Mr. Francis A. Di Bella, P.E. and Dr. Colin Osborne
Concepts NREC (CN)
June 17, 2014

Project ID#: PD017
Project Overview

Timeline

- Project Start: June 1, 2008
- Project End: November 2012
- Percent Complete: Ph. I and Ph. II - 100%; Ph. III in Progress

Budget

- Total Project Funding
  - DOE Share: $3,352,507
  - Contractor Share: $850,055
- FY14 Funding (Phase III)
  - A No Cost Extension with Total Project Expenditure to date: $3.19M

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; reduce R&D risk – utilize commercially available, state-of-the-art components

Project Lead

- Concepts NREC (Chelmsford, MA, and Wilder, VT)

Project Partners

- Texas A&M University (TAMU) (Materials Testing)
- HyGen Industries (Hydrogen Industry Consultant)

Technical Collaboration

- Air Products and Chemicals, Inc.
- Sandia National Lab, Argonne National Lab, Savannah River National Lab
- Artec Machine Systems (gearbox), RMT (Bearings), Flowserve (shaft seal), Tranter HX, Hyundai (Motor)
Demonstrate Advanced Centrifugal Compressor System for High-pressure Hydrogen Pipeline Transport to Support¹

- Delivery of 100,000 to 1,000,000 kg/day of pure hydrogen to forecourt station at less than $1/GGE with less than 0.5% leakage and with pipeline pressures of 1200+ psig
- Reduction in initial system equipment cost to less than $6.3 million which is the uninstalled cost for a hydrogen pipeline based on DOE’s HDSAM 2.0 Economics Model
- Reduction in Operating & Maintenance Costs via improved reliability
  - DOE’s Model also indicates $O&M cost of 3% of installed cost per year, or $0.01/kWhr by 2017
  - Improved reliability eliminates the need for system redundancies
- Reduction in system footprint

¹ Reference: Delivery Section (Sec. 3.2) of the “Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-year Research, Development, and Demonstration Plan”
## A 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 <strong>(COMPLETED)</strong> (06/2008 to 12/2009)</td>
<td>Detailed subsystems modeling</td>
<td>Component Procurement</td>
</tr>
<tr>
<td>Revised Phase II Program Plan</td>
<td>Detailed integrated systems analysis</td>
<td>One-stage centrifugal compressor system assembly</td>
</tr>
<tr>
<td>• Initial design criteria and performance specifications</td>
<td>Critical components design, testing, and development</td>
<td>Performance evaluation test plan</td>
</tr>
<tr>
<td>• Subsystems Modeling: aerodynamic and structural analysis of compressor</td>
<td>Detailed integrated design of full-scale and laboratory validation systems</td>
<td>Lab testing and system maturation</td>
</tr>
<tr>
<td>• Initial integrated systems analysis</td>
<td>Detailed cost analysis of full-scale system</td>
<td>Final design of full-scale system completed</td>
</tr>
<tr>
<td>• Initial design and cost analysis</td>
<td></td>
<td>Field demonstration program plan prepared</td>
</tr>
<tr>
<td>• Final design specifications</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Materials and/or coatings investigated for use in high-pressure hydrogen environment</td>
<td></td>
<td></td>
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</tbody>
</table>

There is a patent pending regarding the subject matter of this presentation.
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.

There is a patent pending regarding the subject matter of this presentation.
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**

Grids for:
- **TIP SPEED, FT/SEC**
- **PRESSURE RATIO**

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

- Desired Pres. Range

There is a patent pending regarding the subject matter of this presentation.
### Summary of 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>
<th>STATUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen Efficiency</td>
<td>[btu/btu]</td>
<td>98%</td>
<td>98%</td>
<td>Objective Met</td>
</tr>
<tr>
<td>Hyd. Capacity (g)</td>
<td>Kg/day</td>
<td>100,000 to 1,000,000</td>
<td>240,000</td>
<td>Objective Met</td>
</tr>
<tr>
<td>Hyd. Leakage (d)</td>
<td>%</td>
<td>&lt; .5</td>
<td>0.2 (per Flowserve Shaft Seal Spec.)</td>
<td>Objective Met</td>
</tr>
<tr>
<td>Hyd. Purity (h)</td>
<td>%</td>
<td>99.99</td>
<td>99.99 (per Flowserve Shaft Seal Spec)</td>
<td>Objective Met</td>
</tr>
<tr>
<td>Discharge Pressure (g)</td>
<td>psig</td>
<td>&gt;1000</td>
<td>1285</td>
<td>Objective Met</td>
</tr>
<tr>
<td>Comp. Package Cost (g)</td>
<td>$M</td>
<td>6.0 +/- 1</td>
<td>4.5 +/- 0.75</td>
<td>Objective Met</td>
</tr>
<tr>
<td>Main. Cost (Table 3.2.2)</td>
<td>$/kWhr</td>
<td>0.007</td>
<td>0.005 (per CN Analysis Model)</td>
<td>Objective Met</td>
</tr>
<tr>
<td>Package Size (g)</td>
<td>sq. ft.</td>
<td>350 (per HyGen Study)</td>
<td>260 (per CN Design)</td>
<td>Objective Met</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>
<td>Objective Met</td>
</tr>
</tbody>
</table>

In Summary: The original DOE proposal requirements were satisfied with the Detailed Design of a Pipeline Hydrogen Compressor that Utilizes all State-of-the-Art AND Commercially Available Components including: High Speed Centrifugal Compressor, Gearbox, Intercooler, Tilt-Pad Bearings, Oil Free Dry Gas Shaft Seal and Controls

**Result of Research Development:** A Pipeline-capacity, Hydrogen Centrifugal Compressor can be made available NOW to meet the Hydrogen Economy needs of the future!
Hydrogen Compressor Phase II Detailed Design Accomplishment:
240,000 kg/day (6.1 Lbm/s); 350 to 1285 psig; 6300 kWe
Compressor Module Design Specifications and Major Components

- Compressor design specifications for near-term gas industry and DOE infrastructure applications
  - $P_{\text{comp.}} = 350 \text{ psig to } 1285 \text{ psig}$; flow rate $= 240,000 \text{ kg/day}$
  - Six-stage, $60,000 \text{ rpm}$, 3.56 pressure ratio compressor
  - 7075-T6 aluminum alloy
  - Nitronic-50 pressure enclosure
  - Integral gearbox pinions driving 6 overhung impellers

- Design of compressor’s major mechanical elements completed and manufacturers selected
  - Artec Machine Systems (Nova Gear, Ltd) gearbox with one-speed step gear operating at acceptable gear tip speeds and loads
  - RMT tilting-pad radial bearing designs confirmed for use
  - Flowserve gas face-seals confirmed to meet necessary specifications for hydrogen applications

- Tranter Plate-type Heat Exchanger design meets specifications to cool hydrogen gas to $105^\circ \text{F}$ between stages using $85^\circ \text{F}$ water

In Summary: All compressor subsystems (from shaft seals to bearings to gearing to aluminum impellers) are available “near-term”.

There is a patent pending regarding the subject matter of this presentation.
Hydrogen Compressor Prototype:
240,000 kg/day (6.1 Lbm/s); 350 to 450 psig; 1,100 kWe
There is a patent pending regarding the subject matter of this presentation.
Focus of Phase II Was Also the Design of a Laboratory Prototype

The 1-Stage Compressor Module is 16 ft long, 8 ft wide, and 9 ft tall. based on the itemized weights shown here:

1. 4160 Vac, 1500 hp Induction Motor (3600 rpm): 7500 Lbf
2. Artec Gearbox (3600 rpm): 4500 Lbf
3. One, Compressor: 2500 Lbf
4. One, Intercooler: 2500 Lbf
5. 6" comp. out. piping (sch. 40, 20ft): 500 Lbf
6. 6" comp. in piping (sch. 40, 30ft): 450 Lbf
7. Fittings: 700 Lbf
8. Purge Tank (12" d. x 6 ft long): 700 Lbf
10. Shut-Off/Recirc. (PRV) valve & Misc 2,500 Lbf

PHASE III- PROTOTYPE SYSTEM COMPONENT PROCUREMENT, BUILD, & TEST:

- COMPLETED – P&I Diagram, Controls Specification, Safety Systems
- COMPLETED – All compressor components
- IN PROGRESS – Assembly of
  - Modified 1-stage Gearbox
  - PLC & Controls
  - Assembly of Prototype (as shown on left)
There is a patent pending regarding the subject matter of this presentation.
Detailed Engineering Design for All Six Compressor Rotors Completed and First Stage Manufactured

Curvic Spline Couples Rotor to Drive Shaft

First Stage of 6-Stage Compressor and Drive Shaft with Pinion and Thrust collar

Overlay of First and Sixth Stages for Size Comparison

There is a patent pending regarding the subject matter of this presentation.
Accomplishment and Progress:
Compressor has been successfully spun to 10% overspeed for 15 minutes (66,000 rpm = 2300 ft/s tip speed)

Spin Test Successful:
1. Fluorescence Penetrate Inspection indicated no micro-stress fractures or strain issues after
2. Structural analysis has also determined that there is not any concern for material creep at operating temperature (145 F) vs. 1,200 F melting temperature and stress
3. The low blade frequency and stress and the operating requirement of 24/7 duty for pipeline compressor applications eliminates any concern of material fatigue

7075-T6 Aluminum (boreless) rotor shown after 5-axis machining; CN and TAMU testing have confirmed compatibility of alum. alloy with hydrogen
Prototype “Lab” Test Site Installation

OUTSIDE BUILDING
Class I, Div. 2 Installation

INSIDE BUILDING

OUTSIDE BUILDING
Class I, Div. 2 Installation

Inside Building

Lube Oil Module

5 hp, 230/460 Vac, 3 Ph

Air Cooled Radiator

5 hp, 230/460 Vac, 3 Ph
for Lube System

Hydrogen Compressor Module

1. Induction Elec. Motor
2. Gear Box
3. Hydrogen Compressor
4. Intercooler
5. Recirc. Valve

1200 kWe; 460 Vac
3 Ph

Hydrogen Bottle Supply

6a, 6b

Nitrogen Bottle Supply

7

A. Lube Oil Control Panel with Disconnect from Concepts NREC
B. Air Fan Motor Starter from Concepts NREC
C. Hydrogen Monitor from Concepts NREC
D. I/O Interconnect panel for connecting PT’s, TT’s and
   Compressor Vib. Monitoring
E. Data Acquisition (combined with PLC?)
F. PLC
G. Motor Disconnect and Soft Start
H.1,2,3 Electrical Conduit for controls and power wiring

There is a patent pending regarding the subject matter of this presentation.
Lab Prototype P&I Diagram

There is a patent pending regarding the subject matter of this presentation.
Project Advisors & Collaborators:
Strengths & Responsibilities of Partners

- **Air Products and Chemicals, Inc.**
  - Provides industrial gas user technical experience and gas industry specification data on major components: electric motor, hydrogen safety system, intercooler design, selection of materials of construction

- **Texas A&M University**
  - Provided 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
Future Phase III Project Work in Progress

Phase III System Validation Testing

- Continue component procurement for the Lab Prototype, Single-stage hydrogen compressor system (Scheduled completion: April 2014)
- Assembly of the one-stage centrifugal compressor and closed-loop, lab prototype as a completely functioning compressor system (Scheduled Completion: May 2014)
- Install lab prototype system and conduct aerodynamic testing and assessment of mechanical integrity of the compressor system (Scheduled Completion: July 2014)
Project Summary

Relevance: An advanced pipeline compressor system has been designed that meets DOE’s performance goals for:
- High reliability with 350 to 1200+ psig compression of 240,000 kg/day at 98% hydrogen efficiency
- footprint 1/4 to 1/3 the size of existing industrial systems at projected cost of less than 80% of DOE’s target

Approach: Utilize state-of-the-art and acceptable engineering practices to reduce developmental risk and provide a near-term solution for the design of a viable hydrogen pipeline compressor:
- Aerodynamic/structural analyses for acceptable stresses in materials (7075-T6 Rotor, Nitride 31 Chrome Moly Shaft, & Nitronic-50 enclosure) compatible with hydrogen
- Industrially proven bearings, seal technology, gearing, heat exchangers, and lube system

Tech. Accomplishments & Progress: Aerodynamic analysis and design of a cost-effective, six-stage centrifugal compressor and a one-stage full-power lab prototype have been completed; spin test of aluminum stage verifies its mechanical integrity, all commercially available compressor subsystems purchased. Research has demonstrated that a Hydrogen Pipeline Centrifugal Compressor is available NOW to meet the Hydrogen Economy requirements of the future!

Technology Transfer/Collaboration: The collaborative team consisted of Air Products, an industrial technical experienced user of hydrogen compressors; a materials researcher, Texas A&M; a hydrogen refueling industry consultant, HyGen; and the coordinated technical support of several National Labs and major component manufacturers.

Proposed Future Research: The laboratory testing of a closed-loop, one-stage prototype hydrogen compressor system.

There is a patent pending regarding the subject matter of this presentation.
The following slides are included here to provide additional support during the question and answer period.
Design Experience Associating Material Properties with Tip Speed of 2200 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)

Figure 4. Theoretical Tip-Speed for Turbomachinery Open Impeller

\[ \text{Umax} = V(\sigma_{\text{ultimate}} \times \text{Life Factor}) / (\rho \times \text{form factor}) \]
Recirc. Control Valve Model Algorithm for Laboratory Prototype

Compressor Surge Analysis with RECURC.MODEL

Representing Suction piping

\[ \text{Pr}_{\text{design}} = 1.255 \text{ psia} \]

Design Point Flowrate, Lbm/s = 6.1

Representing discharge piping and intercooler

\[ \text{CV} = \text{Dischg. Temp.} = \text{Comp. Inlet Temp.} \]

Patm =

\[ \text{Cv} = \text{Piping} \]

Transient Stability Analysis of Recirculation Valve used with 1-Stage Hydrogen Compressor Prototype with \( \text{Cv} = 8.4 \text{ cft/(s-vpsia)} \)

1-Stage, Hydrogen Compressor Performance Map with Recirc. Valve Modeled for Stability (Cv = 8.5 cft/s/vpsid)

There is a patent pending regarding the subject matter of this presentation.
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=42cf/s/Vpstd)

- Pressure ratio & flow rate path of compressor as it almost exceeds surge control with valve Cv=42
FEA by Concepts NREC Confirms Acceptable Rotor Stress Levels at 2100 ft/sec and Rotor Stability at 60,000 rpm

There is a patent pending regarding the subject matter of this presentation.
In Response to Reviewer Ques. #1: Small Punch Test Apparatus by TAMU to Determine Effects of Hydrogen Exposure

The TAMU testing may have limited use with regards determining absolute yield stress but it has provided convincing evidence that the 7075-T6 aluminum is not affected by its long term exposure to a high pres. and high temp. hydrogen environment and that a more common material such as titanium does have compatibility issues. The inexpensive testing protocol also initiates another documented means of comparing materials, if only on a relative basis.

Specially machined fixture for small hole punch testing of metal specimens for project tests at speeds of 0.0021 mm/s

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

Sources:


There is a patent pending regarding the subject matter of this presentation.

Summary Details of Small Punch Test by TAMU

Actual Test Result with Ti Grade 5 showing degradation of strength in hydrogen over time

Force vs. Extension curve showing how the mechanical strength of the Ti-6Al-4V specimens changes over time at room temp. after charging BUT Aluminum specimens are not affected.

Home-made H charge system, soaking samples in a H₂ containing reservoir.
CONCLUSION FROM TESTING:

1. Small Punch Test Methodology can discern relative strength of a materials resistance to hydrogen embrittlement
2. Results without coating now can serve as a baseline for testing (in progress) specimens with coatings
There is a patent pending regarding the subject matter of this presentation.

### Compressor Capital and O&M Costs as Determined from DOE’s HDSAM v.2 Economics Model

#### Hydrogen Piston Cost ($) and Operation & Maintenance ($/kWhr) Using DOE’s HDSAM v.2 Economics

<table>
<thead>
<tr>
<th>No. of Piston Stages</th>
<th>4</th>
<th>3% % Maintenance</th>
<th>2 Multiple of Capital Equip. Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>kWe rating</td>
<td>6,226</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kg/day Hydrogen Flowrate</td>
<td>240,000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| $ compressor= | $ 6,278,724 |
| $, installation= | $ 12,557,447 |
| $, maintenance/yr= | $ 376,723 |
| kW-hr= | 53,978,993 |
| O&M Cost [$/KwHr]= | 0.0070 |

#### Hydrogen Piston Cost ($) and Operation & Maintenance ($/kWhr)

<table>
<thead>
<tr>
<th>No. of Piston Stages</th>
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<tr>
<td>Kg/day Hydrogen Flowrate</td>
<td>240,000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| $ compressor= | $ 4,709,043 |
| $, installation= | $ 9,418,085 |
| $, maintenance/yr= | $ 282,543 |
| kW-hr= | 53,978,993 |
| O&M Cost [$/KwHr]= | 0.0052 |

The two case Studies shown here have been determined from DOE’s HDSAM v.2 Economics model and indicate the cost for a 2 and 4 cylinder Reciprocating compressor. The next slide also provides an independent verification for the cost of commercially available compressors and indicates that the centrifugal hydrogen pipeline compressor that is being developed for DOE is very competitive with the limited systems that are commercially available.
TASK 4: INITIAL DESIGN AND COST ANALYSIS
The manufacturing, operating and maintenance costs for various design approaches and operating conditions will be completed to understand the cost impact and levels of risk in meeting the stated performance goals. Generalized equipment costs and scaling factors will be used to assess the costs for various size systems. A cost-benefit-risk analysis assessment of alternative designs will be prepared.

HyGen S.O.W.: Analyze and investigate the installation, deployment, project development costs, etc., current systems costs – comparison.

“…we have found that there is a clear niche Concepts can exploit. For the technical parameters provided by Concepts, (listed above), there is no significant competition. So far, after contacting more than 30 manufacturers, we have only had 4 responses that would even consider bidding on a competing system. Only one had a single system that could meet the production capacity of 240,000 kg/day, they bid $7.4 million. All others had to combine 2 systems to meet the production demand requested. Those two responders bid $2.5 million for a single system x 2 for a price of $5 million to meet the technical parameters and requirements outlined by CN. The most competitive system was a double system for $2.8 million total. The rest would not attempt to submit because it was outside their technical capabilities. This includes the one other Centrifugal Hydrogen Compressor Manufacturer who stated, “It would take 65 stages to meet 1200 psi”. There appears to be several centrifugal air compressor manufacturers, but only 2 (that we found and submitted to) hydrogen compressor manufacturers that makes a centrifugal hydrogen compressor that performs even close to what Concepts is proposing to produce. The other failed to respond at all.”
An Internal Technical Report was prepared that provided the derivation of an algorithm that is intended to determine the relative Reliability and O&M Cost between a reciprocating compressor and a centrifugal compressor. Two excerpts from this document entitled: “Reliability and Maintenance Cost Algorithms for Piston and Centrifugal Compressor Systems” Prepared by: Frank Di Bella, PE (June 15, 2009) (Internal Tech. Report) is offered as a response to the Reviewers question. The Executive Summary is offered on this slide and a second excerpt (next slide) as well as .ppt slides depicting data from the report are offered on the next 4 slides.

Executive Summary

The determination of the reliability (R) of the centrifugal compressor-based hydrogen pipeline compressor system and the cost to maintain the system ($/kwhr) has been estimated for a hydrogen centrifugal compressor project. The algorithms that are presented in this report can be used to provide a determination of an absolute cost using known reliability data for the individual elements that constitute the complete compressor system. If accurate reliability data for each component is not available or not current, the algorithms can still, as a minimum, provide an accurate comparison of the relative reliabilities and maintenance costs between a piston and a centrifugal compressor. That is, if the reliability of a commercially available compressor is accepted via experience to be “x”, then the methodologies presented in this report will enable the ratio of the reliabilities for the piston and the centrifugal compressors (i.e., ratio = x/y) to be determined. While it may not be appropriate to then determine “y” from the equation, it may be sufficient to know only that the ratio x/y is less than or greater than 1; that the cost or reliability of the piston-type compressor is more or less than the centrifugal-type compressor. It is also useful to be able to determine the effect that changes in the number of components may have on the overall reliability of the compressor. For example, changing from six stages to five stages, or using two bearings per rotor and not one per rotor, will increase the reliability and thus may be of value to the design. The methodology used in the Reliability Model can provide a numerical value to this change that hopefully indicates a proportional improvement in reliability with the value of the cost incurred.

The following report provides a summary of the methodology used to enable a comparison of the reliability and maintenance costs for a piston and a centrifugal compressor. However, the examples of the use of the algorithms are provided only to provide an example of the calculations that have been prepared. Values for the reliabilities of the individual components must continue to be updated based on the most current manufacturer’s data.
Excerpt from Reliability Analysis prepared by F. DiBella

"…Assuming commercially available compressor systems have a reliability of 86.2%, then the calculation of the reliability for a compressor that is composed of the major components as itemized in Figures 1 a&b and using the equations shown above must result in a net reliability of 86.2%. The scaling factor (θ) must first be determined to "fit" this result. The scaling factor that has been calculated for this illustrative Case Study example is 50. The scaling factor is calculated by summing all of the individual hazard rates given in Figures 1a for the piston-type compressor. The result is \(281 \times 10^{-6}\) which results in a MTTF = \(1 \times 10^6/281 = 3553\) hours. However, the MTTF for a system with a reliability of 0.862 is only 528 hrs. Thus a scale factor is calculated to be: 3 years x 8760hrs/year /528= 49.8 . That this scale factor "fits" the assumed reliability value with the reliability that can be calculated from the individual hazard rates can be confirmed by applying the reliability equation (EQN. 3) using the net hazard rate (\(\lambda\)) of \(281 \times 10^{-6}\) for a 3 year MTTF or:

\[ R(t)= \exp\left(-\frac{281 \times 10^{-6}}{49.8 \times 8760 \text{ hrs/yr x 3 yrs}}\right); \quad \text{then: } R= 0.862 \quad \text{---which checks---} \]

By using the same scaling factor with the given values of the hazard rates for the individual components that constitute a centrifugal-type compressor, a comparative reliability can be fairly determined.

Reliability Engineering Analysis equations such as those given above are very much based on probability distribution functions. For any stochastic-dependent analysis, the lack of accurate data, presumably best determined from actual tests, will skew the analysis and render the results of such an analysis almost meaningless. The values of the MTTF or \(\lambda\) are very much dependent on tests performed (typically) by the manufacturer of the components or system of components. To somewhat reduce the uncertainty associated with the use of the reliability data obtained from the B.S. Dhillon reference, it was decided to provide only a comparison of the reliabilities of a conventional piston-based process gas compressor with the advanced, hydrogen centrifugal compressor. The analysis is considered to provide a fair comparison of the two different types of compressors by using the same MTTF (or \(\lambda=1/\text{MTTF}\)) metrics for the compressor components whose engineering function is shared by each compressor. For example, bearings, shaft seals or packing, intercoolers, etc., used in the piston or the centrifugal compressor, are given the same values of MTTF as can be seen in Figures 1 a&b. It is also possible to add a "risk factor" that is associated with one or more of the individual components. The risk factor is a value greater than 1 that attempts to account for any additional risk associated with the individual component as might be affected by its use in the hydrogen centrifugal compressor application. For the Case Study given in the Attachments 1 and 2, the risk factors were assumed to be 1, i.e., no additional risk factor was assumed for the components using hydrogen.

The very preliminary results highlighted in Attachments 1 and 2 would seem to indicate that the reliability of the centrifugal compressor is at least comparable to a piston compressor. It is interesting to note that reducing the number of stages from six to five, improves the reliability by 3%.

It must be noted again that all such conclusions are very much dependent upon the values for the individual components and the 3% improvement stated above is likely to be well within the range of uncertainty for each of the individual components. More definitive results of numerical comparisons of the reliability must wait for more accurate values for the individual hazard rates (\(\lambda\)). These values must be provided by the manufacturers with some adjustment for the way that \(CN\) uses the component in the final hydrogen compressor design and then the values must still be confirmed by our prototype and field testing of the complete system. However, the development of the methodology for comparing a piston and centrifugal compressor is substantially complete and remains the major product of the research conducted to date.
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).
Example of Relative Comparison of Centrifugal vs. Piston Compressor Reliability

Hazard failure Rates (\( \lambda \times 10^6 \)): (ref.: Tables 9.2, 9.3, 9.4, 9.5 in B.S. Dhillon's text)

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Rate (( \lambda \times 10^6 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Gearbox</td>
<td>3.295</td>
</tr>
<tr>
<td>B</td>
<td>Gears</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>spare</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Dynamic Seal</td>
<td>3.295</td>
</tr>
<tr>
<td>E</td>
<td>spare</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Sleeve bearing</td>
<td>4.94</td>
</tr>
<tr>
<td>G</td>
<td>Heat Exchangers</td>
<td>6.11</td>
</tr>
<tr>
<td>H</td>
<td>Generic Compressor</td>
<td>200</td>
</tr>
<tr>
<td>I</td>
<td>Highly Stressed Shaft</td>
<td>0.2</td>
</tr>
<tr>
<td>J</td>
<td>Pinion Gear</td>
<td>5</td>
</tr>
<tr>
<td>K</td>
<td>spare</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>spare</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>spare</td>
<td></td>
</tr>
</tbody>
</table>

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

Individual Reliabilities (R):  
\[
\begin{array}{ccc}
A & Gearbox & 0.990 \\
B & Gears & 0.997 \\
C & spare & 1.000 \\
D & Dynamic Seal & 0.998 \\
E & spare & 1.000 \\
F & Sleeve bearing & 0.997 \\
G & Heat Exchangers & 0.997 \\
H & Generic Compressor & 0.900 \\
I & Highly Stressed Shaft & 1.000 \\
J & Pinion Gear & 0.997 \\
K & spare & 1.000 \\
L & spare & 1.000 \\
M & spare & 1.000 \\
\end{array}
\]

Increased Risk Multiplier Factor:

- Gearbox: 1
- Gears: 1
- Dynamic Seal: 1
- Sleeve bearing: 1
- Heat Exchangers: 1
- Generic Compressor: 1
- Highly Stressed Shaft: 1
- Pinion Gear: 1
- Spare: 1

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

There is a patent pending regarding the subject matter of this presentation.
There is a patent pending regarding the subject matter of this presentation.

## 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>$/Component</th>
<th>Dt x fn</th>
<th>$/Comp Repair</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Piston-type Compressor</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-Step down Gearbox</td>
<td>8</td>
<td>0.16</td>
<td>15000</td>
<td>640</td>
<td>12979</td>
</tr>
<tr>
<td>Crankshaft Roller Bearing</td>
<td>6</td>
<td>0.06</td>
<td>7500</td>
<td>480</td>
<td>3263</td>
</tr>
<tr>
<td>Crankshaft</td>
<td>6</td>
<td>0.29</td>
<td>12000</td>
<td>480</td>
<td>17498</td>
</tr>
<tr>
<td>Pressure Packing</td>
<td>3.5</td>
<td>0.11</td>
<td>8000</td>
<td>280</td>
<td>3784</td>
</tr>
<tr>
<td>Connecting rod sleeve bearing</td>
<td>6</td>
<td>0.17</td>
<td>7500</td>
<td>480</td>
<td>9607</td>
</tr>
<tr>
<td>Heat Exchangers</td>
<td>3</td>
<td>0.16</td>
<td>12500</td>
<td>240</td>
<td>5861</td>
</tr>
<tr>
<td>Pres. Lube. Crosshead @MTTF=</td>
<td>4</td>
<td>1.33</td>
<td>10000</td>
<td>320</td>
<td>56000</td>
</tr>
<tr>
<td>Pinion Gear</td>
<td>4.5</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>Piston</td>
<td>5.5</td>
<td>0.04</td>
<td>7500</td>
<td>440</td>
<td>1805</td>
</tr>
<tr>
<td>Piston Valves</td>
<td>5</td>
<td>0.14</td>
<td>5000</td>
<td>400</td>
<td>6307</td>
</tr>
<tr>
<td>Cylinders</td>
<td>5.5</td>
<td>0.004</td>
<td>8000</td>
<td>440</td>
<td>182</td>
</tr>
<tr>
<td><strong>Routine Maintenance</strong></td>
<td>1</td>
<td>1</td>
<td>20000</td>
<td>80</td>
<td>28000</td>
</tr>
</tbody>
</table>

### Centrifugal Compressor Maintenance Cost Analysis

<table>
<thead>
<tr>
<th>Component</th>
<th>fn</th>
<th>Nfail/s/yr</th>
<th>$/Component</th>
<th>Dt x fn</th>
<th>$/Comp Repair</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gearbox</td>
<td>10</td>
<td>0.16</td>
<td>25000</td>
<td>800</td>
<td>17251</td>
</tr>
<tr>
<td>Gears</td>
<td>8</td>
<td>0.09</td>
<td>7500</td>
<td>640</td>
<td>6263</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>Pinion Gear</td>
<td>4.5</td>
<td>0.26</td>
<td>7500</td>
<td>360</td>
<td>11432</td>
</tr>
<tr>
<td>Pres. Lube. Crosshead @MTTF=</td>
<td>4</td>
<td>1.33</td>
<td>10000</td>
<td>240</td>
<td>357</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>Routine Maintenance</td>
<td>1</td>
<td>1</td>
<td>20000</td>
<td>80</td>
<td>28000</td>
</tr>
</tbody>
</table>

\[
\text{Availability} = 0.51
\]

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

\[
\text{\$maintenance/kWhr} = 0.00696
\]

\[
\text{Availability} = 0.51
\]

There is a patent pending regarding the subject matter of this presentation.
General Piping and Instrumentation Flow Diagram for Hydrogen Compressor System

There is a patent pending regarding the subject matter of this presentation.
### Operating Conditions Applied for Stage Six

#### Material properties: Nitronic 50 (Volute Casing and Backplate)
- Elastic Modulus = 2.8 E7 PSI
- Poisson’s Ratio = 0.30
- Density = 0.285 lb/in³
- Yield Strength (Fty) = 57 KSI
- Operating Pressure = 1280 PSI
- HydroTest Pressure = 1920 PSI

#### Material properties: Aluminum 7075 (Volute)
- Elastic Modulus = 1.03 E7 PSI
- Poisson’s Ratio = 0.33
- Density = 0.1000 lb/in³
- Yield Strength (Fty) = 66.5 KSI

#### Geometry:
- Volute Assembly = from Pro/ENGINEER®
Publications and Presentations

- Presentations have only been made to DOE’s Hydrogen Pipeline Delivery Technical Committee in August 2010 and December 2010 and to DOE Program Managers (Mr. Paul Bakke, Dr. Monterey Gardiner, Dr. Scott Weil, and Ms. S. Dillich) during several site visits by Concepts NREC. Abstract has been accepted for technical paper to the 2012 ASME International Congress & Exhibition (Houston, TX).
  - ASME Technical Paper for 2012 International Mechanical Engineering Congress & Exposition

- Patents Pending (filed March, 2010) on system design and individual components
A Detailed Mass Model Was Created for Compressor Rotor-Drive Shaft Rotordynamics That Included Cross-Coupling Aero Effects

There is a patent pending regarding the subject matter of this presentation.