

# **2013 DOE Hydrogen Program Merit Review**

## **Development of a Centrifugal Hydrogen Pipeline Gas Compressor**

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Concepts NREC (CN)**

**May 15, 2013**

Project ID#: PD017

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# Project Overview

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## Timeline

- ▶ **Project Start: June 1, 2008**
- ▶ **Project End: November 2012**
- ▶ **Percent Complete: Ph. I and Ph. II - 100%; Ph. III in Progress)**

## Budget

- ▶ **Total Project Funding**
  - DOE Share: \$3,352,507
  - Contractor Share: \$850,055
- ▶ **FY12 Funding (Phase III)**
  - \$698,827
- ▶ **Funding for FY13**
  - No Cost Extension

## Barriers/Tech. Objectives

- Pipeline delivery of pure (99.99%) hydrogen at <\$1/GGE with 98% hydrogen efficiency
- Reduce initial capital equipment and O&M cost
- Reduce compressor module footprint & increase reliability; reduce R&D risk – utilize commercially available, state-of-the-art components

## Project Lead

- Concepts NREC (Chelmsford, MA, and Wilder, VT)

## Project Partners

- Air Products (Industrial User/Engineering Assistance)
- Texas A&M University (2008-2012:Materials Testing)
- HyGen Industries (Hydrogen Industry Consultant)

## Technical Collaboration

- Sandia National Lab, Argonne National Lab, Savannah River National Lab
- Artec Machine Systems, RMT, Flowserve, Tranter HX, Hyundai

# Hydrogen Pipeline Compressor Project

## Objectives – Relevance

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- ▶ **Demonstrate Advanced Centrifugal Compressor System for High-pressure Hydrogen Pipeline Transport to Support<sup>1</sup>**
  - Delivery of 100,000 to 1,000,000 kg/day of pure hydrogen to forecourt station at less than \$1/GGE with less than 0.5% leakage and with pipeline pressures of 1200+ psig
  - Reduction in initial system equipment cost to less than \$6.3 million which is the uninstalled cost for a hydrogen pipeline based on DOE's HDSAM 2.0 Economics Model
  - Reduction in Operating & Maintenance Costs via improved reliability
    - ~ DOE's Model also indicates \$O&M cost of 3% of installed cost per year, or \$0.01/kWhr by 2017
    - ~ Improved reliability eliminates the need for system redundancies
  - Reduction in system footprint

1. Reference: Delivery Section (Sec. 3.2) of the *“Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-year Research, Development, and Demonstration Plan”*

# A Three-Phase Program Approach

Phase I  
Initial Design (**COMPLETED**)  
(06/2008 to 12/2009)

Phase II Detailed  
Design  
(**COMPLETED**)  
(01/2010 to 12/2010)

Phase III System  
Validation Testing  
(**IN PROGRESS**)

- Initial design criteria and performance specifications
- Subsystems Modeling: aerodynamic and structural analysis of compressor
- Initial integrated systems analysis
- Initial design and cost analysis
- Final design specifications
- Materials and/or coatings investigated for use in high-pressure hydrogen environment
- Revised Phase II Program Plan

- Detailed subsystems modeling
- Detailed integrated systems analysis
- Critical components design, testing, and development
- Detailed integrated design of full-scale and laboratory validation systems
- Detailed cost analysis of full-scale system

- Component Procurement
- One-stage centrifugal compressor system assembly
- Performance evaluation test plan
- Lab testing and system maturation
- Final design of full-scale system completed
- Field demonstration program plan prepared

# Project Engineering Approach -1

## Innovative Compressor Design

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- **Technical Approach**

- Utilize state-of-the-art aerodynamic/structural analyses to develop a high-performance centrifugal compressor system able to provide high-pressure ratios under acceptable material stresses.
- Utilize proven bearings and seal technology to reduce developmental risk and increase system reliability at a competitive cost.
- Utilize acceptable practice for high-speed gear materials, tip speeds, and loadings.
- With project and industrial collaborators, prepare an implementation plan that can provide for near-term industrial pipeline applications.

- **Methodology**

- Investigate and prioritize alternative system configurations using operating conditions that meet initial capital and operational costs to meet near-term applications.
- Identify critical engineering constraints of commercially available components and operational limitations of state-of-the-art materials, compatible with hydrogen to increase the range of safe compressor operating speeds.
- Design and test critical rotor aerodynamics and material components under design conditions, and demonstrate full-scale components in an integrated compressor system.

# Project Engineering Approach -2

## Primary Engineering Challenge

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### The Engineering Challenge

- Design centrifugal compressor with highest acceptable pressure ratio and thermodynamic efficiency per stage to minimize system size, complexity, and cost, and to maximize system performance and reliability.

### Solution

- Maximize centrifugal compressor tip speed within stress limitations of material.
  - Pressure ratio is proportional to  $\text{rpm}^2 \times \text{radius}^2$ , so small increase in tip speed results in significant increases in pressure.
  - Maximum thermodynamic efficiency is typically achieved at high operating tip speeds.
- Utilize advanced diffuser systems to maximize recovery of dynamic head into static pressure.

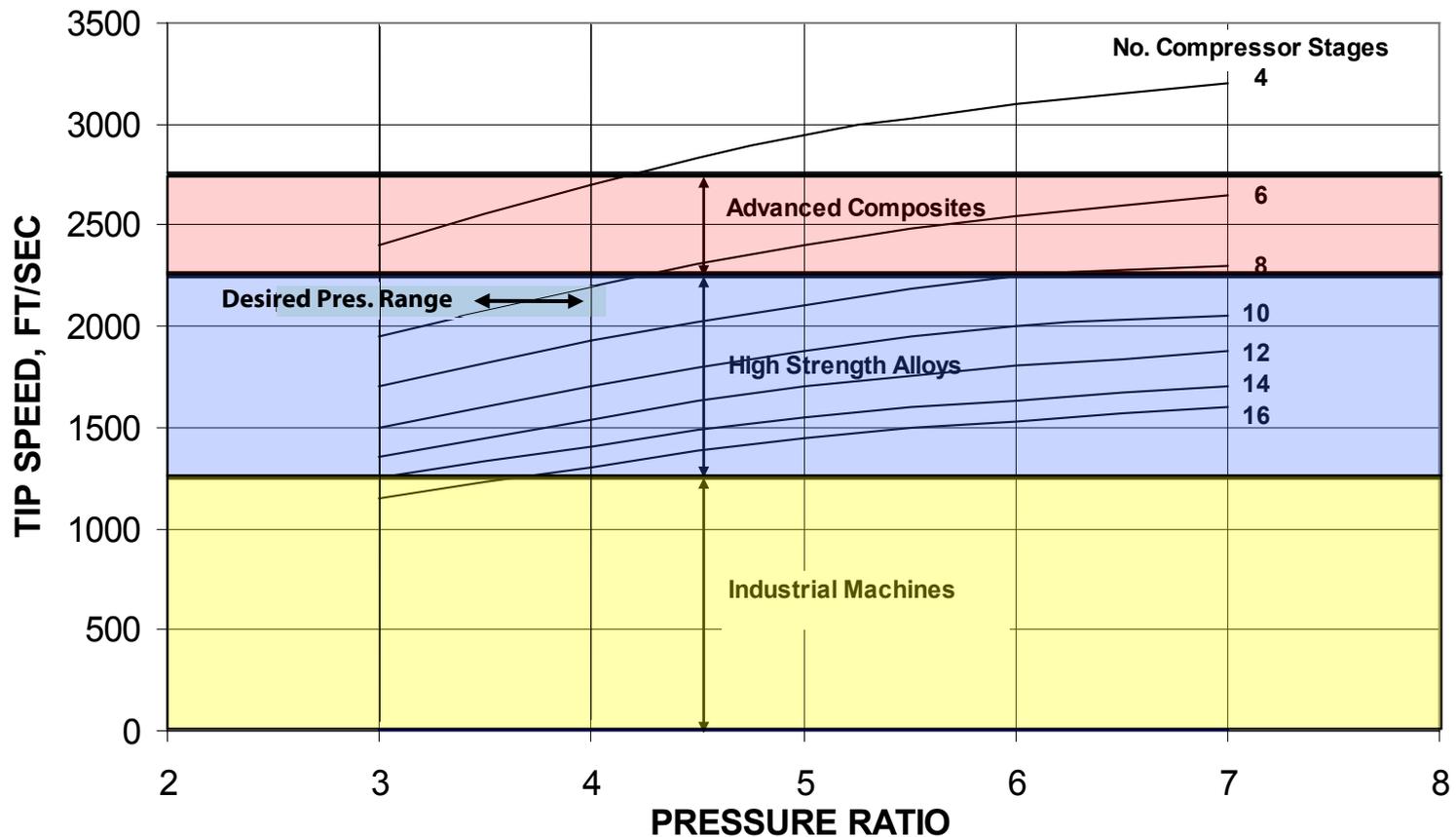
### Constraints

- High operating speeds increase impeller material stresses.
  - Stress is also proportional to  $\text{rpm}^2 \times \text{radius}^2 \times \text{material density}$ . Therefore, pressure rise is limited by maximum stress capability of impeller material.
- Need to select materials that are not significantly affected by hydrogen embrittlement.
- Limited number of materials that have high strength to material density ratio and are resistant to hydrogen embrittlement.

# Project Engineering Approach-3

## Operational Design Envelope

Design Options for Alternative Operating Conditions



# Summary of DOE Target/Goals and Project Accomplishments

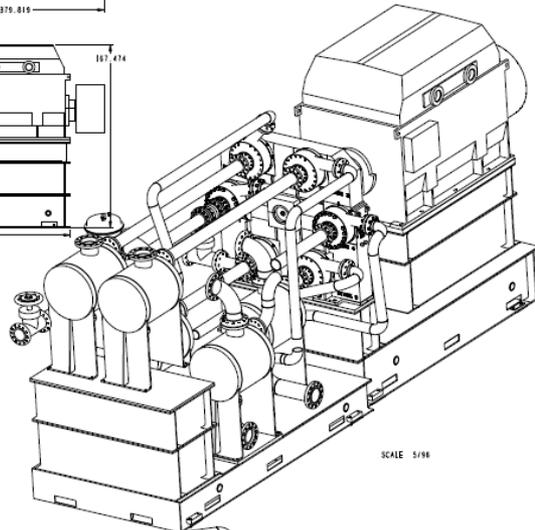
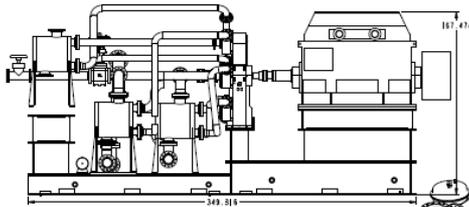
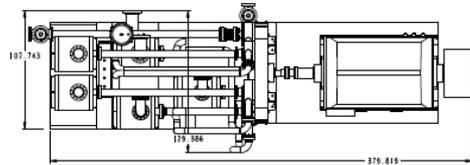
Progress Towards Meeting Technical Targets for Delivery of Hydrogen via Centrifugal Pipeline Compression				
{Note: Letters correspond to DOE's 2007 Technical Plan-Delivery Sec. 3.2-page 16}				
Characteristic	Units	DOE Target	Project Accomplishment	STATUS
Hydrogen Efficiency (f)	[btu/btu]	98%	98%	Objective 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	6.0 +/- 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 redundant system	Modular sys.s with 240K kg/day with no redundancy req.d	Objective Met

**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**

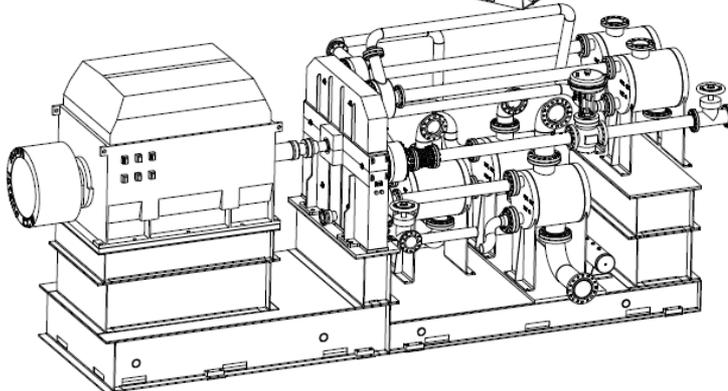
**Result of Research Development: A Pipeline-capacity, Hydrogen Centrifugal Compressor can be made available NOW to meet the Hydrogen Economy needs of the future !**

# Hydrogen Compressor Phase II Detailed Design Accomplishment: 240,000 kg/day (6.1 Lbm/s); 350 to 1285 psig; 6300 kW

NOTES:



SCALE 5/16



QTY	CASE CODE	PARTY NO.	DESCRIPTION	MATERIAL SPECIFICATION	ITEM NO.
1	0C710	SPW-73-L-68-222-1-1	SUPERMAX ASSY LLP X 1LS PASS	316L SS	73
4	0C710	SPW-73-L-68-256-1-1	SUPERMAX ASSY LLP X 1LS PASS	316L SS	74
5	0C710	PIPE-REDUCER-8-YO-5	REDUCER 6 X 5 X 6 LG		75
1	58140	MOTOR-AM-10L	AMS ZINC GENERATOR W/ THERMCT		76
6	0C710	HAUL-100-PIPE	HAUL 100		77
6	0C710	FLOWSEVE-SEAL-40-91	FLOWSEVE SEAL ASSEMBLY	TD	78
1	0C710	01-735-5-LOVE-JOT-013	COUPLING, SIMULS FERRING W/ SMILING DISTR- 6 BOLTS	316 SS	79
38	24567	03144483	FLAT WASHER, 1.125 X 2.00 1/8-8 X	316 SS	80
32	24567	08101019	WASHER, 5/16"	16/3 STAINLESS 316*	81
40	24567	054828242	NUT, 7/8"-9, GRADE 5 ZINC PLATED	STEEL, AMS1818 2.2	82
102	24567	002604839	BOLT, HEX, HD, 1/2 STAINLESS 316-11 X 1/4"	316 STAINLESS	83
22	24567	021844636	CAP SCREW, 1/4"-8 X SOCKET HEAD 316-16 X 5.0LG	ALLOY STEEL 17-15 X 5.75 LG	84
22	24567	021844604	SCREW, 5/16-18 X 3.0 LG, SOCKET HEAD CAP 18-8 SS	ALLOY STEEL	87
16	24567	021844640	CAP SCREW, SOCKET HEAD	18-8 SST, 174-20 X 1.5LG	88
24	24567	021844638	CAP SCREW, 1/4"-8 X 1.5 LG, SOCKET HEAD	18-8 SST, 174-20 X 1.5LG	85
36	24567	021440338	WASHER, 1" SPLIT LOCK	18-8 SST, 7710X 1 BODY 15F	89
36	24567	022519990	HEX HD CAP SCREW, 1"-8 X 1.5 LG, 316 LG GRADE 5 STEEL	STEEL, AMS1818 2.2	84
18	24567	022519441	CAP SCREW, 1 1/4"-20 X 7/16" 18 SOCKET HEAD	ALLOY STEEL, 17-10-20 X 40 LG	87
40	24567	022474892	HEX HD CAP SCREW, 7/8"-8 X 5.0 LG GRADE 5, ZINC PLATED	STEEL, AMS1818 2.2	61
6	0C710	818-SLIPON-FLG-100L	8" NO SLIP ON FLANGE 300# RF - ASME B16.5	STEEL	60
2	0C710	818-SLIPON-FLG-300-0	8" NO SLIP ON FLANGE 300# RF - ASME B16.5	STEEL	58
1	0C710	818-PIPE-SCH-40-SL	8" SCH-STD PIPE-ASME B36.10W	STEEL	57
3	0C710	818-PIPE-SCH-40-SL	8" SCH-STD PIPE-ASME B36.10W	STEEL	56
4	0C710	818-90-DEG-LR-ELBOW	8" 90-DEG LR ELBOW SCH-STD	STEEL	55
6	0C710	8-TE-SS-SLEVE	8-TE-SS-SLEVE		54
6	0C710	8-TE-SS-SLEVE	8-TE-SS-SLEVE		53
2	0C710	818	FLANGE 8" NO SLIP ON 300# RF	STEEL	52
2	0C710	818-SLIPON-FLG-300L	8" NO SLIP ON FLANGE 300# RF - ASME B16.5	STEEL	51
18	0C710	818-SLIPON-FLG-300-0	8" NO SLIP ON FLANGE 300# RF - ASME B16.5	STEEL	50
1	0C710	818-PIPE-SCH-40-SL	8" SCH-STD PIPE-ASME B36.10W	STEEL	49
1	0C710	818-PIPE-SCH-40-SL	8" SCH-STD PIPE-ASME B36.10W	STEEL	48
1	0C710	818-PIPE-SCH-40-SL	8" SCH-STD PIPE-ASME B36.10W	STEEL	47
1	0C710	818-PIPE-SCH-40-SL	8" SCH-STD PIPE-ASME B36.10W	STEEL	46
1	0C710	818-PIPE-SCH-40-SL	8" SCH-STD PIPE-ASME B36.10W	STEEL	45
2	0C710	818-PIPE-SCH-40-SL	8" SCH-STD PIPE-ASME B36.10W	STEEL	44
1	0C710	818-PIPE-SCH-40-SL	8" SCH-STD PIPE-ASME B36.10W	STEEL	43
1	0C710	818-PIPE-SCH-40-SL	8" SCH-STD PIPE-ASME B36.10W	STEEL	42
2	0C710	818-90-DEG-LR-ELBOW	8" 90-DEG LR ELBOW SCH-STD	STEEL	41
6	0C710	818-SLIPON-FLG-100L	8" NO SLIP ON FLANGE 300# RF - ASME B16.5	STEEL	40
5	0C710	818-PIPE-SCH-40-SL	8" SCH-STD PIPE-ASME B36.10W	STEEL	39
1	0C710	818-PIPE-SCH-40-SL	8" SCH-STD PIPE-ASME B36.10W	STEEL	38
1	0C710	818-PIPE-SCH-40-SL	8" SCH-STD PIPE-ASME B36.10W	STEEL	37
1	0C710	818-PIPE-SCH-40-SL	8" SCH-STD PIPE-ASME B36.10W	STEEL	36
1	0C710	818-PIPE-SCH-40-SL	8" SCH-STD PIPE-ASME B36.10W	STEEL	35
1	0C710	818-PIPE-SCH-40-SL	8" SCH-STD PIPE-ASME B36.10W	STEEL	34
1	0C710	818-PIPE-SCH-40-SL	8" SCH-STD PIPE-ASME B36.10W	STEEL	33
1	0C710	818-PIPE-SCH-40-SL	8" SCH-STD PIPE-ASME B36.10W	STEEL	32
1	0C710	818-PIPE-SCH-40-SL	8" SCH-STD PIPE-ASME B36.10W	STEEL	31
1	0C710	818-PIPE-SCH-40-SL	8" SCH-STD PIPE-ASME B36.10W	STEEL	30
2	0C710	818-PIPE-SCH-40-SL	8" SCH-STD PIPE-ASME B36.10W	STEEL	29
19	0C710	818-90-DEG-LR-ELBOW	8" 90-DEG LR ELBOW SCH-STD	STEEL	28
1	0C710	818-90-DEG-LR-ELBOW	8" 90-DEG LR ELBOW SCH-STD	STEEL	27
1	0C710	818-90-DEG-LR-ELBOW	8" 90-DEG LR ELBOW SCH-STD	STEEL	26
1	0C710	818-90-DEG-LR-ELBOW	8" 90-DEG LR ELBOW SCH-STD	STEEL	25
1	0C710	818-90-DEG-LR-ELBOW	8" 90-DEG LR ELBOW SCH-STD	STEEL	24
1	0C710	818-90-DEG-LR-ELBOW	8" 90-DEG LR ELBOW SCH-STD	STEEL	23
1	0C710	818-90-DEG-LR-ELBOW	8" 90-DEG LR ELBOW SCH-STD	STEEL	22
2	0C710	818-90-DEG-LR-ELBOW	8" 90-DEG LR ELBOW SCH-STD	STEEL	21
1	0C710	1035-200-119-1	EXPANSION JOINT W/ 1/4" CLASS 300 FLANGE	FLECKCRAFT MOTOR EXPANSION JOINT	19
1	0C710	10195-201	SMALL FRAME STAGE 1 - 8, GEARBOX & INTERCOOLERS	STEEL	18
1	0C710	10195-201-3-STAGE	ASSY GEARBOX 3-STAGE TURNING LAB PROTOTYPE	STEEL	16
1	0C710	10195-201-3-STAGE	STAGE 3 WHEEL BACKPLATE	STEEL	17
6	0C710	10195-045	818W LAMINATED 302 X 302"	STAINLESS	15
5	0C710	10195-044	STAGE 1 WHEEL BACKPLATE	STEEL	14
81	0C710	10195-045	STAGE 1 AND 2 BACKPLATE	STEEL	13
1	0C710	10195-042	STAGE 2 INLET 8" PIPE 300 LB FLANGE	STEEL	12
1	0C710	10195-041	STAGE 2 SHROUD	STEEL	11
1	0C710	10195-039	STAGE 2 FLOWPATH OUTER VOLUTE EXIT	STEEL	10
1	0C710	10195-037	STAGE 2 LSA	STEEL	9
1	0C710	10195-036	STAGE 2 FLOWPATH	STEEL	8
6	0C710	10195-034	818W LAMINATED 302 X 302"	1100 ALUMINUM	7
5	0C710	10195-033	STAGE 1 INLET 8" PIPE 300 LB FLANGE	STEEL	6
5	0C710	10195-032	STAGE 1 SHROUD	STEEL	5
5	0C710	10195-031	STAGE 1 FLOWPATH OUTER VOLUTE EXIT	STEEL	4
5	0C710	10195-028	STAGE 1 LSA	STEEL	3
5	0C710	10195-026	STAGE 1 FLOWPATH	STEEL	2
1	0C710	10195-024	INPELLER DESIGN STAGE 2-CW	7075-T6 ALUMINUM	1
3	0C710	10195-026	INPELLER DESIGN STAGE 1	7075-T6 ALUMINUM	1
1	0C710	10195-026	INPELLER DESIGN STAGE 1	7075-T6 ALUMINUM	1
1	0C710	10195-026	INPELLER DESIGN STAGE 1	7075-T6 ALUMINUM	1

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# Compressor Module Design Specifications and Major Components

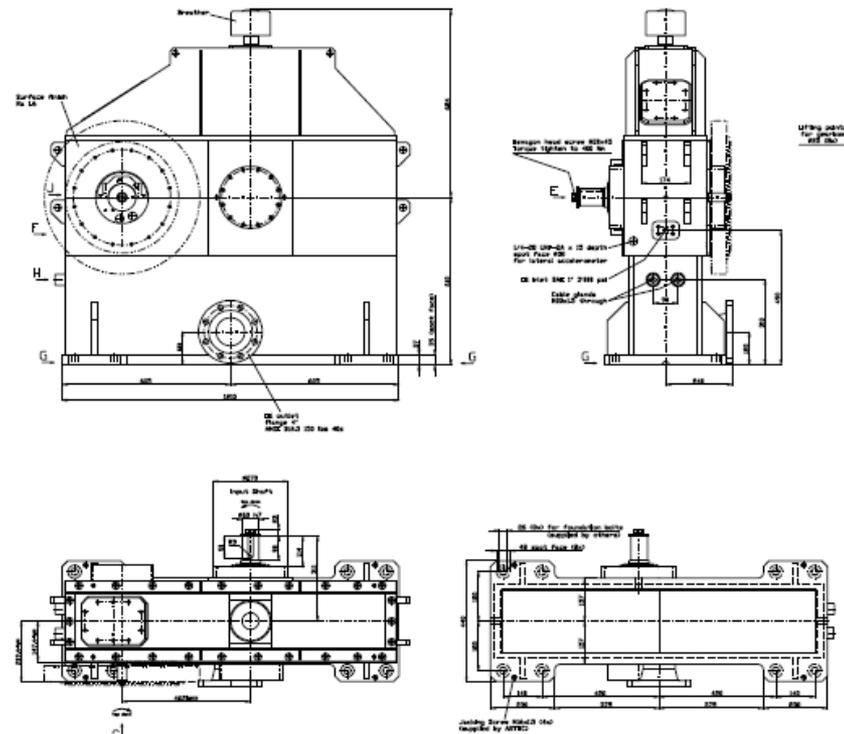
## ► Compressor design specifications for near-term gas industry and DOE infrastructure applications

- $P_{comp.} = 350$  psig to 1285 psig; flow rate = 240,000 kg/day
- Six-stage, 60,000 rpm, 3.56 pressure ratio compressor
- 7075-T6 aluminum alloy
- Nitronic®-50 pressure enclosure
- Integral gearbox pinions driving 6 overhung impellers

## ► Design of compressor's major mechanical elements completed and manufacturers selected

- Artec Machine Systems (Nova Gear, Ltd) gearbox with one-speed step gear operating at acceptable gear tip speeds and loads
- RMT tilting-pad radial bearing designs confirmed for use
- Flowserve gas face-seals confirmed to meet necessary specifications for hydrogen applications

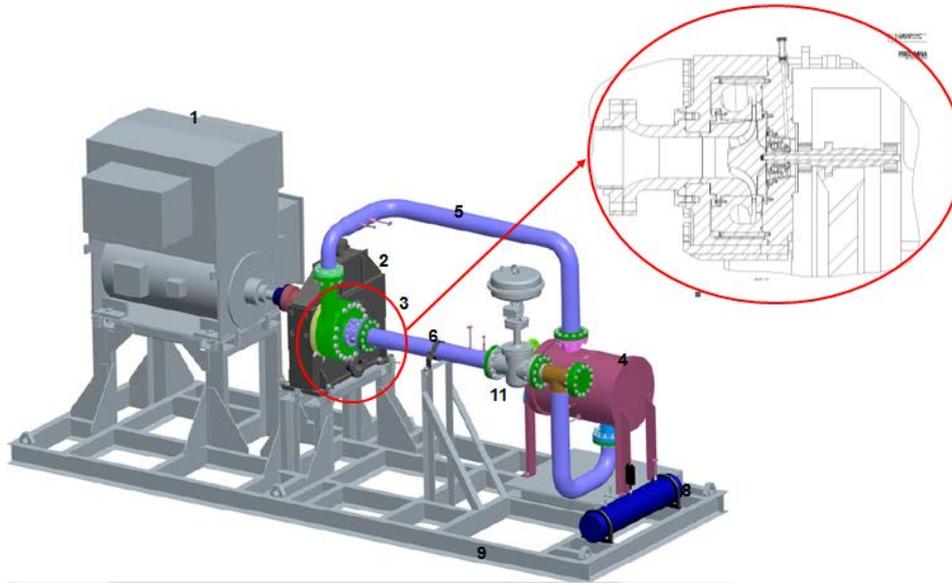
## ► Tranter Plate-type Heat Exchanger design meets specifications to cool hydrogen gas to 105°F between stages using 85°F water



**Full-scale Artec Machine Systems Gearbox for 1-stage System with Bull Gear designed to accommodate 6 Stages**

**In Summary: All compressor subsystems are available "near-term".**

# Focus of Phase II & III: the Design and Assembly of a Laboratory Prototype for Testing



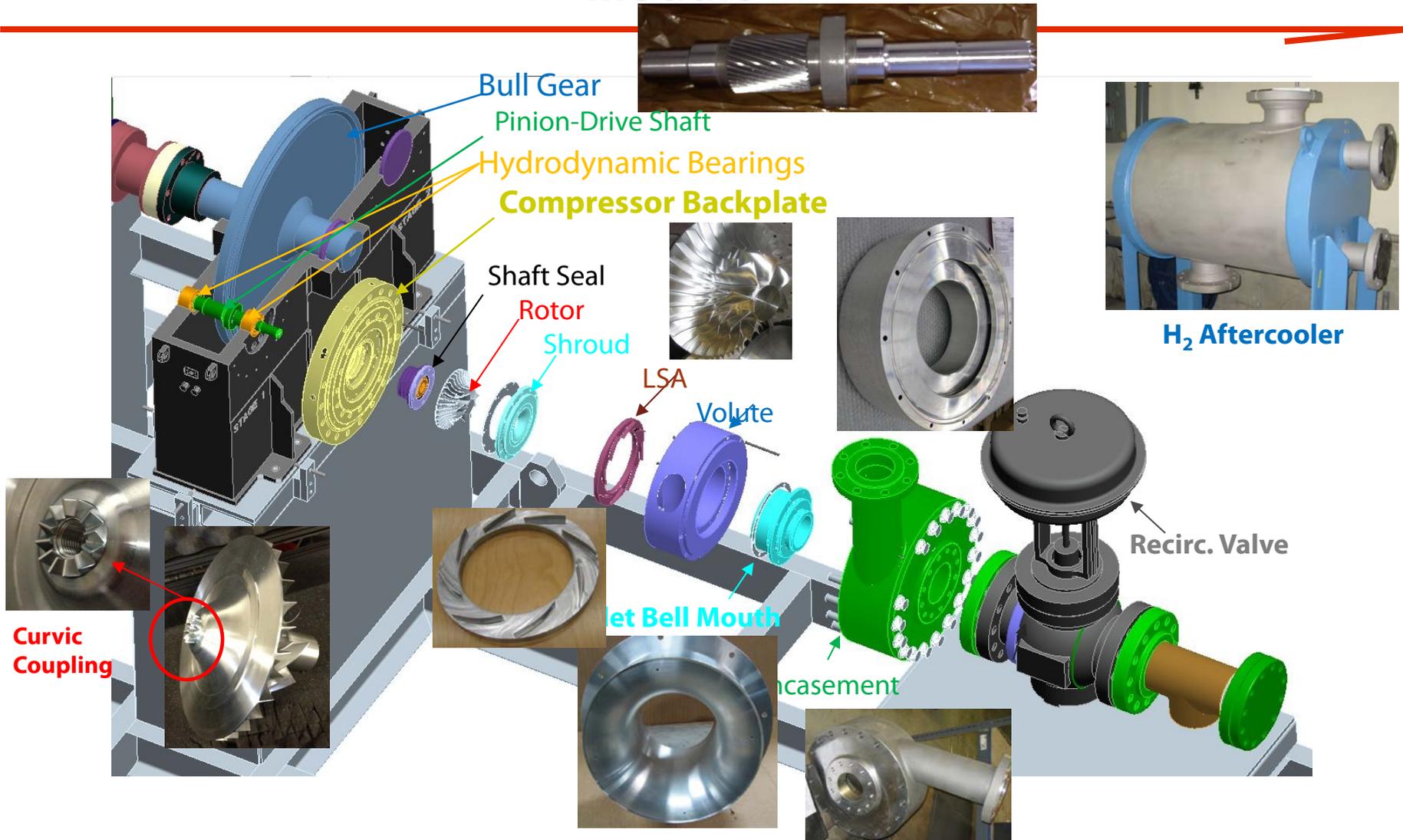
The 1-Stage Compressor Module is 16 ft long, 8 ft wide, and 9 ft tall. based on the itemized weights shown here:

1. 4160 Vac, 1500 hp Induction Motor (3600 rpm):	7500 bf
2. Artec Gearbox (3600 rpm) :	4500 Lbf
3. One, Compressor :	2500 Lbf
4. One, Intercooler:	2500 Lbf
5. 6" comp. out. piping (sch. 40, 20ft):	500 Lbf
6. 6" comp. in piping (sch. 40, 30ft):	450 Lbf
7. Fittings:	700 Lbf
8. Purge Tank (12" d. x 6 ft long):	700 Lbf
9. Base Frame and Support Pedestals:	5000 Lbf
10. Misc.	
11. Shut-Off/Recirc. (PRV) valve	2,500 Lbf

## 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)

# Detail of Prototype, One Stage Hydrogen Compressor Module

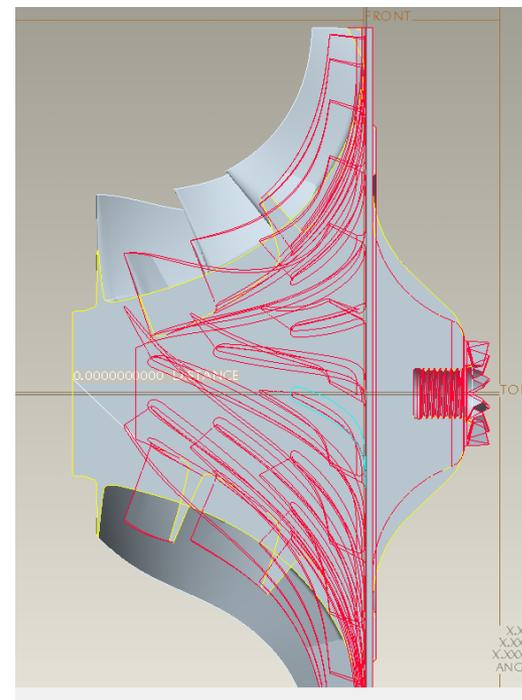


# Detailed Engineering Design for All Six Compressor Rotors Completed and First Stage Manufactured



**Curvic Spline Couples Rotor to Drive Shaft**

**First Stage of 6-Stage Compressor and Drive Shaft with Pinion and Thrust collar**



**Overlay of First and Sixth Stages for Size Comparison**



## Accomplishment and Progress :

### Compressor has been successfully spun to 10% over speed for 15 minutes (66,000 rpm = 2300 ft/s tip speed)

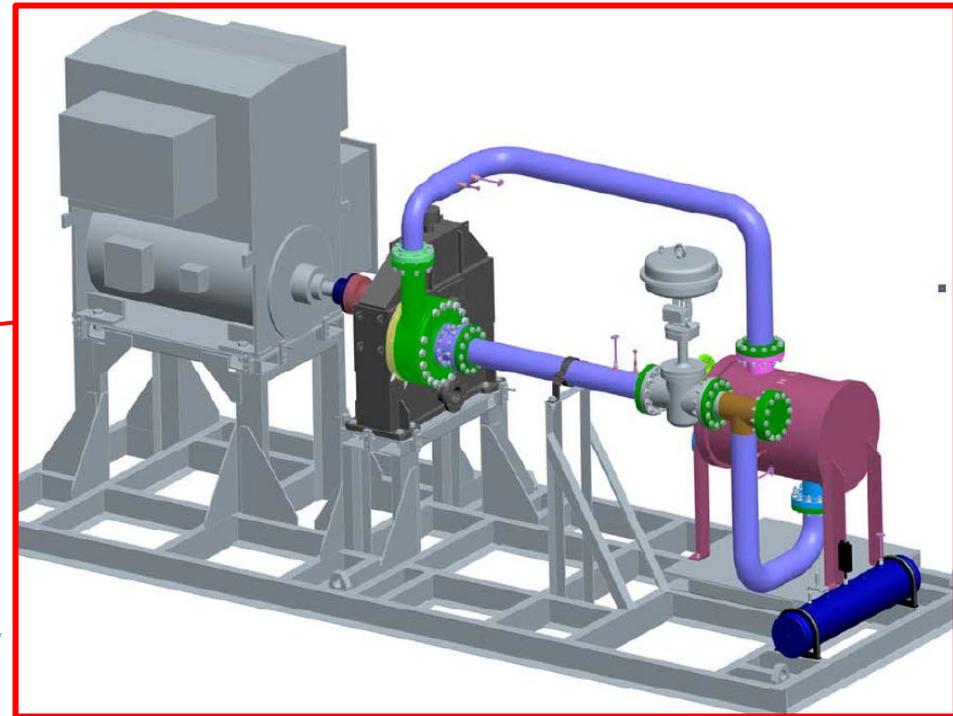
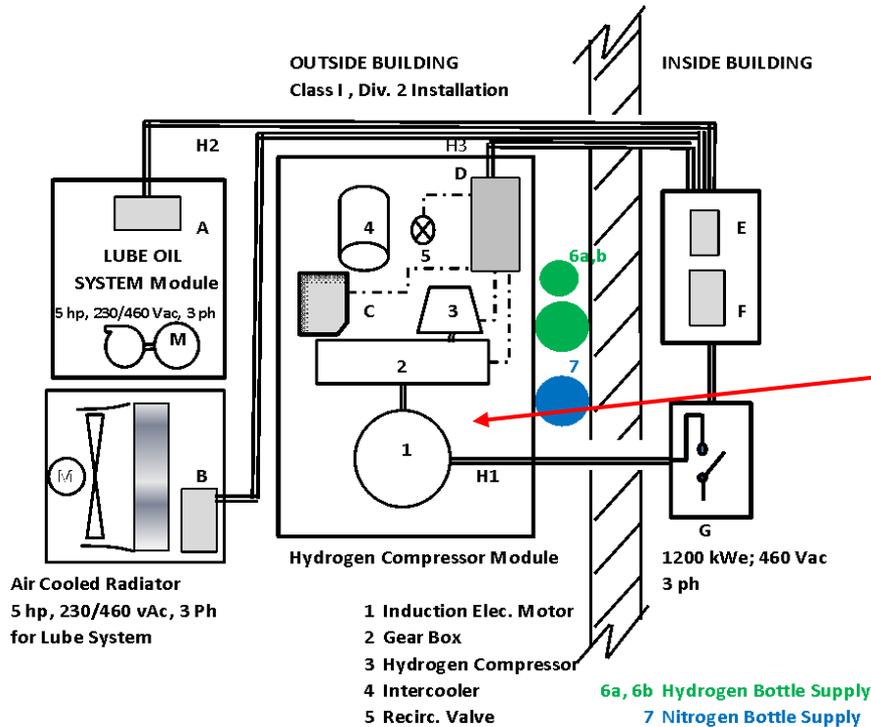


**7075-T6 Aluminum (bore-less) rotor shown after 5-axis machining. CN and TAMU testing has confirmed compatibility of alum. alloy with hydrogen**

#### **Spin test successful:**

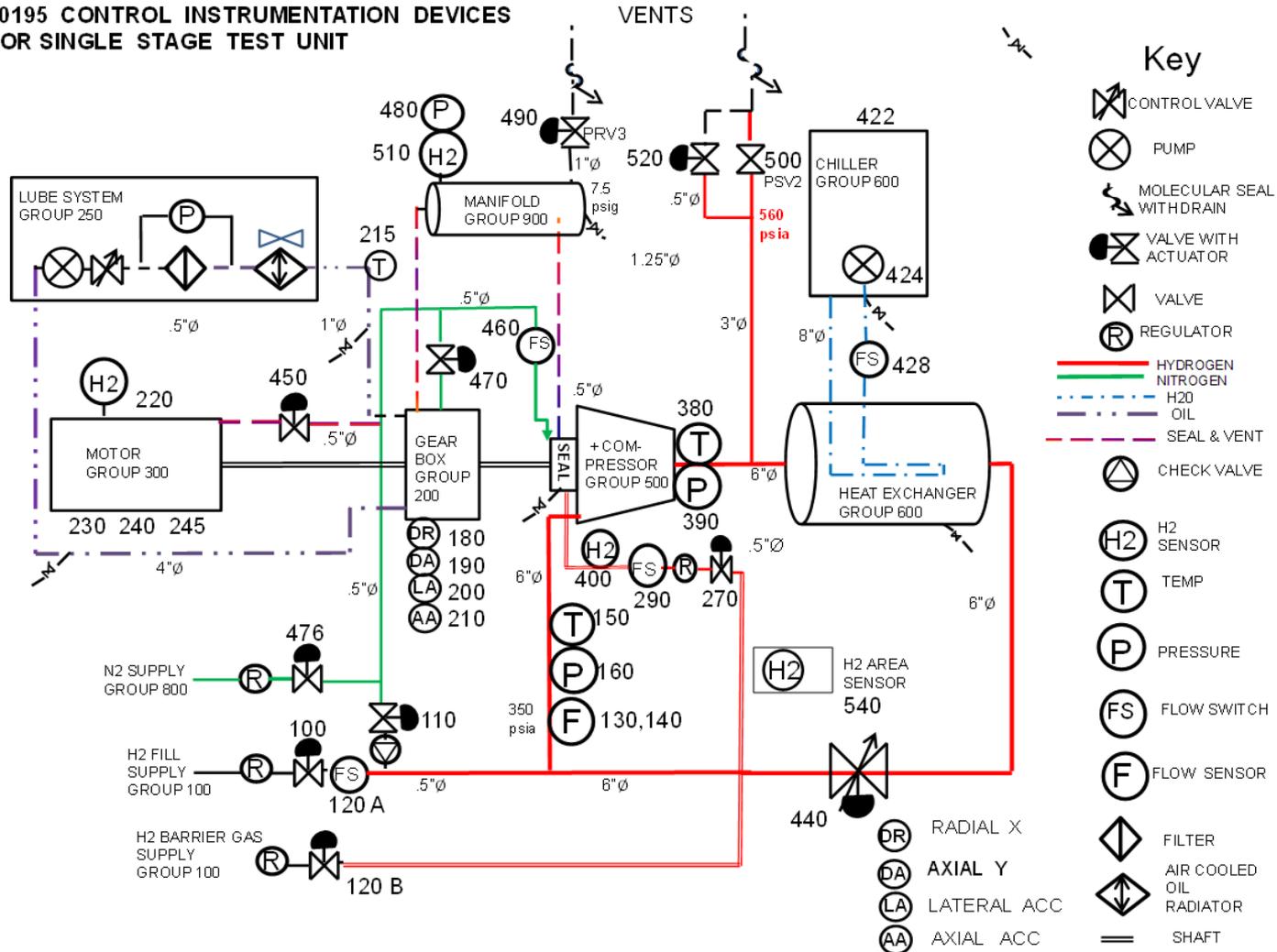
1. Fluorescence Penetrate Inspection indicated no micro-stress fractures or strain issues after
2. Structural analysis has also determined that there is not any concern for material creep at operating temperature (145°F) vs. 1,200°F melting temperature and stress
3. The low blade frequency and stress and the operating requirement of 24/7 duty for pipeline compressor applications eliminates any concern of material fatigue.

# Prototype “Lab” Test Site Installation



# Lab Prototype P&I Diagram

## 10195 CONTROL INSTRUMENTATION DEVICES FOR SINGLE STAGE TEST UNIT



# Project Collaborations: Strengths & Responsibilities of Partners

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## ▶ Air Products and Chemicals, Inc.

- Provides industrial gas user technical experience and gas industry specification data on major components: electric motor, hydrogen safety system, intercooler design, selection of materials of construction

## ▶ Texas A&M University

- Provided material science expertise and coordination of materials testing with Sandia and Savannah River National labs

## ▶ HyGen Industries

- Provides experience in hydrogen fueling infrastructure: pipeline and refueling station systems, has a database of customer-user engineering specifications. Assists in developing implementation plan for pipeline applications for hydrogen compressors

# Future Phase III Project Work in Progress

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## Phase III System Validation Testing

- Continue component procurement for the Lab Prototype, Single-stage hydrogen compressor system (Scheduled completion: July, 2013)
- Assembly of the one-stage centrifugal compressor and closed-loop, lab prototype as a completely functioning compressor system (Scheduled Completion: Sept., 2013)
- Install lab prototype system and conduct aerodynamic testing and assessment of mechanical integrity of the compressor system (Scheduled Completion: Nov. 2013)
- Prepare post-Phase III plan for continuing testing of lab prototype compressor system

# Project Summary

- ▶ **Relevance:** An advanced pipeline compressor system has been designed that meets DOE's performance goals for:
  - High reliability with 350 to 1200+ 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
- ▶ **Approach:** 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 stresses in materials (7075-T6 Rotor, Nitride 31 Chrome Moly Shaft, & Nitronic<sup>®</sup>-50 enclosure) compatible with hydrogen
  - Industrially proven bearings, seal technology, gearing, heat exchangers, and lube system
- ▶ **Tech. Accomplishments & Progress:** Aerodynamic analysis and design of a cost-effective, six-stage centrifugal compressor and a one-stage full-power lab prototype have been completed; spin test of aluminum stage verifies its mechanical integrity, all commercially available compressor subsystems purchased. Research has demonstrated that a Hydrogen Pipeline Centrifugal Compressor is available NOW to meet the Hydrogen Economy requirements of the future!
- ▶ **Technology Transfer/Collaboration:** The collaborative team consists of Air Products, an industrial technical experienced user of hydrogen compressors; a materials researcher, Texas A&M; a hydrogen refueling industry consultant, HyGen; and the coordinated technical support of several National Labs and major component manufacturers.
- ▶ **Proposed Future Research:** Continue the procurement and assembly of the major components for the laboratory testing of a closed-loop, one-stage prototype hydrogen compressor system in Phase III; Prepare Test Plan for the post-Phase III continued testing of lab prototype in a University or Industrial testing lab facility