Advanced Centrifugal Compression and Pumping for CO_2 Applications

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Project Funded by DOE NETL

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11 Divisions

- Engine Emissions
- Fuels & Lubricants
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- Aerospace Electronics
- Space Science
- Nuclear Waste
- Applied Physics
- Applied Power
- Chemistry
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- **Mechanical Engineering**
- Rotating Machinery Group

- 1200 Acres
- 2 million Ft^2

- 3200 Employees
- 1200 Engineers
- 170 Buildings

Project Motivation

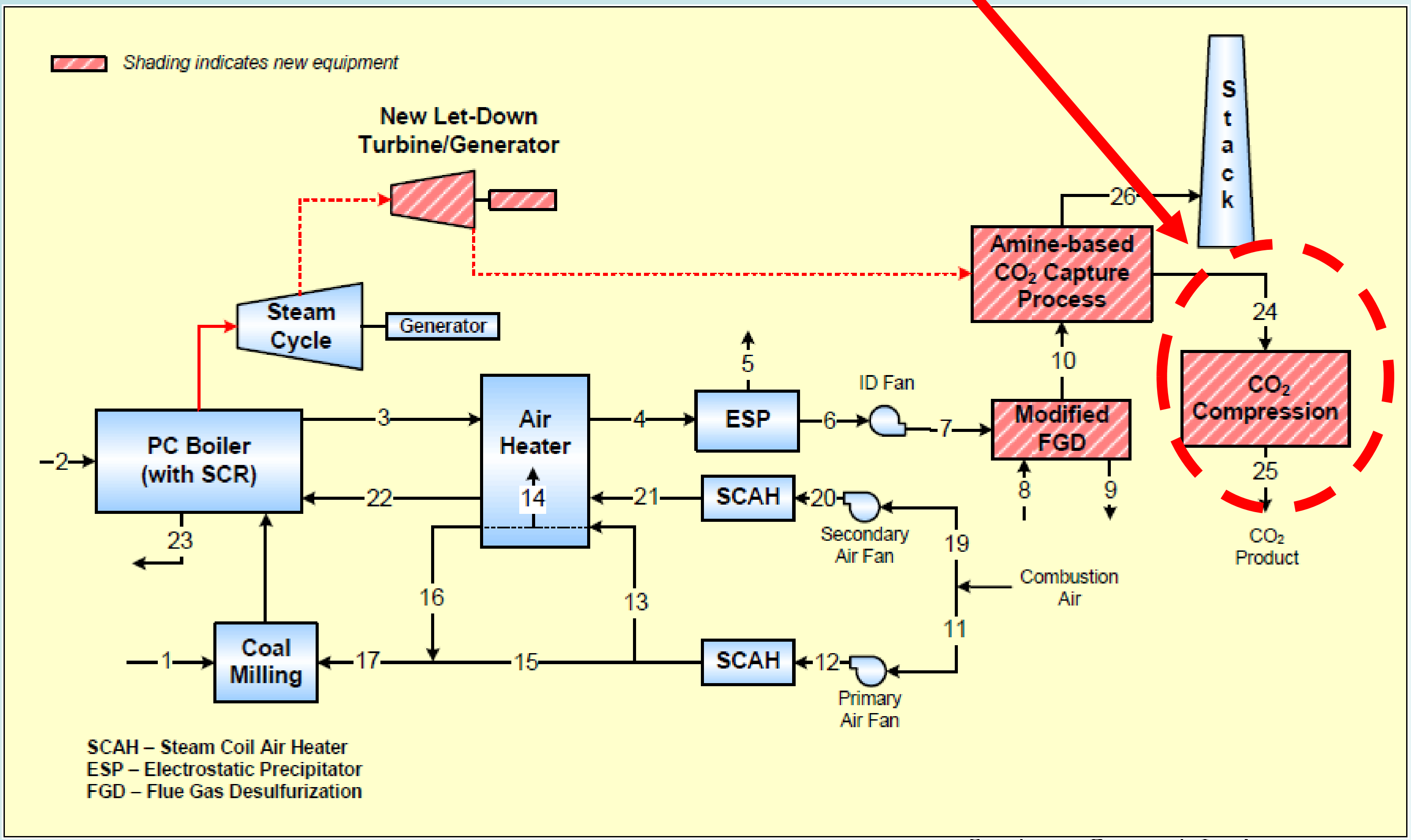
- CO_2 capture has a significant compression penalty - as high as 8 to 12%.
- Final pressure around 1,500 to 2,200 psia for pipeline transport or re-injection.
- Based on a 400 MW coal plant, the typical flow rate is ~600,000 to 700,000 lbm/hr.
- Project goal: Double-digit reduction of compression power 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 2^{nd} Qtr 2011)
  - Pilot scale compression plant
  - 55,000 lbm/hr

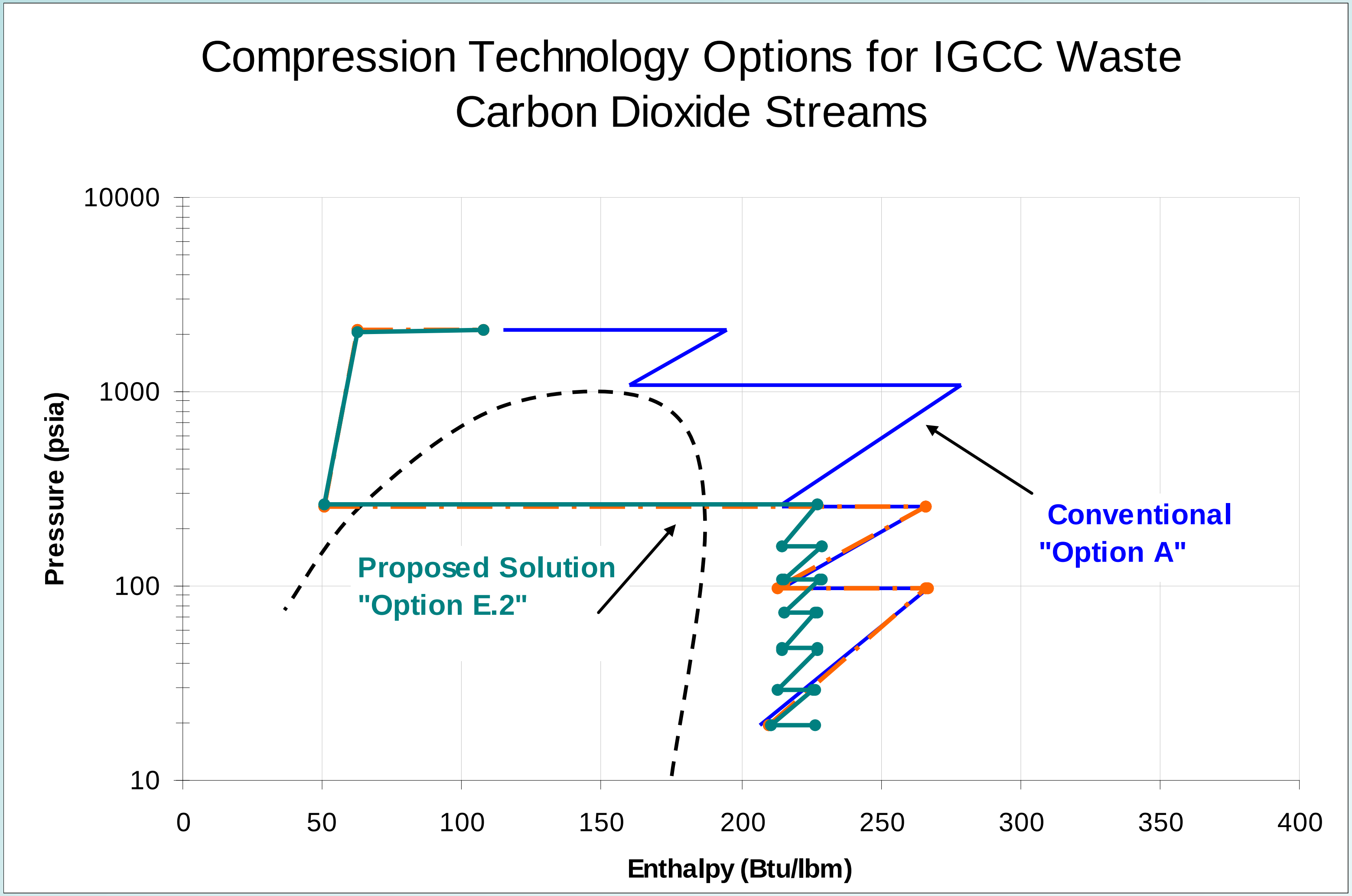
DOE PC Reference Case

- 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.

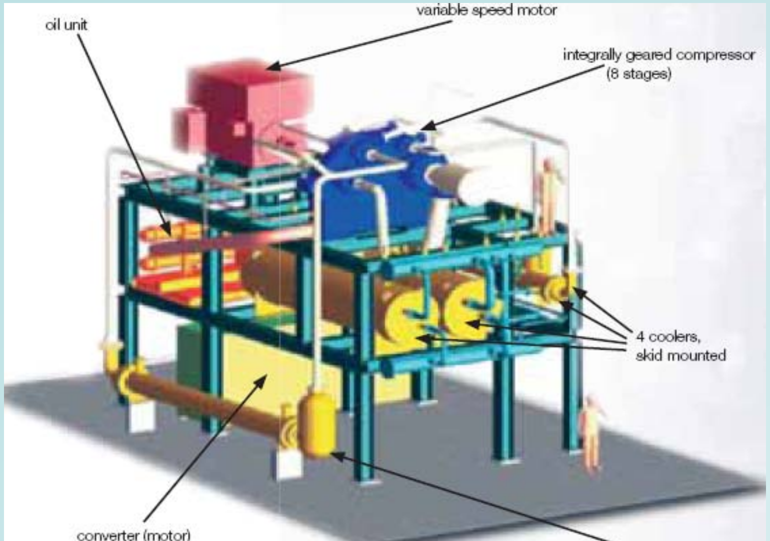
Updated Thermodynamic Calculations

Results for 4 input streams, IGCC power plant application

Option	Compression Technology	Power Requirements	% Diff from Option A	Cooling Technology	Cooling Requirements
A	Conventional Dresser-Rand Centrifugal 16-stage Compression	23,251 BHP	0.0%	Air-cool streams between separate stages	Air Mass Flow = 2.03e6 lbm/hr
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.	To be determined
E.1 Old	Centrifugal compression to 250 psia, Liquid cryo-pump from 250-2215 psia	17,055 BHP (Includes 7,814 BHP for Refrigeration) [1]	-26.6%	Air cool up to 250 psia, Refrigeration to reduce CO2 to -25degF to liquefy	Refrigeration requires 7814 HP for 3428 tons, Air Mass Flow = 6.3e5 lbm/hr
E.2 Old	Centrifugal compression to 250 psia with semi-isothermal cooling at 100 degF, Liquid cryo-pump from 250-2215 psia	16,001 BHP (Includes 7,814 BHP for Refrigeration) [1]	-31.2%	Air cool up to 250 psia between centrifugal stages, Refrigeration to reduce CO2 to -25degF to liquefy	Refrigeration requires 7814 HP for 3428 tons, Air Mass Flow = 5.1e5 lbm/hr
E.1 Updated	Centrifugal compression to 250 psia, Liquid cryo-pump from 250-2215 psia, Measured pump eff. No N2 Cooling, Updated cooling cost to 1.582 kW/ton	22,721 BHP (Includes 13,480 BHP for Refrigeration) [1]	-2.3%	Air cool up to 250 psia, Refrigeration to reduce CO2 to -25degF to liquefy	Refrigeration requires 13480 HP for 6354 tons.
E.2 Updated	Centrifugal compression to 250 psia with semi-isothermal cooling at 100 degF, Liquid cryo-pump from 250-2215 psia, , Measured pump eff. No N2 Cooling, Updated cooling cost to 1.582 kW/ton	21,667 BHP (Includes 13,470 BHP for Refrigeration) [1]	-6.8%	Air cool up to 250 psia between centrifugal stages, Refrigeration to reduce CO2 to -25degF to liquefy	Refrigeration requires 13480 HP for 6354 tons.

Challenges: High Reliability

Integrally Geared Isothermal Compressor

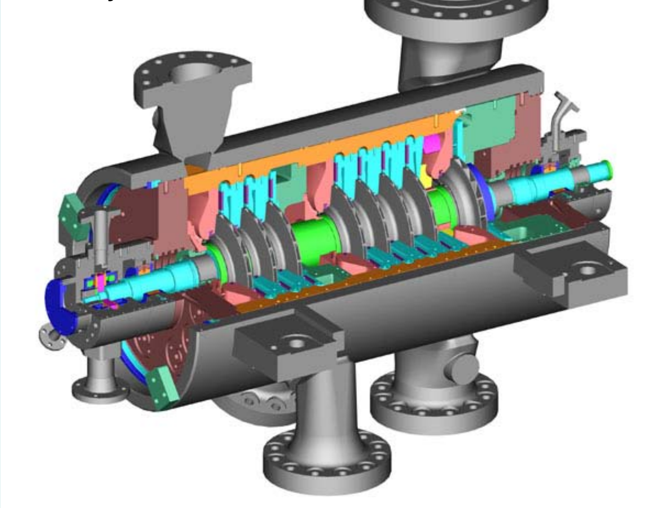


Courtesy of MAN

- 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



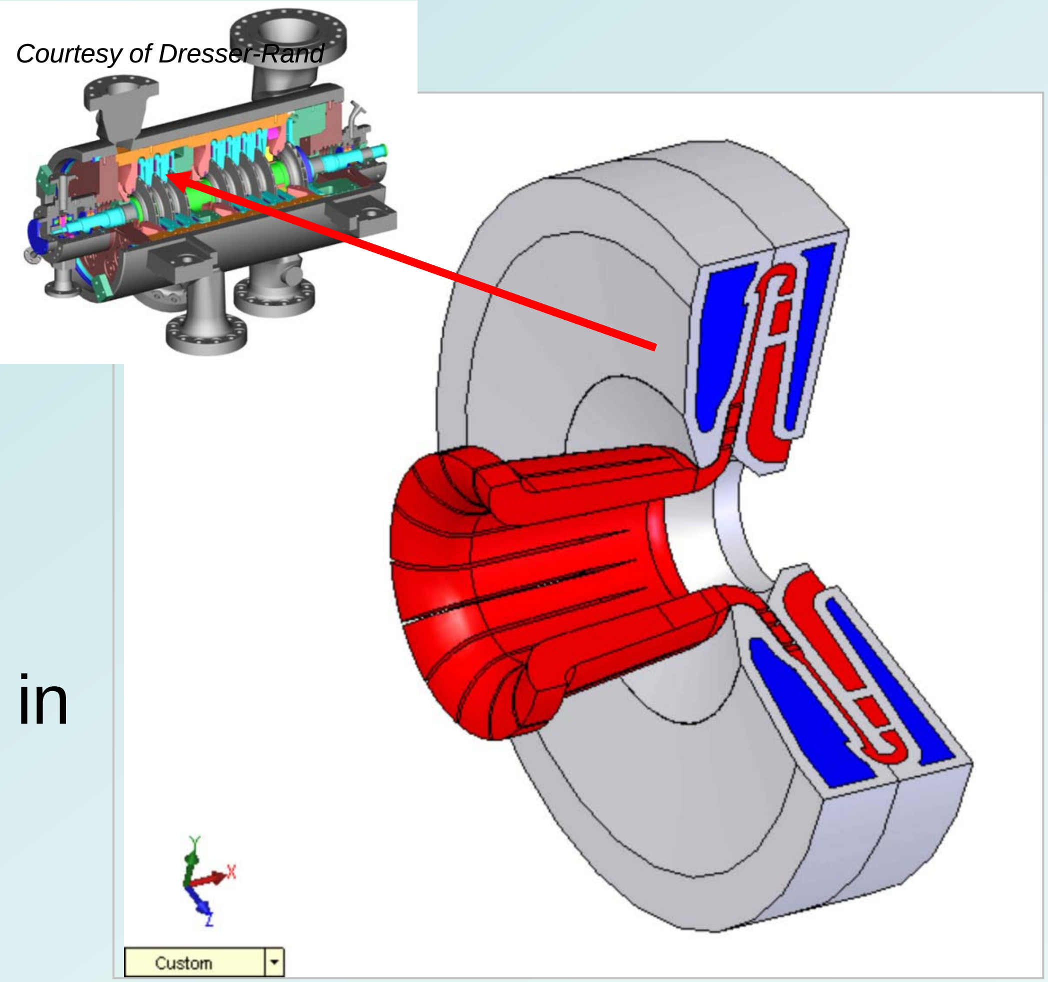
- Multi-stage centrifugal proven reliable and used in many critical service applications currently (oil refining, LNG production, etc.)
- Fewer bearings and seals
  - (4 brgs & seals for 2 body train)
- Can be direct driven by steam turbine

Phase 2 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

Internally Cooled Compressor Concept

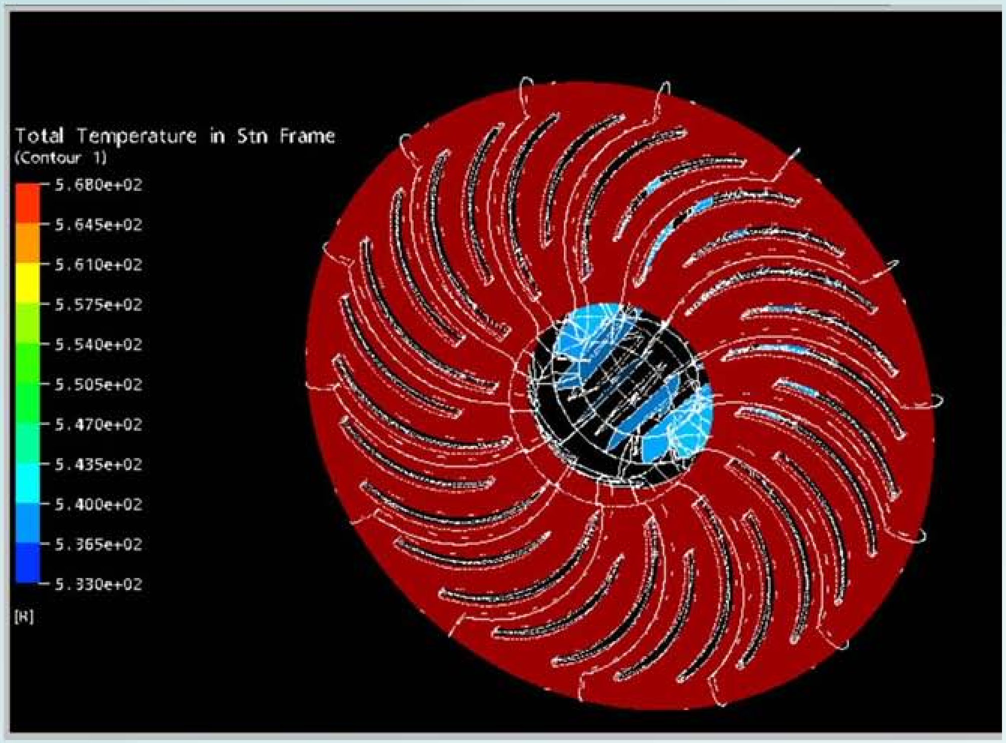
- Investigate an internally-cooled compressor concept
  - Red - CO_2 flow path through compressor stage
  - Blue - Liquid cooling in the diaphragm
  - Grey - Solid



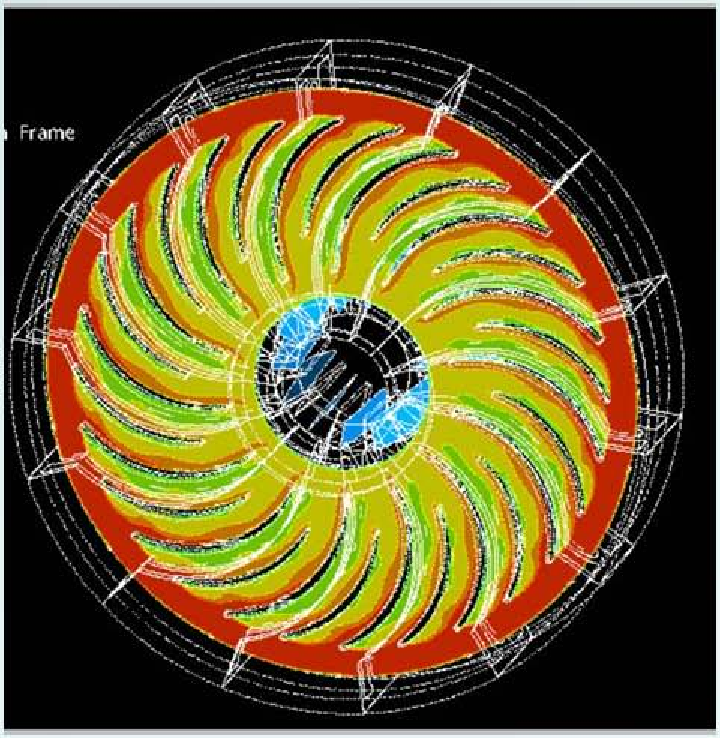
Conjugate Heat Transfer CFD Model

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

Without Heat Transfer



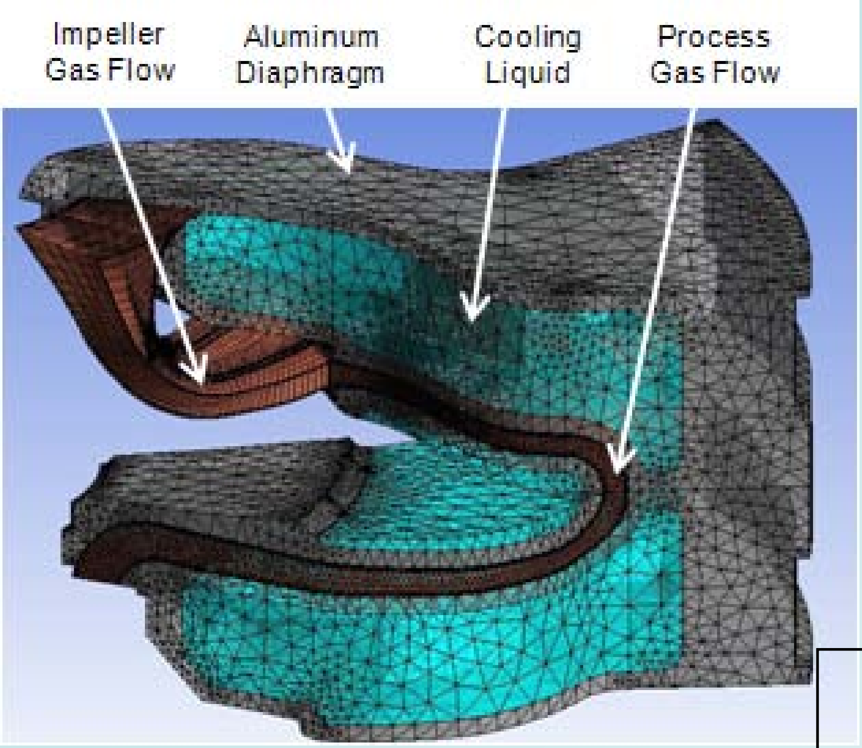
With Heat Transfer



Benefits of a Cooled Diaphragm

- Provides similar 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 an external intercooler
- In some applications, a cooled diaphragm can eliminate the need for an external cooler
  - Use straight through vs. back-to-back
  - Reduce number of compressor bodies
- Compressor fouling can be reduced by lowering the gas temperature below the polymerization point (e.g. ethylene)

Conjugate Heat Transfer CFD Model



Grid from Full Conjugate Heat Transfer (2-fluid) Section Model

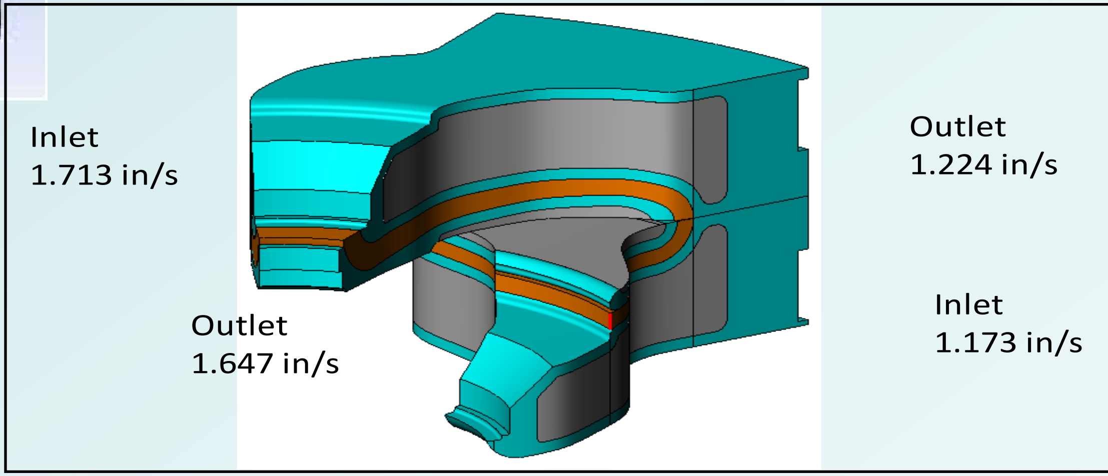
Models Used:

1. **Heat transfer coefficients on liquid interface**
2. **Full conjugate heat transfer model**

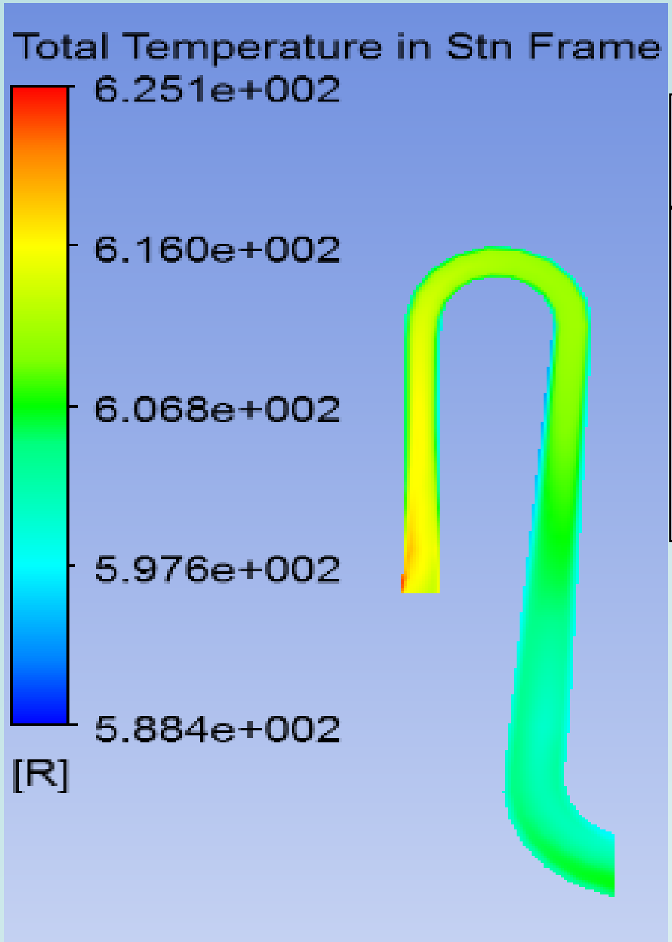
Adiabatic Results (No cooling)

	OEM Data	Model	(%) Difference
Total Pressure Ratio	1.550	1.648	6.3
Total Temperature Ratio	1.136	1.139	0.3
Gas Power [HP]	102.0	104.3	2.3

Flow Boundary Conditions for Cooling Fluid



CFD Results of Adiabatic and Conjugate Heat Transfer Models

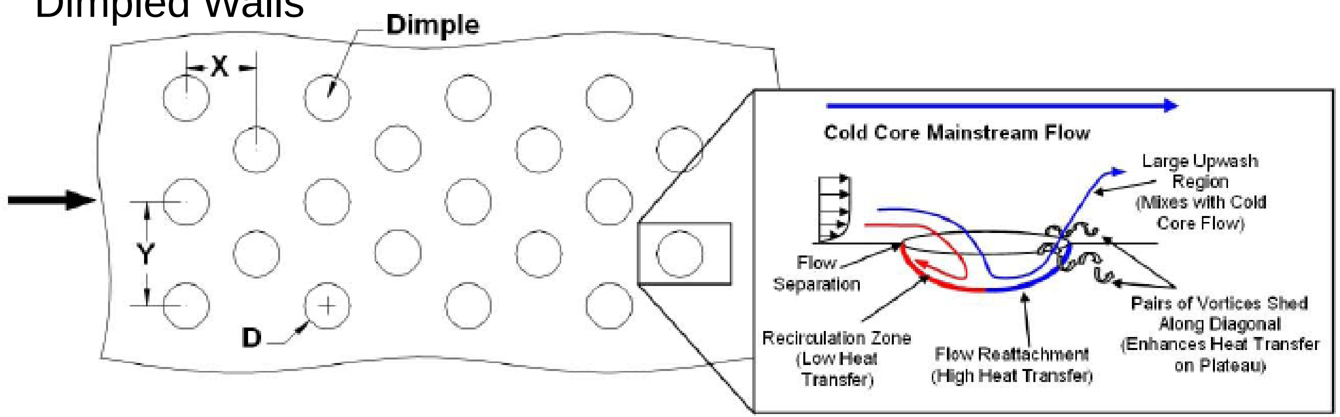


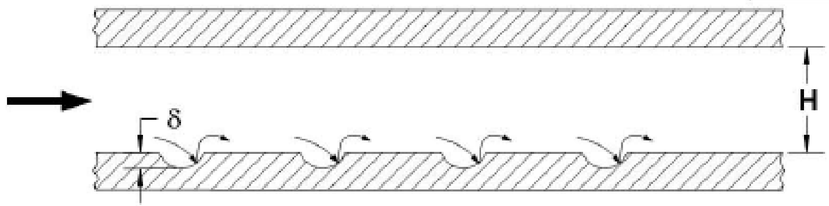
Model	Quantity	Impeller Ratio	Stage Ratio
Adiabatic	Total Pressure	1.773	1.670
	Total Temperature	1.142	1.142
Diabatic with Heat Transfer Coefficients	Total Pressure	1.764	1.671
	Total Temperature	1.141	1.116
Diabatic with Full Conjugate Heat Transfer	Total Pressure	1.767	1.678
	Total Temperature	1.141	1.117

Good correlation between model using heat transfer coefficients on the liquid interface and the full two-fluid model

Heat Transfer Enhancement

Dimpled Walls





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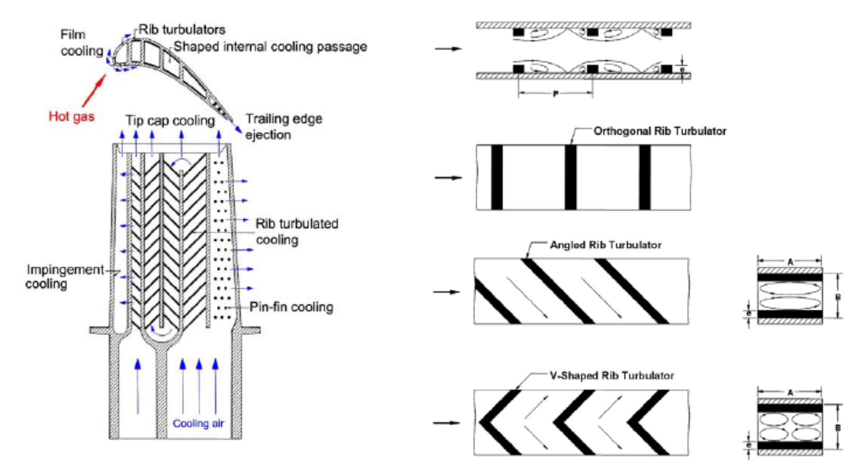
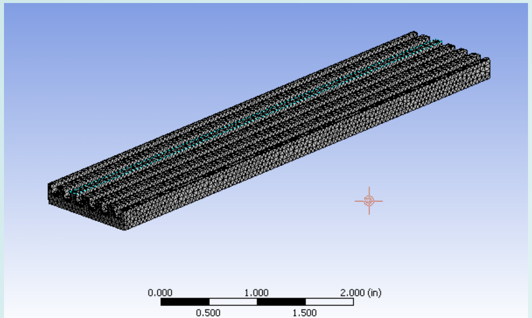
Ribs on Walls



Grooved Airfoil Surface



Analysis of Design Configurations

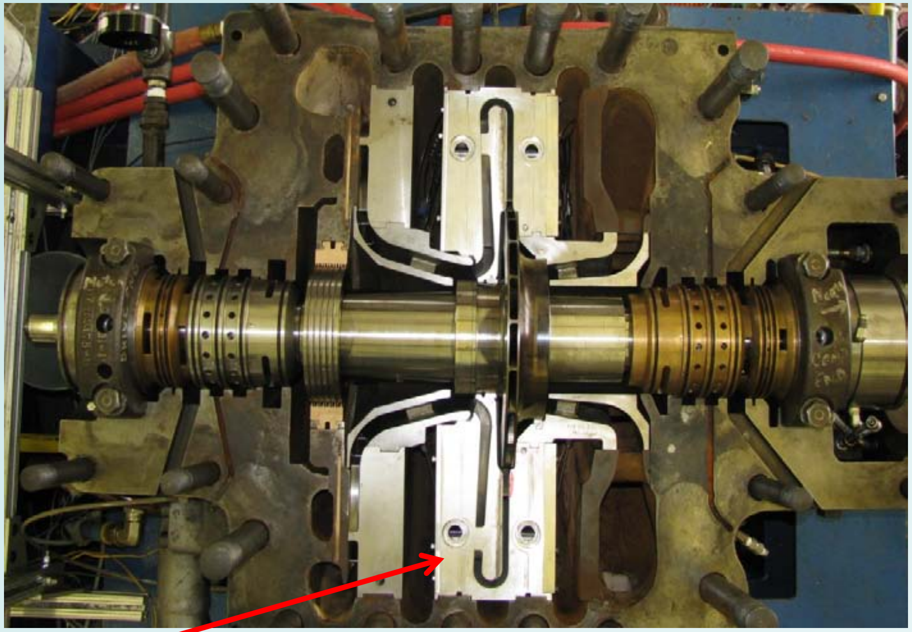
- *Adiabatic* – No heat transfer from CO_2, serves as the baseline for other cases.
- *Smooth wall (SW) heat transfer* – Smooth walls on both the water and CO_2 sides, i.e., no convection coefficient augmentation geometry used.
- *Smooth wall heat transfer at 9,155 rpm* – Same smooth wall geometry, as previous case; however, operated with a reduced stage pressure ratio to simulate a slower speed.
- *Smooth wall with higher radius ratio* – In order to increase heat exchanger effectiveness, surface area was increased by using a longer diffuser.
- *Ribbed water side walls and dimpled CO_2 side walls* – A convection coefficient augmentation case.
- *Ribbed water side walls, dimpled CO_2 side walls, and grooved airfoils* – The second convection coefficient augmentation case.

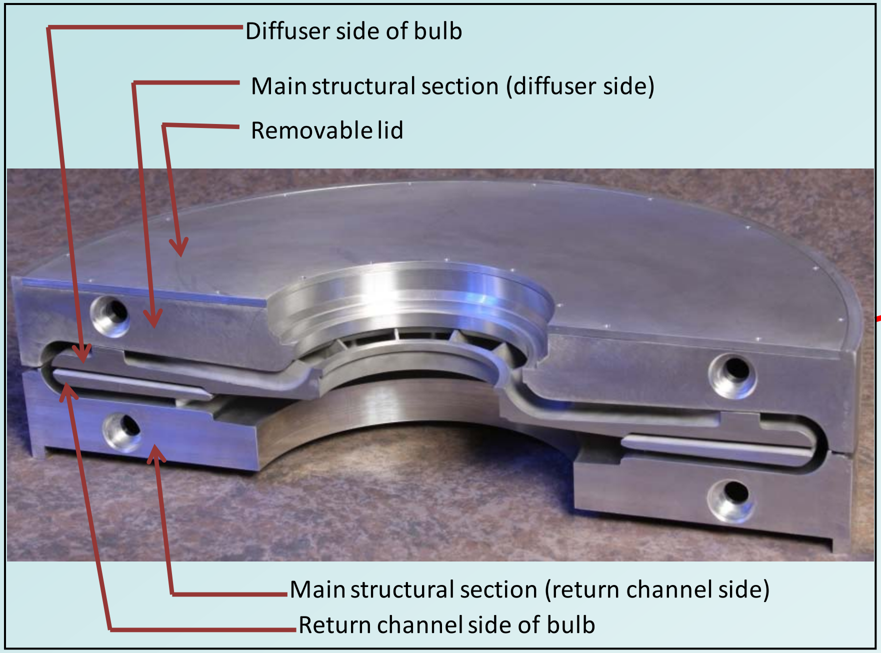
Updated Estimates – Low P

- Comparison with previous straight-through estimates
  - Same stage P1 & P2, first stage T1, efficiencies, and HX effectiveness values
  - Gas properties from REFPROP

Geometry	RPM	Radius Ratio	# Stages	HX Effectiveness	Gas Power Savings
Adiabatic Reference	12850	1.5	5	NA	0%
Smooth Wall	12850	1.5	5	0.15	7.0%
Smooth Wall	12850	1.8	5	0.197	8.6%
Ribs and Dimples	12850	1.5	5	0.25	1.2%
Ribs, Dimples, and Grooves	12850	1.5	5	0.31	-0.93%
Adiabatic Reference	9155	1.5	9	NA	0%
Smooth Wall	9155	1.5	9	0.15	13.3%
Smooth Wall	9155	1.8	9	0.197	15.3%

Test Rig Construction

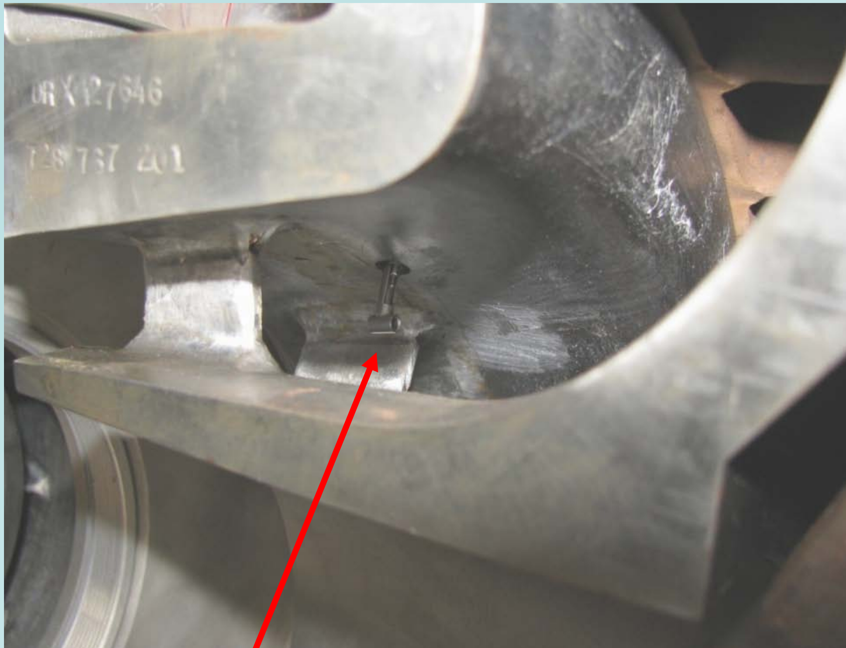


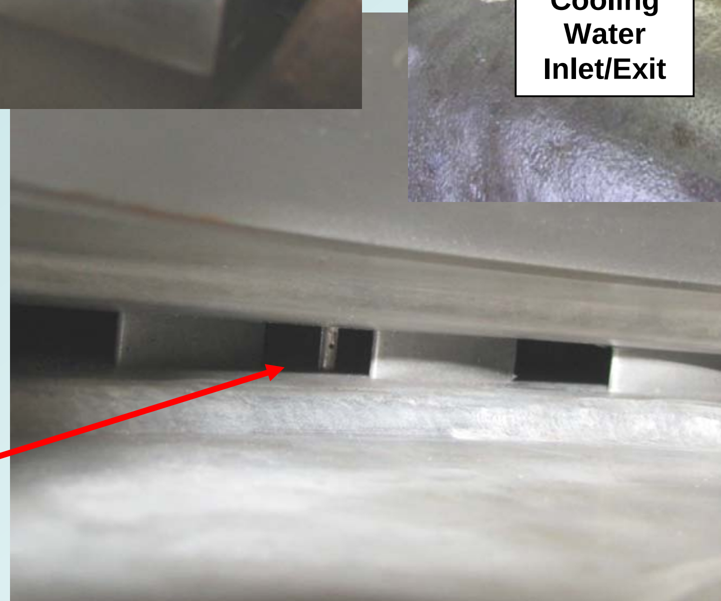


Closed Loop Test Facility

- 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

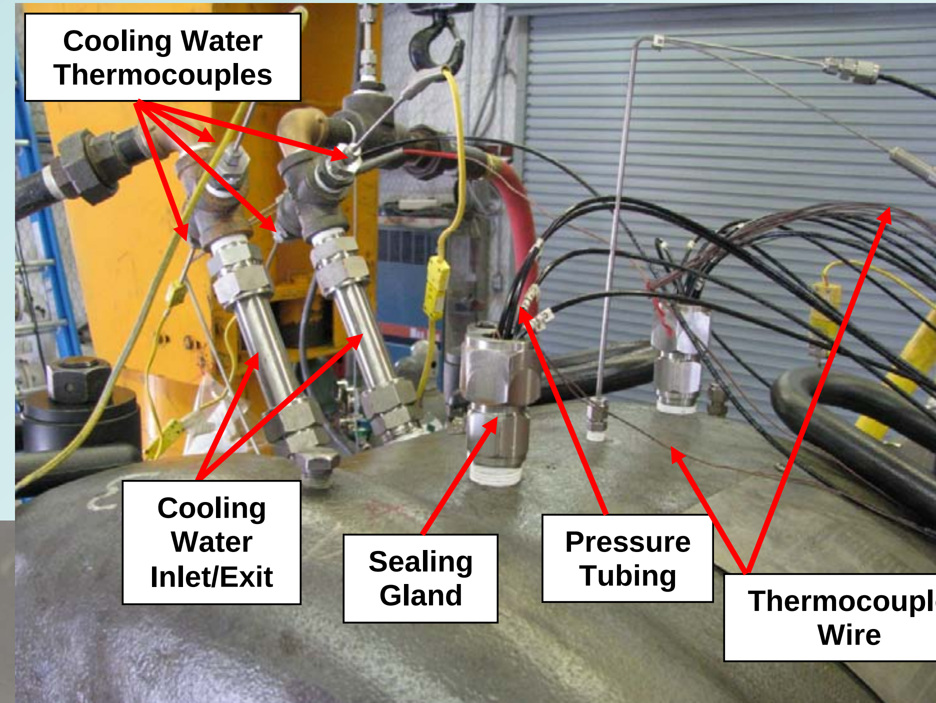
Instrumentation





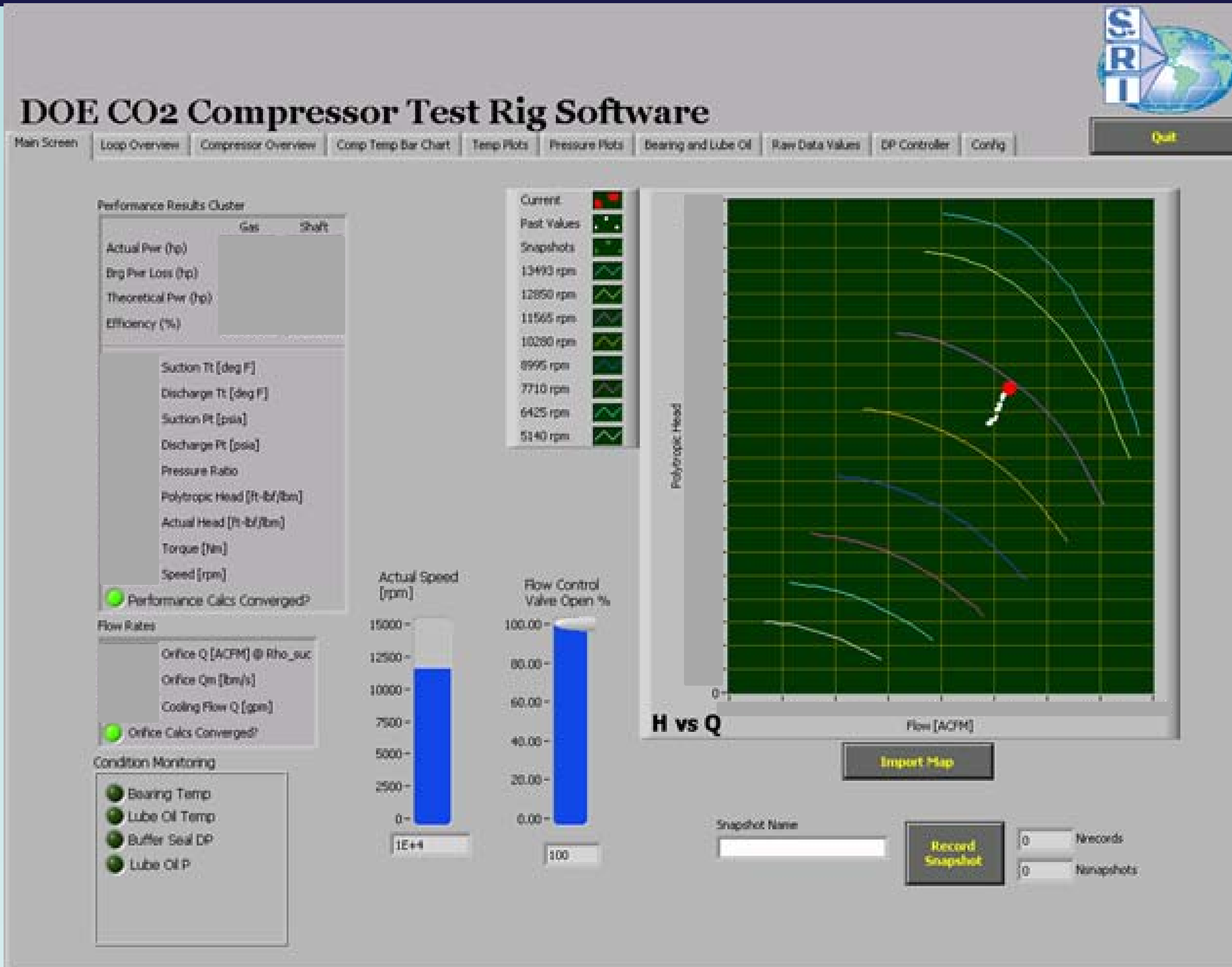
Combination Kiel Head Pressure/Temperature Probe at Suction and Discharge Bridge-over

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

Main Screen of Data Acquisition Code



Some Definitions

- Heat Exchanger Effectiveness

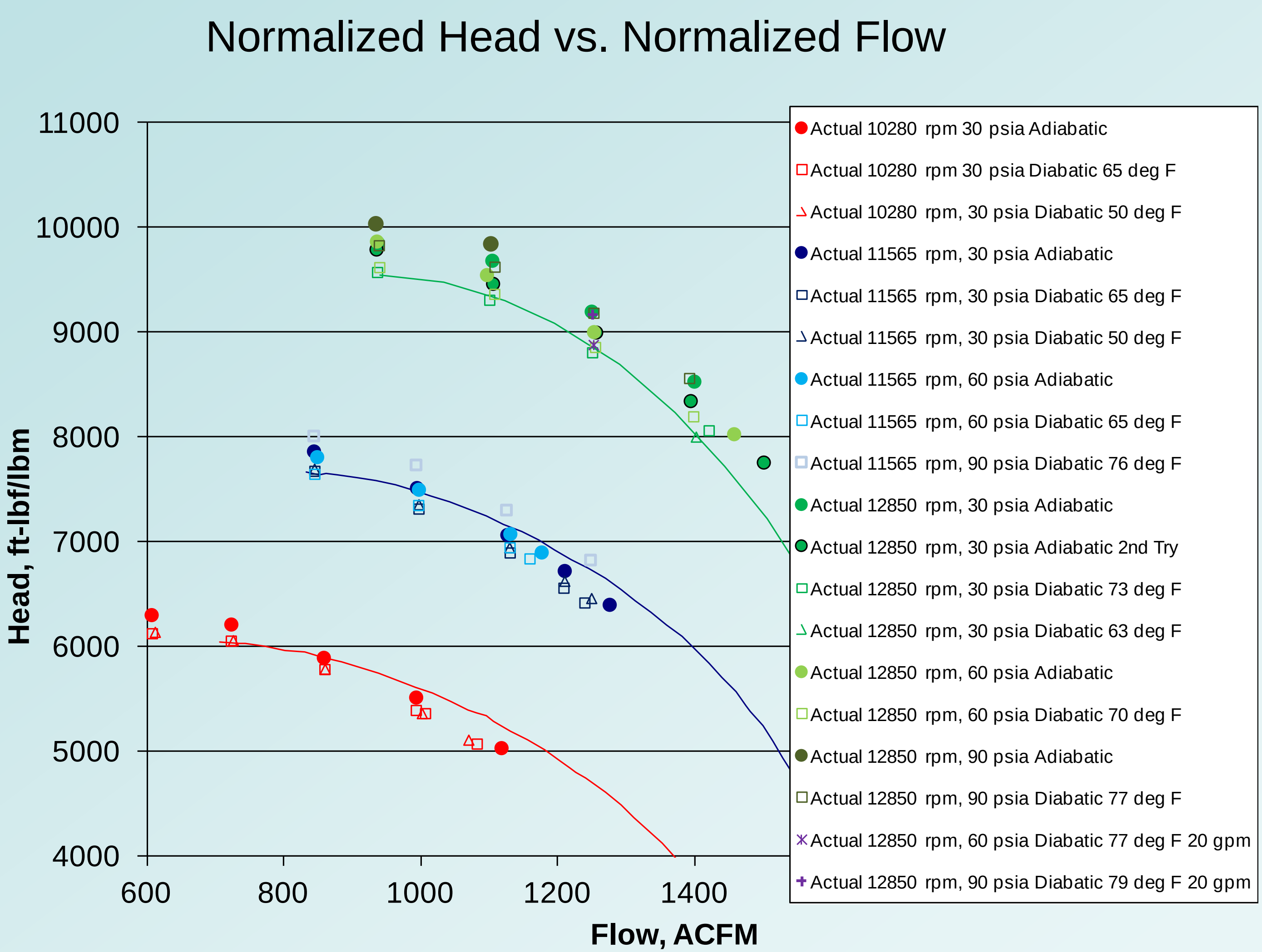
$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}} = \frac{Actual\ Heat\ Transfer\ Rate}{Maximum\ Possible\ Heat\ Transfer\ Rate}$$

where

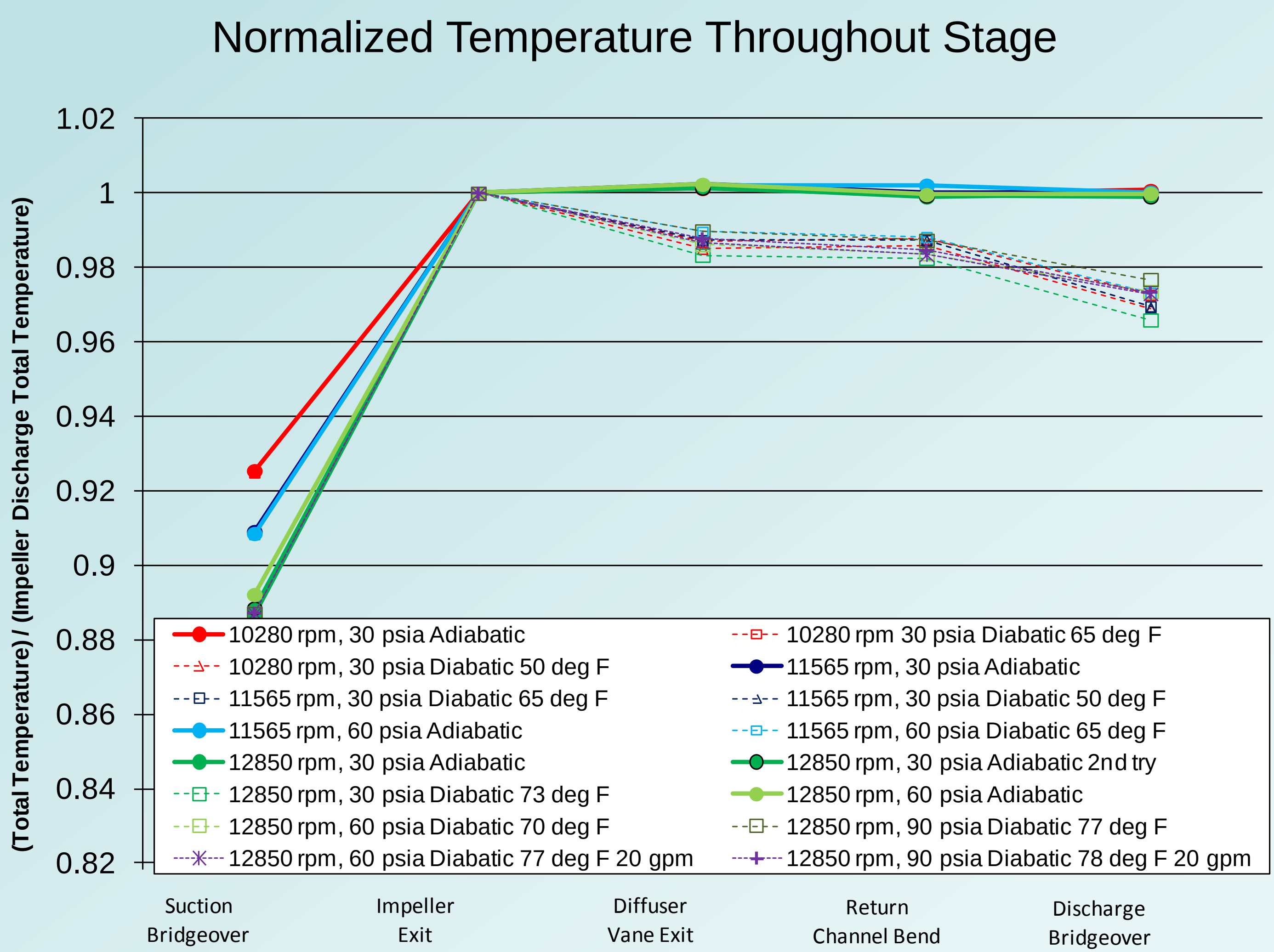
$$\dot{Q} = C_{H2O}\left(T_{H2O,out} - T_{H2O,in}\right) = C_{CO2}\left(T_{CO2,in} - T_{CO2,out}\right)$$

$$\dot{Q}_{max} = C_{min}\left(T_{CO2,in} - T_{H2O,in}\right)$$

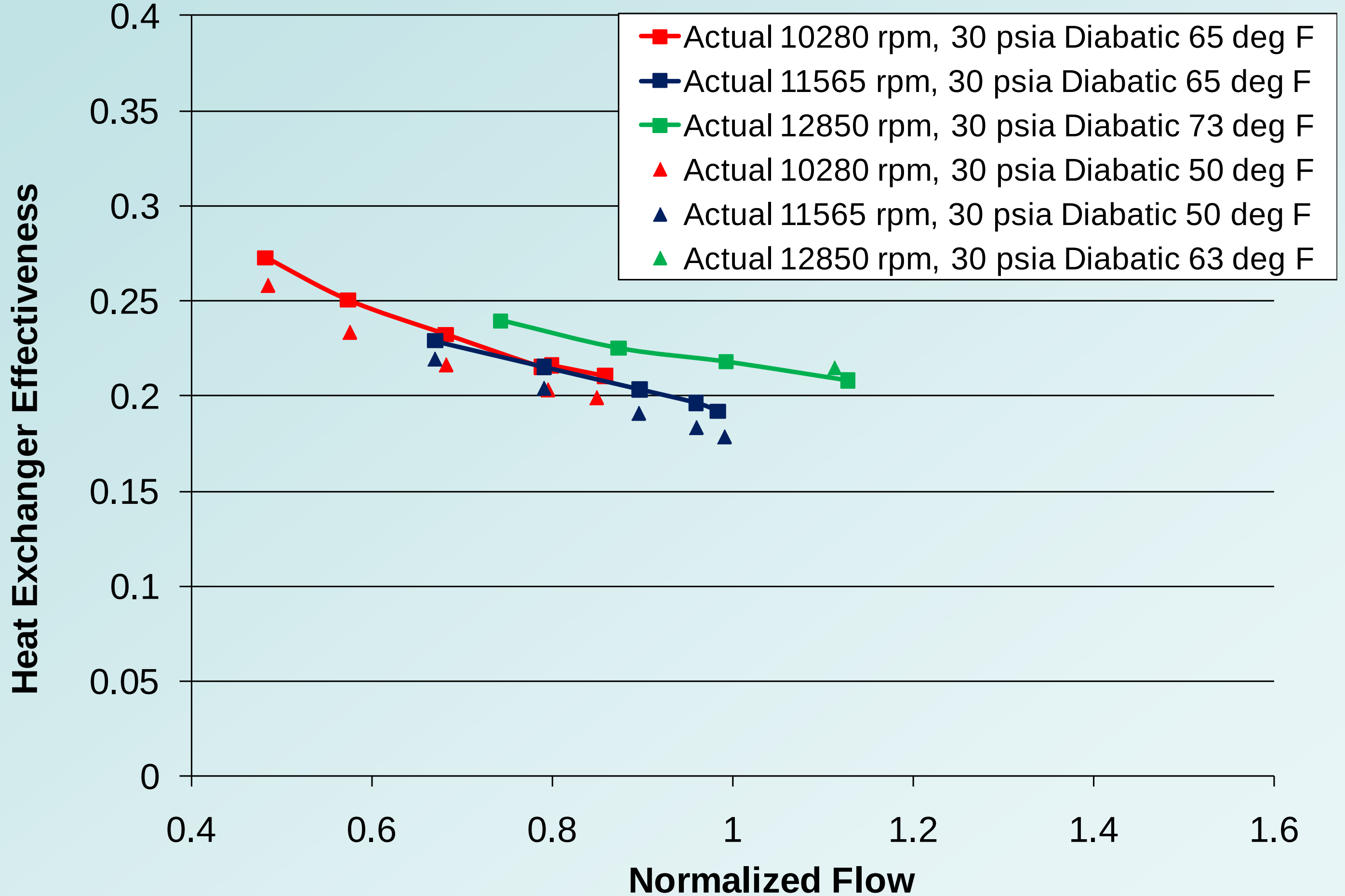
Measured Polytropic Head vs. Flow 30-90 psia (2-6 bar) Suction Pressure



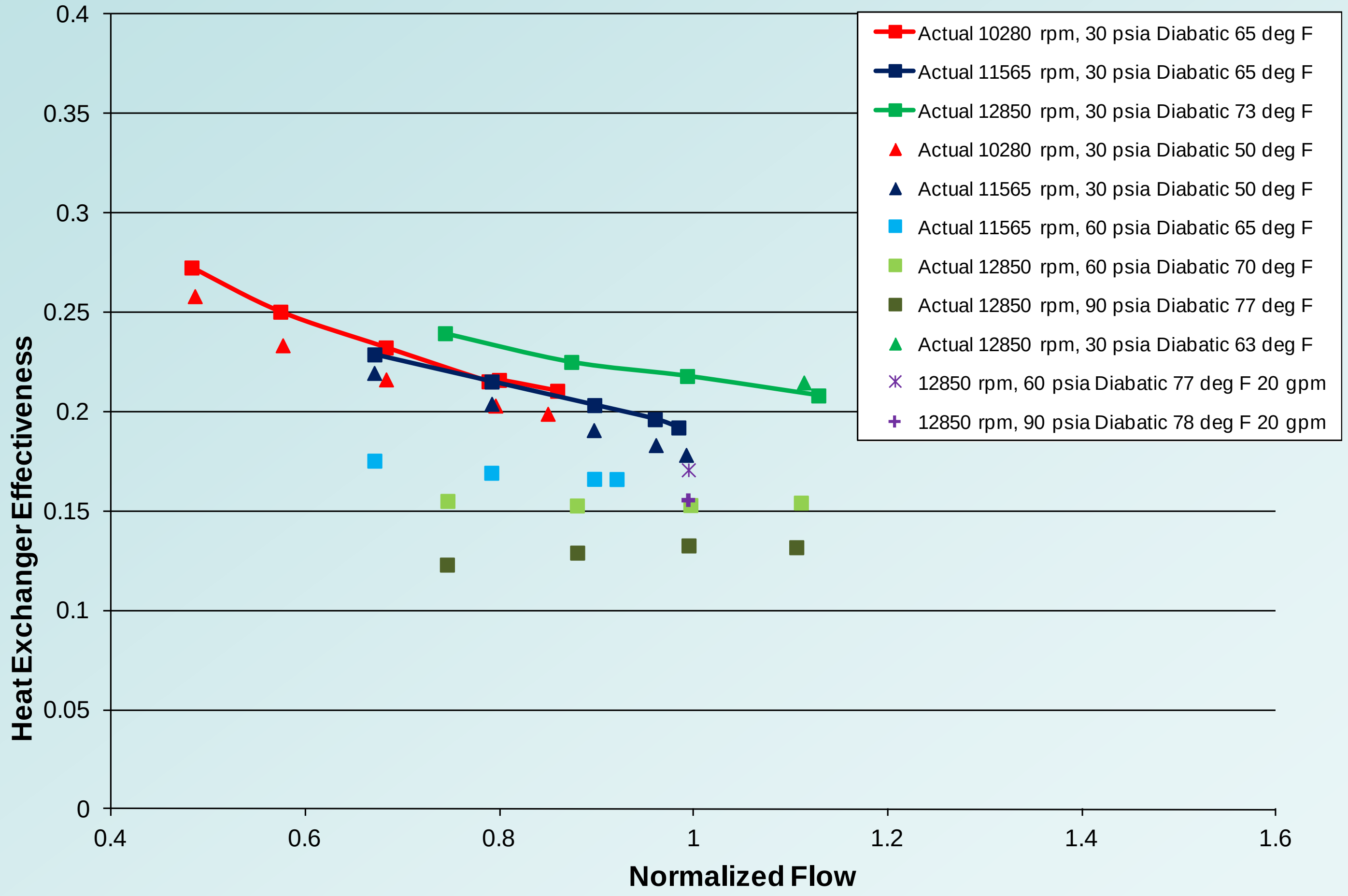
Measured Total Temperature Profiles



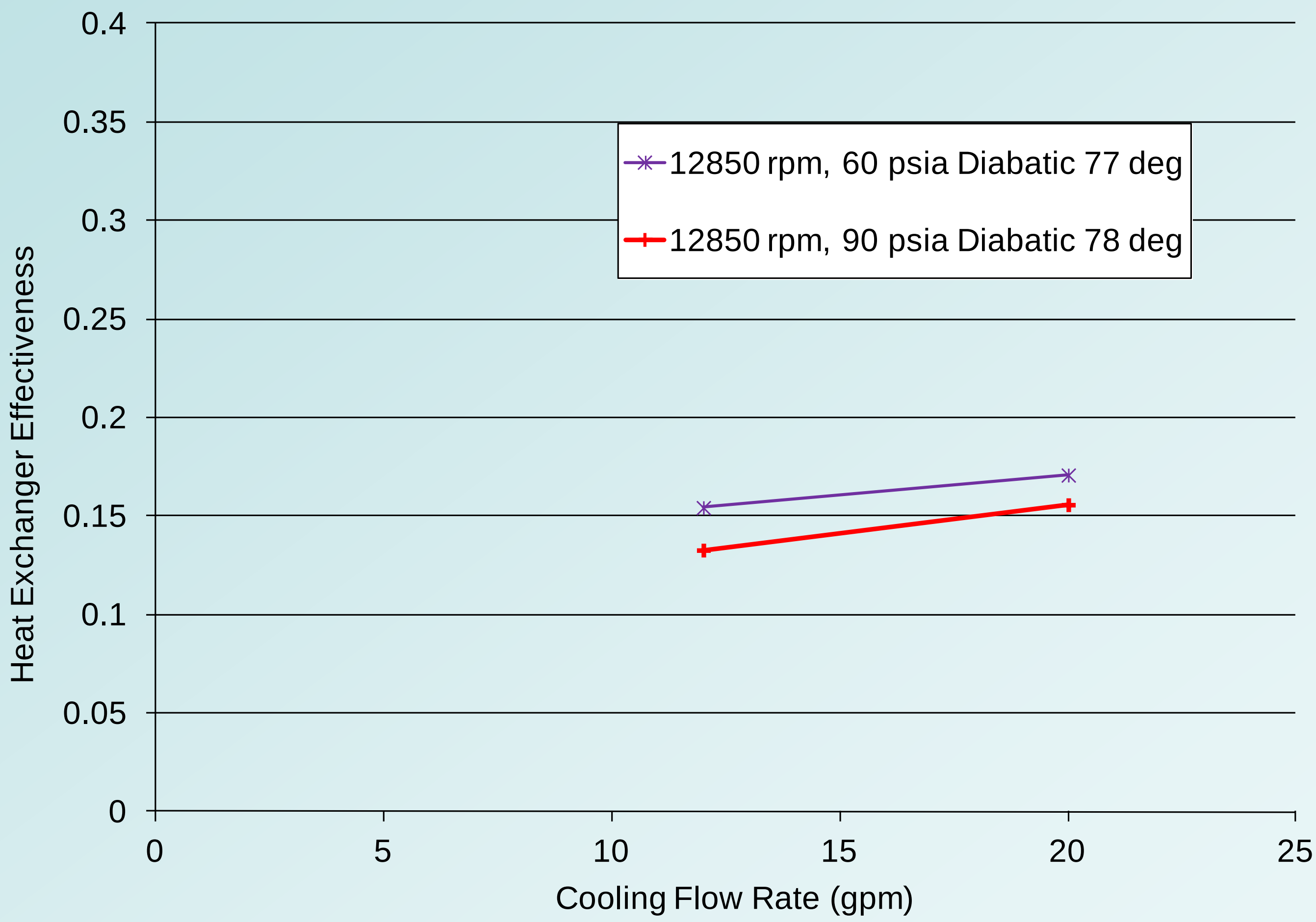
Measured Heat Exchanger Effectiveness vs. Flow at 30 psia Suction Pressure



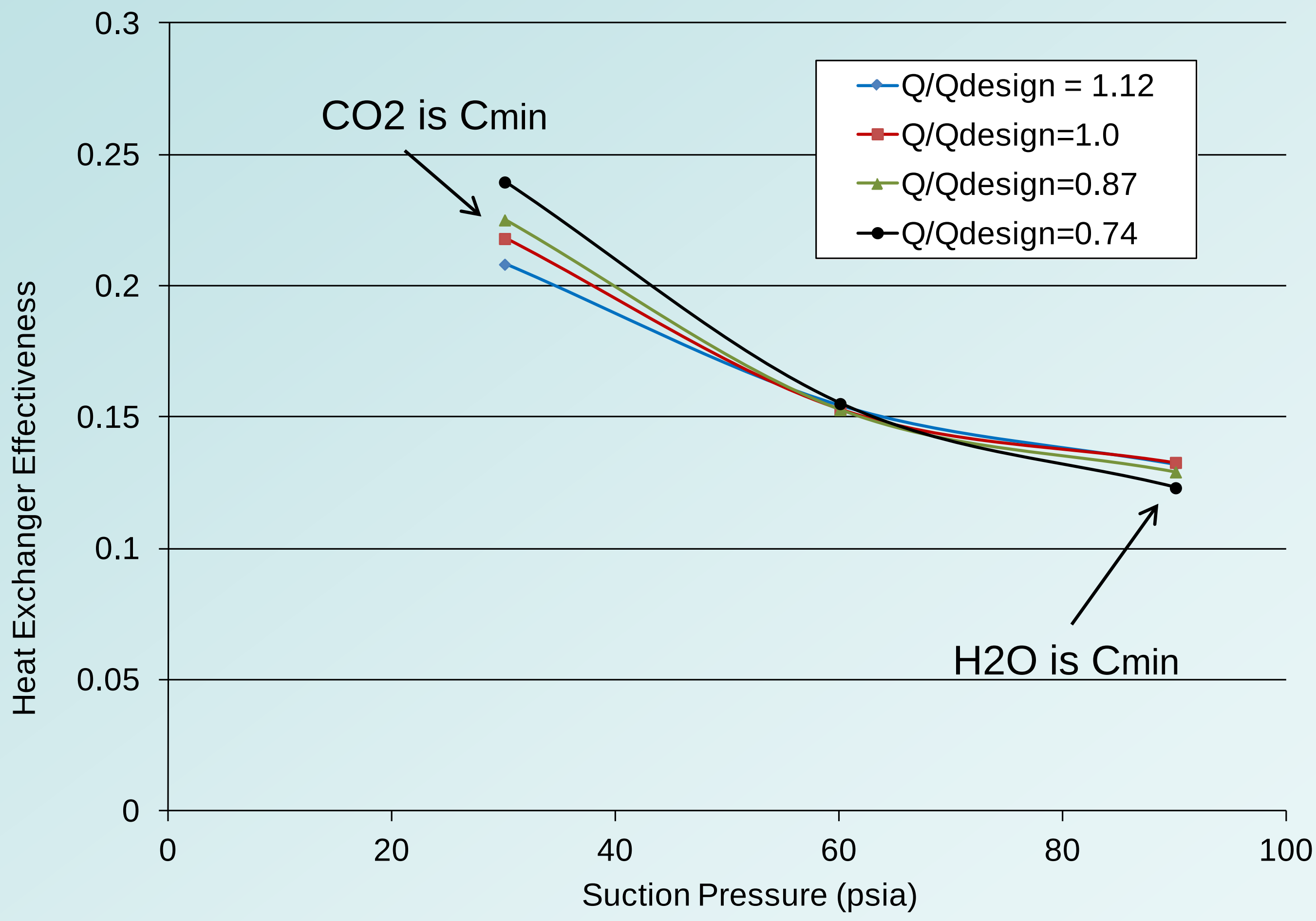
Measured Heat Exchanger Effectiveness vs. Flow 30-90 psia (2-6 bar) Suction Pressure



Heat Exchanger Effectiveness vs. Cooling Flow Rate

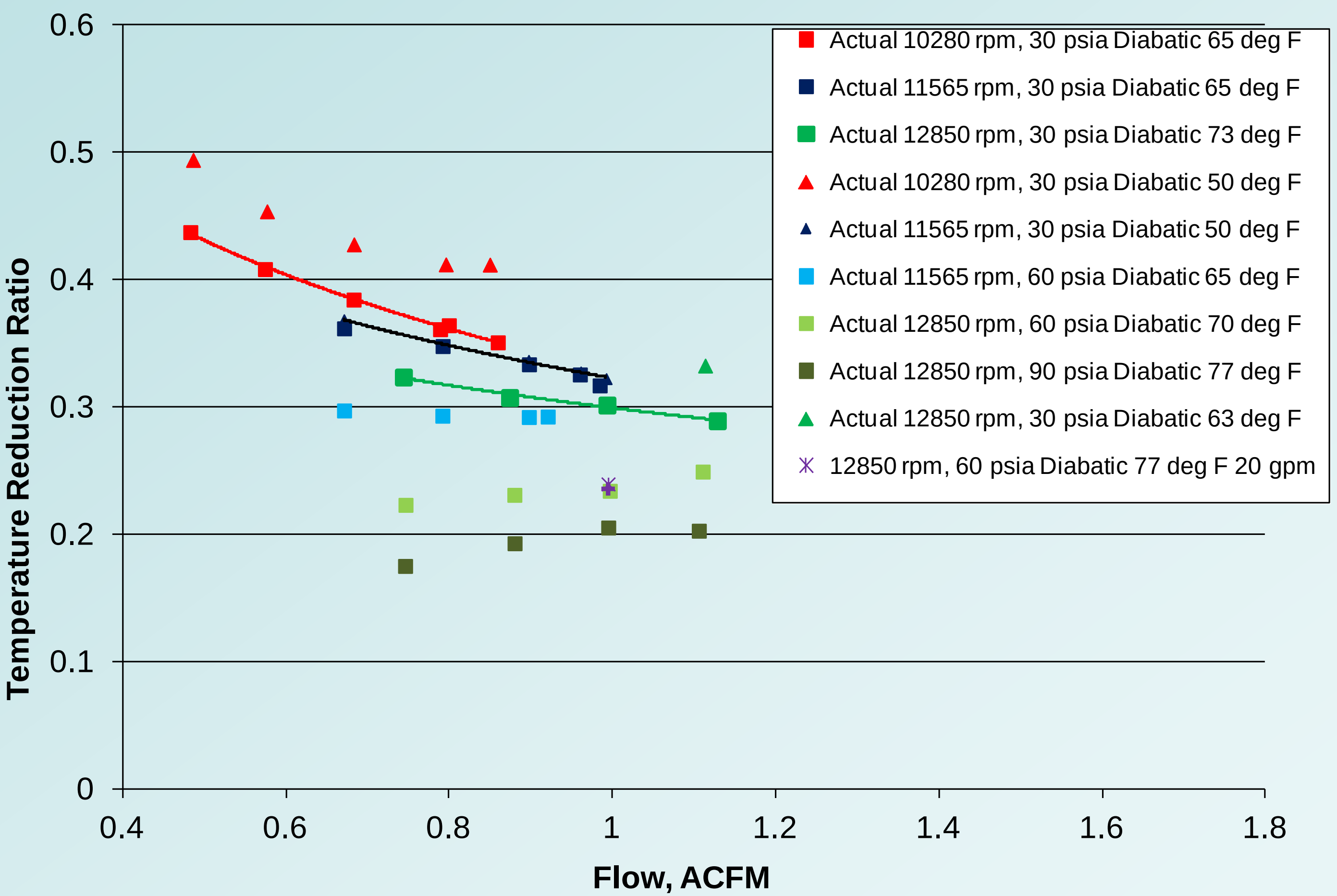


Heat Exchanger Effectiveness vs. Suction Pressure

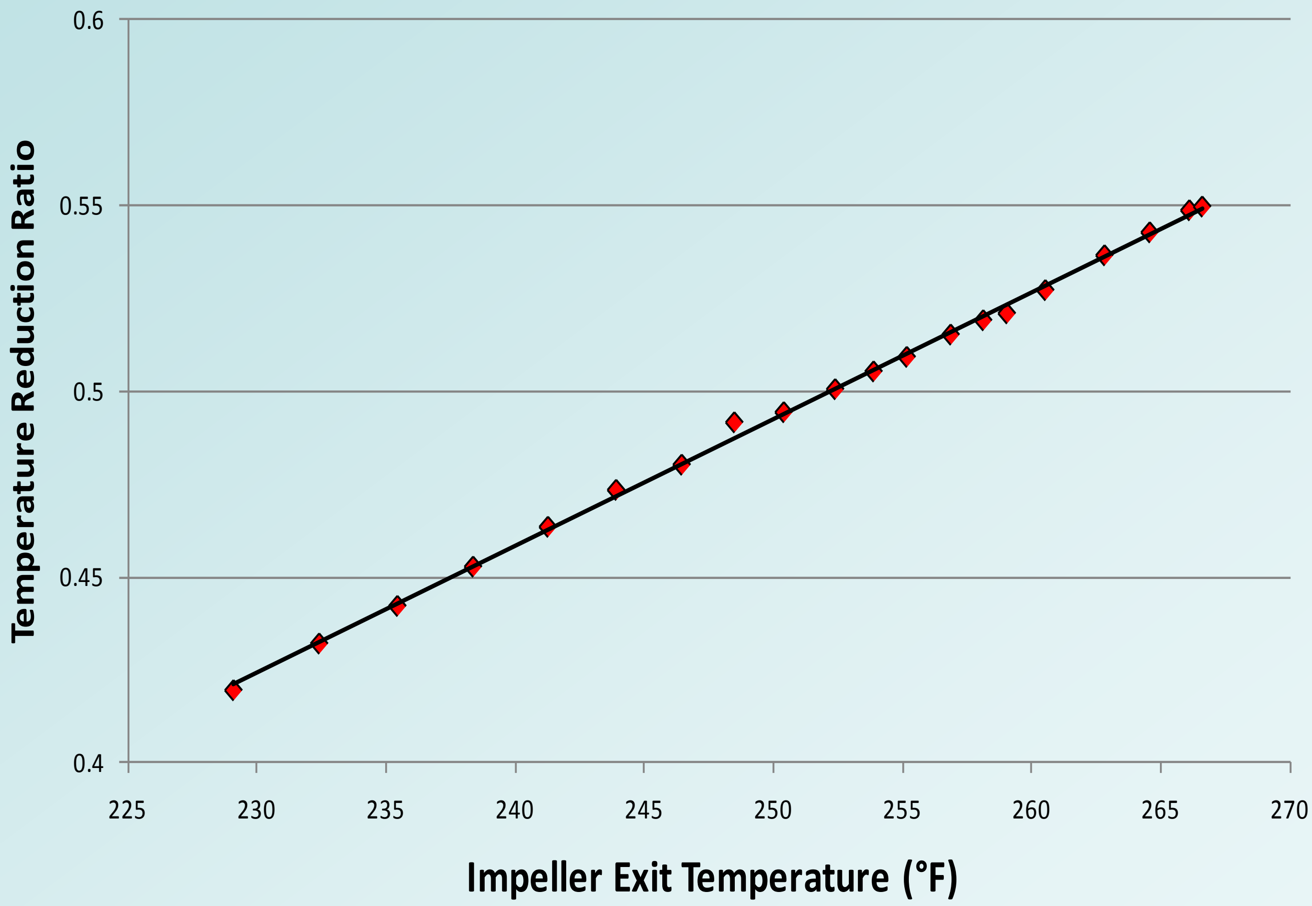


Fraction of Heat Removal in the Stage vs. Flow

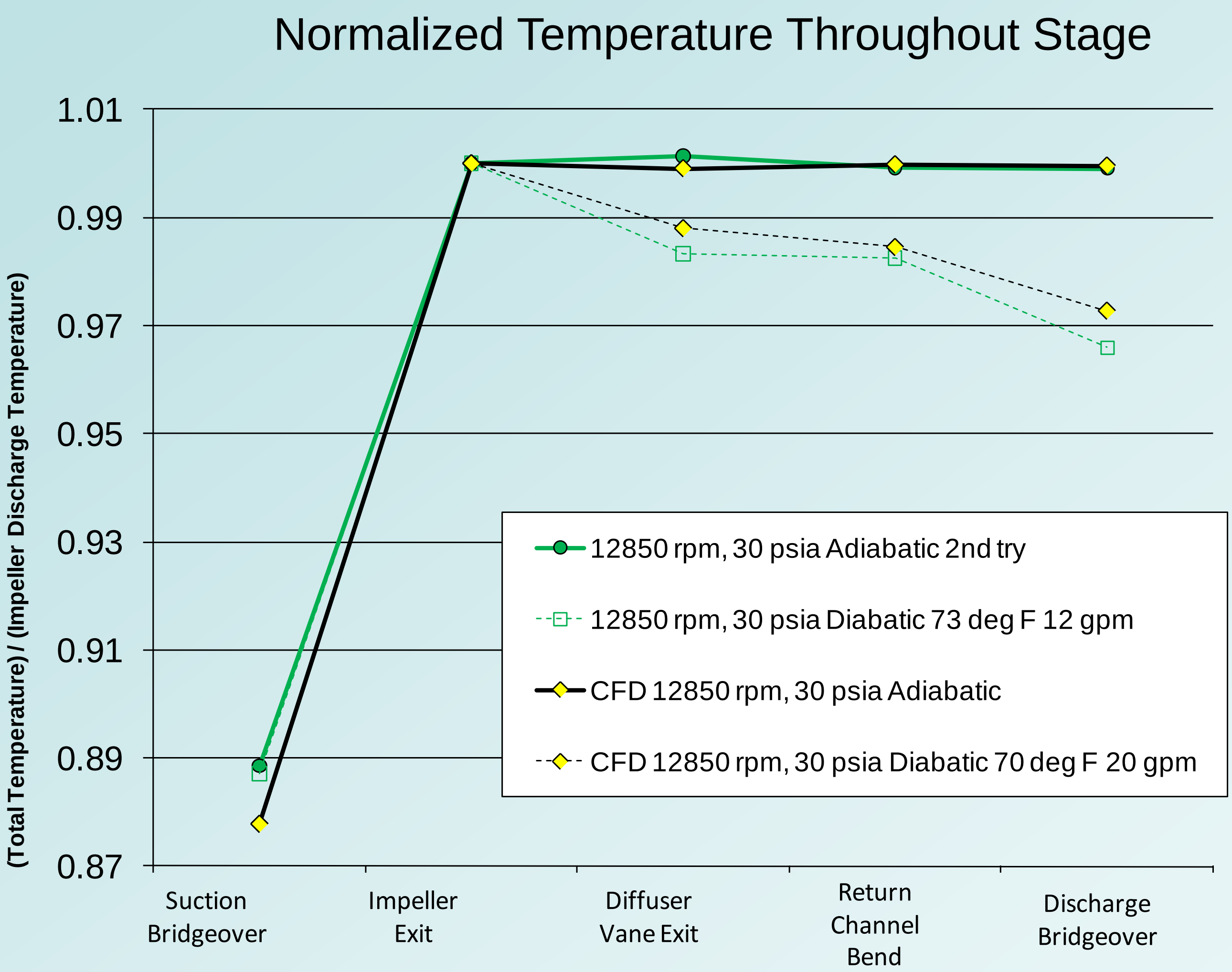
$$TRR = \frac{\Delta T_{\text{Cooled Temp Reduction}}}{\Delta T_{\text{Adiabatic Stage Temp Rise}}}$$



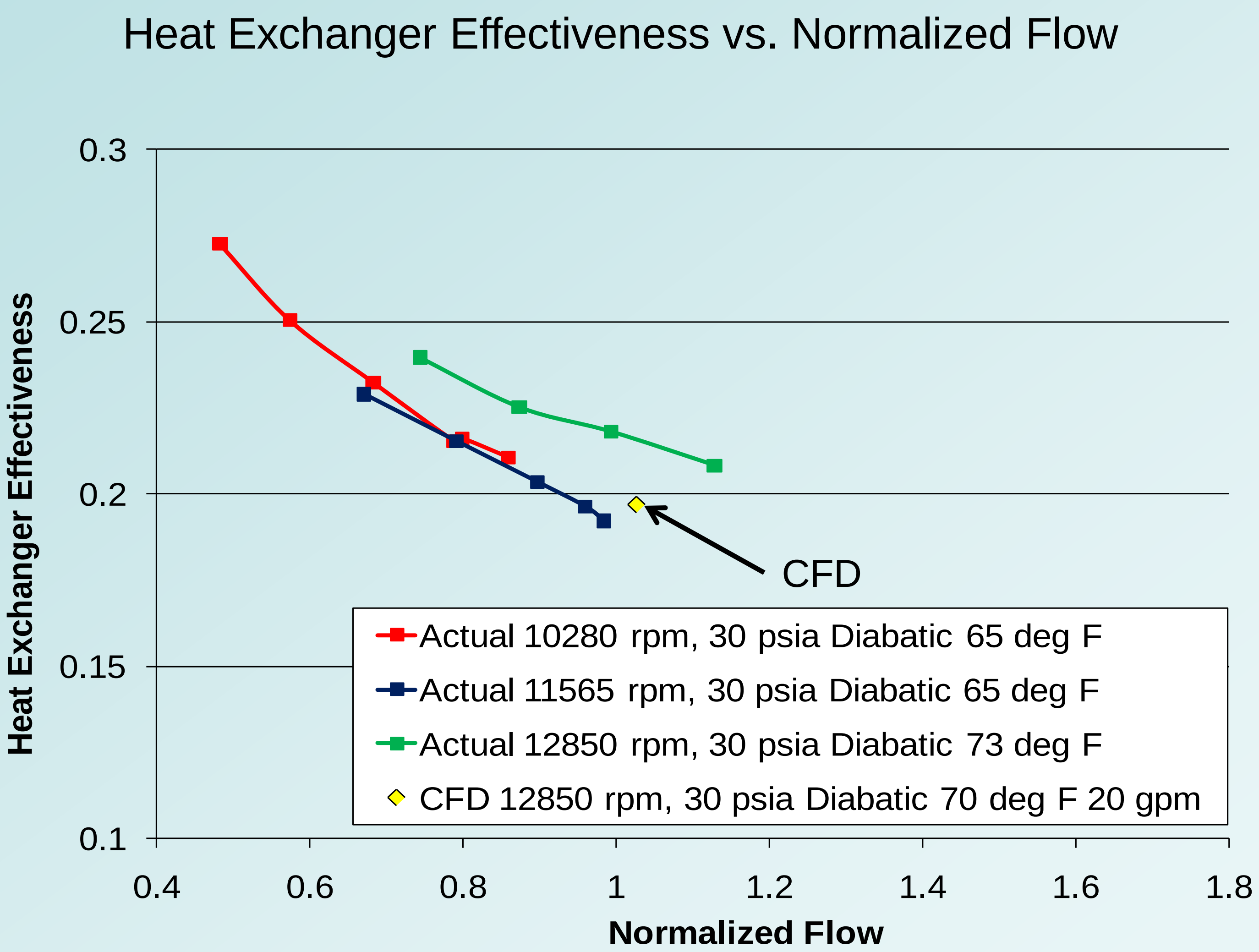
Fraction of Heat Removal in the Stage vs. Impeller Exit Temperature



Comparison to CFD Predictions



Comparison to Predictions



Phase 2 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 exchanger effectiveness decreases slightly with increasing pressure
  - Heat removal improves in latter stages of a multi-stage compressor
  - Optimum cooling flow rate a function of the gas conditions.
  - Over 15% reduction in power is possible for a multi-stage application
- Technology is applicable to other compression applications with high pressure ratio
- Development of a pilot scale compression facility currently under design

Phase 3 Deliverables

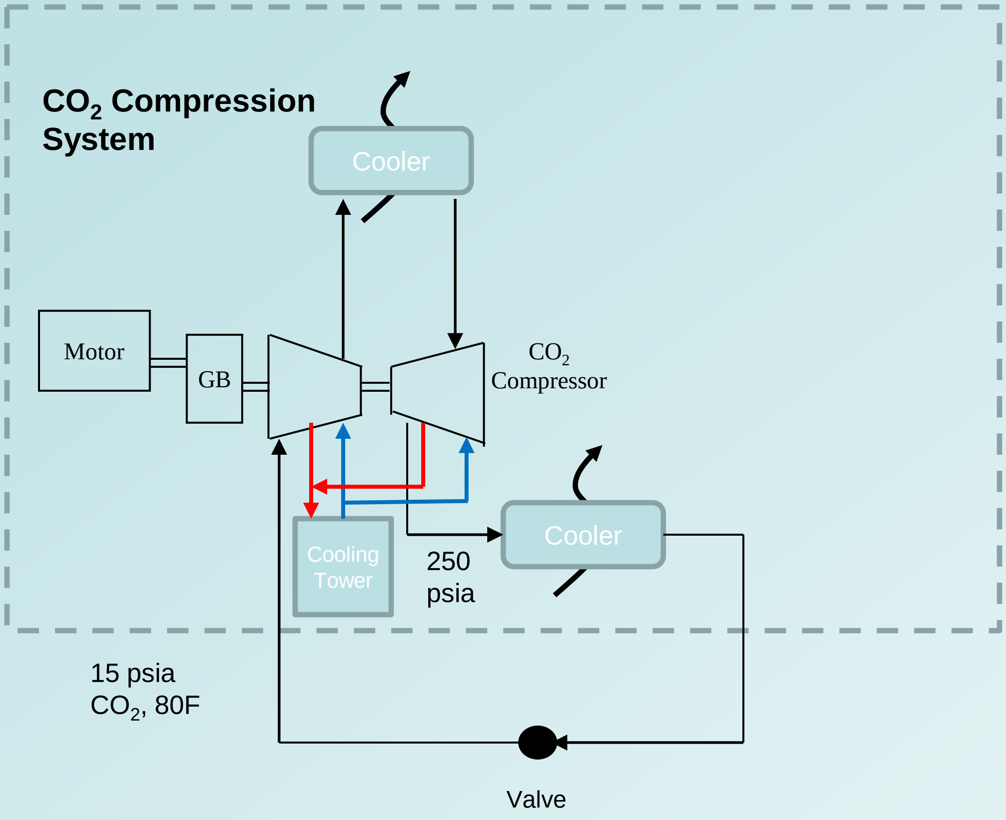
- Deliverables:
  - The cooled diaphragm concept will be extended to a multi-stage design. Many design challenges remain to mature the design for commercialization. Since the cooled diaphragm concept works by reducing the power required in the downstream stages, actual power reduction will be measured.
  - 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 1 – Cooled Diaphragm and Loop Design

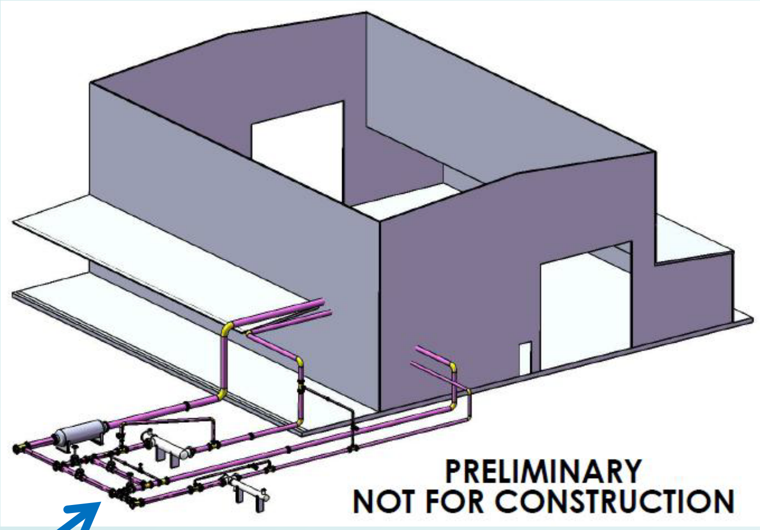
- Finalize compressor selection
- Perform conjugate heat transfer CFD analysis
- Support D-R with FEA analysis of multi-stage diaphragm and cooling circuit
- Develop functional requirement of flow loop including process diagram and P&ID
- Design liquefaction system
- Select major pieces of equipment
- 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

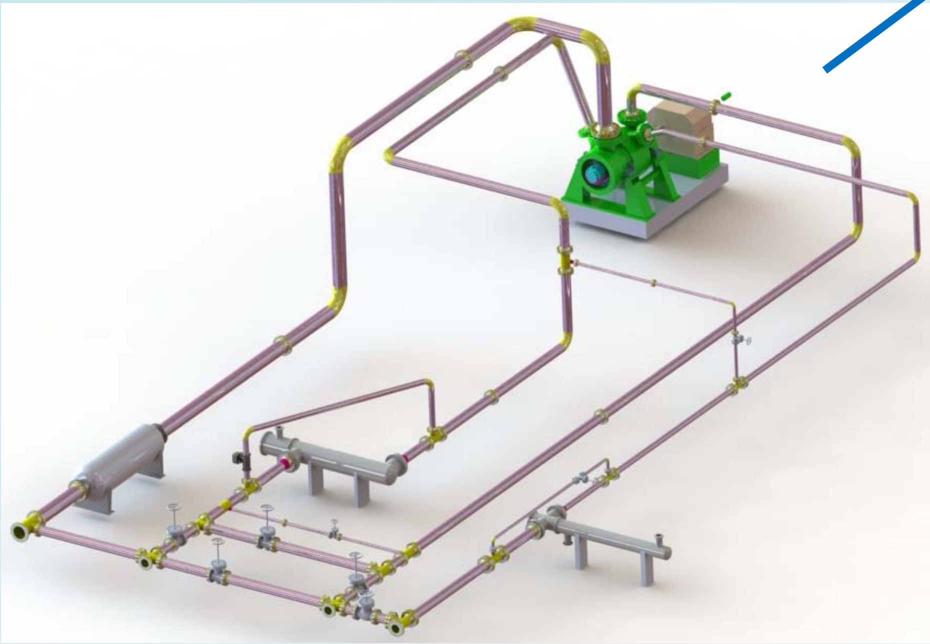
Phase 3 Pilot Test Facility



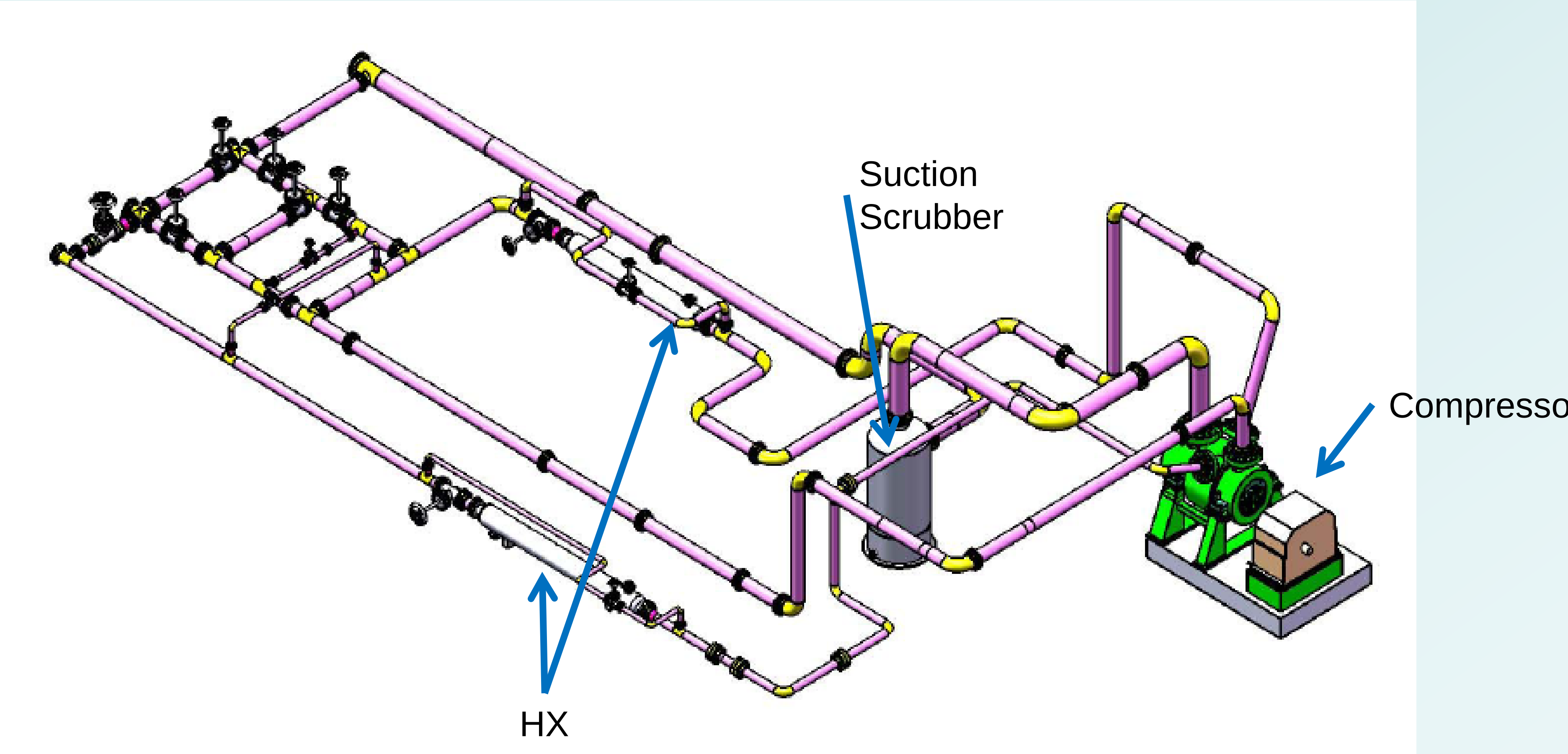
New Building and Compressor Facility

- New facility with high-bay to house compressor
- Piping system permits series or parallel operation of back-to-back compressor
- Compressor loop with be mated to liquefaction plant and liquid CO_2 pump

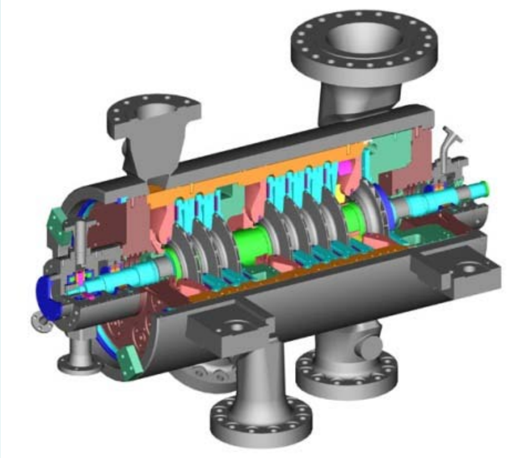




3 MW Compression Facility



Compressor Specifications



- Dresser-Rand DATUM D12R6B
- 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.

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

Phase 3 Work Breakdown and Budget

2011 – Design of Multi-Stage Diaphragm and Test Loop
2012 – Hardware Procurement and Site Preparation
2013 – Test Loop Assembly, Commissioning, and Testing

- Work is proceeding on Schedule

- Total Project Budget: $9.86 million

Questions???

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