III.4 Development of a Centrifugal Hydrogen Pipeline Gas Compressor

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Subcontractors:
- Praxair Corporation, Tonawanda, NY
- Texas A&M University, College Station, Texas
- 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 (compressor package of $5.4M) for 240,000 kg/day system by FY 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 capital investment by Fiscal Year (FY) 2017.
- Increase system reliability to avoid purchasing 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 3) 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 and Figure 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**
Hydrogen Efficiency (f)	[btu/btu]	98%	98%
Hyd. Capacity (g)	kg/day	100,000 to 1,000,000	240,000
Hyd. Leakage (d)	%	<.5	0.2 (per Flowserve Shaft Seal Spec.)
Hyd. Purity (h)	%	99.99	99.99 (per Flowserve Shaft Seal Spec.)
Discharge Pressure (g)	psig	>1000	1285
Comp. Package Cost (g)	$M	6.2	4.5
Main. Cost (Table 3.2.2)	$/kWhr	0.007	0.005 (per CN Analysis Model)
Package Size (g)	sq. ft.	300 to 350 (per HyGen Study)	175 to 200 (per CN Design)
Reliability (e)	# sys req'd	Eliminate redundant system	Modular systems with 240K kg/day with no redundancy req'd

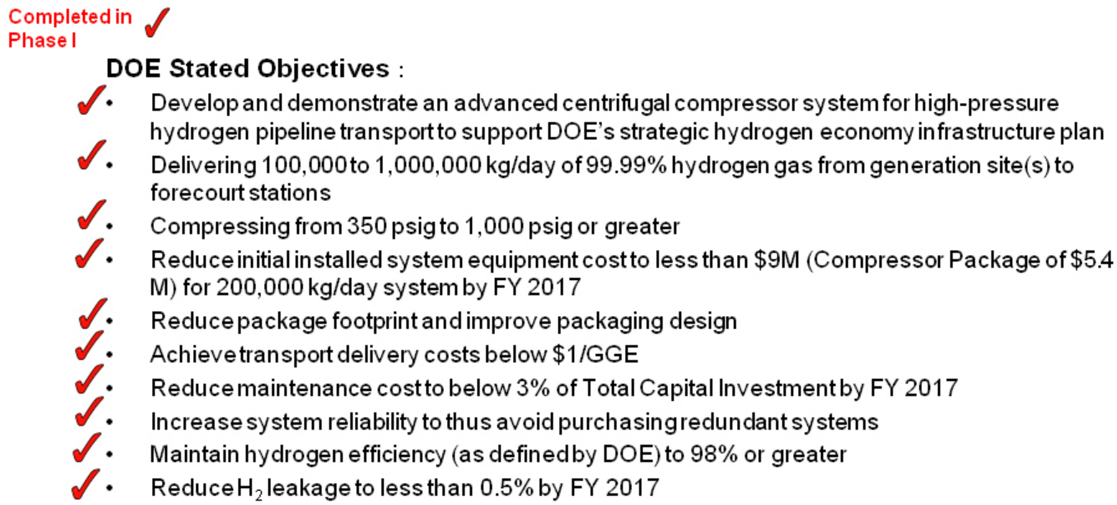

FIGURE 1. Project Objectives – Relevance to DOE Hydrogen Economy Planning

Accomplishments for Phase I (Completed) and Phase II (in Progress)

Developed computer models to aid in analysis of hydrogen compressor:

- System Cost and Performance Model
  - Suitable as a macro for DOE "HDSAM v2.0" economics model.
  - Identifies hydrogen compressor package performance and component cost with respect to a variety 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 (FMEA) 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 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.
- Design of compressor's major mechanical elements completed and satisfied by two manufacturers per component:
  - Titling-pad radial and thrust bearings designs validated for use.
  - Two commercially available gas face seals have been validated for use.
- Interconnect pipe diameters selected to minimize pressure drop.
  - Including volute with low solidity airfoil as the flow guide vanes and diffusing and Bellmouth at the inlet of the volute.
- 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).
- Piping and instrumentation diagram for module.

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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 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). 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. This approach is summarized in Figure 2.

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

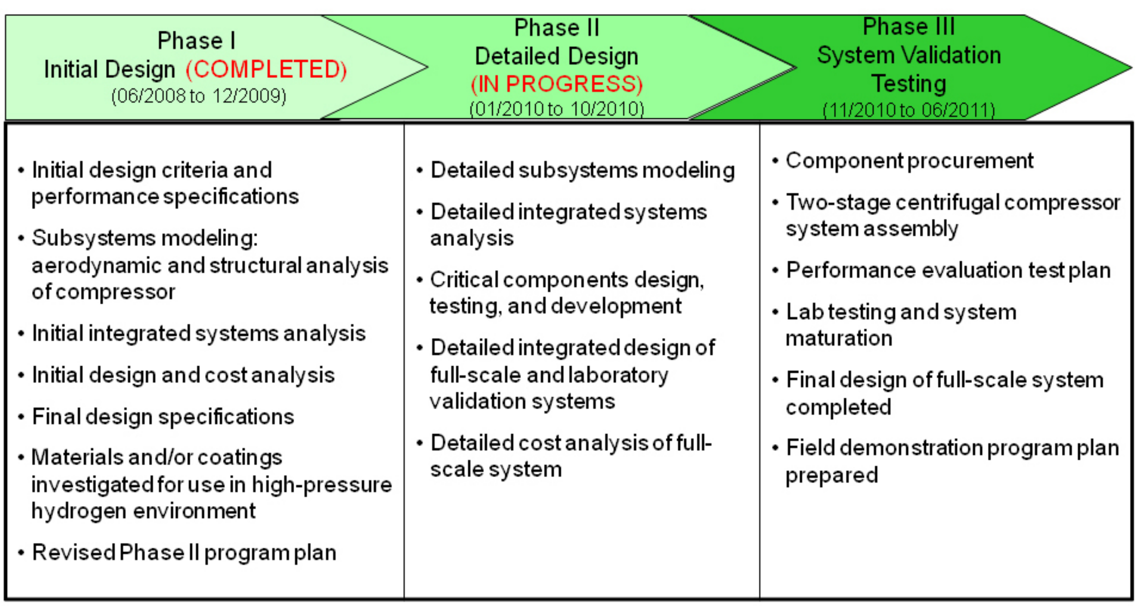

FIGURE 2. Three-Phase Program Approach

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 square of the radius ($radius^2$). 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 rpm^2 and $radius^2$, 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. 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. To eliminate other more conventional challenges when developing a new compressor, the engineering directive was also to select only 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. Principal among these components is the choice of the bearings, shaft seals, gearing, and hydrogen controls and safety instrumentation.

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

Concepts NREC has developed several computer design models that have helped to optimize the design choice for the pipeline compressor module that complies with DOE requirements. These models include:

1. Compressor Package Performance Model,
2. Cost Model using algorithms to determine the relative component cost and operational risks,
3. Engineering Reliability and Maintenance Cost Model [2,3],
4. Anti-surge Algorithm for providing anti-surge component specifications; and
5. Failure Mode and Effects Analysis (FMEA).

The engineering analysis, conducted in Phase I and continuing in Phase II, resulted in the design of the pipeline compressor package shown in Figure 3. The complete modular compressor package 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

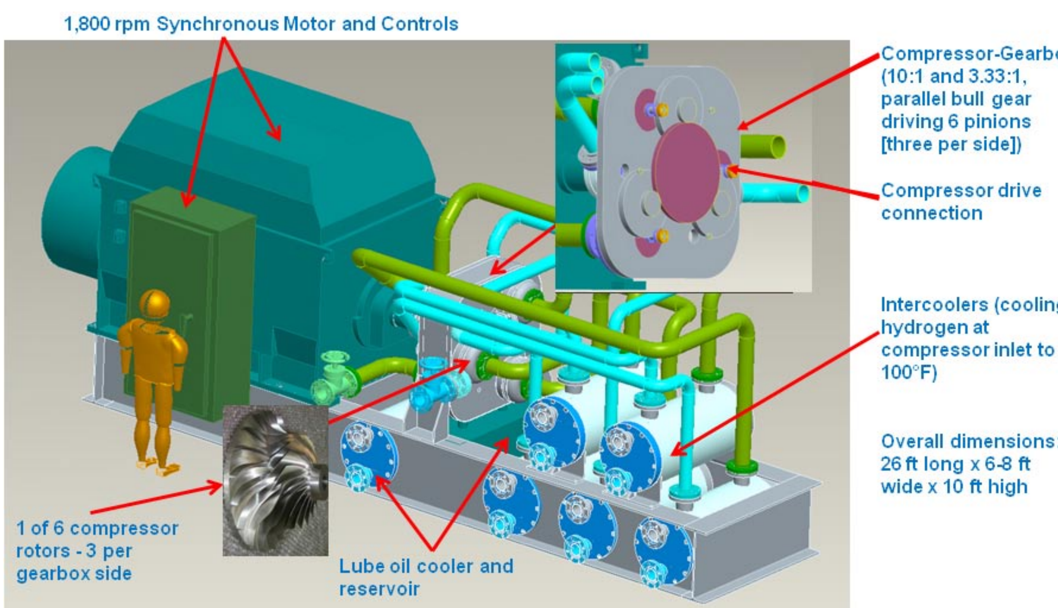

FIGURE 3. Engineering Analysis and Design Results: Pipeline Hydrogen Centrifugal Compressor 240,000 kg/day; 350 to 1,285 psig; 6,300 kWe

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.

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 4, 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%. Each compressor impeller 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 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 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 aluminum have 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.

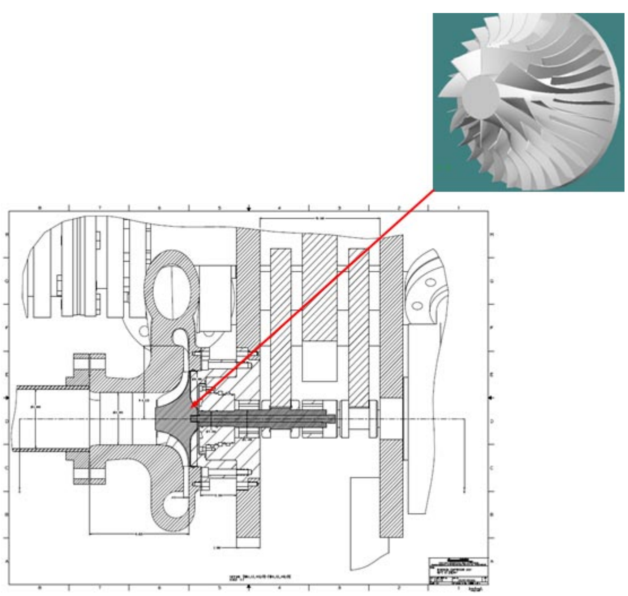

FIGURE 4. Mechanical Detailed Assembly of One of Six Stages of Pipeline Compressor

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 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. 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 team determined that a small punch test (Figure 5) is appropriate for properly assessing the relative effects that hydrogen has on the strength of the material. A protocol for hydrogen charging of the 3 mm diameter x 0.5 mm thick specimens included prolonged exposure (4 months) in an atmosphere of hydrogen at 10,000 psig and 200°F.

The results of a preliminary test, also shown in Figure 5, indicate that the 2618-T61 and 3003-H14 aluminum alloys appeared to be minimally (if at all) affected by hydrogen, whereas the titanium Ti-6AI-4v was affected by the presence of hydrogen.

Conclusions and Future Directions

The preliminary engineering and design of an advanced pipeline compressor system has been completed and 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 75% of DOE's target, and a maintenance cost that is less than the $0.01/kWh. The detailed analysis of this pipeline compressor system is in progress in Phase II of the project. The advanced centrifugal compressor-based system can provide 240,000 kg/day of hydrogen from

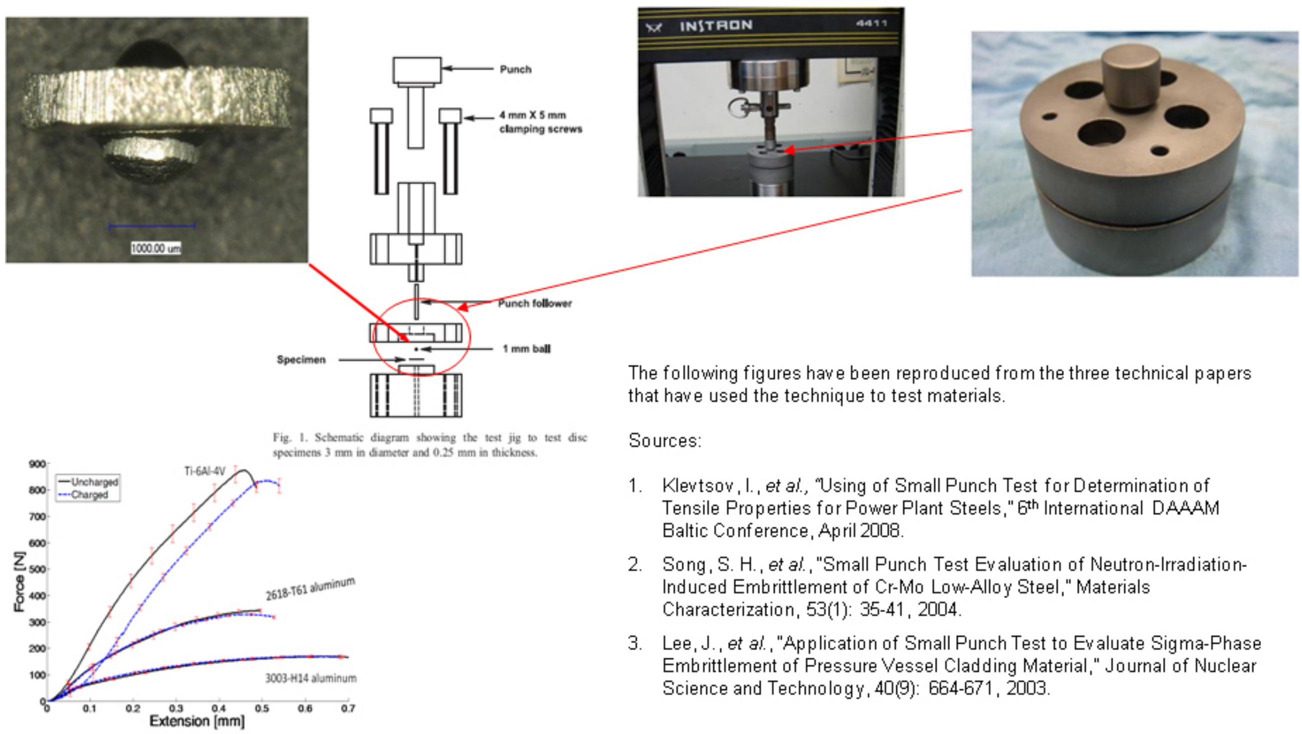

FIGURE 5. Small Punch Test Materials Testing Apparatus Used by Texas A&M (sketch from research papers by: I. Klevtsov, S.H. Song, and J. Lee)

350 to 1,280 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 using 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). This team is committed to producing the first commercially reliable hydrogen compressor for hydrogen pipeline delivery.

Future efforts include:

- **Phase II.** Continue with Detailed Design (January 2010 to October 2010)
  - Detailed subsystems modeling.
  - Detailed integrated systems analysis.
  - Critical components design, testing, and development.
- **Phase III.** System Validation Testing (November 2010 to June 2011)
  - Component procurement.
  - Two-stage centrifugal compressor system assembly.

Special Recognitions and Awards/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 2010 Publications/Presentations

1. NASA Tech Briefs article for "Green Design & Manufacturing," (January 2010).

2. Poster Session at the National Hydrogen Association Conference & Exhibit, May 2010.

References

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

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

3. Harrell Jr., J. and Smalley, A., "Benchmarking the Industry: Factors Affecting Compressor Station Maintenance Costs," A presentation at the GMRC Gas Machinery Conference, October 2000.