III.5 Development of a Centrifugal Hydrogen Pipeline Gas Compressor

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Subcontractors:
- Praxair Corporation, Tonawanda, NY
- Texas A&M University, College Station, TX
- HyGen Industries, Eureka, CA

Project Start Date: June 1, 2008
Project End Date: July 30, 2011

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 (for a compressor package of $5.4M for 200,000 kg/day (note: $6.2M for a 240,000 kg/day) system by Fiscal Year 2017:

- Reduce package footprint and improve packaging design.

Achieve transport delivery costs below $1/gasoline gallon equivalent (gge):

- Reduce maintenance cost to below 3% of total installed cost by FY 2017.
- Increase system reliability thus avoiding purchase of redundant systems.
- Maintain hydrogen efficiency (as defined by DOE) to 98% or greater.
- Reduce H_2 leakage to less than 0.5% by FY 2017.

Technical Barriers

This project addresses the following technical barriers from the Delivery section of the **"Hydrogen, Fuel Cells, and Infrastructure Technologies Program Multi-Year Research, Development, and Demonstration Plan"** [1]:

(B) Reliability and Costs of Hydrogen Compression

Technical Targets

The project has met the DOE Targets as presented in DOE's **"2007 Technical Plan for Hydrogen Delivery"** Projects (Table 1).

TABLE 1. Progress Towards Meeting Technical Targets for Delivery of Hydrogen via Centrifugal Pipeline Compression

Characteristic	Units	DOE Target	Project Accomplishment
Hydrogen Efficiency (f)	[btu/btu]	98%	98%
Hyd. Capacity (g)	kg/day	100,000 to 1,000,000	240,000
Hyd. Leakage (d)	%	<0.5	0.2 (goal)
Hyd. Purity (h)	%	99.99	99.99
Discharge Pressure (g)	psig	>1,000	1,200
Comp. Package Cost (g)	$	6.2	4.5
Main. Cost (Table 3.2.2)	$/kWhr	0.007	0.005 (goal)
Package Size (g)	sq. ft.	300 to 350	175 to 200
Reliability (e)	# Sys.s Req.d	I redundant sys. Reduced from 2	Modular sys.s with 240K kg/day with no redundancy req.d

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

Accomplishments

Developed computer models to aid in analysis of hydrogen compressor:

- Performance and Equipment Cost Model
  - Suitable as a macro for DOE "HDSAM v2.0" economics model.
  - Identifies hydrogen compressor package performance and component cost. 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.

- System Reliability and Maintenance Cost Model
  - Estimates comparative reliabilities for piston and centrifugal compressors for pipeline compressors developed.
    - Failure Mode Effects Analysis (FMEA) for component risk and reliability assessment.
  - Estimates operation and maintenance costs for compressor system.

Preliminary design details of pipeline compressor module completed including:

- Compressor design conditions confirmed by project collaborators.
  - P_{inlet}= 350 psig, P_{outlet}=1,200 psig; flow rate = 240,000 kg/day
- Six-stage, 60,000 revolutions per minute (rpm), 3.33 pressure ratio compressor.
- Integral gearbox pinions driving individual, overhung impellers.
- Design of compressor's major mechanical elements completed and satisfied by two manufacturers per component:
  - Tilting pad radial and thrust bearings designs validated for use.
  - Two commercially available gas face-seals have been validated for use.
- 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).

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Introduction

The DOE has prepared a Multi-Year Research, Development, and Demonstration Plan to provide hydrogen as a viable fuel for transportation after 2020, in order to reduce the consumption of limited fossil fuels in the transportation industry. Hydrogen fuel can be derived from a variety of renewable energy sources and has a very high energy content per kg, equivalent to the energy content in a gallon of gasoline. The switch to hydrogen-based fuel requires the development of an infrastructure to produce, deliver, store, and refuel vehicles. The least expensive delivery option for hydrogen involves the pipeline transport of the hydrogen from the production sites to the population centers where the vehicles will see the highest demand, and thus, have the greatest impact on reducing the U.S. dependency on fossil fuel. The cost to deliver the hydrogen resource to the refueling stations will add to the ultimate cost per kg or per gallon equivalent that needs to be charged for the hydrogen fuel. Therefore, it is necessary that the cost to deliver the hydrogen be kept as low as possible, which implies that the cost of the compressor stations, their installation costs, and their efficiency in pumping the hydrogen fuel to the refueling stations must be kept low. DOE has set a target of $1/gge.

The delivery cost target can be met if the compressor system can be made more reliable (to reduce maintenance costs), more efficient (to reduce operation costs), and be a smaller, more complete, modular package (to reduce the compressor system equipment, shipment, and its installation costs).

Approach

The technical approach used by Concepts NREC to accomplish these goals is to utilize state-of-the-art aerodynamic/structural analyses to develop a high-performance centrifugal compressor system for pipeline service. The centrifugal-type compressor is able to provide high pressure ratios under acceptable material stresses for relatively high capacities -- flow rates that are higher than what a piston compressor can provide. Concepts NREC's technical approach also includes the decision to utilize commercially available, and thus, proven bearings and seal technology to reduce developmental risk and increase system reliability at a competitive cost. Using its expertise in turbomachinery analysis, design, machining, and testing, Concepts NREC is researching the use of a material that is compatible with hydrogen and that can enable the highest possible impeller tip speeds, reducing the number of required stages while meeting DOE's goals for overall pressure ratio and efficiency. In order to minimize the development time and ensure industrial acceptance of the design for the new pipeline compressor system, Concepts NREC has assembled a project team that will assist in the advanced engineering of the compressor while also preparing an implementation plan that can provide for near-term industrial pipeline applications.

The engineering challenge to implement this technical approach is to design a compressor stage that can achieve the highest acceptable pressure ratio and thermodynamic efficiency per stage, while also using as few stages as possible and employing the smallest diameter impeller. For centrifugal-type compressors, the pressure ratio is proportional to the square of the rotor speed, rpm^2, and the $radius^2$. Thus, even a small increase in tip speed or impeller radius results in significant increases in pressure. The aerodynamic design challenge in reducing the number of stages is to maximize tip speed of the centrifugal compressor impeller while staying within acceptable design safety levels of the strength limitations of the material in addition to utilizing advanced diffuser systems to maximize recovery of dynamic head into static pressure. However, material stresses also increase proportionally to the square of the rotor speed (rpm^2) and radius ($radius^2$), and also by material density. Ultimately, the major constraint is imposed by the limitations of the maximum stress capability of impeller material. This constraint is further aggravated by the need for the material selection to consider the effects of hydrogen embrittlement on the strength of the material.

These engineering challenges are best summarized by their inter-dependencies, as illustrated in Figure 1. As may be observed from Figure 1, high impeller tip speeds will enable high pressure ratios to be attained with fewer stages. Thus, a major challenge for the project was to identify the material that can enable the highest tip speeds to be attained while also sustaining the stresses that are imposed by these tip speeds.

The need for high operating tip speeds is also constrained by the desire to have a small radius impeller, resulting in the adoption of a relatively high operating speed. The need to operate at high speed requires careful consideration of the rotor dynamics of the compressor and high-speed assembly, and the design of an adequate, high-speed ratio gearbox. All of these critical engineering constraints need to be satisfied by employing commercially available components that are operated within the manufacturer's design guidelines for state-of-the-art materials, loads, stresses, operating speeds, and power ratings.

Concepts NREC has met all of these engineering challenges in order to provide a pipeline compressor system that meets DOE's specifications for near-term deployment.

Results

In order to achieve a packaged pipeline centrifugal compressor-based design that complies with the major engineering constraints imposed by state-of-the art materials and commercially available components, and that satisfies all of the DOE requirements, Concepts NREC has developed several computer design models that would optimize the design choice. These models include:

1. Compressor Package Performance Model that 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 and component efficiencies.
   - Compressor shaft diameter sizing based on fatigue loading.
   - Calculation of impeller radial and axial loadings.

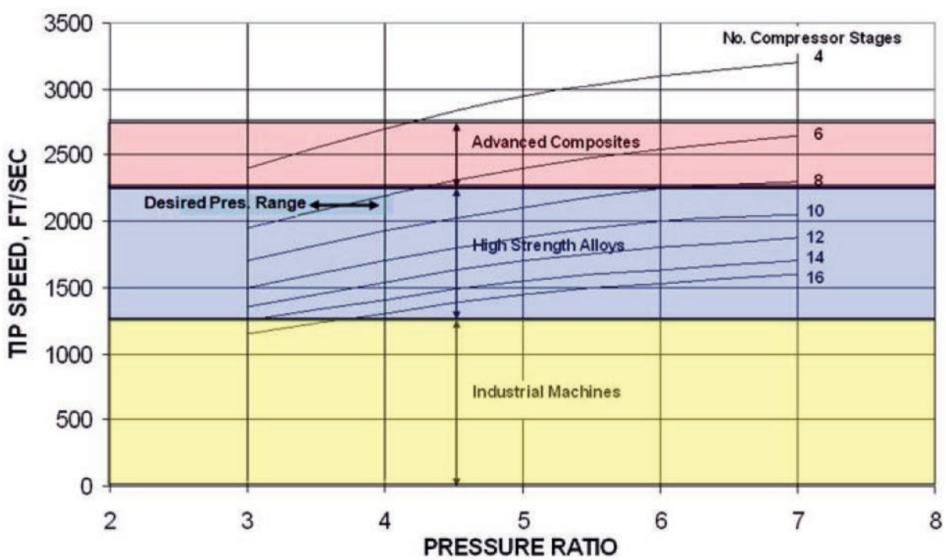

FIGURE 1. Engineering Analysis Illustrating Design Dependencies and Constraints

2. Cost Model using algorithms to determine the relative component cost and operational risks associated with compressor design specifications such as:
   - Number of compressor stages, single or back-to-back.
   - Number of volute housings (one 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.
3. 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 that:
   - Uses either manufacturers' reliability of individual components or sub-systems that constitute a compressor system (preferred), or textbook values.
   - Uses Federal Energy Regulatory Comission operation and maintenance database as the basis for determining the maintenance costs for a centrifugal compressor.
   - Uses FMEA as developed by Concepts NREC for this project

The Cost and Performance Model enabled the analysis of over 30 combinations of centrifugal compressor impeller speeds, the number of stages, with a single or dual impeller-shaft design using a one or two-step gearbox, with a high or low-speed prime mover drive arrangement. A summary of the options considered is shown in Figure 2. The best choice with respect to conformity to commercially available system specifications and high efficiency and low operational risk is highlighted. This choice is a single, overhung (cantilevered) impeller attached to a drive shaft that includes a shaft seal, bearing, and drive pinion. The impeller rotor is designed without a bored-hub in order to reduce the hub "hoop" stresses. This requires the impeller to be mechanically attached to the high strength steel alloy, a drive shaft with a patented design attachment system that enables the rotor to be removed from the gearbox without removing the drive shaft, and thus, not disturbing the shaft seal and bearings.

The compressor selection uses six stages, each operating at 60,000 rpm with a tip speed of less than 2,100 ft/s. Each compressor, shown in Figure 3, is 8 inches in diameter and has an overall stage efficiency of between 79.5 and 80.5%, for an overall compressor efficiency of 80.3%. A gas face-seal will provide the isolation of the hydrogen from the lubricating oil. The 1,400 hp per stage can be sustained by using two, tilting pad hydrodynamic bearings on either side of a 2.5 inch-long drive-pinion gear. The face seal and bearings are commercially available from Flowserve or Eagle-Burgmann and KMC or Waukesha, respectively. The pinion is part of a custom gearbox manufactured by Cotta Transmission Company and utilizes commercially available gear materials that are subjected to stresses and pitch line speeds that meet acceptable engineering practice.

The material chosen for the compressor is an aluminum alloy. The choice is based on its mechanical strength-to-density ratio or (S_{yield}/ρ) which can be shown to be a characteristic of the material's ability to withstand centrifugal forces. Several grades of

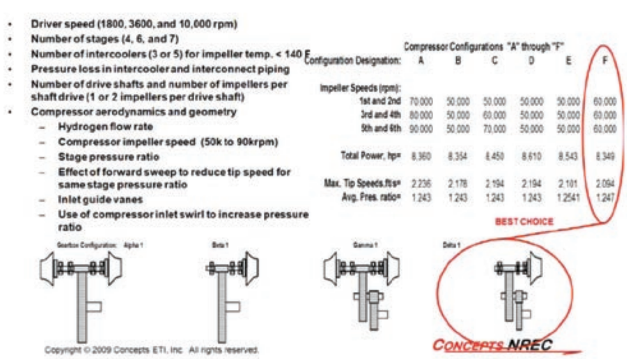

FIGURE 2. A Summary of the Design Selection Process for Choosing an Optimum Arrangement for the Compressor and the Gearbox

FIGURE 3. Bore-Less Centrifugal Compressor

aluminum have a strength-to-density ratio that is similar to titanium and high strength steels at the 140°F (max) operating temperature that will be experienced by the hydrogen compressor, as may be observed in Figure 4. However, unlike titanium and most steels, aluminum is recognized by the industry as being very compatible with hydrogen, not showing any susceptibility for hydrogen embrittlement.

Aluminum also helps to reduce the weight of the rotor, which leads to an improved rotor dynamic stability at the 60,000 operating speed. A rotor stability and critical speed analysis has confirmed that the overhung design is viable.

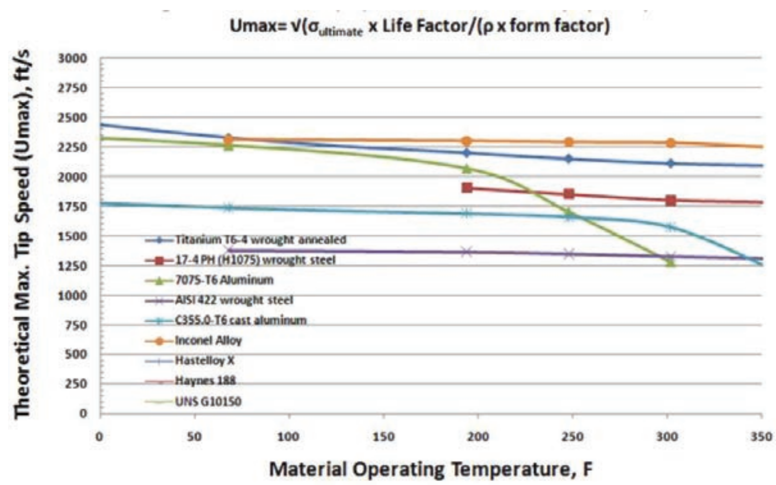

FIGURE 4. Theoretical Tip Speed for Turbomachinery with Open Impeller

The project team includes researchers at Texas A&M (Dr. Hong Liang) who are collaborating with Concepts NREC to confirm the viability of aluminum alloys for this compressor application. A test protocol has been established based on a series of discussions with notable researchers in several national laboratories including:

1. Sandia National Laboratories (fracture mechanics testing; Dr. Chris San Marchi).
2. Savannah River National Laboratory (specimen "charging" with hydrogen plus tensile testing with H_2; Dr. Andrew Duncan).
3. Argonne National Laboratory (Dr. George Fenske).

The test protocol includes the baseline testing of titanium alloy in order to later test the viability of surface coatings that may prohibit hydrogen embrittlement and thus allow the use of titanium. The testing is in progress as of the writing of this annual report.

The maximum hydrogen compression temperature is maintained at 140°F by providing intercoolers between each of the six stages. The intercoolers have an effectiveness of 63% and cool the hydrogen to 100°F at the inlet to each stage, thus maintaining the necessary high strength-to-density ratio required for the aluminum rotor.

The complete hydrogen pipeline compressor package that integrates all of these major components is shown in Figure 5. The complete modular package, as shown, is 26 ft long x 10 ft tall x 6 ft wide (at the base) x 8 ft wide at the control panel, approximately one-half of the footprint of a piston-type, hydrogen compressor. The packaged module can be transported to the installation site as a pre-assembled package with a minimum of final alignment, water piping and electrical power connections, and instrumentation and controls start-up.

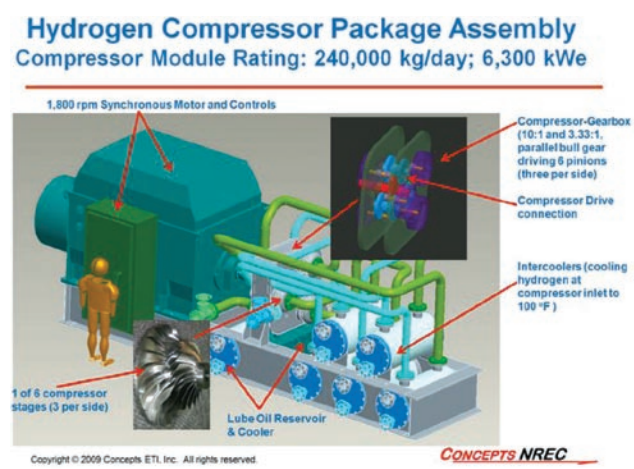

FIGURE 5. Hydrogen Compressor Packaged Assembly

Conclusions and Future Directions

The preliminary engineering and design of an advanced pipeline compressor system has been completed that meets DOE's performance goals for a reliable 98% hydrogen efficiency compressor system with a footprint one-half the size of existing industrial systems and at a projected system cost of approximately 70 to 75% of DOE's target, and a maintenance cost that is less than the $0.01/kWh. The advanced centrifugal compressor-based system can provide 240,000 kg/day hydrogen from 350 to 1,200 psig high for pipeline-grade service. This has been accomplished by utilizing a state-of-the-art aerodynamic and structural analysis of the centrifugal compressor impeller to provide high pressure ratios under acceptable material stresses. The technical approach that has been successfully implemented includes using commercially available, and thus proven, bearings and shaft seal technology. This technical approach reduces the developmental risk and increases system reliability while maintaining a competitive cost.

The resultant design provides a compressor that not only meets DOE's Hydrogen Plan for future (but near-term) pipeline delivery, but also a compressor package that can be used by the industrial, hydrogen gas industry where there is presently 1,200 miles of pipeline providing 9 million tons per year of hydrogen gas for industrial process chemical applications. The collaborative team that has been assembled consists of an industrial user, Praxair (who has engineering experience in pipeline compressors), a materials researcher (Texas A&M), and a hydrogen refueling industry consultant (HyGen Industries) who are all committed to producing the first commercially reliable hydrogen compressor for hydrogen pipeline delivery.

Future efforts include:

Complete Current Phase 1 Effort

- Continue to update compressor station Performance and Cost Module:
  - Including reliability of individual compressor components and the maintenance costs ($\$_{O\&M}$/kg/day) for centrifugal compressors working with hydrogen.
  - Programming a more "user-friendly" version of the Performance and Cost Model that could be used as a spreadsheet Macro to DOE's HDSAM v.2 Economics Model.
- 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 (August 2009 to April 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.

Special Recognitions & Awards/Patents Issued

1. Provisional patent application filed on several innovations to centrifugal compressor design.

References

1. DOE Multi-Year Research, Development, and Demonstration Plan.

2. "Evaluation and Application of Data Sources for Assessing Operating Costs for Mechanical Drive Gas Turbines in Pipeline Service", Dr. Anthony Smalley *et al*., Transactions of ASME Vol. 122, July 2000.

3. "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, Oct., 2000).