# III.7 Development of a Centrifugal Hydrogen Pipeline Gas Compressor


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

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Project End Date: May, 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% 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 $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) 2012 Objectives

- Procure compressor components for one-stage prototype compressor
- Assemble prototype components
- Prepare test plan for prototype testing

## Technical Barriers

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

(B) Reliability and Costs of Hydrogen Compression

## Technical Targets

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

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

| 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) | | | | |
| **Characteristic** | **Units** | **DOE Target** | **Project Accomplishment** | **STATUS** |
| Hydrogen Efficiency (f) | [btu/btu] | 98% | 98% | Objective Met |
| Hyd. Capacity (g) | kg/day | 100,000 to 1,000,000 | 240,000 | Objective Met |
| Hyd. Leakage (d) | % | <0.5 | 0.2 (per Flowserve Shaft Seal Spec.) | Objective Met |
| Hyd. Purity (h) | % | 99.99 | 99.99 (per Flowserve Shaft Seal Spec) | Objective Met |
| Discharge Pressure (g) | psig | >1,000 | 1,285 | Objective Met |
| Comp. Package Cost (g) | $M | 6.0 +/- 1 | 4.0 +/- 0.5 | 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) | # Systems Required | Eliminate redundant system | Modular systems with 240K kg/day with no redundancy required | Objective Met |

## Accomplishments for Phases I and II (completed from 2008 to 2010) 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 BTU energy content per kg, equivalent to the BTU 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 responsibility of the Production and Delivery sub-programs within the DOE. 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 as 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 less than $2/gasoline gallon equivalent (2010 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 its 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 a 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 acceptable pressure ratio and thermodynamic efficiency per stage, while also using as few stages as possible and employing the smallest diameter impeller necessary. 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 selected as the major technical challenge for the project.

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.

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

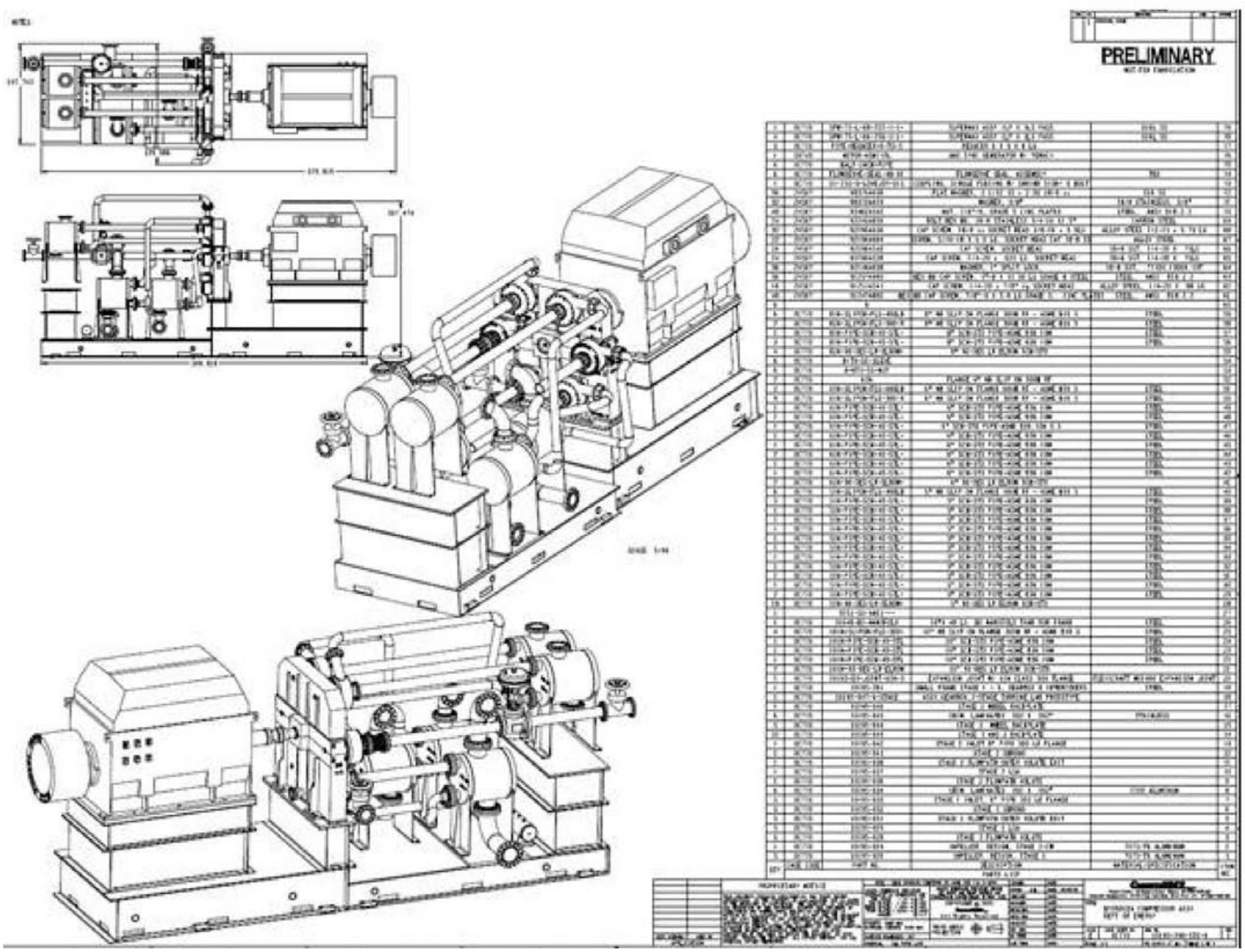


**FIGURE 1.** Pipeline Hydrogen Centrifugal Compressor: 240,000 kg/day; 350 to 1,285 psig

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 efficiency of 80.3%. The first and last stages have a slightly different length, which helps to improve the rotordynamics for the 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 (Zurich, Switzerland) 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. The choice is based on its mechanical strength-to-density ratio or ($S_{yield}/\rho$), 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 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 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 3a and 3b. 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 2012 and into 2013.

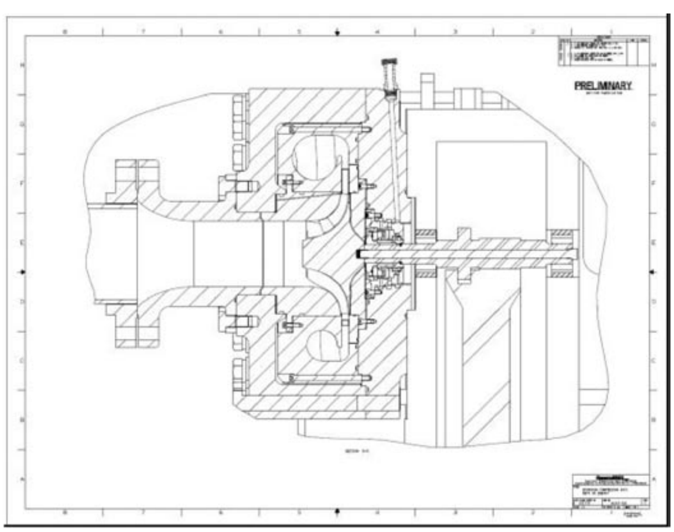


**FIGURE 2.** Mechanical Detailed Assembly of One Stage, Prototype Compressor

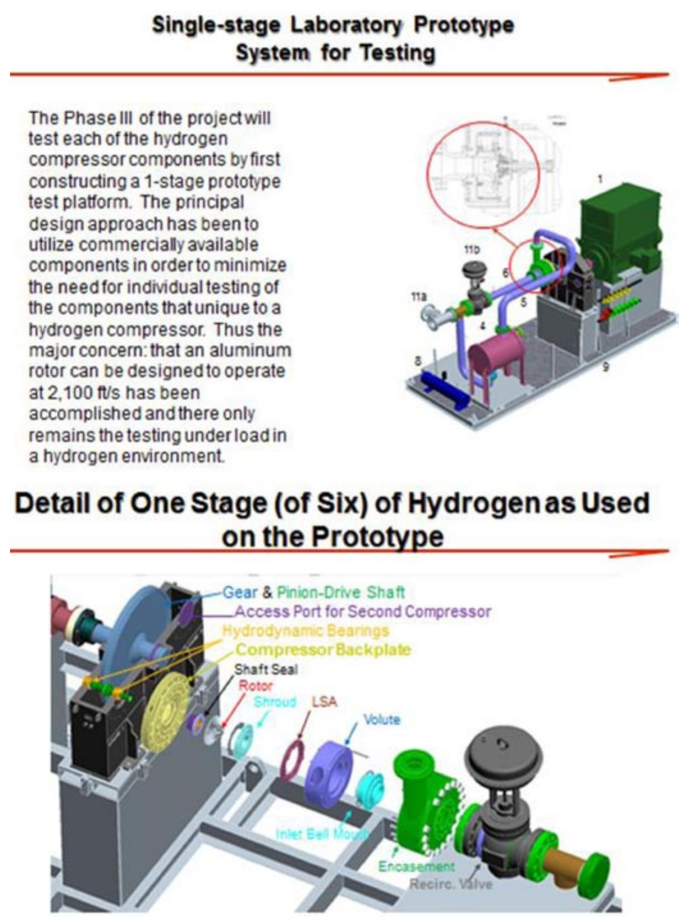


**FIGURE 3.** Detail Specification for the One-Stage Prototype Compressor


**FIGURE 4.** Components Prepared for the One-Stage Laboratory Prototype Compressor

## 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 high (6,300 kWe) for pipeline-grade service. The system is 1/4 to 1/3 the size of existing industrial systems at projected cost of less than 80% of DOE's target and a maintenance cost that is less than the $0.01/kWh. 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.

### Phase III System Component Procurement, Construction, and Validation Testing (January 2011 to May, 2013)

- Continue component procurement for the one-stage prototype hydrogen compressor system.
- Assembly of 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 the deployment in an industrial gas user or a university research laboratory.

## Patents Issued

**1.** 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 2012 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 Multi-Year Research, Development, and Demonstration Plan.