Advanced Centrifugal Compression and Pumping for CO_2 Applications

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- Space Science
- Nuclear Waste
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- Applied Power
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- Electronics

- **Mechanical Engineering**
  - Rotating Machinery Group

- 1200 Acres
- 2 million Ft^2

- 3200 Employees
- 1200 Engineers
- 170 Buildings

Project Motivation

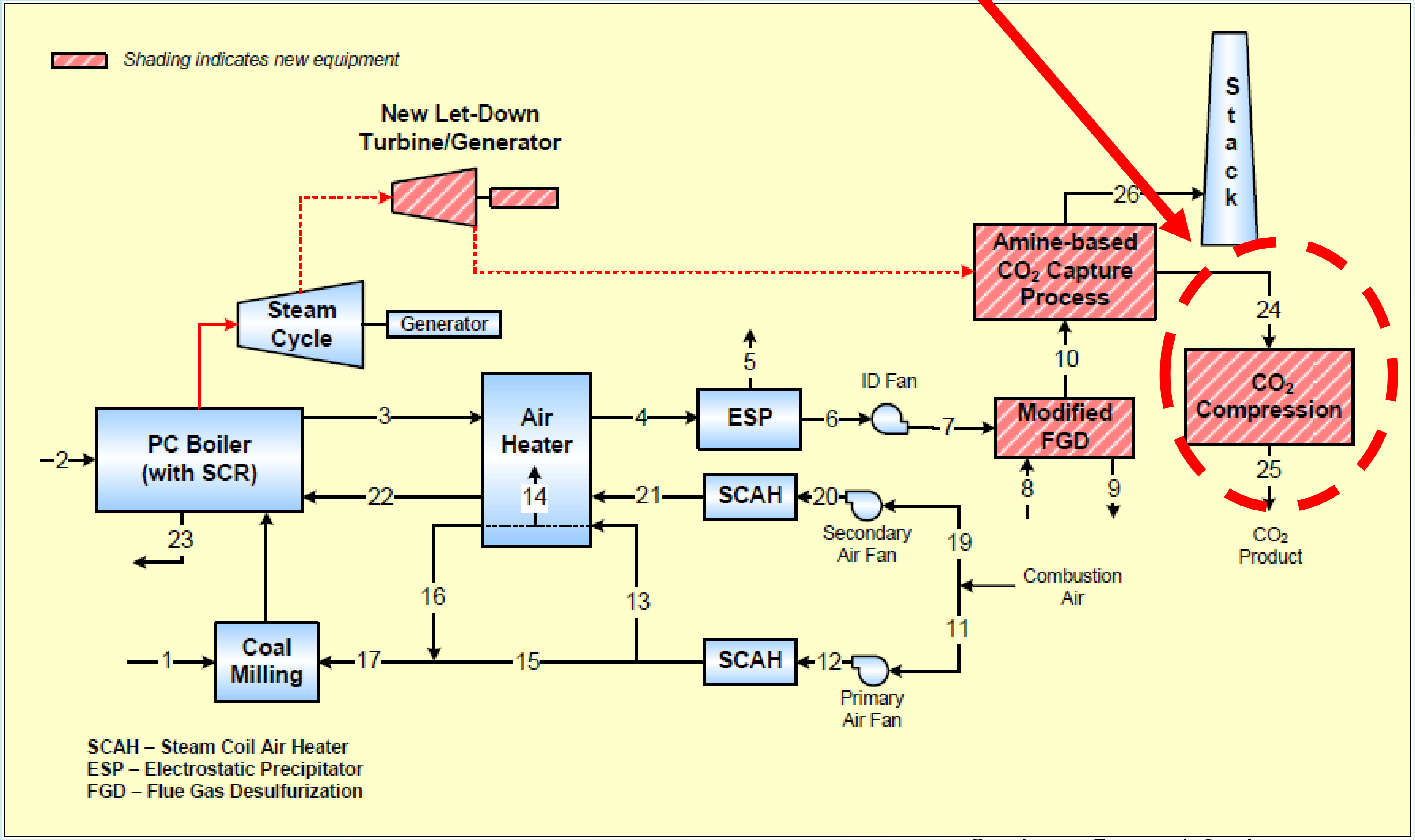
- CO_2 capture has a significant compression penalty - as high as 8 to 12%.
- Final pressure around 1,500 to 2,200 psia for pipeline transport or re-injection.
- Based on a 400 MW coal plant, the typical flow rate is ~600,000 to 700,000 lbm/hr.
- Project goal: Double-digit reduction of compression power for CO_2 capture
- Many thermodynamic processes studied.
- Several challenges with the application discussed.

Project Overview

- Phase I (Completed)
  - Perform thermodynamic study to identify optimal compression schemes
- Phase II (Completed in 2010)
  - Test Rig testing of two concepts:
    - Isothermal compression (complete)
    - Liquid CO_2 pumping (complete)
- Phase III (Kicked off 2nd Qtr 2011)
  - Pilot scale compression plant
  - 55,000 lbm/hr

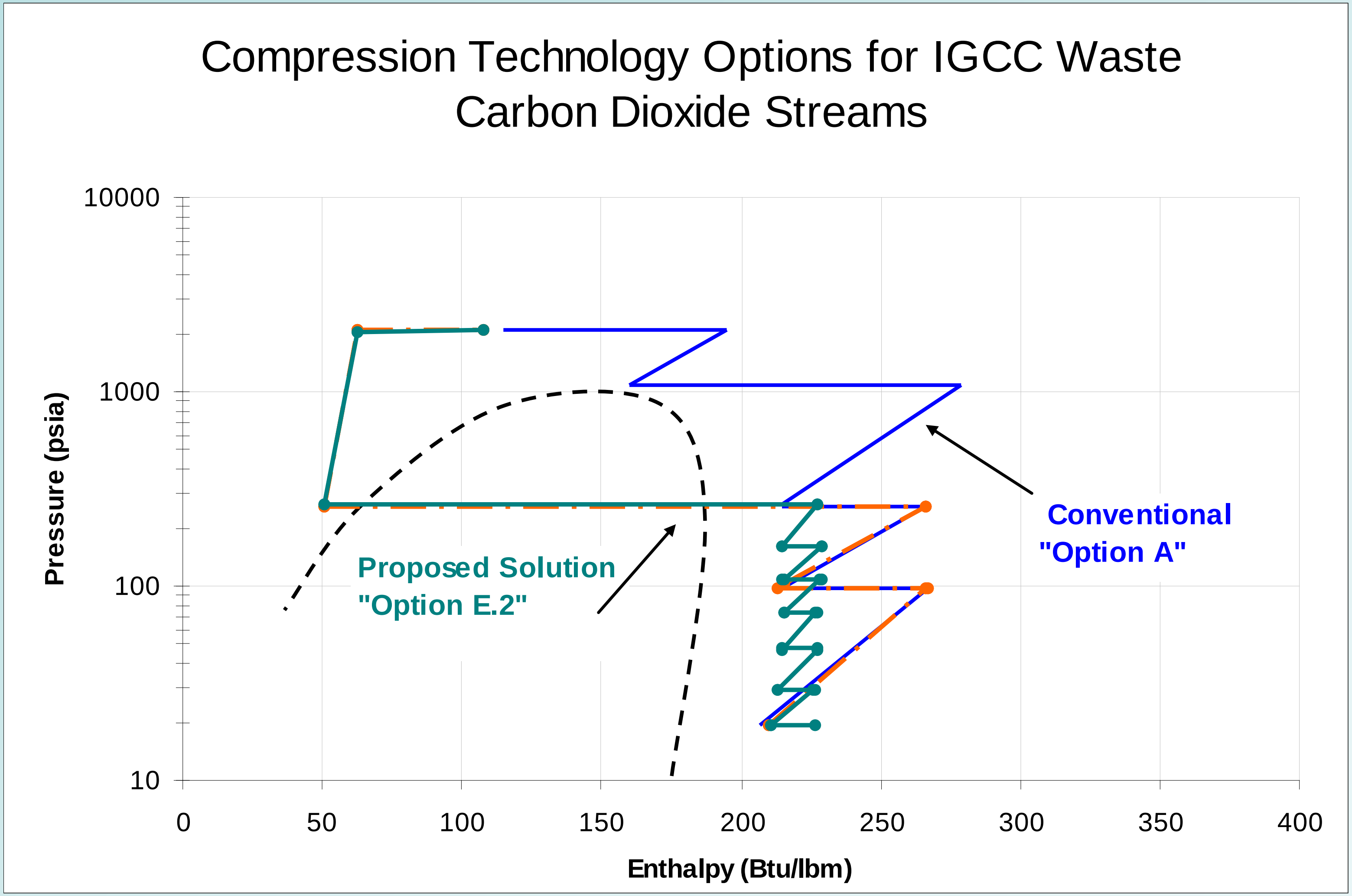
DOE PC Reference Case

- Only CO_2 stream considered



DOE/NETL report 401/110907

Proposed Solution for Optimal Efficiency



Optimal solution combines inter-stage cooling and a liquefaction approach.

Summary of Thermodynamic Analysis for IGCC Plant

Option	Compression Technology	Power Requirements	% Diff from Option A	Cooling Technology
A	Conventional Dresser-Rand Centrifugal 16-stage Compression	23,251 BHP	0.0%	Air-cool streams between separate stages
B	Conventional Dresser-Rand Centrifugal 16-stage Compression with additional cooling	21,522 BHP	-7.4%	Air-cool streams between separate stages using ASU cool N2 stream
C.1	Isothermal compression at 70 degF and 80% efficiency	14,840 BHP	-36.2%	Tc = 70 degF inlet temp throughout
C.4	Semi-isothermal compression at 70 degF, Pressure Ratio ~ 1.55	17,025 BHP (Required Cooling Power TBD)	-26.8%	Tc = 70degF in between each stage.
C.7	Semi-isothermal compression at 100 degF, Pressure Ratio ~ 1.55	17,979 BHP (Required Cooling Power TBD)	-22.7%	Tc = 100degF in between each stage.

Summary of Thermodynamic Analysis for IGCC Plant Cont.

Option	Compression Technology	Power Requirements	% Diff from Option A	Cooling Technology
E.1	Centrifugal compression to 250 psia, Liquid cryo-pump from 250-2215 psia	16,198 BHP (Includes 7,814 BHP for Refrigeration) [1]	-30.33%	Air cool up to 250 psia, Refrigeration to reduce CO_2 to -25degF to liquify
E.2	Centrifugal compression to 250 psia with semi-isothermal cooling at 100 degF, Liquid cryo-pump from 250-2215 psia	15,145 BHP (Includes 7,814 BHP for Refrigeration) [1]	-34.86%	Air cool up to 250 psia between centrifugal stages, Refrigeration to reduce CO_2 to -25degF to liquify

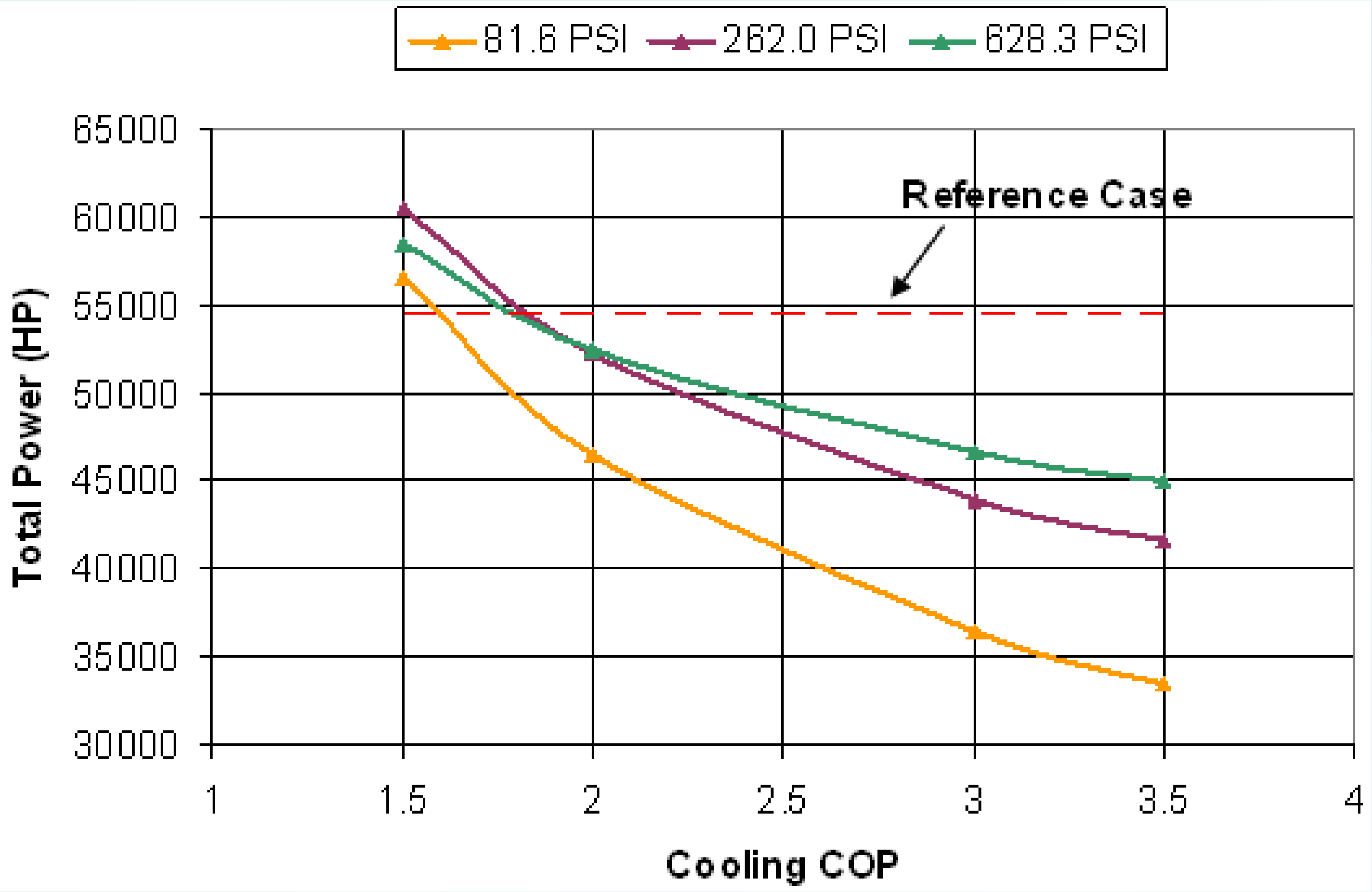
Note: Heat recovery not accounted for.

Summary of Thermodynamic Analysis

- Liquefaction process
  - Utilize a refrigeration system to condense CO_2 at 250 psia and -12ºF.
  - Liquid then pumped from 250 to 2,200 psia.
  - Requires significantly less power to pump liquid than to compress a gas.
  - The cost of the refrigeration system must be accounted for.

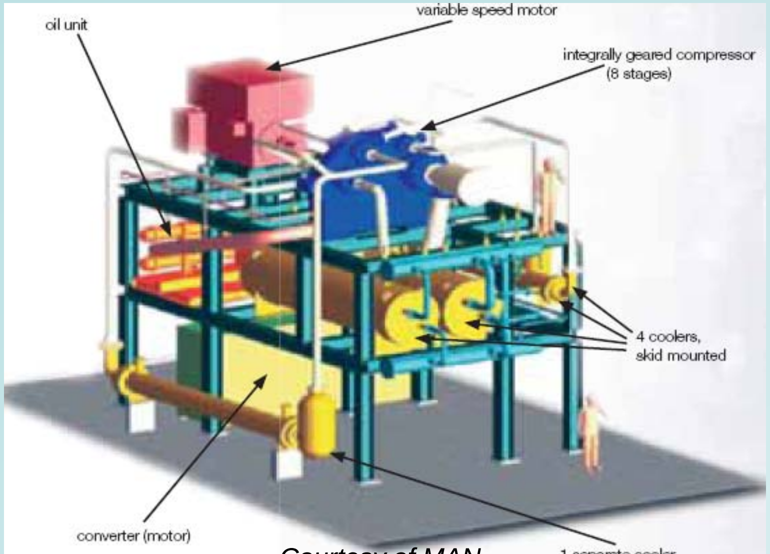
Compression Power for PC Plant

Liquefaction/Pumping Compression



Challenges: High Reliability

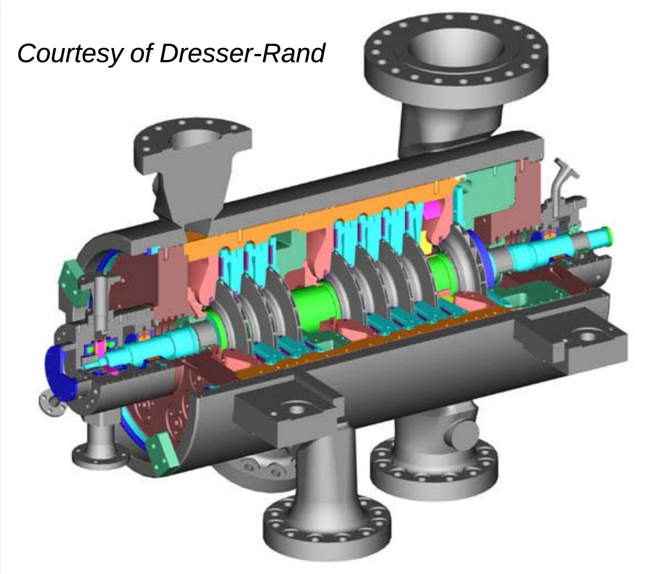
Integrally Geared Isothermal Compressor



Courtesy of MAN

- Integrally geared can achieve near isothermal compression
- Can contain up to 12 bearings, 10 gas seals plus gearbox
- Typically driven by electric motor
- Impellers spin at different rates
  - Maintain optimum flow coef.

Single-Shaft Multi-stage Centrifugal Compressor



Courtesy of Dresser-Rand

- Multi-stage centrifugal proven reliable and used in many critical service applications currently (oil refining, LNG production, etc.)
- Fewer bearings and seals
  - (4 brgs & seals for 2 body train)
- Can be direct driven by steam turbine

Project Goals

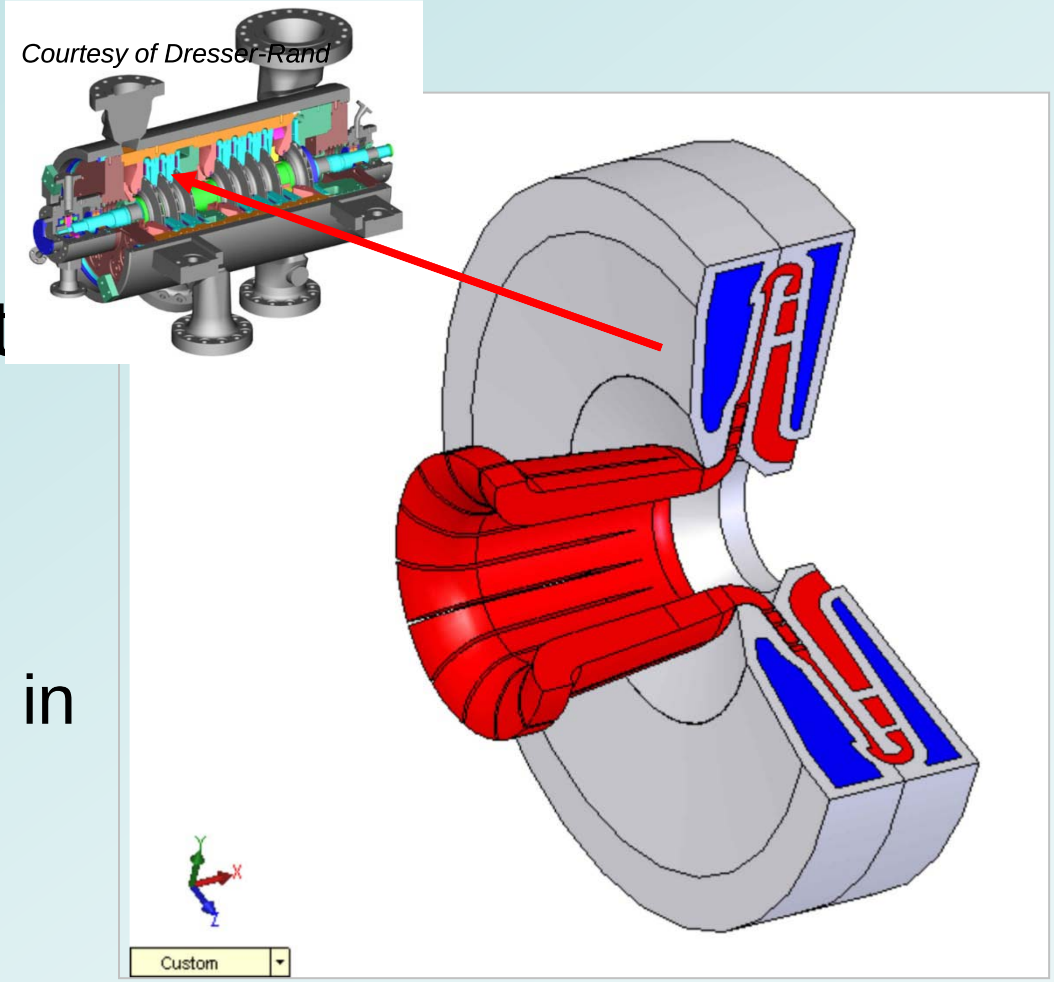
- Develop internally cooled compressor stage that:
  - Provides performance of an integrally geared compressor
  - Has the reliability of a in-line centrifugal compressor
  - Reduces the overall footprint of the package
  - Has less pressure drop than a external intercooler
- Perform qualification testing of a refrigerated liquid CO2 pump

Phase 2 Project Plan

- Experimentally validate thermodynamic predictions.
- Two test programs envisaged:
  - Liquid CO_2 pumping loop
  - Closed-loop CO_2 compressor test with internal cooling
- Power savings will be quantified in both tests.

Internally Cooled Compressor Concept

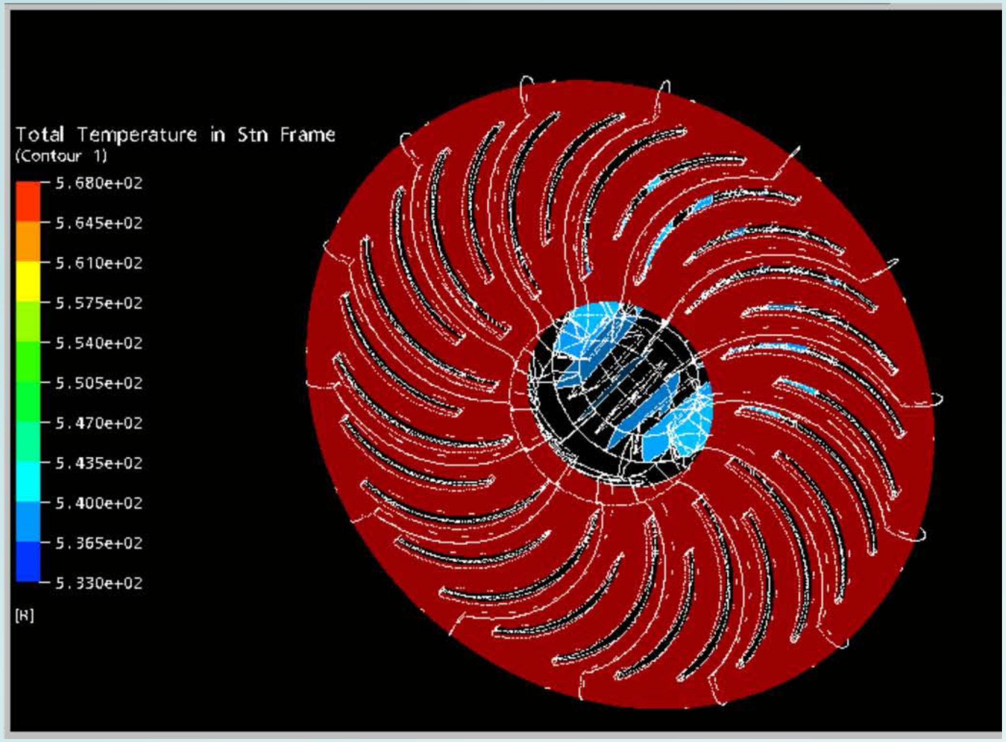
- Investigate an internally-cooled compressor concept
  - Red - CO_2 flow path through compressor stage
  - Blue - Liquid cooling in the diaphragm
  - Grey - Solid



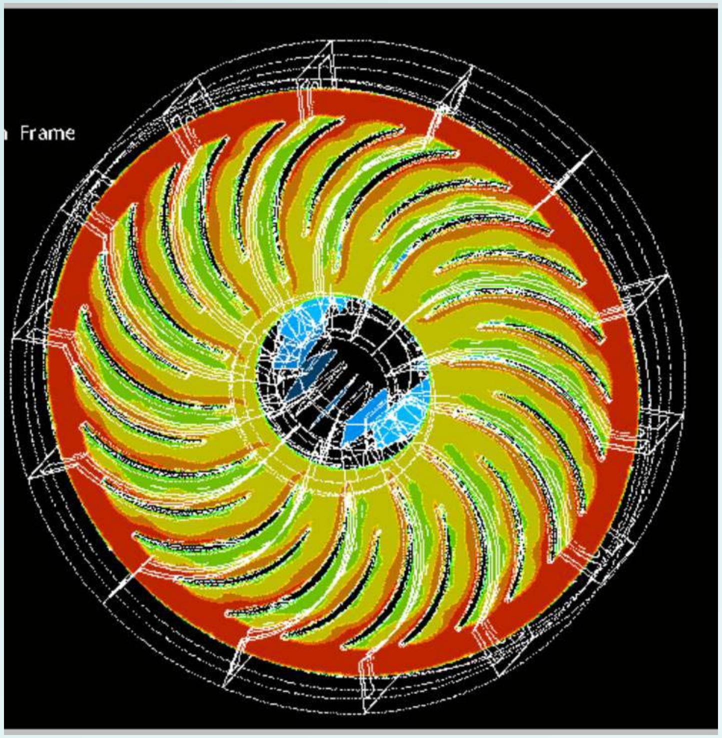
Conjugate Heat Transfer CFD Model

- Predicted temperature in return channel with and without internal cooling.

Without Heat Transfer

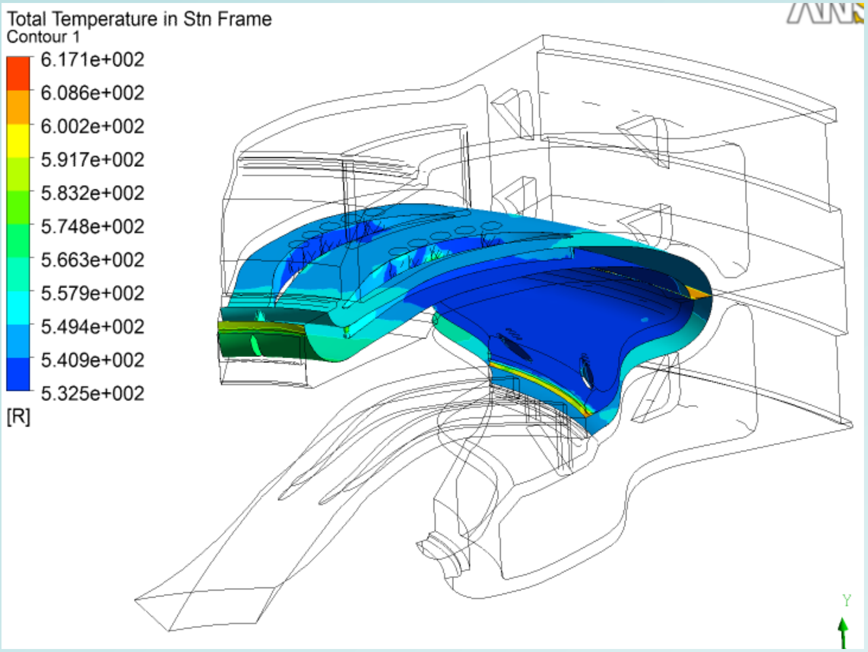


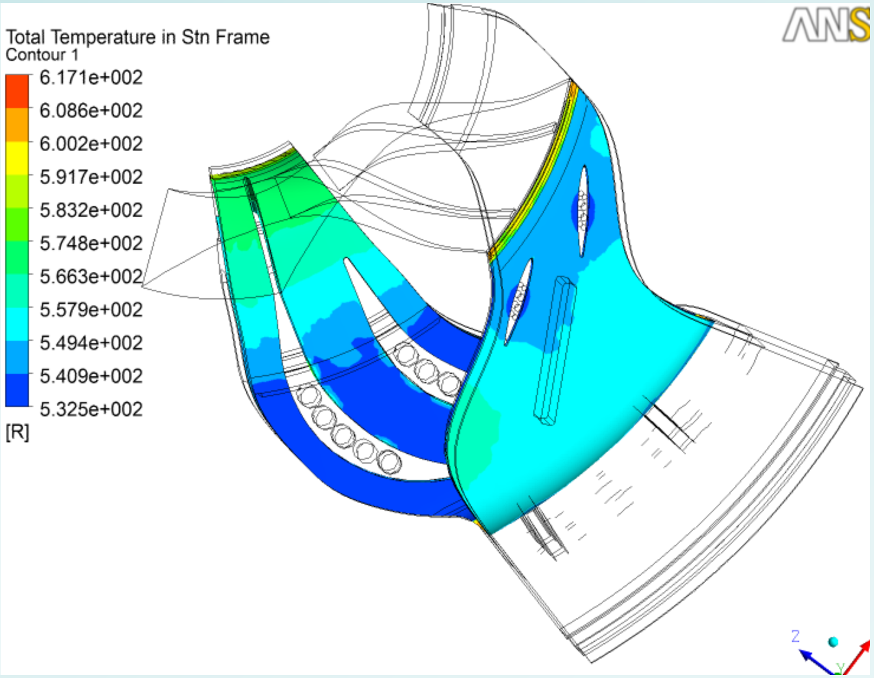
With Heat Transfer



Final Design

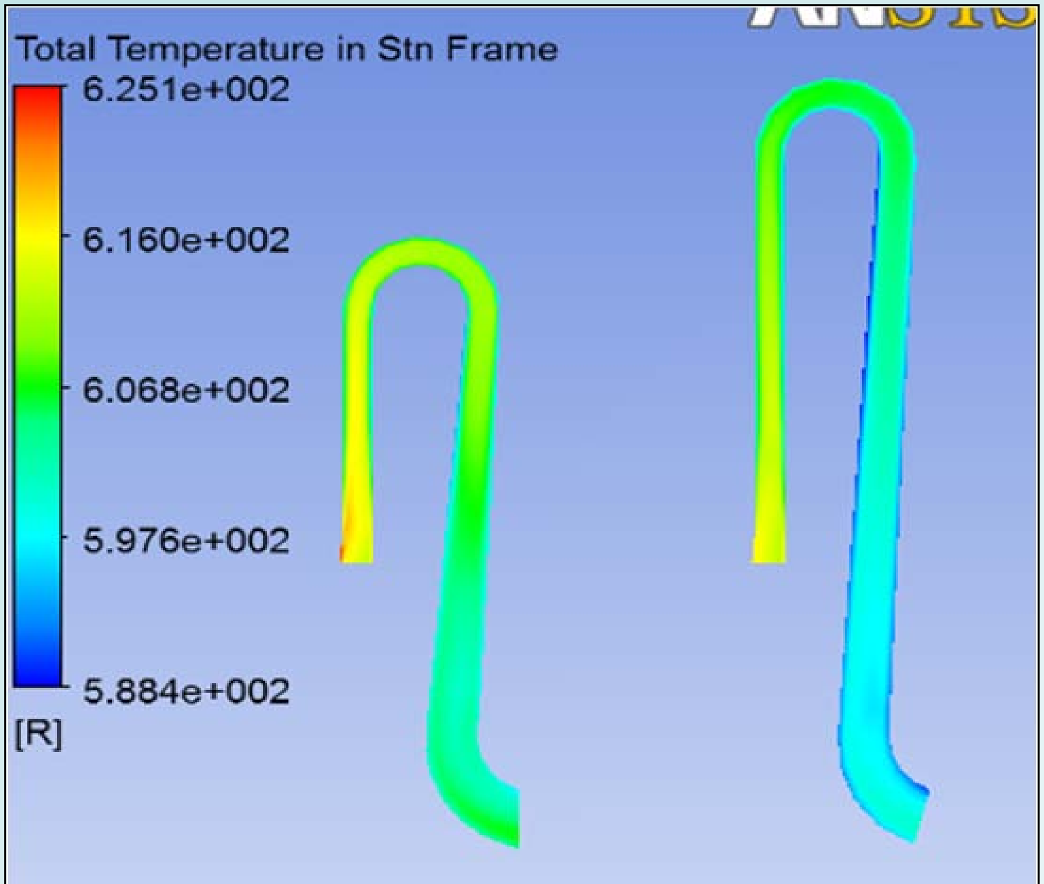
Case 4- Conjugate heat transfer model with enhanced heat transfer coefficients to simulate ribbed surfaces for the cooling liquid



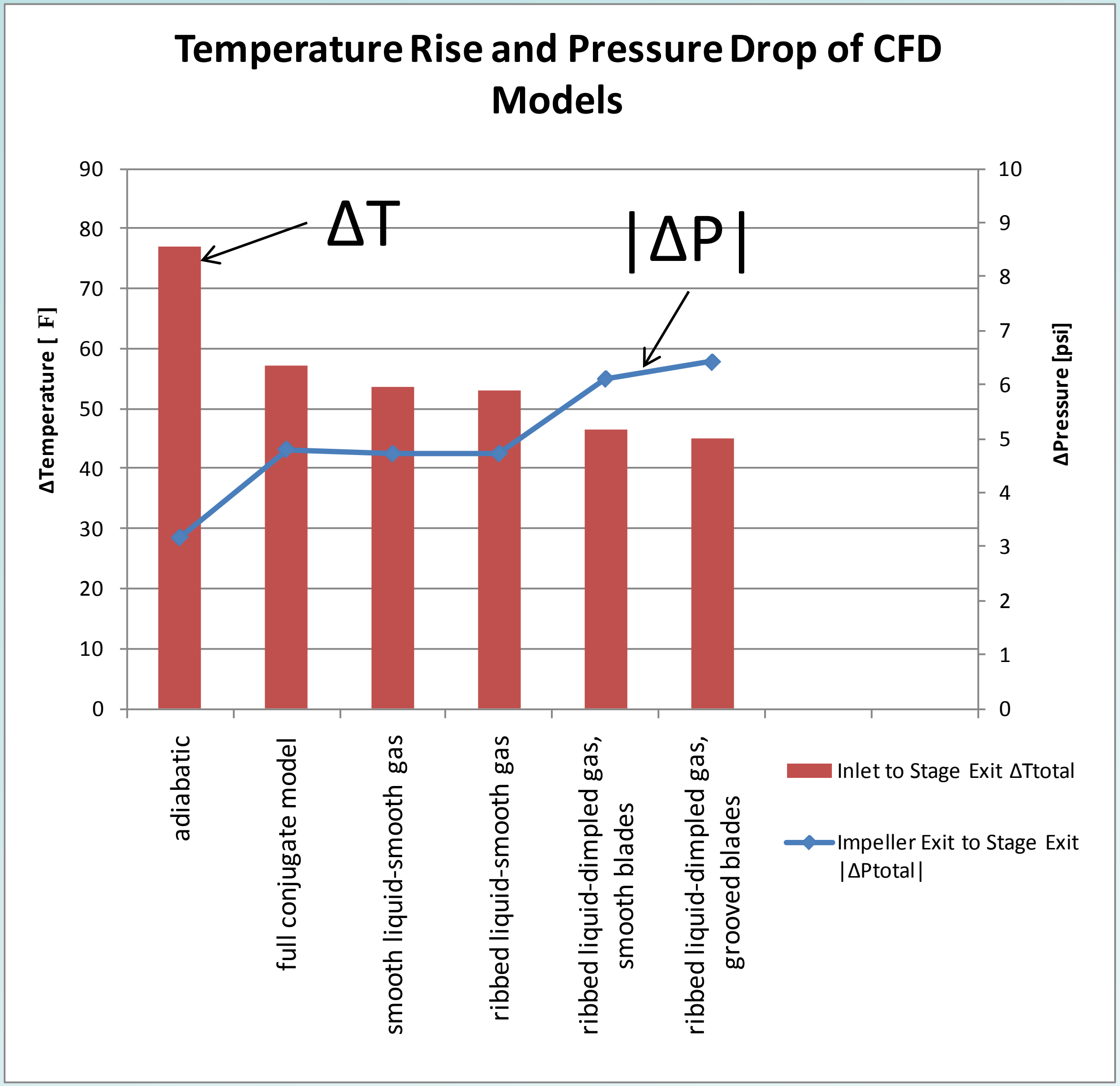


Final Design

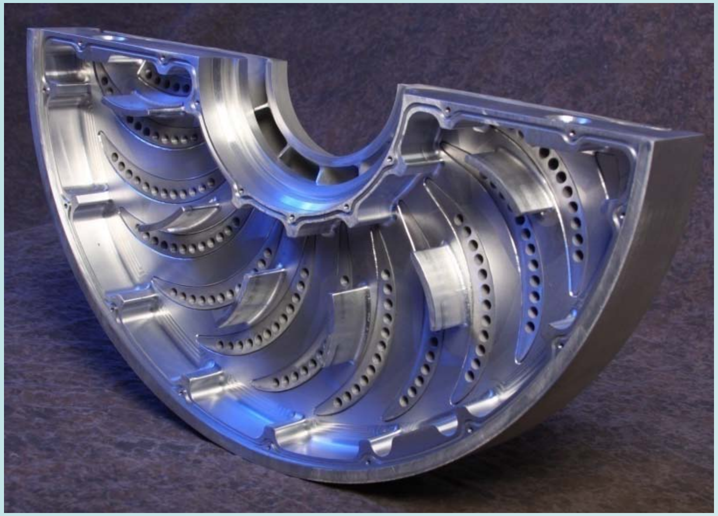
• Conjugate heat transfer model with enhanced heat transfer coefficients to simulate ribbed surfaces for the cooling liquid
• Two radius ratios shown

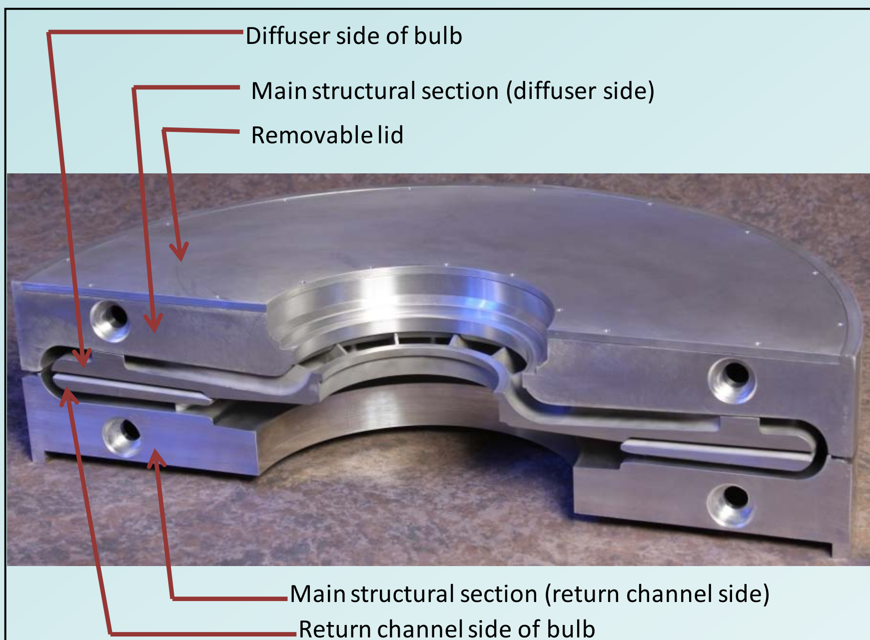


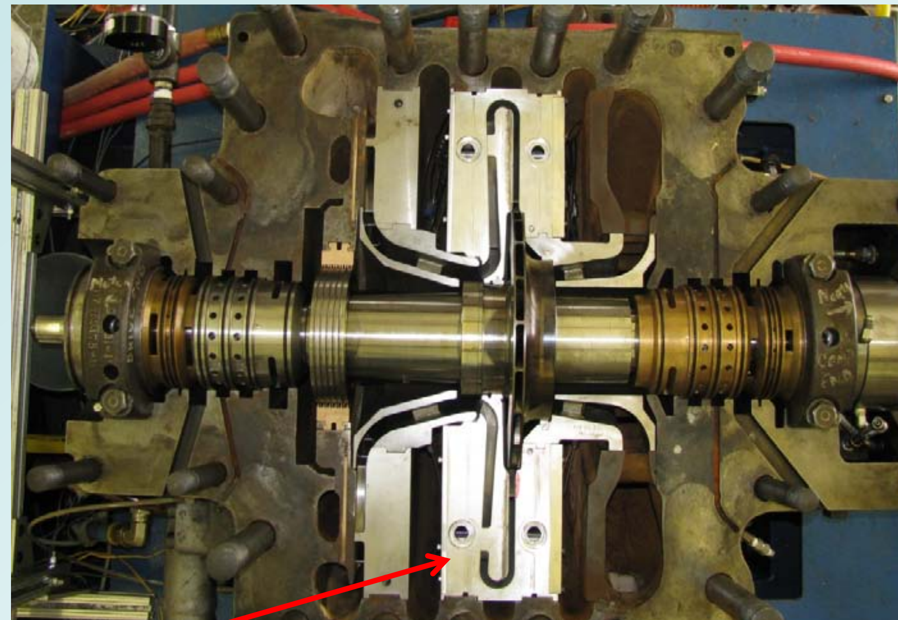
Summary of CFD Results



Test Rig Construction



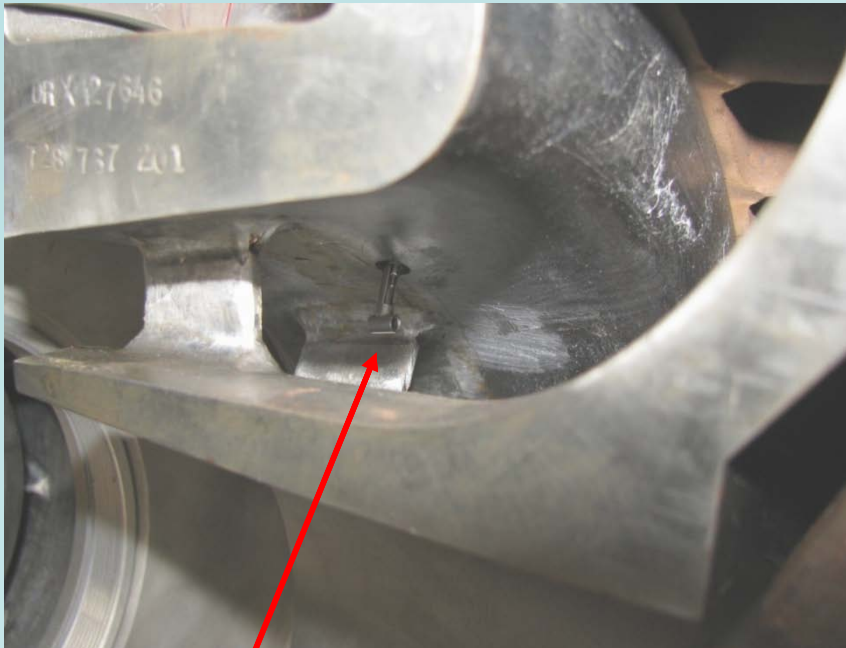


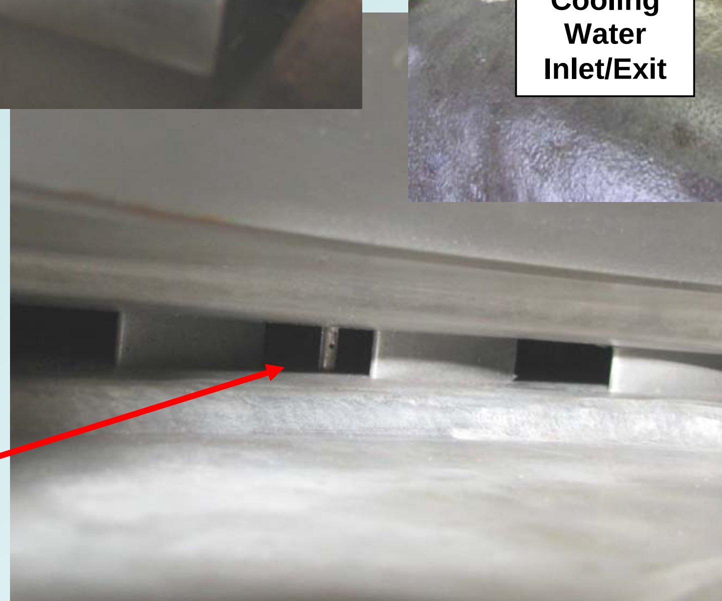


Closed Loop Test Facility

- Driven by 700 hp electric motor through gearbox
- Torque meter installed to measure power
- Loop rated to 300 psi suction and 500 psi discharge
- Test speeds up to 14,300 rpm

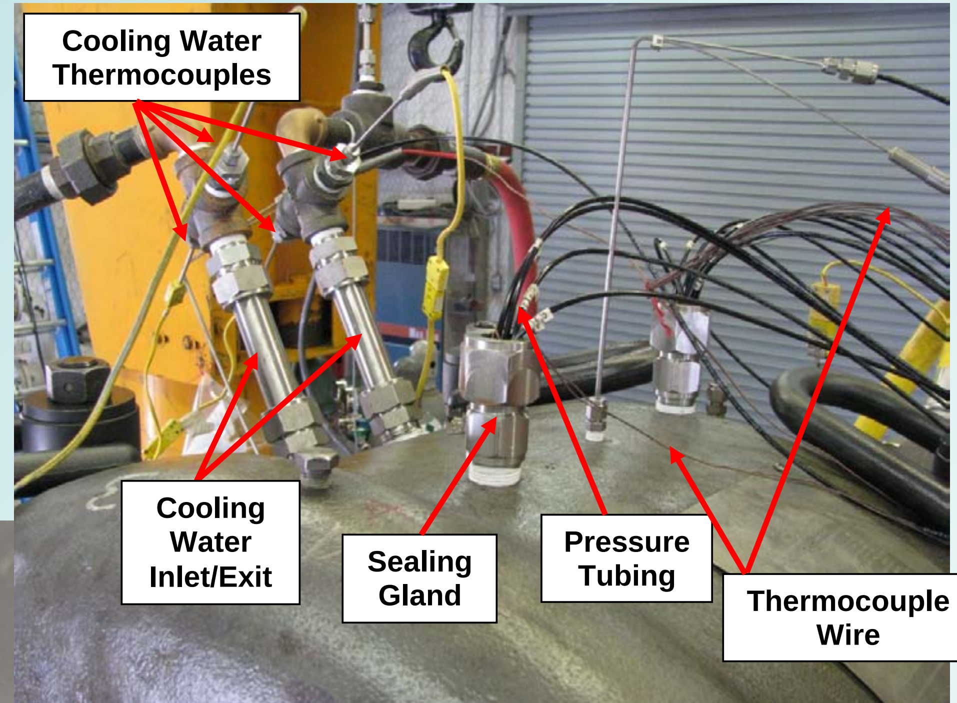
Instrumentation





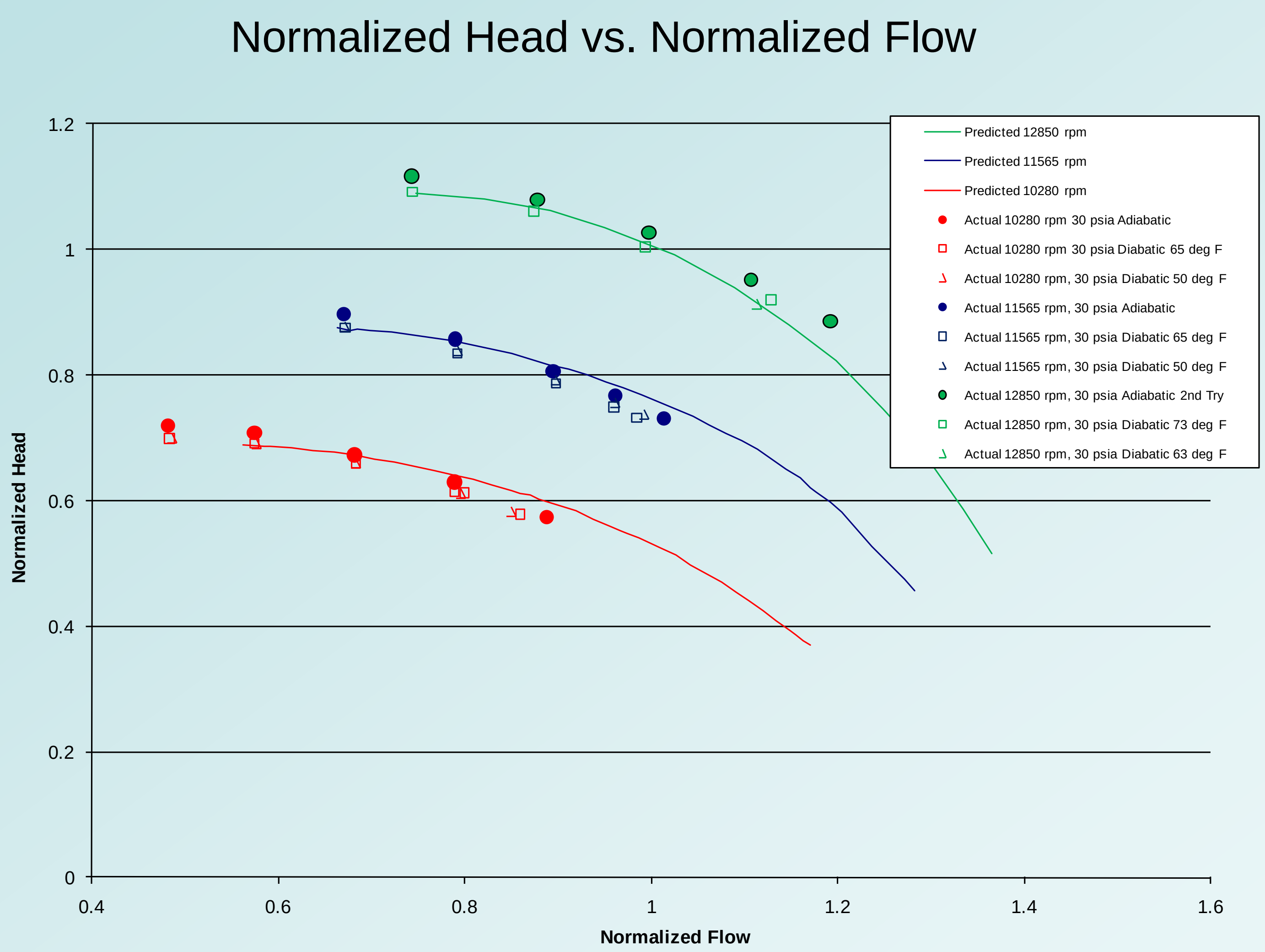
Combination Kiel Head Pressure/Temperature Probe at Suction and Discharge Bridge-over

Half-Shielded Thermocouple Probe Near Impeller Exit



- 28 Temperature Probes
- 30 Pressure Measurements
- Flow Rate (CO_2 and Cooling)
- Speed
- Shaft Torque
- Axial Thrust
- Gas Samples Taken

Compressor Test Results



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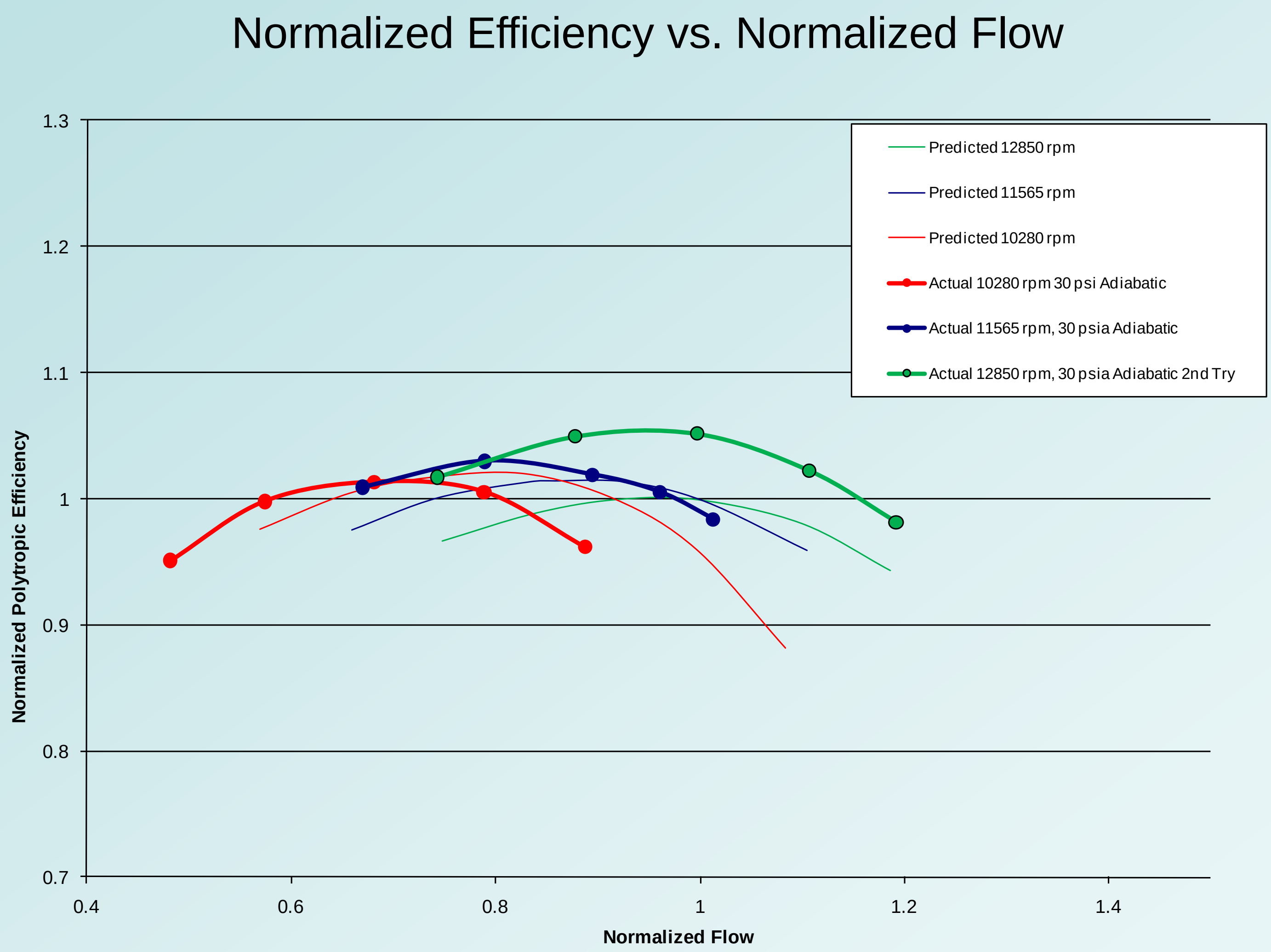
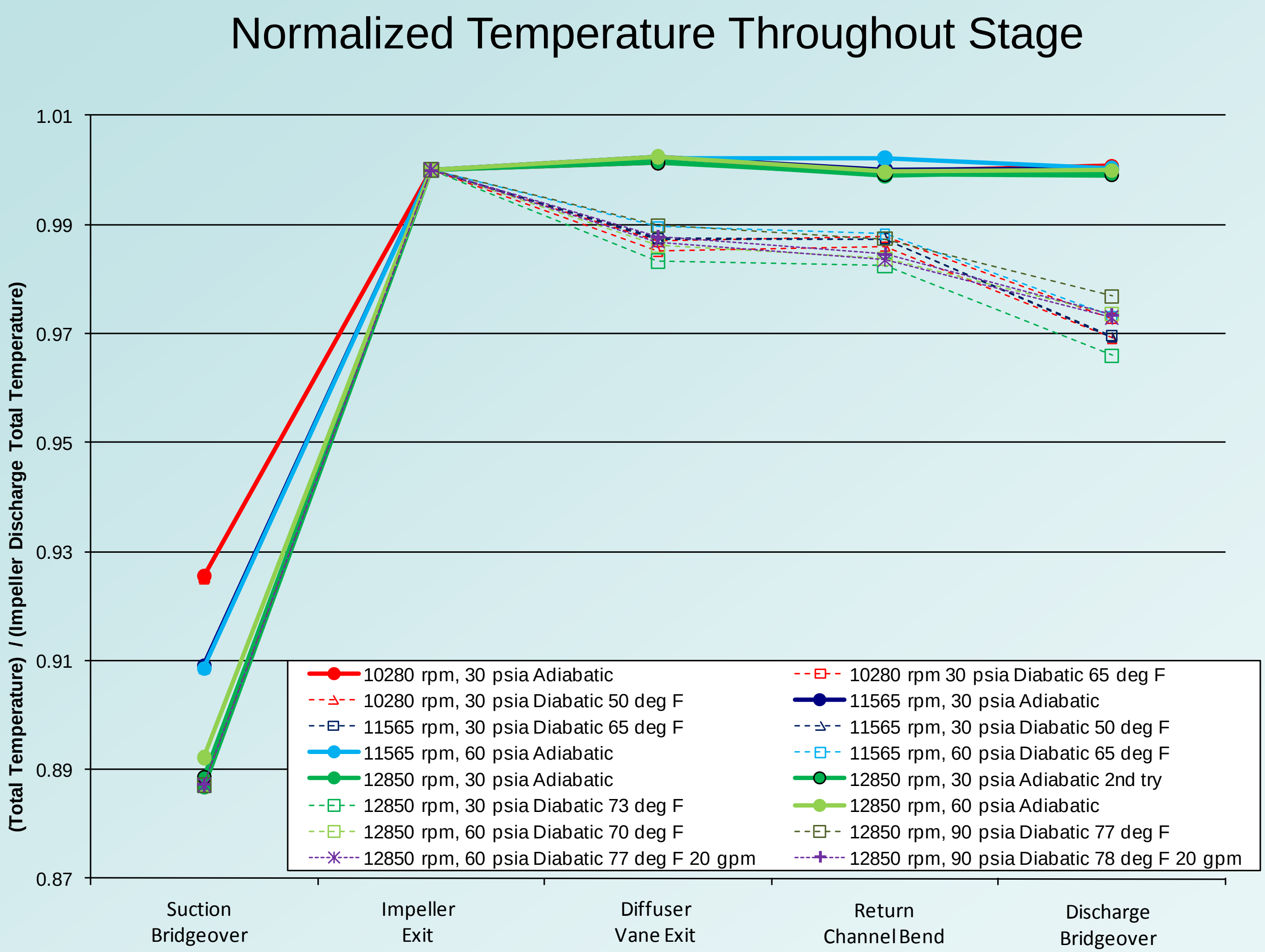
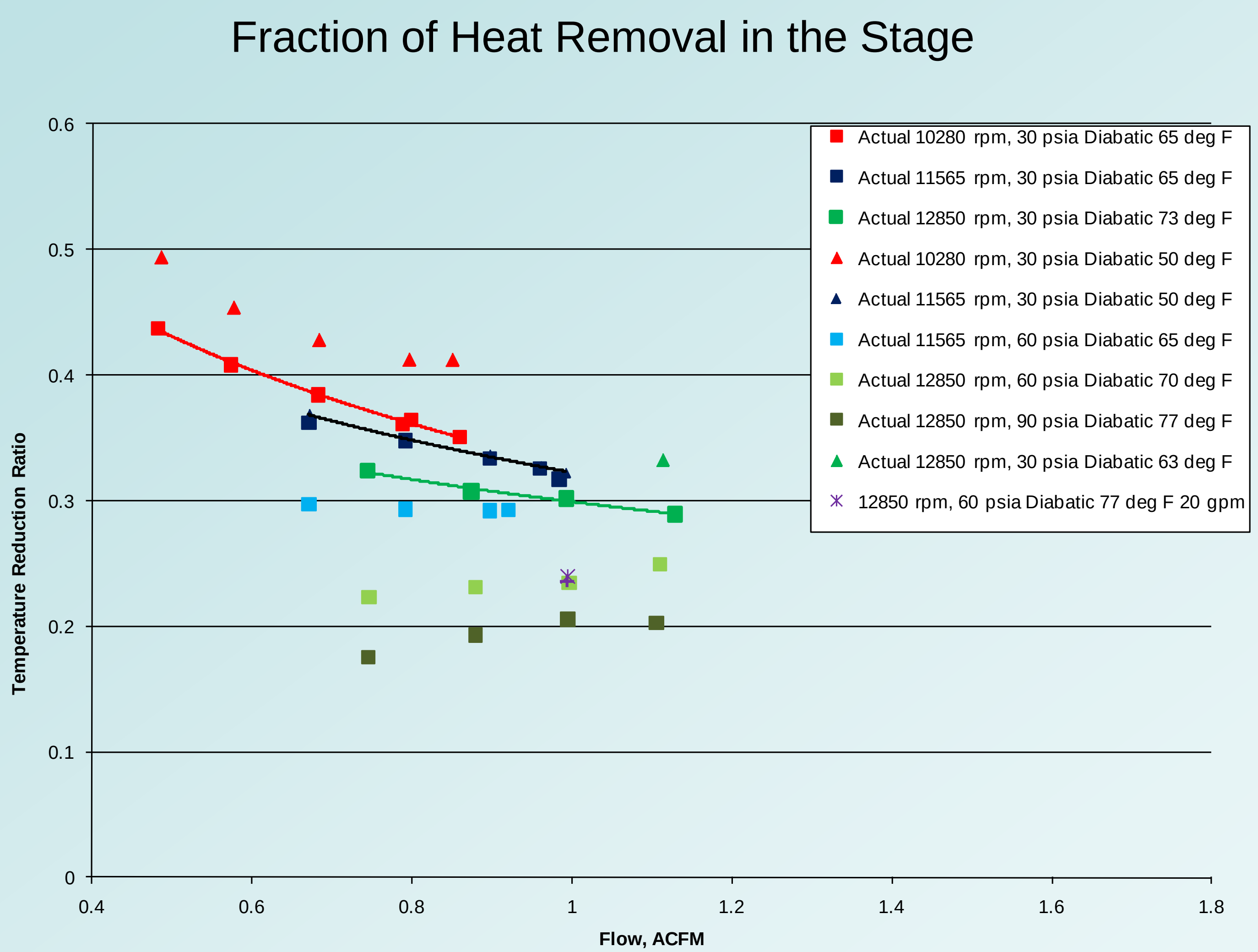


Compressor Test Results

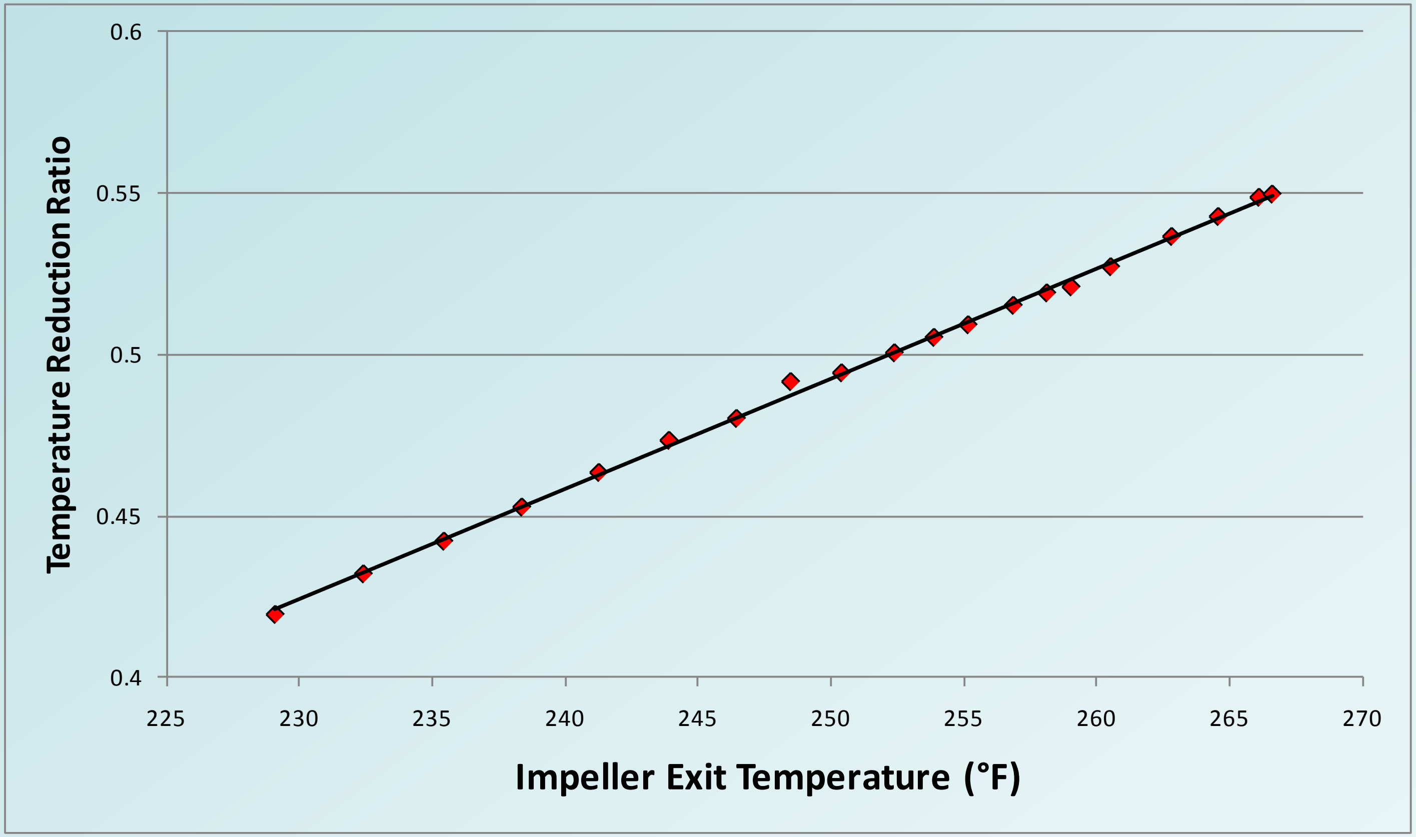


Compressor Test Results

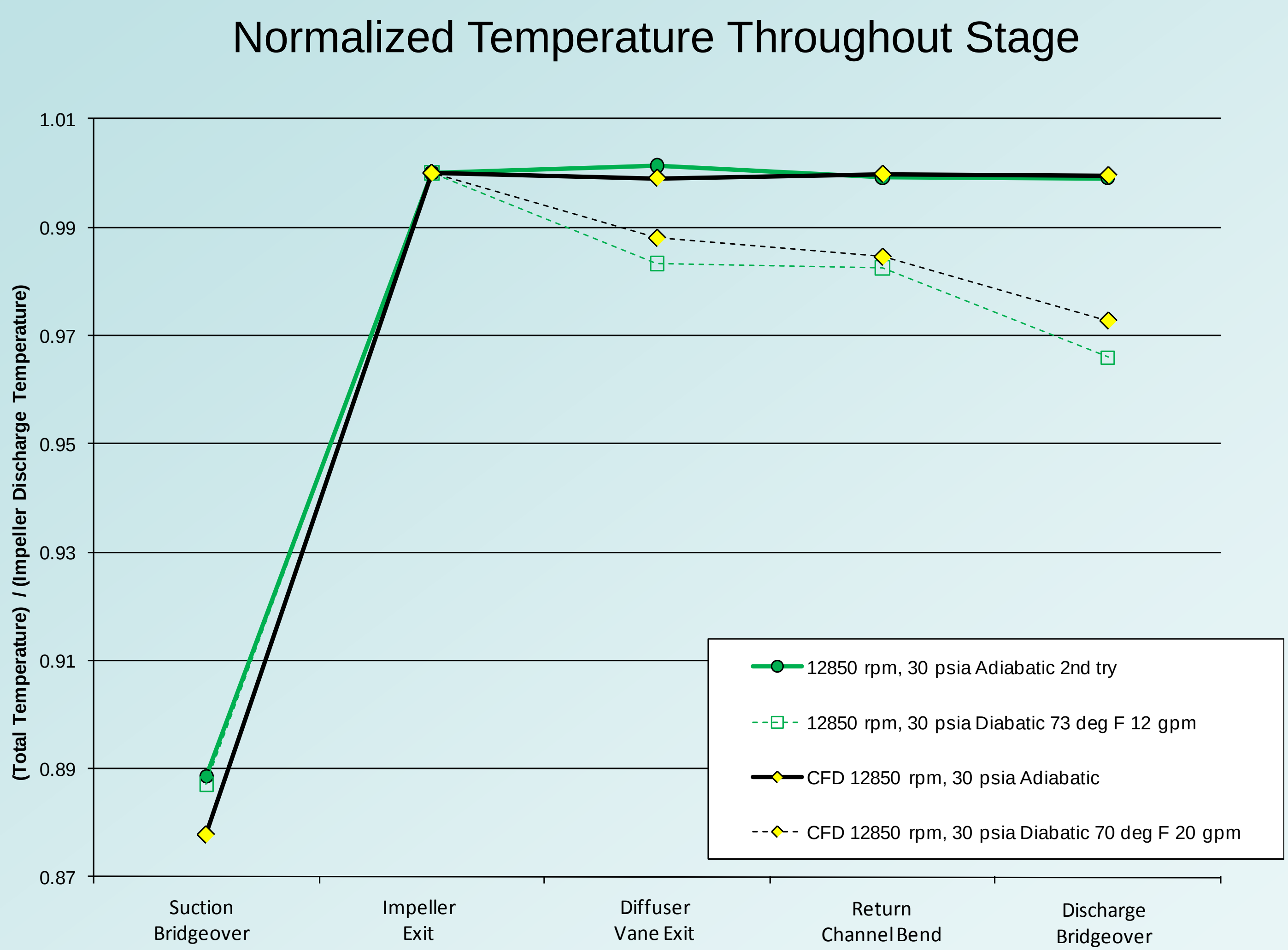


Compressor Test Results

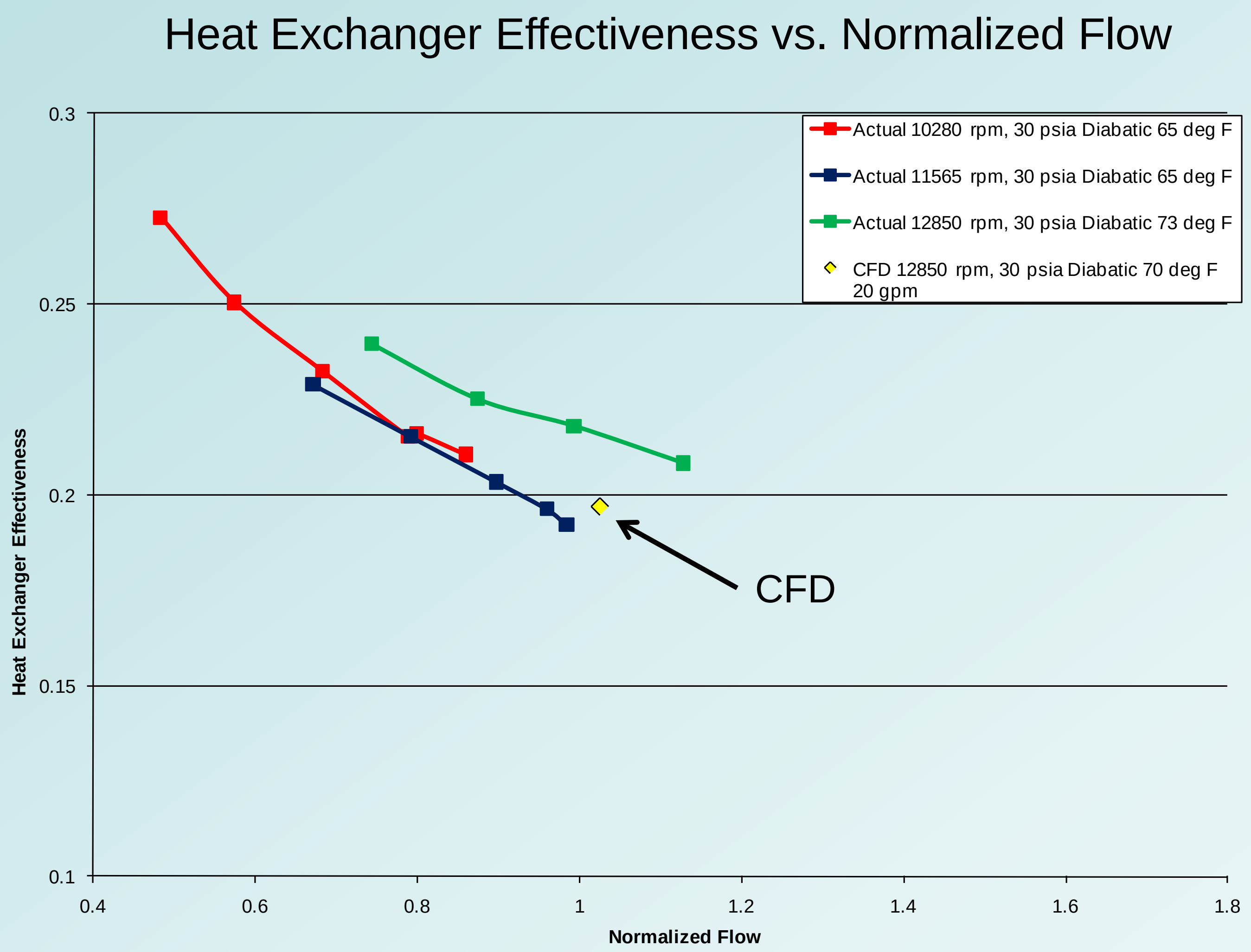
Fraction of Heat Removal in the Stage vs. Impeller Exit Temperature



Comparison to Predictions



Comparison to Predictions



Multi-Stage Compressor Example

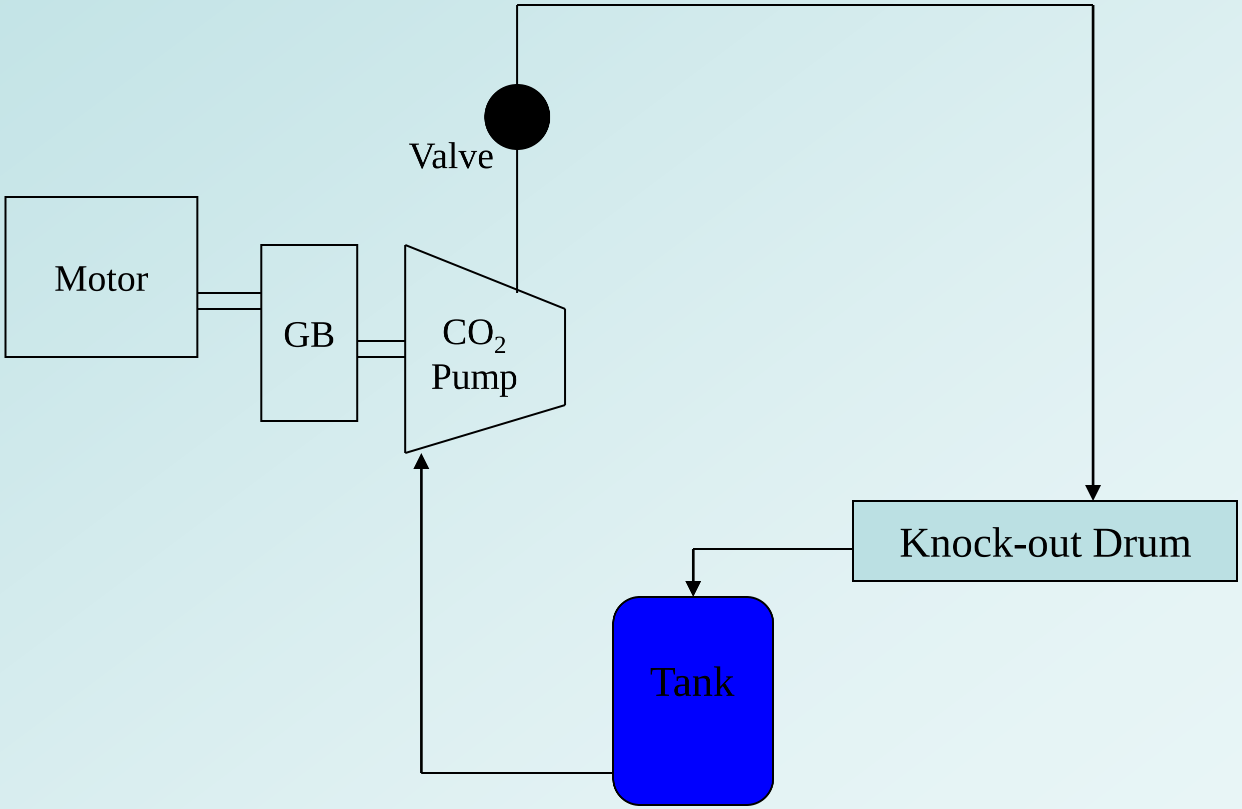
Geometry	RPM	Radius Ratio	Power Savings* (%)
Adiabatic reference	*12850*	*1.5*	*0.0*
Smooth wall	12850	1.5	9.5
Smooth wall	9155	1.5	16.6
Smooth wall	12850	1.8	12.3

- 5-Stage straight-through compressor
- Suction Pressure = 30 psia, Discharge Pressure = 250 psia
- Uses heat exchanger effectiveness of 0.22 for 1.8 radius ratio
- Savings for the 1.8 radius ratio at the reduced speed of 9155 rpm is expected to approach 20% due to an increased number of stages required.

Cryogenic Turbopump Validation Testing

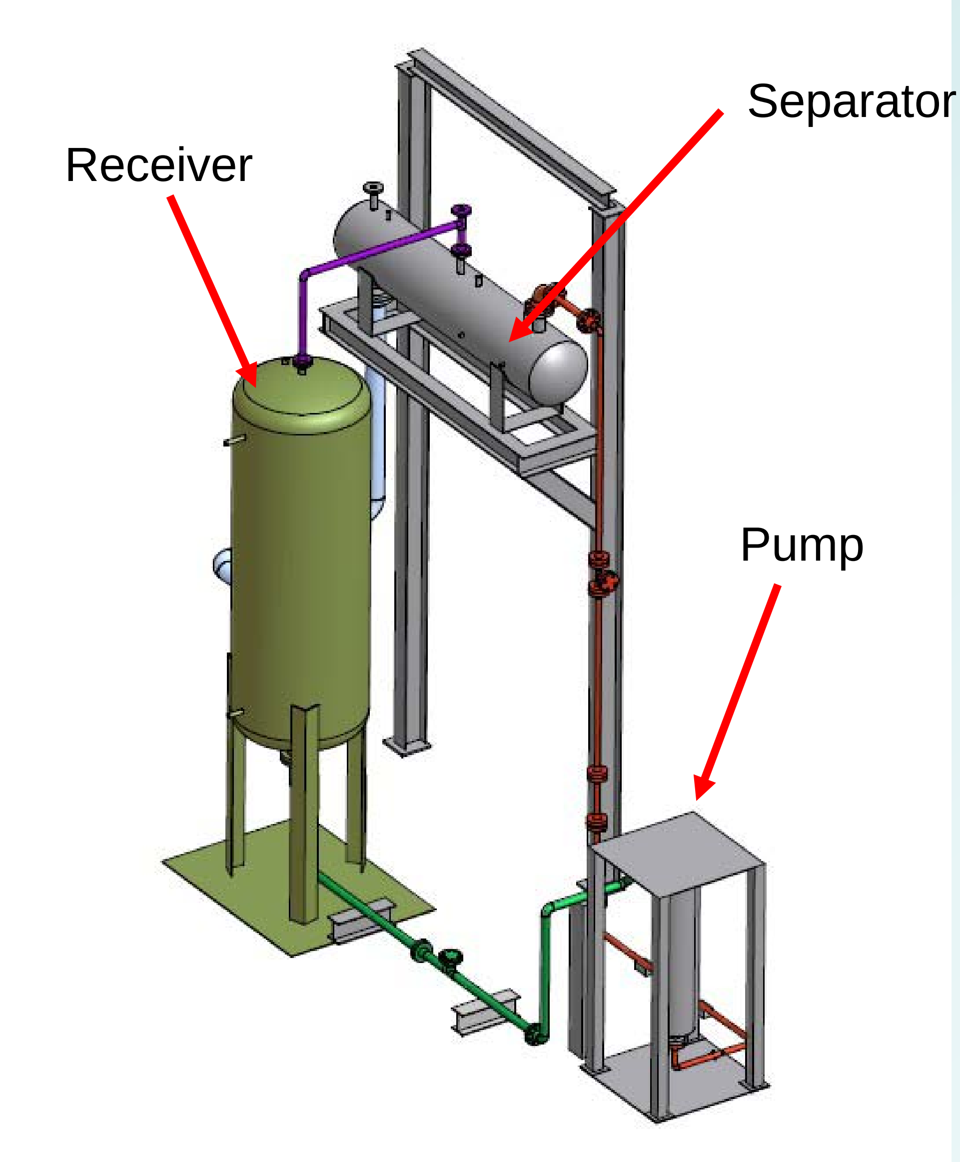
Liquid CO_2 Pumping Pilot Scale Testing

- Testing will measure pump efficiency
- Validate pump design
- Measure NPSH requirements looking for signs of cavitation
- An industrial pump manufacturer supplied the pump
  - 250 KW, 100 gpm, 53,000 lbm/hr



Liquid CO_2 Loop Design

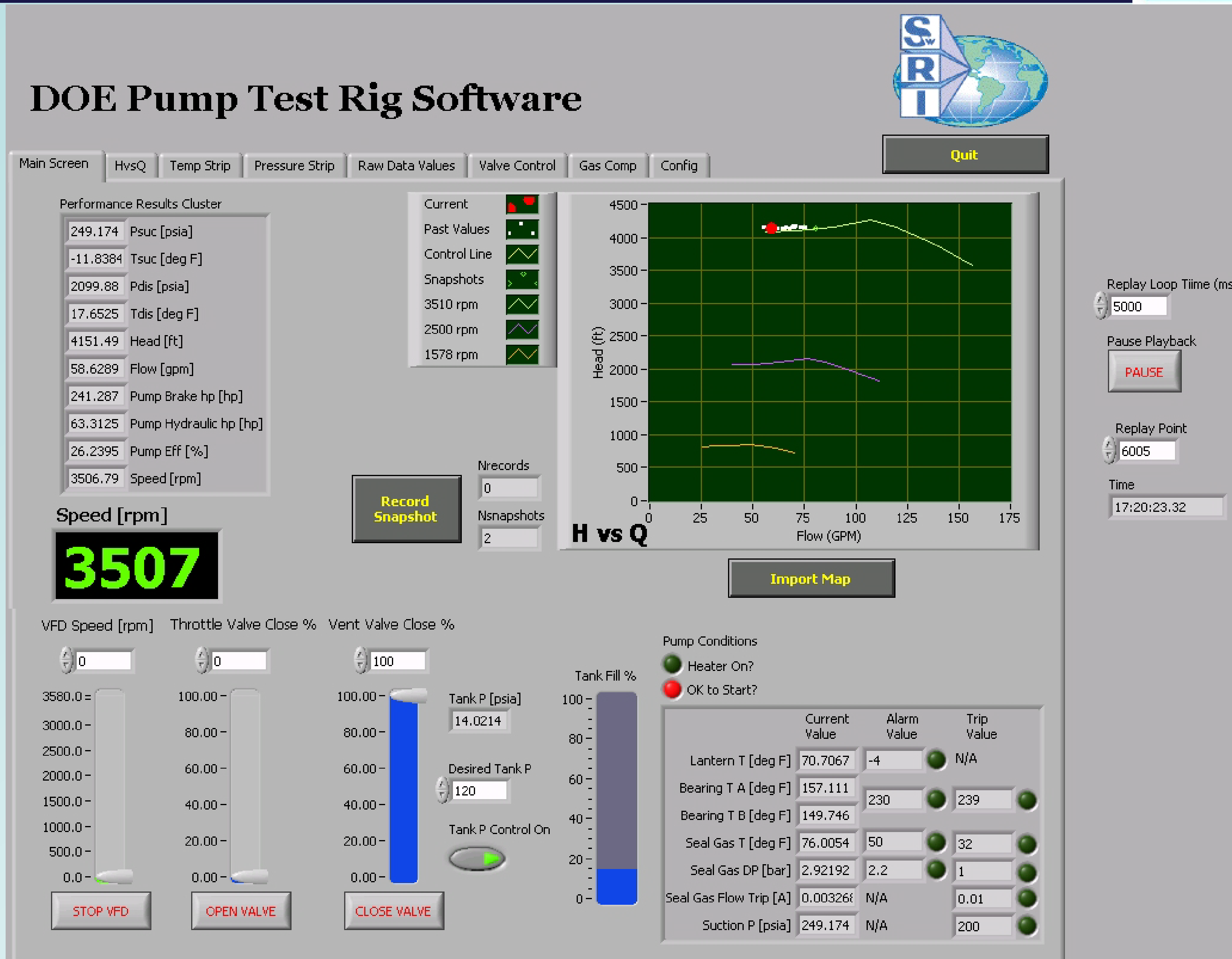
- Vessel layout showing elevated reservoir and knock-out drum
- Pump is mounted at ground level.
- Orifice run located between pump and control valve (in supercritical regime)



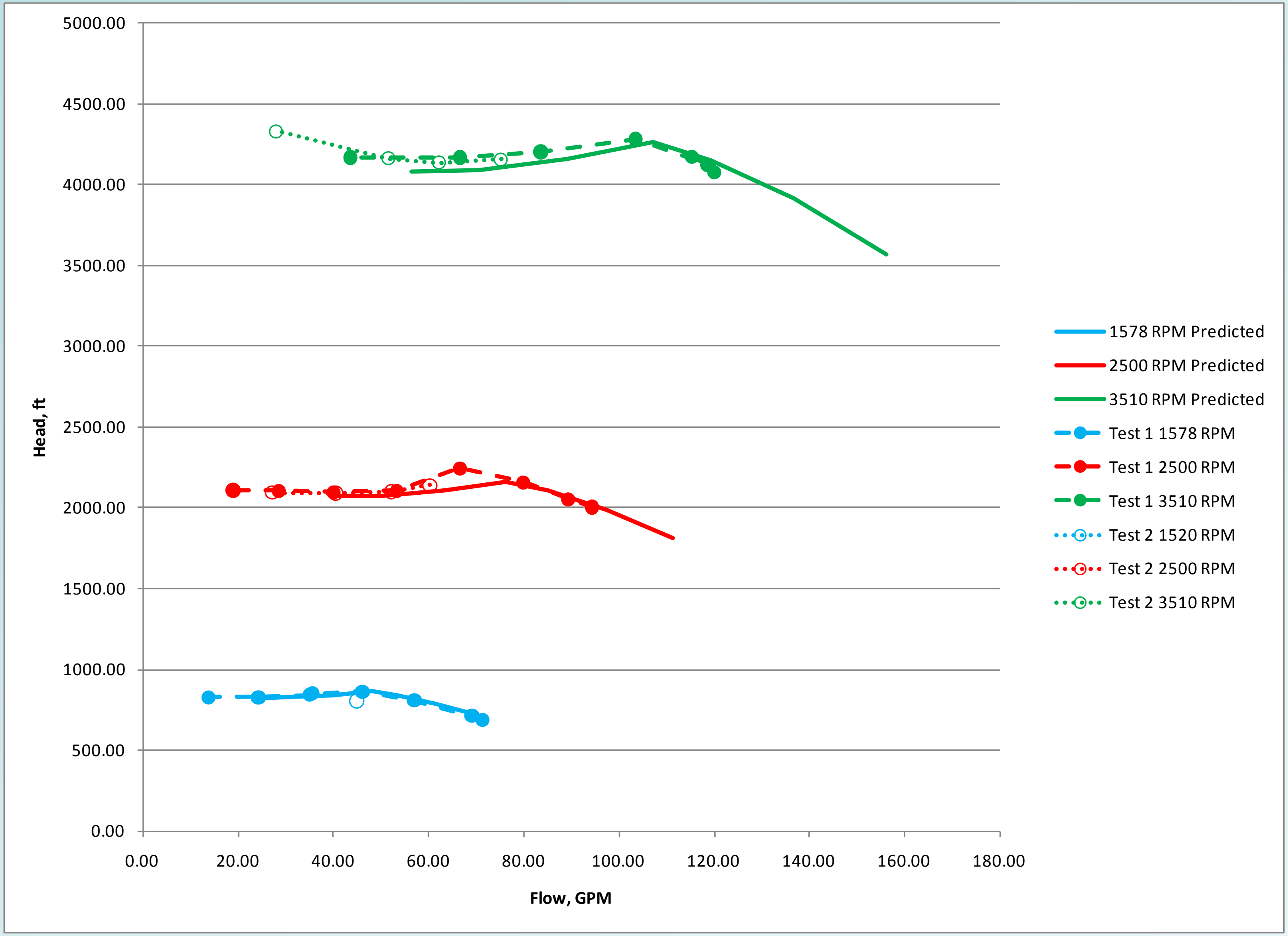
Pump Loop Construction

Cryogenic Turbopump Validation Testing

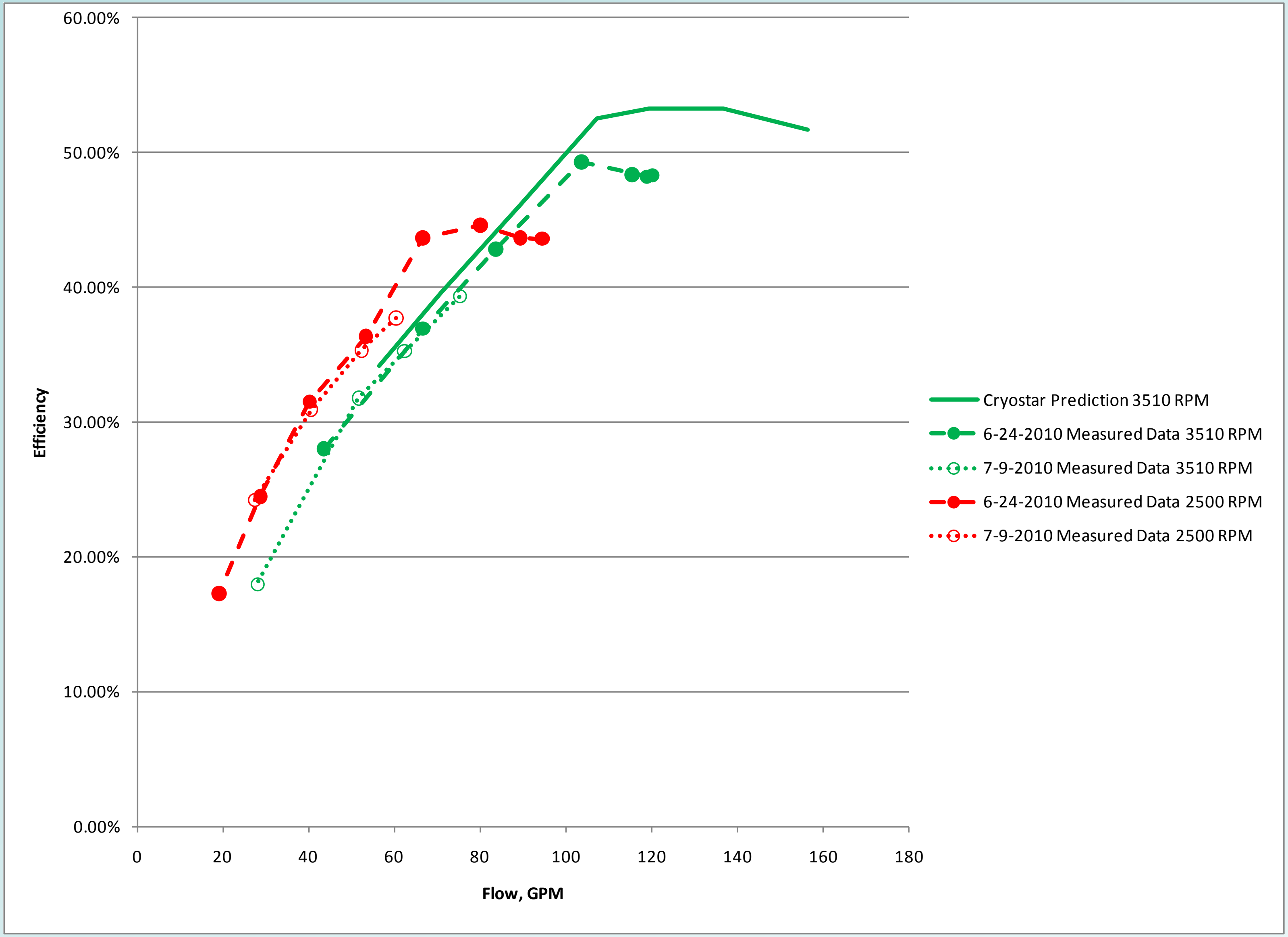
Data Acquisition Code



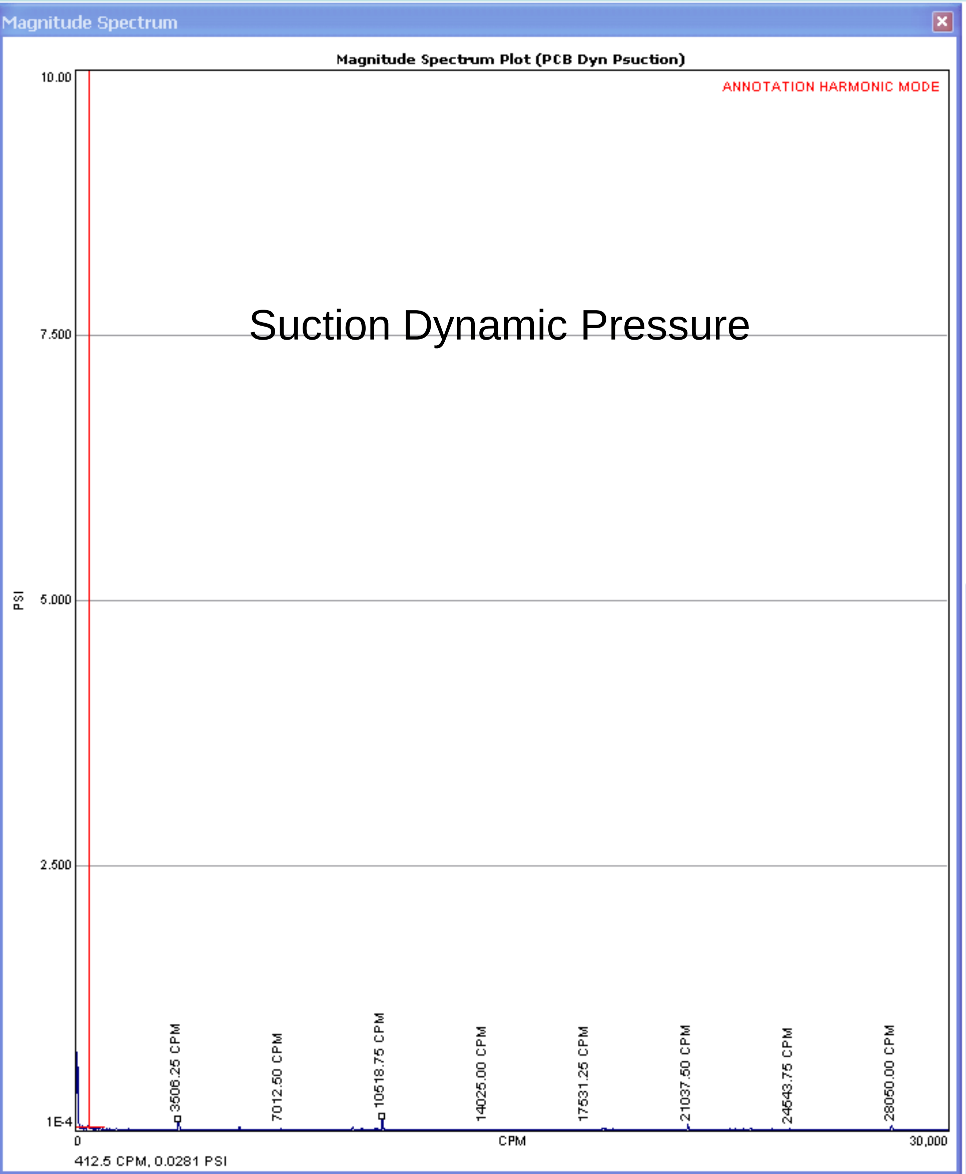
Test Results

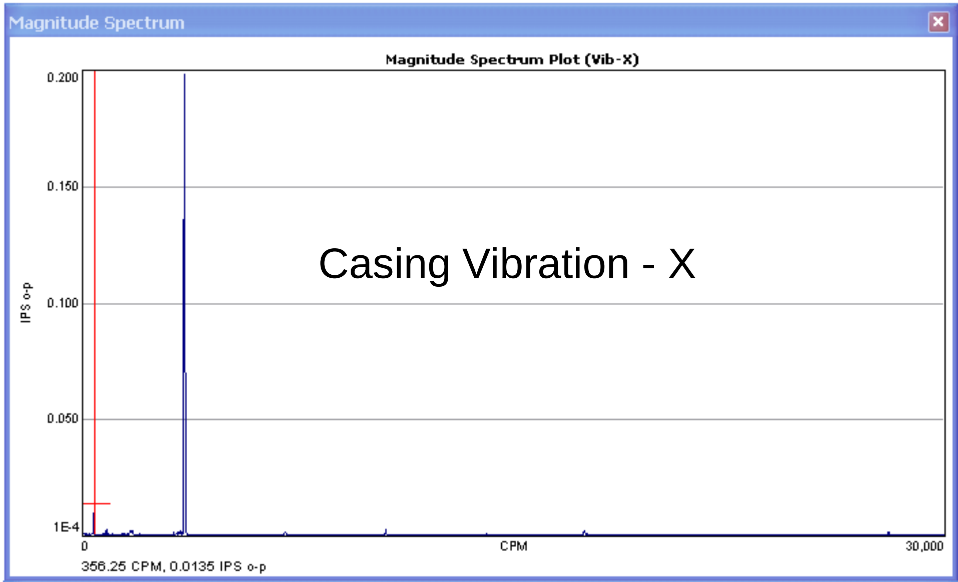


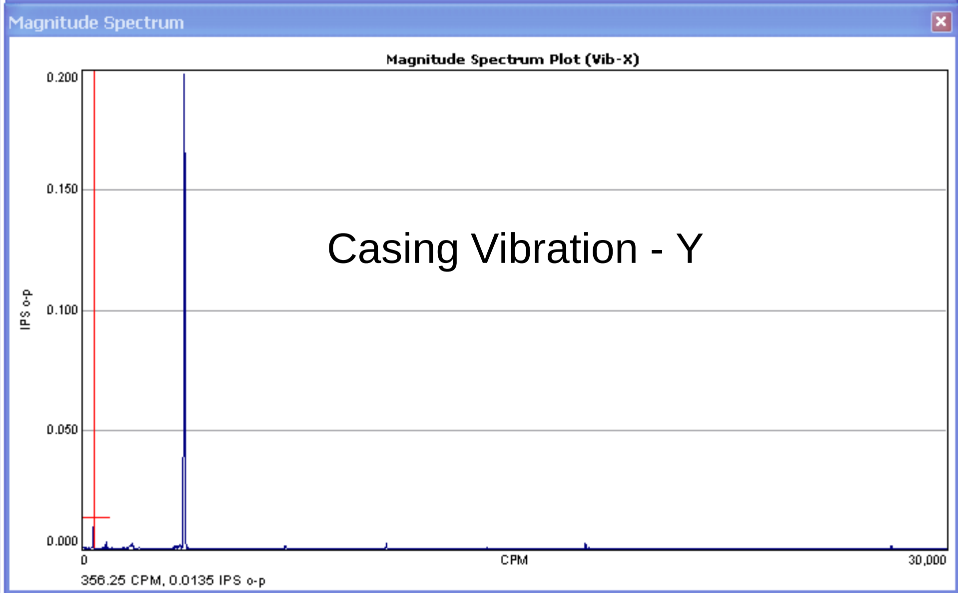
Test Results



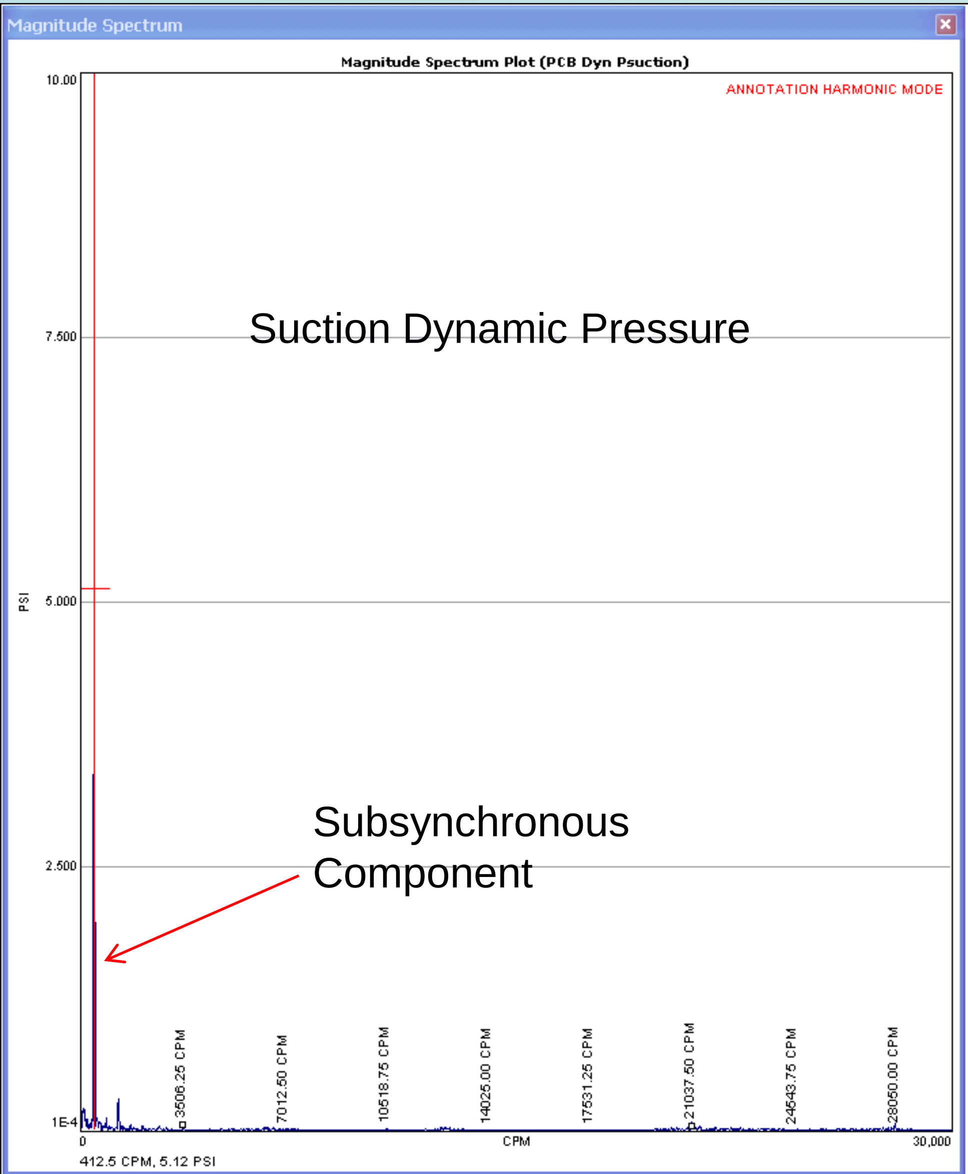
Dynamic Data – Design Point

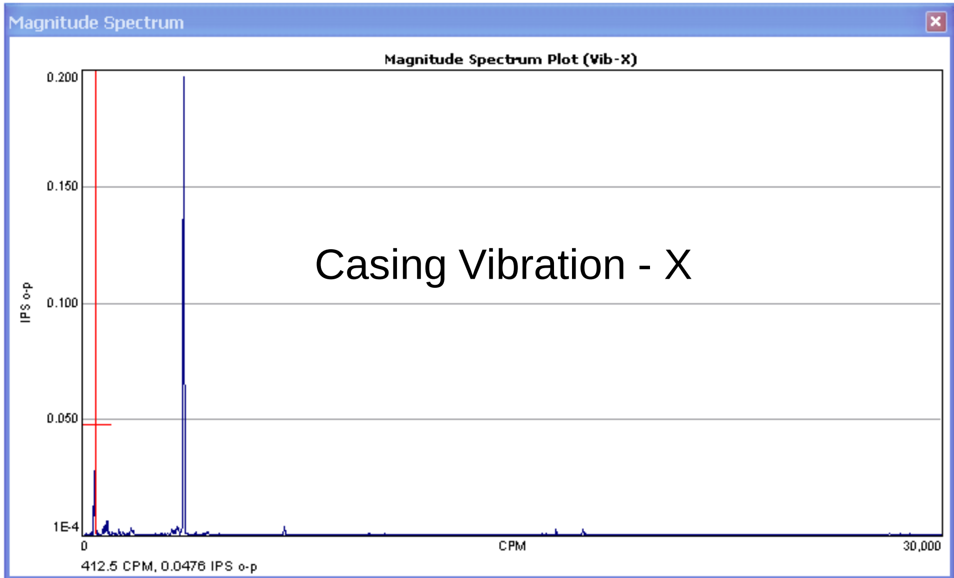


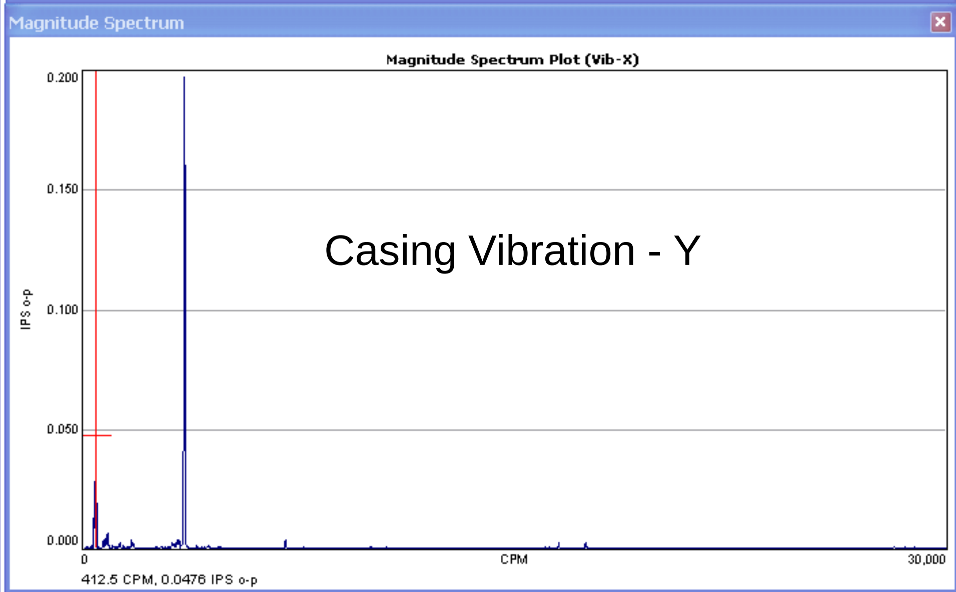




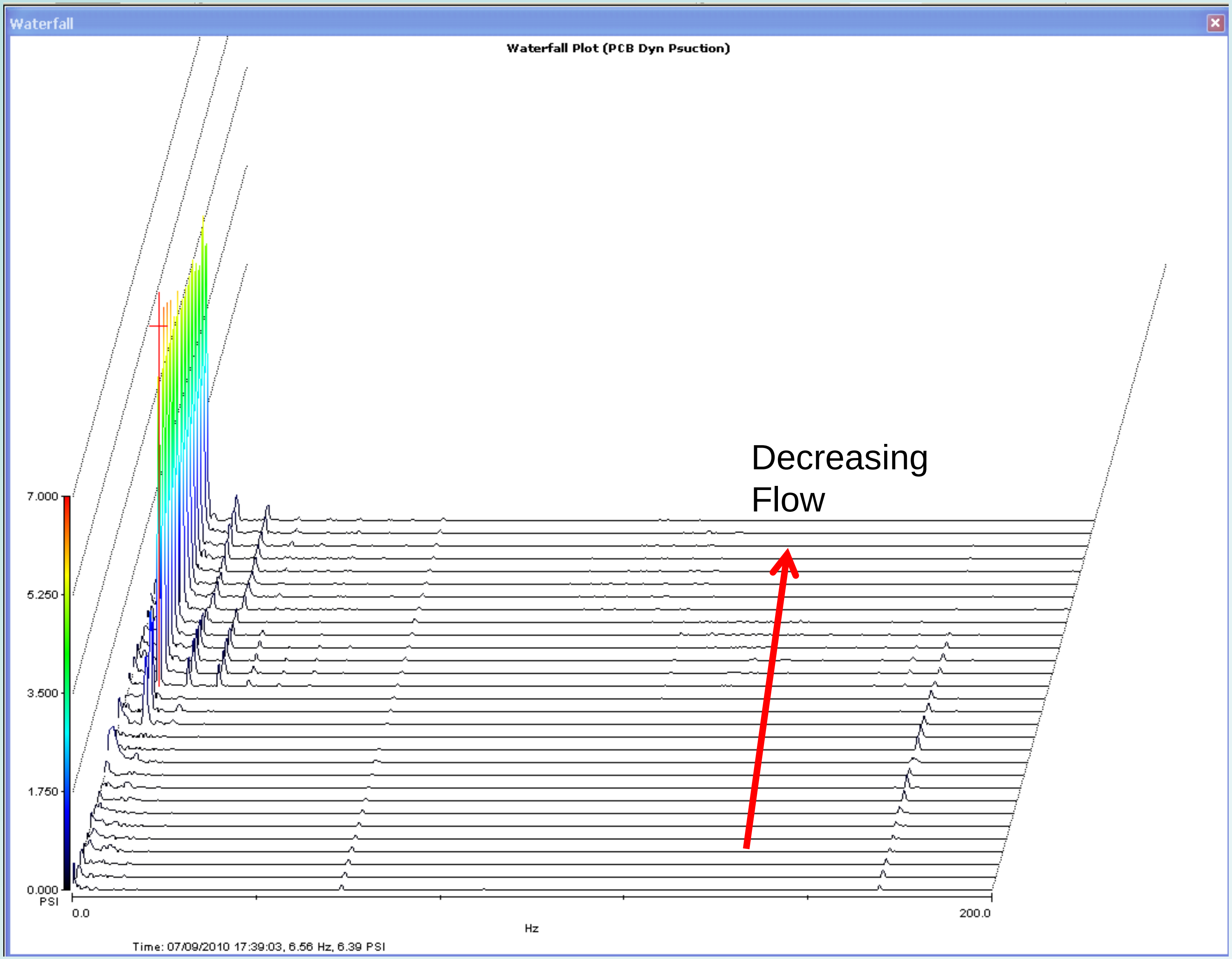
Dynamic Data – Minimum Flow Point







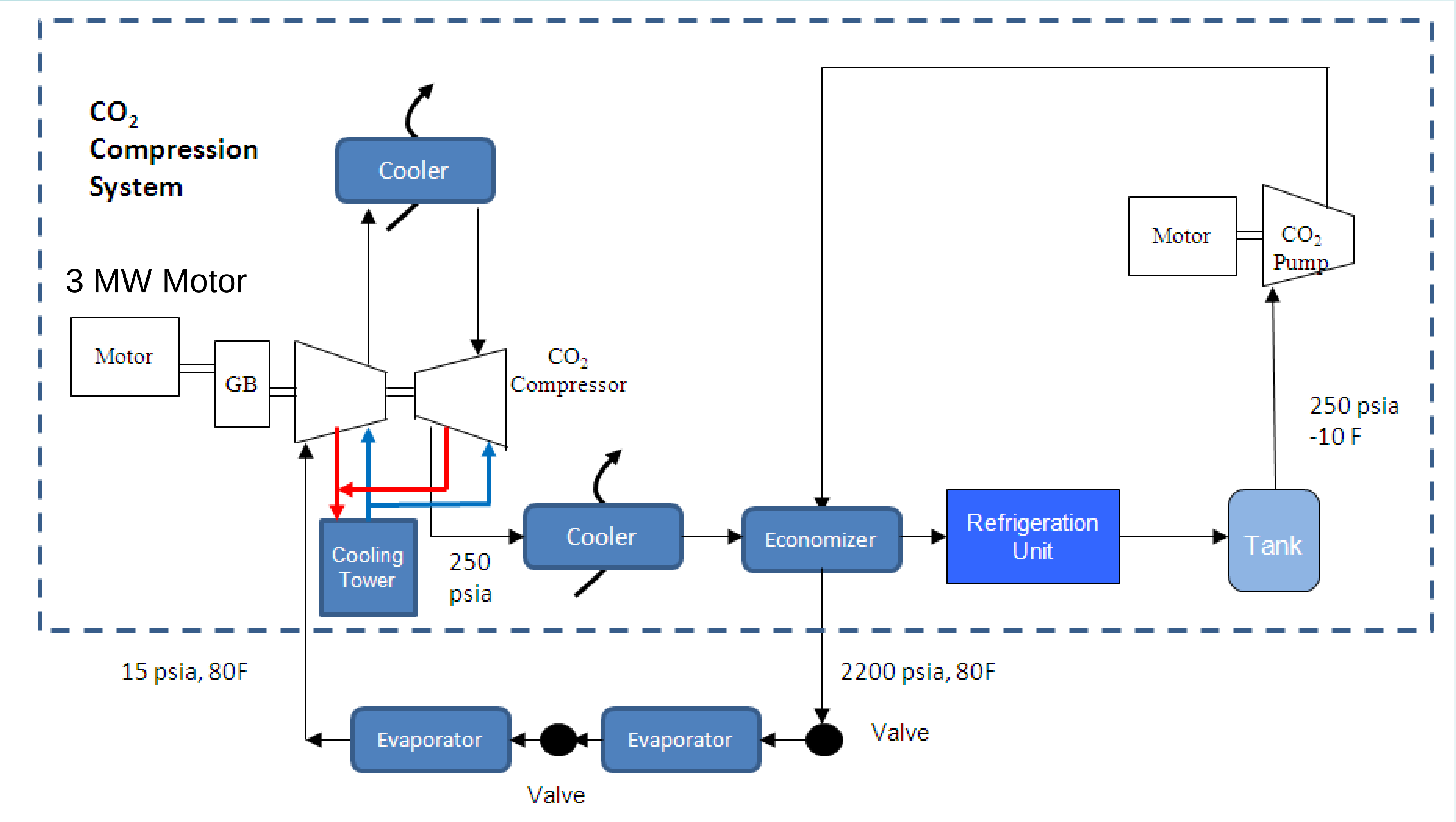
Dynamic Suction Pressure Waterfall while Throttling



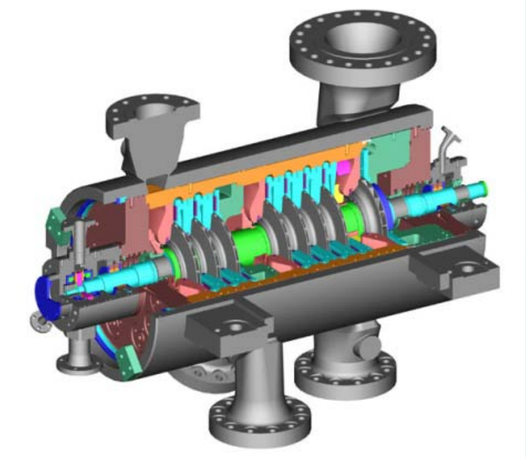
Phase 2 Testing Summary

- Compressor Testing
  - Testing performed for a range of speeds, flows, suction pressure, suction temperature, cooling water flow and temperature
  - Testing performed both adiabatic and diabatic (with cooling)
  - Results show cooled diaphragm can remove up to 55% of the heat of compression in each stage
  - Heat removal improves in latter stages of a multi-stage compressor
  - Over 20% reduction in power is possible for a multi-stage application
- Pump Testing
  - Pump performed match the measured performance during factory testing on LN_2
  - Met discharge pressure goals
  - LCO_2 introduced no mechanical issues for the pump
  - Vibration levels were acceptable
  - A subsynchronous vibration occurred at minimum flow point but only at very low flow rates
- Both Technologies are Ready for Commercial Implementation

Phase 3 Pilot Test Facility



Compressor Specifications



- Dresser-Rand DATUM D6R6B
- Approximate operating conditions are:
  - Suction Pressure: 15-25 psi
  - Discharge Pressure: 230-260 psi
  - Mass Flow =55,000-75,000 lbm/hr
  - Power: 3,000 hp
- Design: Multistage centrifugal compressor with back-to-back sections with internally cooled diaphragm technology
- Intercooling and aftercooling will be supplied to run compressor in adiabatic mode
- The compressor will be mounted with a variable speed electric motor and gearbox on a single skid.
- Dry gas seal system and the variable frequency drive will also be supplied.

SwRI WBS – Year 1

- Finalize compressor selection
- Perform conjugate heat transfer CFD analysis
- Support D-R with FEA analysis of multi-stage diaphragm and cooling circuit
- Develop functional requirement of flow loop including process diagram and P&ID
- Design liquefaction system
- Select major pieces of equipment
- Develop solid model of flow loop
- Perform piping and pressure vessel analysis
- Simulate flow loop using pipeline simulation software
- Generate complete BOM and cost summary

Phase 3 Deliverables

- Deliverables:
  - The cooled diaphragm concept will be extended to a multi-stage design. Many design challenges remain to mature the design for commercialization. Since the cooled diaphragm concept works by reducing the power required in the downstream stages, actual power reduction will be measured.
  - The refrigeration system, including an economizer, will be designed and tested. The actual power required for the refrigeration system will be quantified. The effect of entrained gases found in actual carbon capture and sequestration applications will be tested by injecting nitrogen upstream of the liquefaction process and separating this gas.
  - The system dynamics and interaction between the compressor and the pump will be measured, including required recycle lines.
  - An overall power balance will be measured, including all coolers and chillers.
- Technology will be considered field ready following this demonstration program

Phase 3 Work Breakdown

Year 2 – Hardware Procurement and Site Preparation

- Compressor Procurement
- Procure all Major Equipment
  - Piping, Valves, Coolers, Liquefaction System, and Vaporizer
- Procure Instrumentation and Develop Data Acquisition and Control Program
- Prepare Site
  - Pour Concrete Pad
  - Install Electrical Supply and Transformer
- Construct Control Room and Laboratory

Phase 3 Work Breakdown

Year 3 – Test Loop Assembly, Commissioning, and Testing

- Test Loop Assembly
  - Install major pieces of equipment including coolers, heat exchangers, cooling tower and compressor
  - Relocate pump loop to new facility
- Install compressor package including cooling water and lube oil to the coolers.
- Install electrical connections to all equipment
- Install instrumentation on both compressor and pump skids
- Commission compressor loop
- Commission pump loop
- Commission liquefaction plant
- Test fully integrated compression/liquefaction/pumping system

Questions???

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