with significant clean-up costs / disastrous effects on the environment</td>
<td>Total loss of production for more than 3 months</td>
<td>Loss of device</td>
</tr>
</tbody>
</table>

#### Risk Categories:

<table>
<thead>
<tr>
<th>Prob.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Low</td>
<td>Med</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>4</td>
<td>Low</td>
<td>Low</td>
<td>Med</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>3</td>
<td>Low</td>
<td>Low</td>
<td>Med</td>
<td>Med</td>
<td>Med</td>
</tr>
<tr>
<td>2</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Med</td>
</tr>
<tr>
<td>1</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

#### Detection Classes:

<table>
<thead>
<tr>
<th>Detection Rating</th>
<th>Description</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Remote / Uncertainty</td>
<td>Remote chance Design Control will detect, or Design Control will not and/or cannot detect a potential cause/mechanism and subsequent failure mode; or there is no Design Control</td>
</tr>
<tr>
<td>4</td>
<td>Remote</td>
<td>Remote chance the Design Control will detect a potential cause/mechanism and subsequent failure mode</td>
</tr>
<tr>
<td>3</td>
<td>Low</td>
<td>Low to Moderate chance the Design Control will detect a potential cause/mechanism and subsequent failure mode</td>
</tr>
<tr>
<td>2</td>
<td>Moderately High</td>
<td>Moderately High to High chance the Design Control will detect a potential cause/mechanism and subsequent failure mode</td>
</tr>
<tr>
<td>1</td>
<td>Very High / Almost Certain</td>
<td>Design Controls will almost certainly detect a potential cause/mechanism and subsequent failure mode</td>
</tr>
</tbody>
</table>
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)
  - Metallic hydride, tungsten and tungsten carbide, TiO$_2$, CrO$_3$
  - Accuratus (APS Company)
  - Alodine EC$^2$ 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?
Technical Accomplishments and Progress

Materials Selection and Testing Summary

- A wide-ranging literature search and personal discussions with materials researchers (Sandia, Savannah River, Argonne National Laboratories, Failure Analysis Associates) have been conducted (and are continuing)
  - 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: 1100, 2024, 3003, 2618-T6, 2918-T81 and 7075 - Matl. design choice) 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 researchers as affected by hydrogen embrittlement, but alloy Ti Grade 2 will be tested to check coating efficacy
- Collaboration with Texas A&M (Dr. Hong Liang) and coordinating their tests with two National Labs (using a small diameter punch test apparatus) 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)
Accomplishment Details (1)

- Developed Computer Models to Aid in Analysis of Hydrogen Compressor
  - Compressor Module Performance and Cost Model
    - Suitable as a macro for DOE “HDSAM v2.0” Economics Model
    - Provides a single point summary of each of the components within the package:
      1. Compressor rotor aerodynamics (pressure ratio, power, speed vs. flow rate, and intercooler pressure drop)
      2. Intercooler size vs. effectiveness (i.e., desired outlet temperature)
      3. Electric motor power
      4. Overall hydrogen efficiency based on compressor power, component efficiencies
      5. Compressor shaft diameter sizing based on fatigue loading
      6. Impeller radial and axial loadings calculated
System Reliability and Maintenance Cost Model

- Engineering Reliability and Maintenance Cost Model that uses a consistent methodology and algorithms to determine the relative reliability and maintenance cost for a piston and centrifugal compressor pipeline package
- Uses either manufacturer’s reliability of individual components or subsystems that constitute a compressor system (preferred) or textbook values
- Uses FERC operation and maintenance database as the basis for determining the maintenance costs for a centrifugal compressor.
- Uses Failure Mode Effects Analysis as developed by Concepts NREC for this project.
Technical Accomplishments and Progress
Aluminum Material Selection based on Prior Research combined with Compressor Aerodynamic Design Experience Applied - 1

Material's Specific Strength under 10,000-psi Gas
-room temperature, notched specimens-
Aluminum Alloy shows no effect from hydrogen in Rocketdyne Lab Tests
.... AND Aluminum is an excellent aerodynamic, structural material

Technical Accomplishments and Progress
Compressor-Gearbox “Best Case” Selection Based on Relative O&M and Mechanical Risk Analysis

- Driver speed (1,800, 3,600, 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
- 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 for the compressor package

<table>
<thead>
<tr>
<th>Configuration Designation:</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impeller Speeds (rpm):</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st and 2nd</td>
<td>70,000</td>
<td>50,000</td>
<td>50,000</td>
<td>50,000</td>
<td>50,000</td>
<td>60,000</td>
</tr>
<tr>
<td>3rd and 4th</td>
<td>80,000</td>
<td>50,000</td>
<td>60,000</td>
<td>50,000</td>
<td>50,000</td>
<td>60,000</td>
</tr>
<tr>
<td>5th and 6th</td>
<td>90,000</td>
<td>50,000</td>
<td>70,000</td>
<td>50,000</td>
<td>50,000</td>
<td>60,000</td>
</tr>
<tr>
<td>Total Power, hp=</td>
<td>8,360</td>
<td>8,354</td>
<td>8,450</td>
<td>8,610</td>
<td>8,543</td>
<td>8,349</td>
</tr>
<tr>
<td>Max. Tip Speeds,ft/s=</td>
<td>2,236</td>
<td>2,178</td>
<td>2,194</td>
<td>2,194</td>
<td>2,101</td>
<td>2,094</td>
</tr>
</tbody>
</table>

Gearbox Configuration: Alpha 1
Beta 1
Gamma 1
Delta 1

BEST CHOICE

CONCEPTS NREC
Typical output from compressor station performance model - showing first of six stages
Developed a System Reliability and Maintenance Cost Analysis Methodology

A consistent methodology has been prepared to eventually use MTBF test data and maintenance experience to compare piston and centrifugal reliability and maintenance performance for hydrogen compression.

Analysis uses FERC data as reported in several studies by Dr. Anthony Smalley, et al. in a paper entitled: "Evaluation and Application of Data Sources for Assessing Operating Costs for Mechanical Drive Gas Turbines in Pipeline Service (Vol. 122, July 2000, Transactions of ASME) and "Benchmarking the Industry: Factors Affecting Compressor Station Maintenance Costs" by John Harrell, Jr. and A. Smalley of Southwest Research Institute® (a presentation at the GMRC Gas Machinery Conference, October 2000).
## Hydrogen Piston Cost ($) and Operation & Maintenance ($/kWhr) Using DOE's HDSAM v.2 Economics

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Piston Stages</td>
<td>4</td>
</tr>
<tr>
<td>kWe rating</td>
<td>6,226</td>
</tr>
<tr>
<td>Kg/day Hydrogen Flowrate</td>
<td>240,000</td>
</tr>
<tr>
<td>$ compressor</td>
<td>$ 6,278,724</td>
</tr>
<tr>
<td>$, installation</td>
<td>$ 12,557,447</td>
</tr>
<tr>
<td>$, maintenance/yr</td>
<td>$ 376,723</td>
</tr>
<tr>
<td>kW-hr</td>
<td>53,978,993</td>
</tr>
<tr>
<td>O&amp;M Cost [$/KwHr]</td>
<td>0.0070</td>
</tr>
</tbody>
</table>

$3\%$ % Maintenance

2 Multiple of Capital Equip. Cost
Anti-surge Analysis: Emergency Shutdown Model

Compressor Surge Analysis at Emergency Shut-Down Model

Overall Compressor Pressure Ratio

Mass Flow Rate, lbm/s

Stage, Hydrogen Compressor Performance Map with Surge Modeling at Emergency Shut-down (Cv=50 cft/s/√psid)

Gear box and Compressor Mass Moments of Inertia

Lg. Bull Gear
Dia. inch = 35
Speed Ratio = 10
Avg. Thickness = 2.5
No. of Gears = 2
No. of Stages = 6
Inertia = 1448 Lbm-ft²
Corrected with speed = 1177

Sml. Bull Gear
Dia. = 10.5
Speed Ratio = 3.33
Avg. Thickness = 2.5
No. of Gears = 6
Inertia = 12 Lbm-ft²

Compressor Rotor
Dia. in. dia. = 8
Speed Ratio = 33.3
Avg. Thickness = 2.5
No. of Stages = 6
Inertia = 1500 Lbm-ft²

Design Point Flowrate, Lbm/s

Disp. Temp. = 360 °R

Avg. Pipe Dia. (Inch) = 8

Avg. Pipe Length (ft) = 10

Total Gear Box Inertia = 4717

Inertia = 28910 Lbm-ft² @ 1800 rpm

Time Delay due Sound speed = 0.00209 sec.s

Comp. Eff. = 0.8

Total Volume = 103.2 ft³ (including intercoolers)

Rgas Constante = 772.5 Lb-ft/Lbm/R

Temp. = 560 °R

Controls time delay = 0.1 sec.s

Time Increment = 0.025 sec.s

Electric Motor Mass = 13860 Lbm

Motor Avg. diameter = 3.7 ft.

Correction Factor = 1

Electric Motor = 24193 Lbm-ft²

Total = 28910 Lbm-ft² @ 1800 rpm

Total Rotational Energy Avail. = 2.90E+04 hp-sec.

Non-Braked Stopping Time = 5 sec.s

6-Stage, Hydrogen Compressor Performance Map with Surge Modeling at Emergency Shut-down (Cv=50 cft/s/√psid)
DOE Stated Objectives:
- Develop and demonstrate an advanced centrifugal compressor system for high-pressure hydrogen pipeline transport to support DOE’s strategic hydrogen economy infrastructure plan
- Deliver 100,000 to 1,000,000 kg/day of 99.99% hydrogen gas from generation site(s) to forecourt stations
- Compress from 350 psig to 1,000 psig or greater
- Reduce initial installed system equipment cost to less than $9M (Compressor Package of $5.4M) for 200,000 kg/day system by FY 2017
- Reduce package footprint and improve packaging design
- Achieve transport delivery costs below $1/GGE
- Reduce maintenance cost to below 3% of Total Capital Investment by FY 2017
- Increase system reliability to thus avoid purchasing redundant systems
- Maintain hydrogen efficiency (as defined by DOE) to 98% or greater
- Reduce H2 Leakage to less than 0.5% by FY 2017

DOE Stated Technical Barriers to Establishing Hydrogen as Viable Alt. Fuel:
- This project addresses the following technical barriers from the Delivery (Section 3) of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-year Research, Development and Demonstration Plan:
  (B) Reliability and Costs of Hydrogen Compression
PHASE II – Detailed Engineering Design

OBJECTIVE:
The overall objective of Phase II is to undertake critical components testing and development, and based on the results, prepare a detailed design and cost analysis of a complete pipeline compressor system. This design will incorporate all the necessary subsystems for stand-alone testing in an actual pipeline system environment. In particular, fabrication and laboratory testing will be performed to verify design parameters for bearings, seals, impellers, and materials in a hydrogen environment. In addition, a laboratory validation test unit will be designed to enable the testing of a partial integrated assembly to take place in Phase III. At the conclusion of this task, a Go/No-Go decision will be made with regard to proceeding into Phase III.

2.1 Detailed Subsystems Modeling
The objective of this task is to prepare detailed analytical models of the centrifugal compressors, gearbox, intercoolers, and prime mover to establish the specific design parameters from which to prepare detailed designs. Analytical modeling will be conducted with regard to various aerodynamic design tradeoffs that affect compressor performance, impeller stress, and dynamic stability. This work will also include the design of the high-speed gearbox (bearing loads, seals, lubrication, etc.), prime mover, and control system. Current design practices, as well as advanced concepts, will be factored into the model to identify critical areas of concern, design approaches, and if necessary, future mitigation design strategies.

2.2 Detailed Integrated Systems Analysis
In parallel with Task 3.2.1, Subsystems Modeling, a detailed integrated system analysis will be performed that defines the predicted performance of the system under alternative operating conditions consistent with the design criteria and specifications defined in Task 3.1.5. This work will include process flow and instrumentation diagrams, mass flow and energy balances, and control strategies.

2.4 Critical Components Testing and Development
The objective of this task is to design, fabricate, and test critical components under simulated operating conditions to validate predicted design. Worst-case operating conditions of the impellers, seals, and bearings will be defined, and high-speed dynamic testing under controlled laboratory conditions will be undertaken. High-speed spin tests will be conducted to validate predicted stresses at various speeds, including operation to failure to define the ultimate stress limit of the impeller. Dynamic stability limits will also be verified.
2.5 Integrated System Design
In this task, two designs, the first for a complete multistage system, and a second for a limited overall pressure ratio two-stage compressor system will be prepared in sufficient detail to estimate the cost of each system. The two-stage compressor system will include all the subsystems, but will operate at a reduced overall pressure ratio and power input to facilitate laboratory testing and development. This will include the compressors, intercoolers, gearbox, motor, lubrication system, skid, and controls. Quotations will be requested for the two-stage compressor equipment to be built and tested in Phase III.

2.6 Detailed Cost Analysis
A detailed manufacturing, operating, and maintenance costs analysis of the proposed system will be prepared. Using established scaling laws, the capital costs of various size systems up to 1 million kg/day will be estimated.

2.7 Revised Phase III Program Plan (Go/No-Go Decision)
This task is to revise the original Phase II Plan to reflect the current program development status. This task reflects the second Go/No-Go decision point in the program. Given the decision to move ahead, a revised program plan will be prepared reflecting the present level of development and critical technology hurdles that must be overcome to achieve the design goals. This plan will include a revised task, schedule, and cost plan with recommendations regarding accelerating, eliminating or redirecting certain activities. This plan will be submitted to the DOE Program for review and approval before proceeding into the next phase of the program.

2.8 Program Management and Reporting
The Program Manager will set goals, plan their accomplishment, maintain effective personnel on the project, negotiate and administer agreements between all participants including subcontractors, and deliver all contract commitments. Periodic status and other report obligations will be submitted to document and summarize the program. A DOE Phase II Final Report, including Topical reports for Tasks 3.2.5, 3.2.6, and 3.2.7, will be prepared.