2013 DOE Hydrogen Program Merit Review

Development of a Centrifugal Hydrogen Pipeline Gas Compressor

Mr. Francis A. Di Bella, P.E. and Dr. Colin Osborne
Concepts NREC (*CN*)

May 15, 2013

Project ID#: PD017

Project Overview

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

- **Demonstrate Advanced Centrifugal Compressor System for High-pressure Hydrogen Pipeline Transport to Support[1]**
  - 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

- 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

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

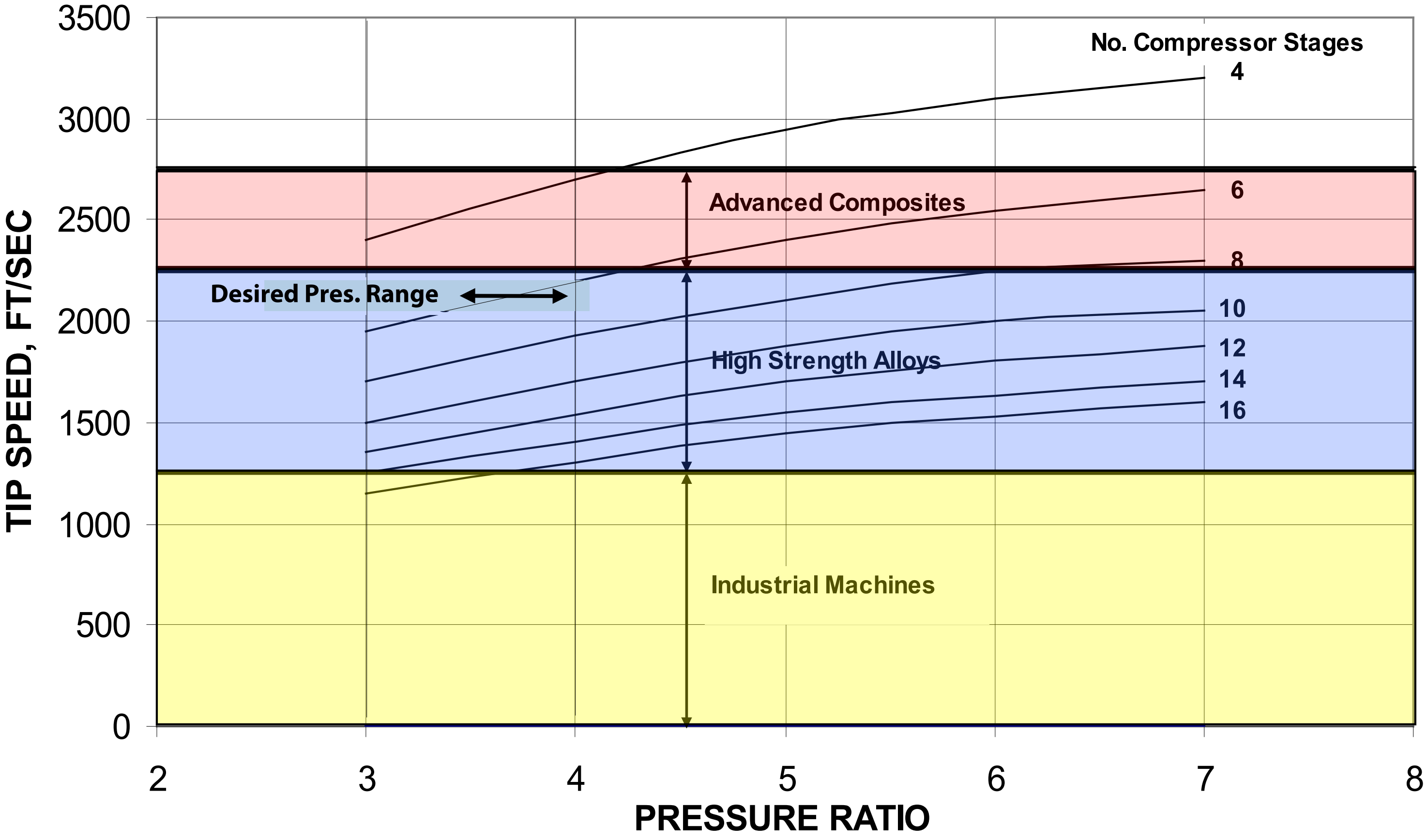
- Maximize centrifugal compressor tip speed within stress limitations of material.
  - Pressure ratio is proportional to $\text{rpm}^2 \times \text{radius}^2$, so small increase in tip speed results in significant increases in pressure.
  - Maximum thermodynamic efficiency is typically achieved at high 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 $\text{rpm}^2 \times \text{radius}^2 \times$ 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

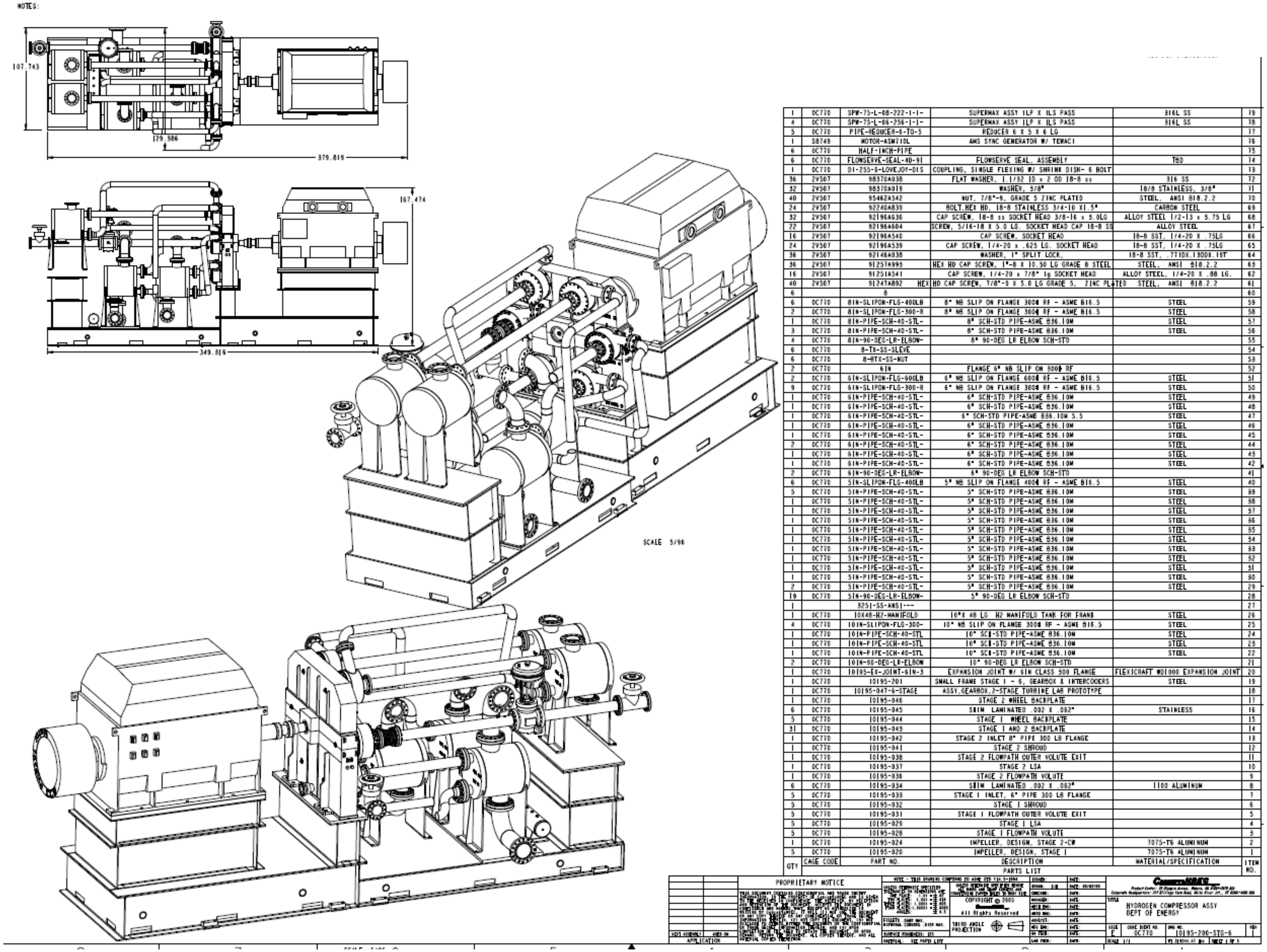
{Note: Letters correspond to DOE's 2007 Technical Plan-Delivery Sec. 3.2-page 16}

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 redundent system	Modular sys.s with 240K kg/day with no redundency 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 kWe



QTY	CAGE CODE	PART NO.	DESCRIPTION	MATERIAL/SPECIFICATION	ITEM NO.
1	0C770	SPW-75-L-08-222-1-1-	SUPERMAX ASSY ILP X ILS PASS	316L SS	79
4	0C770	SPW-75-L-06-256-1-1-	SUPERMAX ASSY ILP X ILS PASS	316L SS	78
5	0C770	PIPE-REDUCER-6-TO-5	REDUCER 6 X 5 X 6 LG		77
1	58749	MOTOR-ASM710L	AMS SYNC GENERATOR W/ TEWAC1		76
6	0C770	HALF-INCH-PIPE			75
6	0C770	FLOWSERVE-SEAL-40-91	FLOWSERVE SEAL, ASSEMBLY	TBD	74
1	0C770	DI-255-6-LOVEJOY-DIS	COUPLING, SINGLE FLEXING W/ SHRINK DISK- 6 BOLT		73
36	2V507	98370A038	FLAT WASHER, 1.1/32 ID x 2 OD 18-8 ss	316 SS	72
32	2V507	98370A019	WASHER, 3/8"	18/8 STAINLESS, 3/8"	71
40	2V507	95462A542	NUT, 7/8"-9, GRADE 5 ZINC PLATED	STEEL, ANSI B18.2.2	70
24	2V507	92240A839	BOLT.HEX HD, 18-8 STAINLESS 3/4-10 X1.5"	CARBON STEEL	69
32	2V507	92196A636	CAP SCREW, 18-8 ss SOCKET HEAD 3/8-16 x 5.0LG	ALLOY STEEL 1/2-13 x 5.75 LG	68
22	2V507	92196A604	SCREW, 5/16-18 X 5.0 LG, SOCKET HEAD CAP 18-8 SS	ALLOY STEEL	67
16	2V507	92196A540	CAP SCREW, SOCKET HEAD	18-8 SST, 1/4-20 X .75LG	66
24	2V507	92196A539	CAP SCREW, 1/4-20 x .625 LG, SOCKET HEAD	18-8 SST, 1/4-20 X .75LG	65
36	2V507	92146A038	WASHER, 1" SPLIT LOCK,	18-8 SST, .771IDX.1300X.19T	64
36	2V507	91257A995	HEX HD CAP SCREW, 1"-8 X 10.50 LG GRADE 8 STEEL	STEEL, ANSI B18.2.2	63
16	2V507	91251A541	CAP SCREW, 1/4-20 x 7/8" lg SOCKET HEAD	ALLOY STEEL, 1/4-20 X .88 LG.	62
40	2V507	91247A892	HEX HD CAP SCREW, 7/8"-9 X 5.0 LG GRADE 5, ZINC PLATED	STEEL, ANSI B18.2.2	61
6		8			60
6	0C770	8IN-SLIPON-FLG-400LB	8" NB SLIP ON FLANGE 300# RF - ASME B16.5	STEEL	59
2	0C770	8IN-SLIPON-FLG-300-R	8" NB SLIP ON FLANGE 300# RF - ASME B16.5	STEEL	58
1	0C770	8IN-PIPE-SCH-40-STL-	8" SCH-STD PIPE-ASME B36.10M	STEEL	57
3	0C770	8IN-PIPE-SCH-40-STL-	8" SCH-STD PIPE-ASME B36.10M	STEEL	56
4	0C770	8IN-90-DEG-LR-ELBOW-	8" 90-DEG LR ELBOW SCH-STD		55
6	0C770	8-TX-SS-SLEVE			54
6	0C770	8-BTX-SS-NUT			53
2	0C770	6IN	FLANGE 6" NB SLIP ON 300# RF		52
2	0C770	6IN-SLIPON-FLG-600LB	6" NB SLIP ON FLANGE 600# RF - ASME B16.5	STEEL	51
9	0C770	6IN-SLIPON-FLG-300-R	6" NB SLIP ON FLANGE 300# RF - ASME B16.5	STEEL	50
1	0C770	6IN-PIPE-SCH-40-STL-	6" SCH-STD PIPE-ASME B36.10M	STEEL	49
1	0C770	6IN-PIPE-SCH-40-STL-	6" SCH-STD PIPE-ASME B36.10M	STEEL	48
1	0C770	6IN-PIPE-SCH-40-STL-	6" SCH-STD PIPE-ASME B36.10M 5.5	STEEL	47
1	0C770	6IN-PIPE-SCH-40-STL-	6" SCH-STD PIPE-ASME B36.10M	STEEL	46
1	0C770	6IN-PIPE-SCH-40-STL-	6" SCH-STD PIPE-ASME B36.10M	STEEL	45
2	0C770	6IN-PIPE-SCH-40-STL-	6" SCH-STD PIPE-ASME B36.10M	STEEL	44
1	0C770	6IN-PIPE-SCH-40-STL-	6" SCH-STD PIPE-ASME B36.10M	STEEL	43
1	0C770	6IN-PIPE-SCH-40-STL-	6" SCH-STD PIPE-ASME B36.10M	STEEL	42
2	0C770	6IN-90-DEG-LR-ELBOW-	6" 90-DEG LR ELBOW SCH-STD		41
6	0C770	5IN-SLIPON-FLG-400LB	5" NB SLIP ON FLANGE 400# RF - ASME B16.5	STEEL	40
5	0C770	5IN-PIPE-SCH-40-STL-	5" SCH-STD PIPE-ASME B36.10M	STEEL	39
1	0C770	5IN-PIPE-SCH-40-STL-	5" SCH-STD PIPE-ASME B36.10M	STEEL	38
1	0C770	5IN-PIPE-SCH-40-STL-	5" SCH-STD PIPE-ASME B36.10M	STEEL	37
1	0C770	5IN-PIPE-SCH-40-STL-	5" SCH-STD PIPE-ASME B36.10M	STEEL	36
1	0C770	5IN-PIPE-SCH-40-STL-	5" SCH-STD PIPE-ASME B36.10M	STEEL	35
1	0C770	5IN-PIPE-SCH-40-STL-	5" SCH-STD PIPE-ASME B36.10M	STEEL	34
1	0C770	5IN-PIPE-SCH-40-STL-	5" SCH-STD PIPE-ASME B36.10M	STEEL	33
1	0C770	5IN-PIPE-SCH-40-STL-	5" SCH-STD PIPE-ASME B36.10M	STEEL	32
1	0C770	5IN-PIPE-SCH-40-STL-	5" SCH-STD PIPE-ASME B36.10M	STEEL	31
1	0C770	5IN-PIPE-SCH-40-STL-	5" SCH-STD PIPE-ASME B36.10M	STEEL	30
2	0C770	5IN-PIPE-SCH-40-STL-	5" SCH-STD PIPE-ASME B36.10M	STEEL	29
19	0C770	5IN-90-DEG-LR-ELBOW-	5" 90-DEG LR ELBOW SCH-STD		28
1		3251-SS-ANSI---			27
1	0C770	10X48-H2-MANIFOLD	10"X 48 LG H2 MANIFOLD TANK FOR FRAME	STEEL	26
4	0C770	10IN-SLIPON-FLG-300-	10" NB SLIP ON FLANGE 300# RF - ASME B16.5	STEEL	25
1	0C770	10IN-PIPE-SCH-40-STL	10" SCH-STD PIPE-ASME B36.10M	STEEL	24
1	0C770	10IN-PIPE-SCH-40-STL	10" SCH-STD PIPE-ASME B36.10M	STEEL	23
1	0C770	10IN-PIPE-SCH-40-STL	10" SCH-STD PIPE-ASME B36.10M	STEEL	22
2	0C770	10IN-90-DEG-LR-ELBOW	10" 90-DEG LR ELBOW SCH-STD		21
1	0C770	10195-EX-JOINT-6IN-3	EXPANSION JOINT W/ 6IN CLASS 300 FLANGE	FLEXICRAFT WD1000 EXPANSION JOINT	20
1	0C770	10195-201	SMALL FRAME STAGE 1 - 6, GEARBOX & INTERCOOLERS	STEEL	19
1	0C770	10195-047-6-STAGE	ASSY,GEARBOX,2-STAGE TURBINE LAB PROTOTYPE		18
1	0C770	10195-046	STAGE 2 WHEEL BACKPLATE		17
6	0C770	10195-045	SHIM LAMINATED .002 X .062"	STAINLESS	16
5	0C770	10195-044	STAGE 1 WHEEL BACKPLATE		15
31	0C770	10195-043	STAGE 1 AND 2 BACKPLATE		14
1	0C770	10195-042	STAGE 2 INLET 8" PIPE 300 LB FLANGE		13
1	0C770	10195-041	STAGE 2 SHROUD		12
1	0C770	10195-038	STAGE 2 FLOWPATH OUTER VOLUTE EXIT		11
1	0C770	10195-037	STAGE 2 LSA		10
1	0C770	10195-036	STAGE 2 FLOWPATH VOLUTE		9
6	0C770	10195-034	SHIM LAMINATED .002 X .062"	1100 ALUMINUM	8
5	0C770	10195-033	STAGE 1 INLET, 6" PIPE 300 LB FLANGE		7
5	0C770	10195-032	STAGE 1 SHROUD		6
5	0C770	10195-031	STAGE 1 FLOWPATH OUTER VOLUTE EXIT		5
5	0C770	10195-029	STAGE 1 LSA		4
5	0C770	10195-028	STAGE 1 FLOWPATH VOLUTE		3
1	0C770	10195-024	IMPELLER, DESIGN, STAGE 2-CW	7075-T6 ALUMINUM	2
5	0C770	10195-020	IMPELLER, DESIGN, STAGE 1	7075-T6 ALUMINUM	1

PARTS LIST

PROPRIETARY NOTICE

COPYRIGHT © 2005

All Rights Reserved

THIRD ANGLE PROJECTION

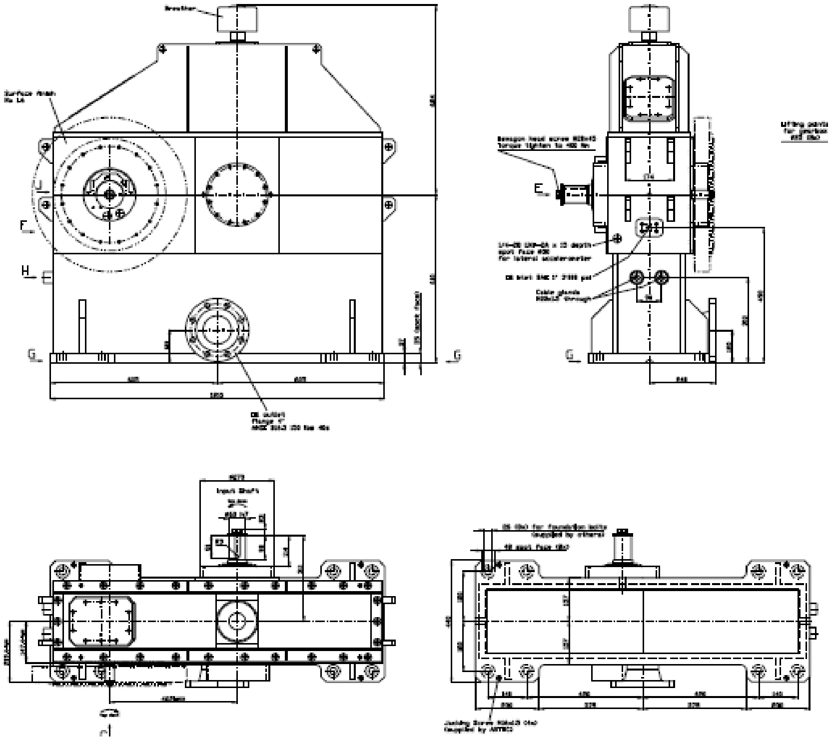
TITLE
HYDROGEN COMPRESSOR ASSY
DEPT OF ENERGY

SIZE E
CAGE CODE 0C770
DWG NO. 10195-200-STG-6
REV 1

![Concepts NREC]

Compressor Module Design Specifications and Major Components

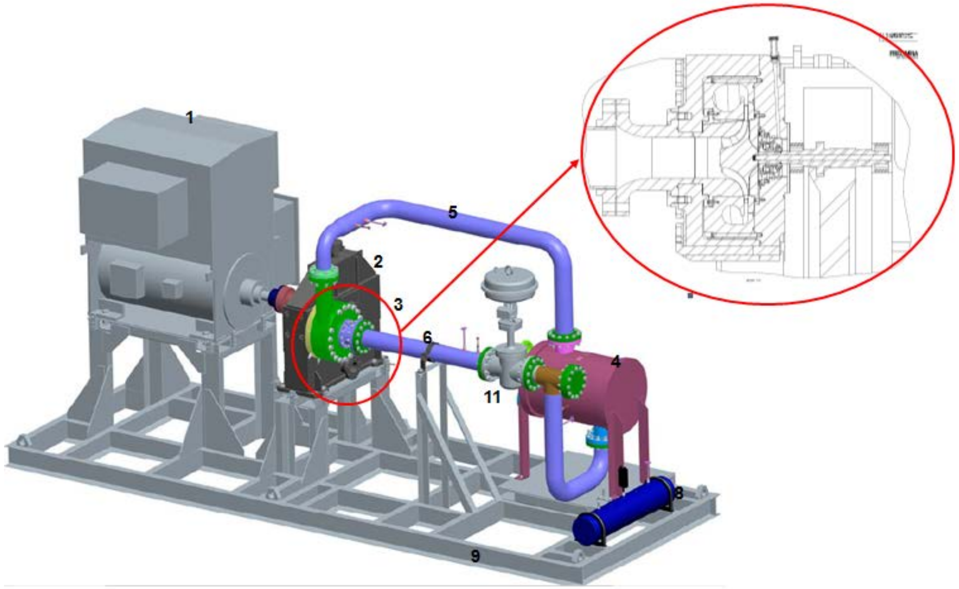
- **Compressor design specifications for near-term gas industry and DOE infrastructure applications**
  - $P_{comp.}$ = 350 psig to 1285 psig; flow rate = 240,000 kg/day
  - Six-stage, 60,000 rpm, 3.56 pressure ratio compressor
  - 7075-T6 aluminum alloy
  - Nitronic®-50 pressure enclosure
  - Integral 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



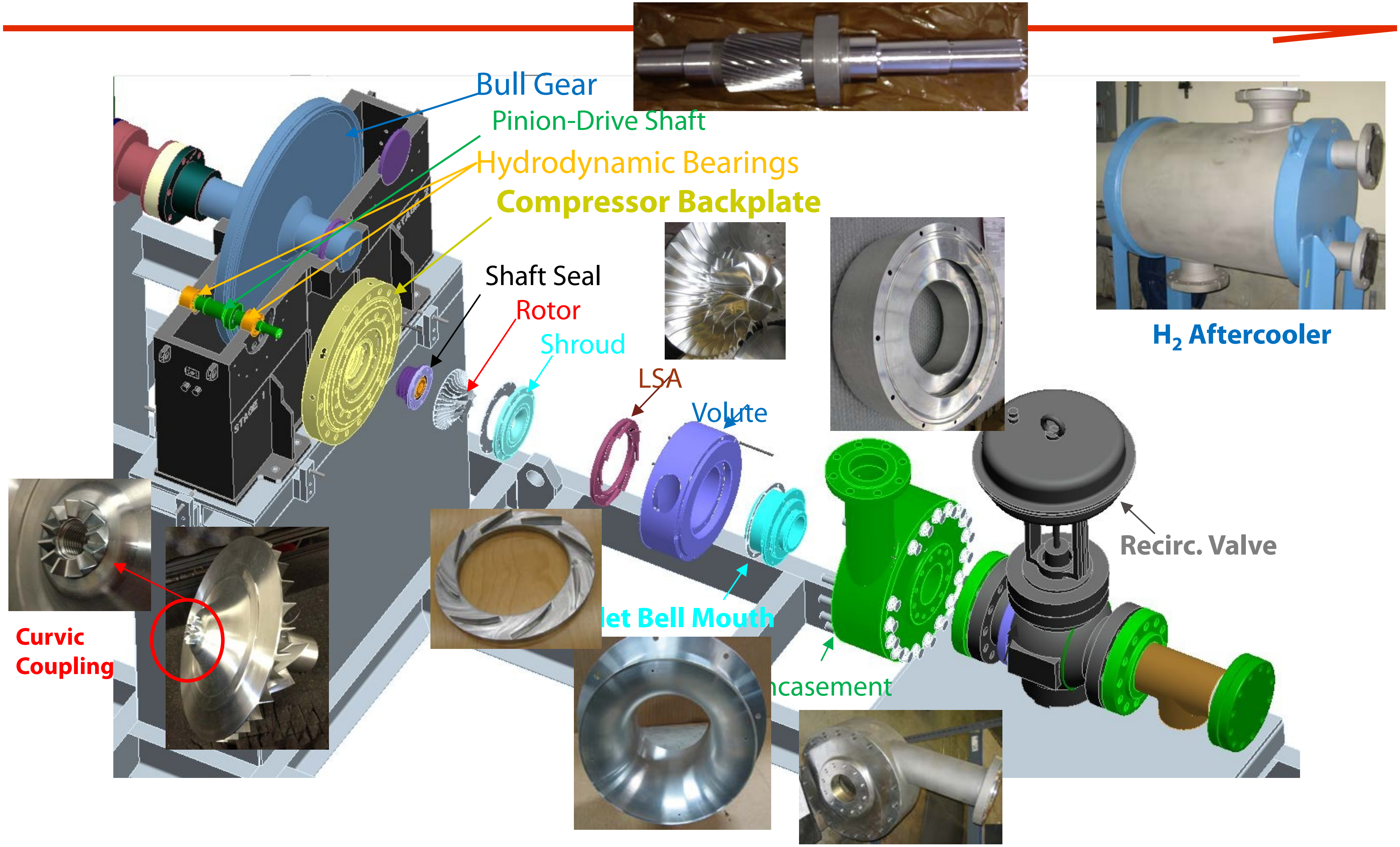
The 1-Stage Compressor Module is 16 ft long, 8 ft wide, and 9 ft tall. based on the itemized weights shown here:

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)**

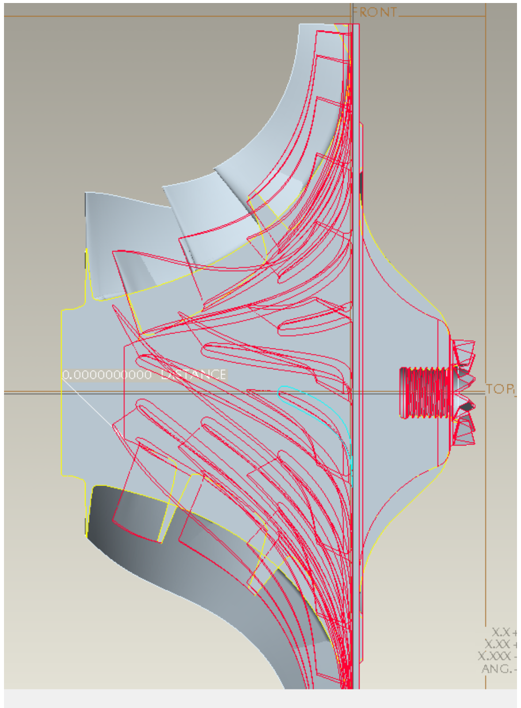
Detail of Prototype, One Stage Hydrogen Compressor Module



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

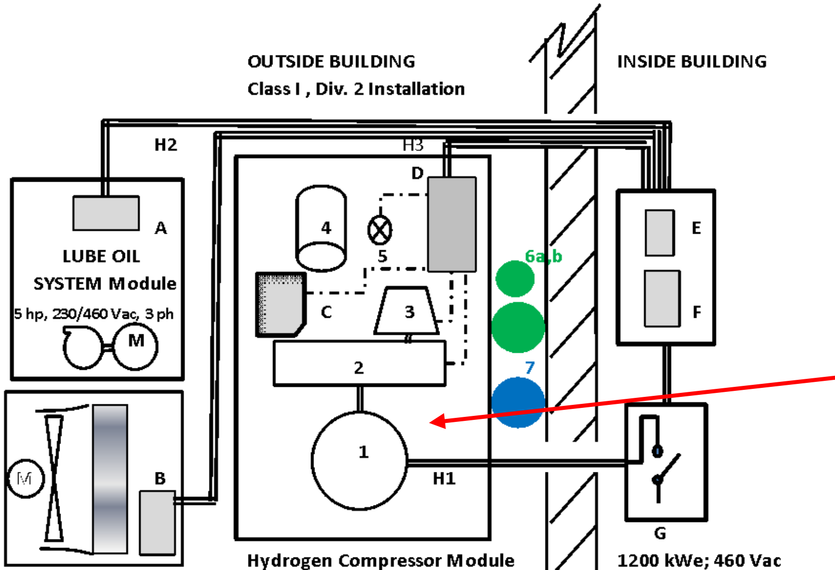
Accomplishment and Progress : Compressor has been successfully spun to 10% over speed for 15 minutes (66,000 rpm = 2300 ft/s tip speed)

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



OUTSIDE BUILDING
Class I , Div. 2 Installation

INSIDE BUILDING

Hydrogen Compressor Module

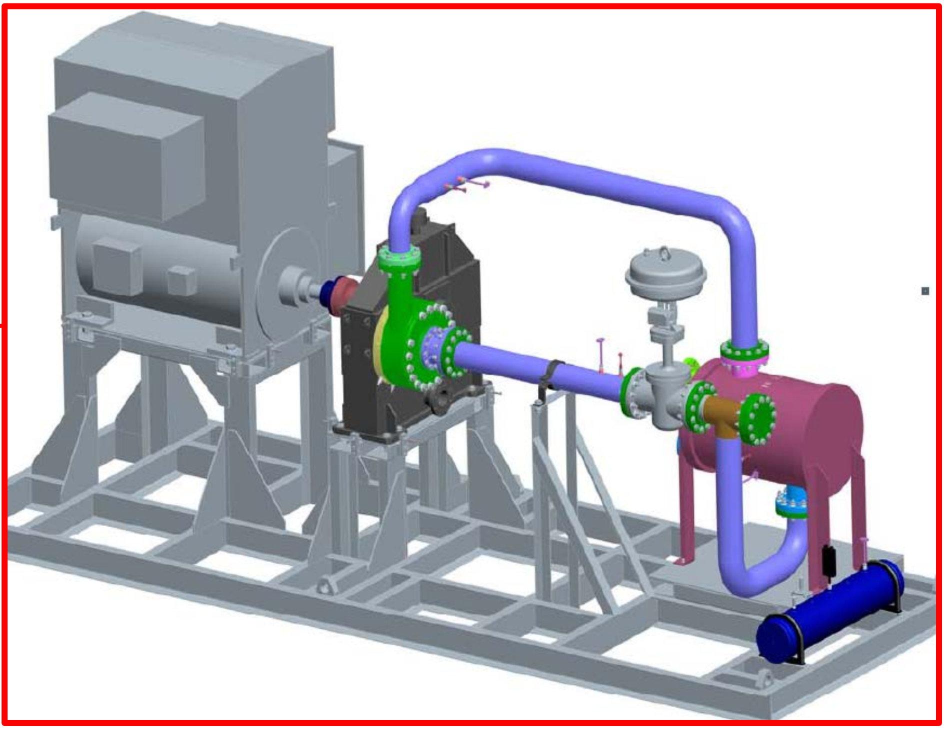
Air Cooled Radiator
5 hp, 230/460 vAc, 3 Ph
for Lube System

1200 kWe; 460 Vac
3 ph

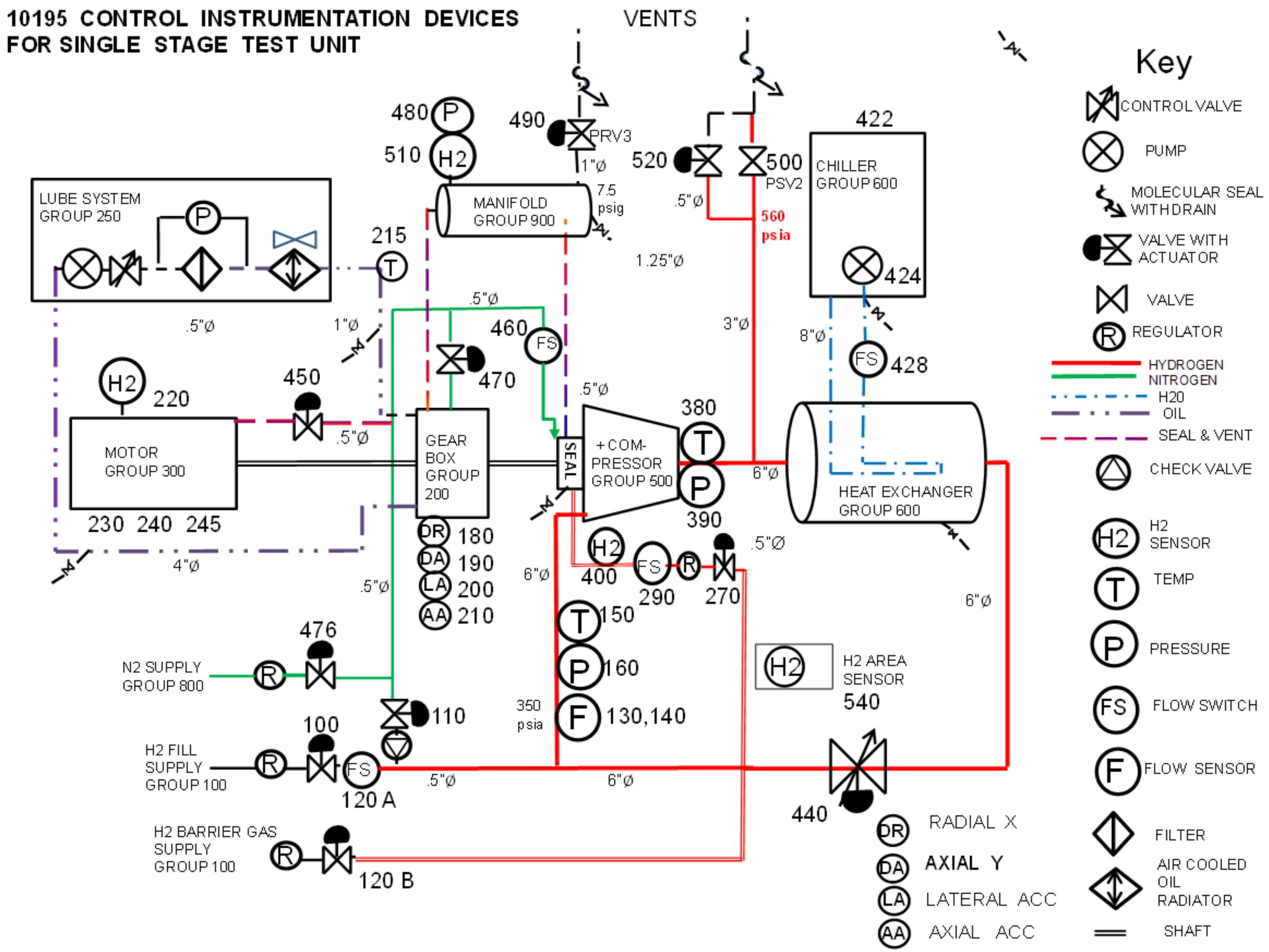
1 Induction Elec. Motor
2 Gear Box
3 Hydrogen Compressor
4 Intercooler
5 Recirc. Valve

6a, 6b Hydrogen Bottle Supply
7 Nitrogen Bottle Supply

A Lube Oil Control Panel with Disconnect from Concepts NREC
B Air Fan Motor Starter from Concepts NREC
C Hydrogen Monitor from Concepts NREC
D I/O Interconnect panel for connecting PT's, TT's and
Compressor Vib. Monitoring
E Data Acquisition (combined with PLC ?)
F PLC
G Motor Disconnect and Soft Start
H1,2,3 Electrical Conduit for controls and power wiring



Lab Prototype P&I Diagram



Project Collaborations: Strengths & Responsibilities of Partners

- **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

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®-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. <u>Research has demonstrated that a Hydrogen Pipeline Centrifugal Compressor is available NOW to meet the Hydrogen Economy requirements of the future!</u>**
- **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**