III.8 Development of a Centrifugal Hydrogen Pipeline Gas Compressor

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

Project Start Date: June 1, 2008
Project End Date: September 1, 2012

Fiscal Year (FY) 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 $9 M (compressor package of $5.4 M) for 240,000 kg/day system.
- Reduce package footprint and improve packaging design. Achieve transport delivery costs below $1/gasoline gallon equivalent (gge) ($2008 goal).
- Reduce maintenance cost to below 3% of total capital investment.
- 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%.

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).

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
  - Suitable as a macro for DOE "HDSAM v2.0" economics model.

TABLE 1. 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)	%	< .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	>1000	1285	Objective Met
Comp. Package Cost (g)	$M	6.4	4.8	Objective Met
Main. Cost (Table 3.2.2)	$/kW hr	0.007	0.005 (per CN Analysis Model)	Objective Met
Package Size (g)	sq. ft.	350 (per HyGen Study)	280 (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

    - 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 (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 of preliminary design (completed) and detailed design of pipeline compressor module (in progress).
- 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 two-stage laboratory prototype compressor system to verify mechanical integrity of major components at full power ratings per stage.

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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 ($2008 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. This approach is summarized in Figure 1.

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

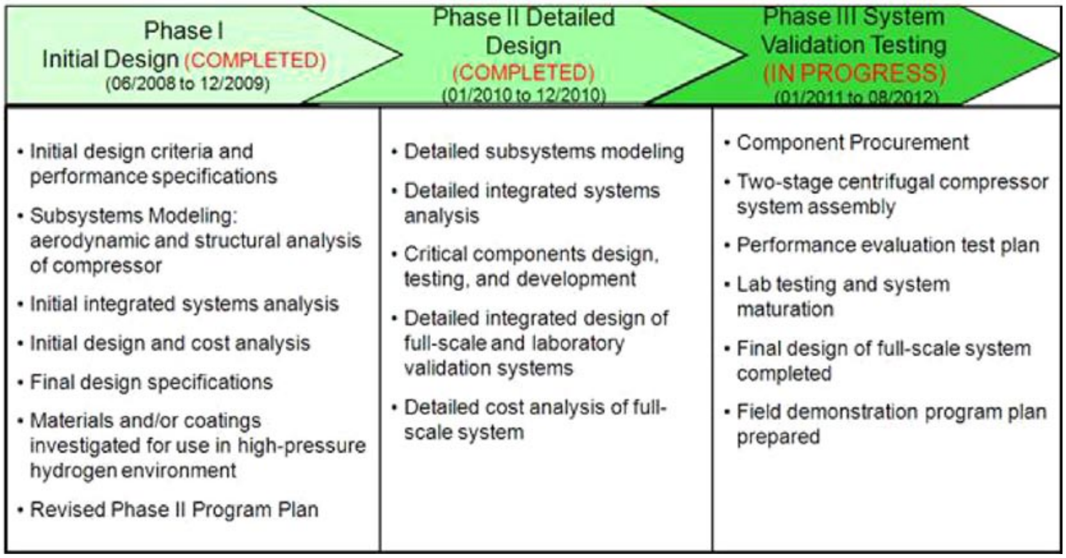

FIGURE 1. Three-Phase Project Approach

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 and Cost Model using algorithms to determine the relative component cost and operational risks.
2. FMEA and Engineering Reliability and Maintenance Cost Model [2,3].
3. Completed detailed mechanical integration of compressor rotor-drive shaft with gearbox.
4. Detailed design of a six-stage centrifugal compressor module.
5. Detailed design of a 2-stage laboratory prototype compressor system for testing the mechanical integrity of the major compressor components: rotor, shaft seal, bearings, and gearing.
6. Successfully machined and spun compressor rotor (60,000 rpm to operating speed).

The engineering analysis conducted in Phase I and continuing in Phase II resulted in the design of the pipeline compressor package shown in Figure 2. 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 packaged module can be transported to the installation site as a pre-assembled

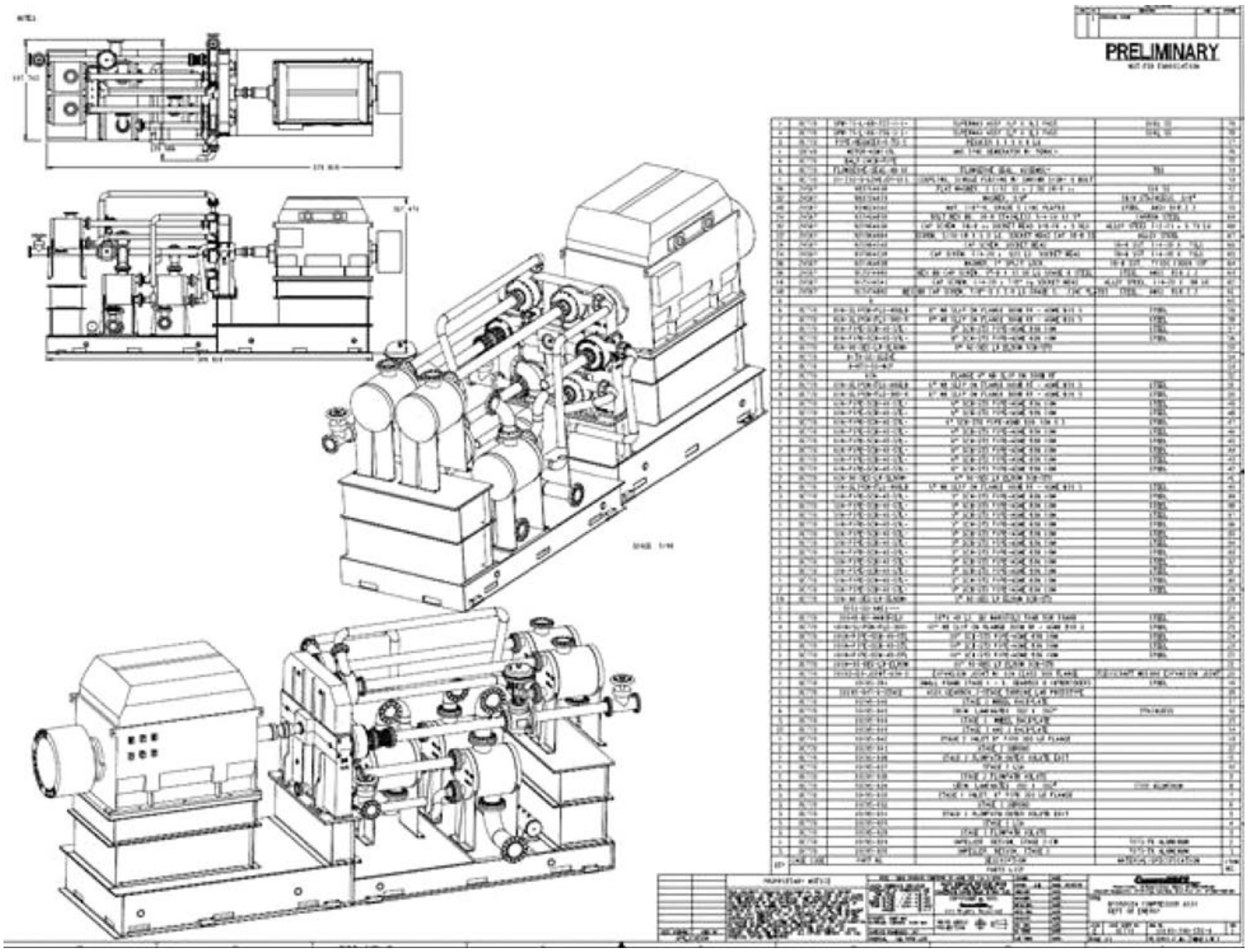

FIGURE 2. Engineering analysis and design results: pipeline hydrogen centrifugal compressor 240,000 kg/day; 350 to 1,285 psig; 6,300 kWe.

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 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 3) 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, 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 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.

Also shown in Figure 3 is the encasement of each compressor rotor and (pressure recovery) volute. The encasement is made of nitronic-50 steel that is designed to sustain the highest compression pressure.

The material chosen for the compressor rotor and volute 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

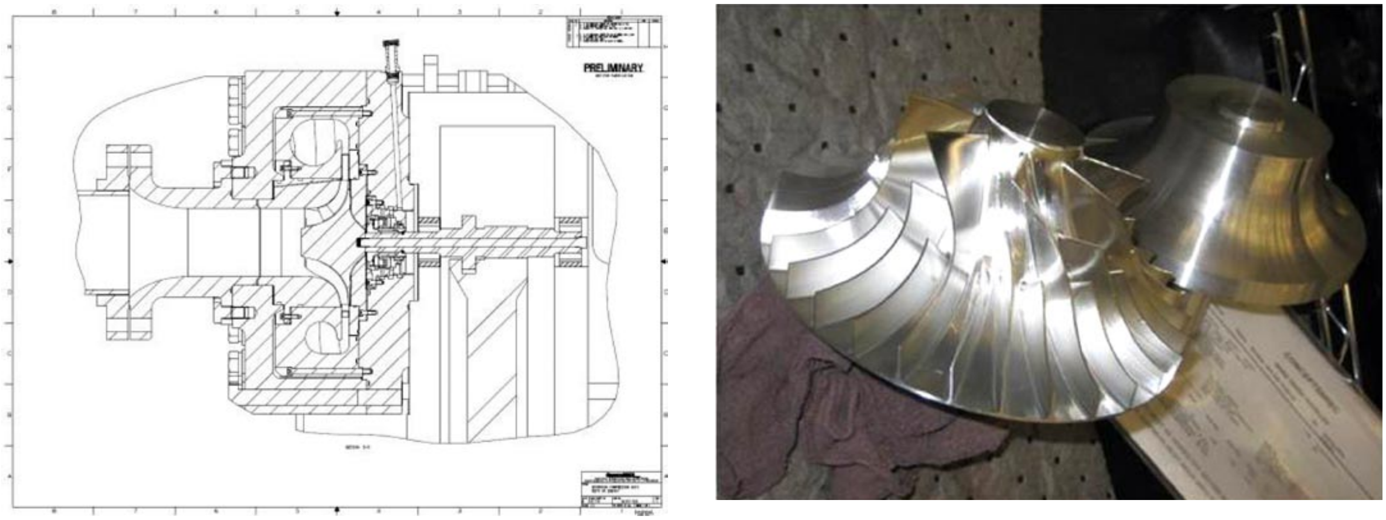

FIGURE 3. Mechanical Detailed Assembly of One of Six Stages of Pipeline Compressor

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 1st stage compressor rotor has been manufactured (Figure 3) and successfully spun to 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 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).

The Phase II work also completed the detailed design of a closed-loop one and two-stage prototype compressor modules. One of these modules will be selected for laboratory testing in Phase III of the project. The laboratory prototype is shown in Figure 4.

Conclusions and Future Directions

- An advanced pipeline compressor system has been designed that meets DOE's performance goals for:
  - High reliability with 350 to 1,200$^+$ 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.
- 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 material (7075-T6 and Nitronic-50) stresses in hydrogen.
  - Industrially proven bearings, seal technology, gearing, heat exchangers, and lube system.
- Aerodynamic analysis and design of a cost-effective, 6-stage centrifugal compressor and a 2-stage full-power lab prototype have been completed. The 1-stage laboratory prototype will be tested at Praxair's facility.
- The collaborative team consists of Praxair, an industrial technical experienced user and host of lab prototype test; a materials researcher, Texas A&M; a hydrogen refueling industry consultant, HyGen; and the coordinated technical support of several national labs.
- Complete materials coating testing of specimens with Texas A&M: actual rotor forensics after high-speed testing as necessary.
- Start the procurement of major components for the laboratory testing of a prototype compressor-gearbox in Phase III; prepare test plan for lab test and coordination with Praxair.

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

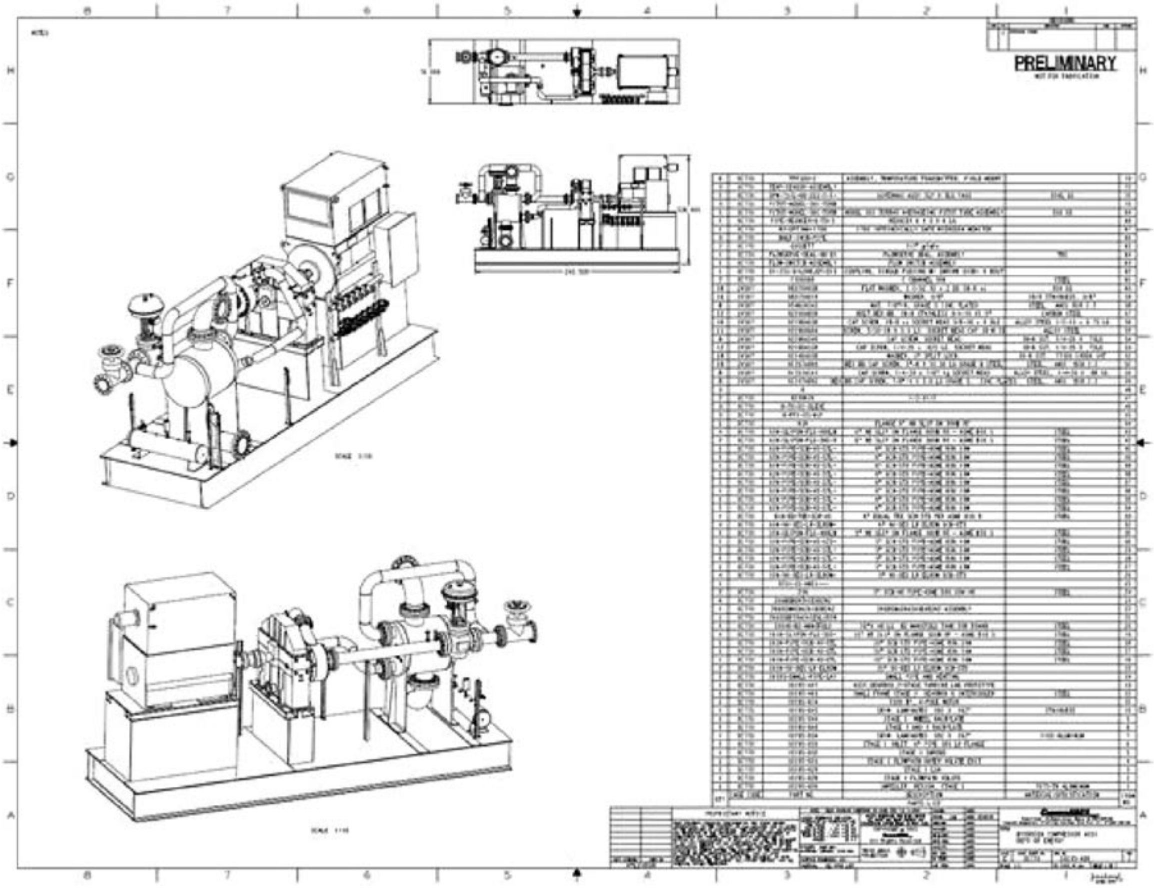

FIGURE 4. Detailed Design of a 1-Stage, Laboratory Prototype Compressor

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 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 who has experience with hydrogen as a fuel source and as an industrial gas, a materials researcher (Texas A&M), and a consultant (HyGen Industries) with hands-on experience with the hydrogen refueling industry. This team is committed to producing the first commercially reliable hydrogen compressor for hydrogen pipeline delivery.

Future efforts include:

Phase III System Component Procurement, Construction, and Validation Testing (January 2011 to September 2012):

- Continue materials testing at Texas A&M University with hydrogen to determine effects of coatings that can be used with titanium.
- Component procurement for the 1- or 2-stage functional hydrogen compressor system.
- Assembly of the 1-stage centrifugal compressor system.
- Coordinating the integration of a laboratory prototype compressor module for testing with hydrogen.
- Conduct aerodynamic testing and assessment of mechanical integrity of the compressor system.

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".

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