III.10 Development of a Centrifugal Hydrogen Pipeline Gas Compressor

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Subcontractors:

- Texas A&M University, College Station, TX
- HyGen Industries, Eureka, CA

Project Start Date: June 1, 2008
Project End Date: December 2013

Overall Project 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% pure hydrogen gas from generation site(s) to forecourt stations at a compression ratio of 2.8 or greater. Reduce initial installed system equipment cost to less than $9 M (compressor package of $5.4 M) for 240,000 kg/day system.
- Reduce package footprint and improve packaging design.
- Reduce maintenance cost to below 3% of total capital investment. Increase system reliability to avoid purchasing redundant systems.

Fiscal Year (FY) 2013 Objectives

- Procure compressor components for one-stage prototype compressor
- Design control system and procure programmable logic controller and program
- Assemble prototype components
- Prepare test plan for prototype testing

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Delivery (section 3.2) of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan [1]:

(B) Reliability and Costs of Gaseous Hydrogen Compression

Technical Targets

The project has met the following targets as presented in DOE's 2007 Technical Plan for Hydrogen Delivery Projects [1] (Table 1).

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. The testing of the prototype hydrogen compressor system will quantify these design objectives.

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

Characteristic	Units	DOE Target	Project Accomplishment	STATUS
Hydrogen Efficiency (f)	[btu/btu]	98%	98%	Objective Met
Hydrogen Capacity (g)	kg/day	100,000 to 1,000,000	240,000	Objective Met
Hydrogen Leakage (d)	%	< .5	0.2 (per Flowserve Shaft Seal Spec)	Objective Met
Hydrogen Purity (h)	%	99.99	99.99 (per Flowserve Shaft Seal Spec)	Objective Met
Discharge Pressure (g)	psig	>1000	1285	Objective Met
Comp. Package Cost (g)	$M	6.0 +/- 1	4.5 +/- 0.75	Objective Met
Main. Cost (Table 3.2.2)	$/kWhr	0.007	0.005 (per CN Analysis Model)	Objective Met
Package Size (g)	sq. ft.	350 (per HyGen Study)	260 (per CN Design)	Objective Met
Reliability (e)	# Sys.s Req.d	Eliminate redundent system	Modular sys.s with 240K kg/day with no redundency req.d	Objective Met

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

Results of Research Development: A pipeline-capacity, hydrogen centrifugal compressor can be made available now to meet the hydrogen economy needs of the future!

Accomplishments for Phases I and II (completed from 2008 to 2011) and Phase III (in progress)

Developed computer models to aid in analysis of hydrogen compressor:

- System Cost and Performance Model
  - Identifies hydrogen compressor package performance and component cost with respect to a variety of compressor-gearbox configurations
- System Reliability and Maintenance Cost Model
  - Estimates comparative reliabilities for piston and centrifugal compressors for pipeline compressors developed
    - Failure mode and effects analysis for component risk and reliability assessment
  - Estimates operation and maintenance costs for compressor system
    - Uses Federal Energy Regulatory Commission operation and maintenance database as the basis for determining the maintenance costs for a centrifugal compressor
- Anti-surge algorithm developed to assist in controls analysis and component selection of preliminary design (completed) and detailed design of pipeline compressor module (in progress), including:
  - Compressor design conditions confirmed by project collaborators
    - P_{inlet} = 350 psig, P_{outlet} = 1,250 psig; flow rate = 240,000 kg/day
    - A six-stage, 60,000 revolutions per minute (rpm), 3.6 (max) pressure ratio compressor with a mechanical assembly of integrally geared, overhung compressor impellers
    - Stress analysis completed
    - Volute (compressor housing) design in progress for two-stage prototype
    - Rotordynamics completed to verify shaft-seal-bearing integrity at operating speeds
- Completed critical component development (compressor rotor, shaft seal, bearings, gearing, safety systems) and specifications for near-term manufacturing availability
- Completed detailed design and cost analysis of a complete pipeline compressor and a laboratory-scale prototype for future performance lab verification testing
- Completed a one-stage laboratory prototype compressor system to verify mechanical integrity of major components at full power ratings per stage
- Procuring system components for one-stage prototype compressor

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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. This technology development is the focus of the Hydrogen Production and Delivery sub-programs within the DOE. Pipeline transport of the hydrogen from the production sites to the population centers can reduce the costs of hydrogen delivery at market volumes. The cost to deliver the hydrogen resource to the refueling stations contributes to the cost per kg or per gasoline gallon equivalent (gge) that needs to be charged for the hydrogen fuel. Therefore, it is necessary that the cost to deliver the hydrogen be reducd, 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 reduced as well in order to meet the ultimate hydrogen delivery cost target of $2/gge (2040 goal).

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 installation costs). To meet these goals, the DOE has commissioned Concepts NREC with the project entitled: The Development of a Centrifugal Hydrogen Pipeline Gas Compressor.

APPROACH

A three-phase approach has been programmed to implement the technical solutions required to complete a viable hydrogen compressor for pipeline delivery of hydrogen. The three phases include: Phase I-Preliminary Design, Phase II-Detailed Design of both a Full-Scale and Prototype Hydrogen Compressor, and Phase III-The Assembly and Testing of the Prototype Compressor.

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, shaft seal technology, and high-speed gearing to reduce developmental risk and increase system reliability at a competitive cost.

The engineering challenge to implement this technical approach is to design a compressor stage that can achieve the highest compression ratio and thermodynamic efficiency, while also minimizing the number of stages and the impeller diameter. 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. The selection of a rotor material that can enable the high tip speeds to be achieved while avoiding damage from hydrogen embrittlement was determined to be the major technical challenge for the project.

The Concepts NREC design is projected to meet all of these engineering challenges in order to provide a pipeline compressor system that meets DOE's specifications for near-term deployment.

The project team includes researchers at Texas A&M, led by Dr. Hong Liang, who are collaborating with Concepts NREC to confirm the viability of aluminum alloys for this compressor application. Also assisting with a collegial collaboration of suggestions are several national laboratories, including Sandia National Laboratories (fracture mechanics testing; Dr. Chris San Marchi), Savannah River National Laboratory (specimen "charging" with hydrogen plus tensile testing with H_2; Dr. Andrew Duncan and Dr. Thad Adams), and Argonne National Laboratory (Dr. George Fenske).

RESULTS

The engineering analysis has resulted in the design of the pipeline compressor package shown in Figure 1. The complete modular compressor package is 29 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 compressor selection uses six stages, each operating at 60,000 rpm, with a tip speed of less than 2,100 ft/s. Each compressor rotor and drive shaft is 8 inches in diameter and has an overall stage efficiency of between 79.5 and 80.5%, for an overall compressor isentropic efficiency of 80.3%. The first and last stages have a slightly different length, which helps to improve the rotordynamics for the

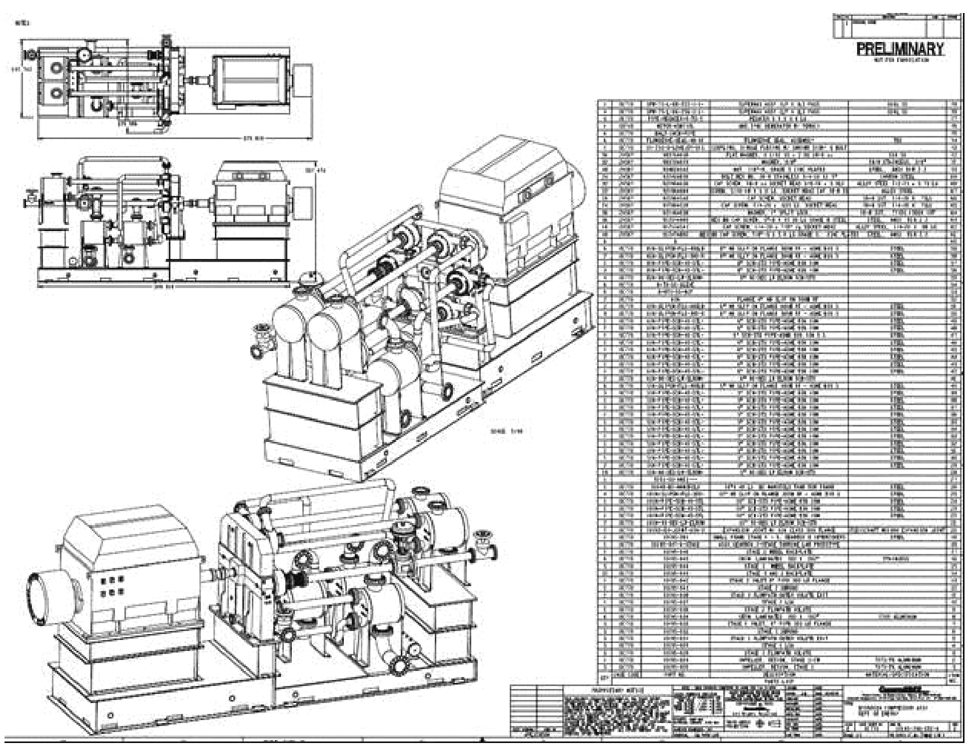


FIGURE 1. Pipeline Hydrogen Centrifugal Compressor: 240,000 kg/day; 350 to 1,285 psig

last stages. Each compressor impeller is a single, overhung (cantilevered) impeller attached to a drive shaft that includes a shaft seal, bearing, and drive pinion (Figure 2) integrated with the gearbox drive. 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, so it does not disturb the shaft seal and bearings. 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 and KMC, respectively. The pinion and bull gear is part of a custom gearbox manufactured by Artec Machine Systems representing NOVAGEAR 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 rotor and volute is an aluminum alloy: 7075-T6 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. This aluminum alloy has a strength-to-density ratio that is similar to titanium and high-strength steels at the 140°F (max) operating temperatures that will be experienced by the hydrogen compressor. However, unlike titanium and most steels, aluminum is recognized by the industry as being very compatible with hydrogen.

Aluminum also helps to reduce the weight of the rotor, which leads to an improved rotordynamic stability at the 60,000 rpm operating speed. A rotor stability and critical speed analysis has confirmed that the overhung design is viable. The first stage compressor rotor has been manufactured and successfully spun to 110% of its 60,000 rpm operating speed. A subsequent fluorescent penetrant inspection and strain measurements of the rotor after the spin test indicated no creep or micro-crack design flaws as a result of the test.

The one-stage prototype compressor has been chosen for laboratory testing in Phase III of the project. The laboratory prototype is shown in Figures 3 and 4. The compressor components are being manufactured, and the balance of the system components are being purchased. The system will be assembled and tested starting in 2013 and will be completed in early 2014.

CONCLUSIONS AND FUTURE DIRECTIONS

The advanced, six-stage, intercooled, centrifugal compressor-based system can provide 240,000 kg/day of hydrogen from 350 to 1,280 psig (6,300 kWe) for pipeline-grade service. 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. As a result of the sponsored research and development, a pipeline-capacity, hydrogen centrifugal compressor has been designed to meet the high volume hydrogen markets using commercially available, state-of-the-art components!

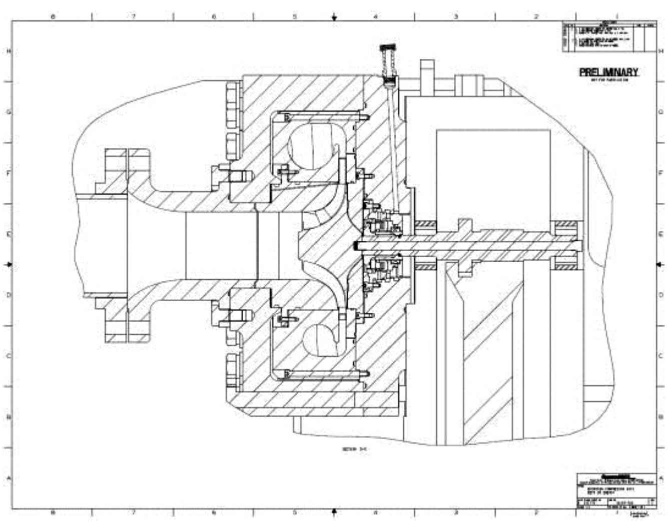
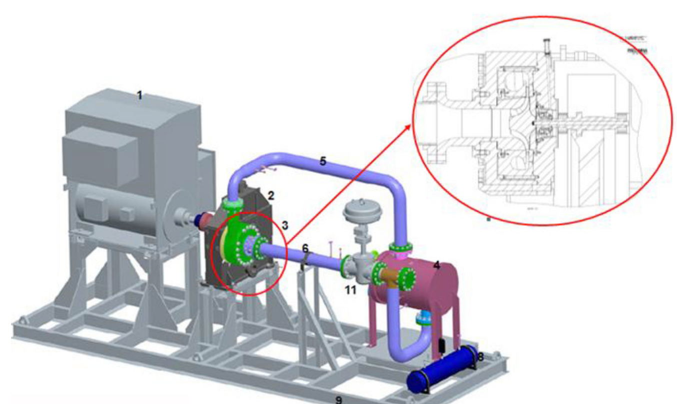


FIGURE 2. Mechanical Detailed Assembly of One-Stage, Prototype Compressor



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

- COMPLETED – P&I Diagram, Controls Specification, Safety Systems, One Test Site Selected (others under review)
- COMPLETED – All compressor components
- IN PROGRESS – Component Procurement Included Some Redesign for Cost Reduction of Prototype
  - Modified 1–stage Gearbox
  - Revised base frame
  - PLC & Controls purchased
  - Hyundai 4160 Vac Motor & Soft Start (not shown)

P&I - piping and instrumentation
PLC - programmable logic controller

FIGURE 3. Detailed Specification for the One-Stage Prototype Compressor

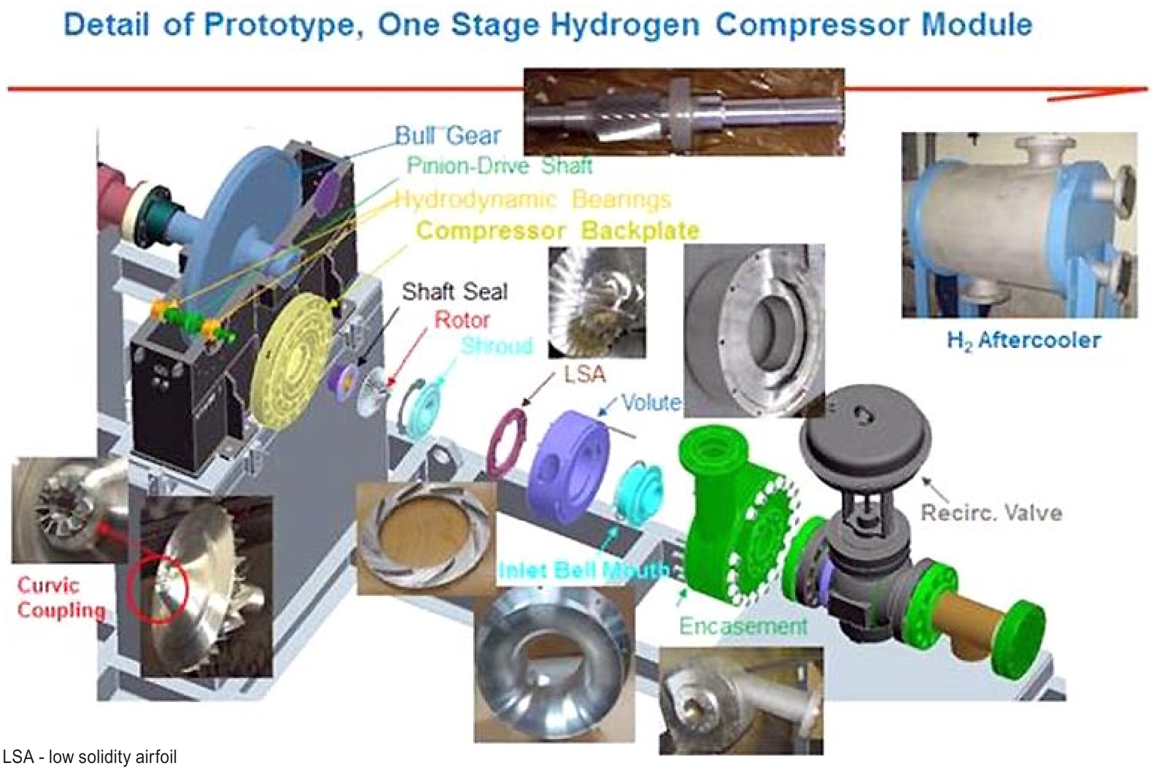


FIGURE 4. Detail of Prototype, One-Stage Hydrogen Compressor Module

Objectives for This Year

Phase III System Component Procurement, Construction, and Validation Testing

- Continue component procurement for the one-stage prototype hydrogen compressor system
- Assemble the one-stage centrifugal compressor system
- Conduct aerodynamic testing and assessment of mechanical integrity of the compressor system
- Prepare a plan for placement of the prototype compressor for continued testing, including deployment at an industrial gas user or a university research laboratory

SPECIAL RECOGNITIONS AND AWARDS/ PATENTS ISSUED

Patent application filed on several innovations for centrifugal compressor design; filed March 2010 (provision file March 2009: SN 60/896985): "Centrifugal Compressor Design for Hydrogen Compression."

FY 2013 PUBLICATIONS/PRESENTATIONS

1. "Development of a 240,000 kg/day Hydrogen Pipeline Centrifugal Compressor for the Department of Energy's Hydrogen Delivery and Production Program," IMECE2012-88965.

REFERENCES

1. DOE Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.