Research and Development Needs for Advanced Compression of Large Volumes of Carbon Dioxide

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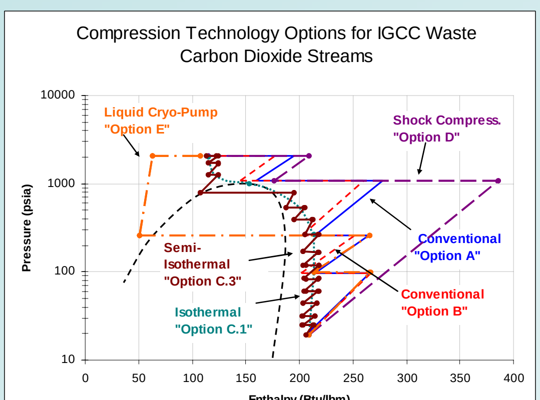

Workshop on Future Large CO2 Compression Systems
Sponsored by
DOE Office of Clean Energy Systems,
EPRI, and NIST

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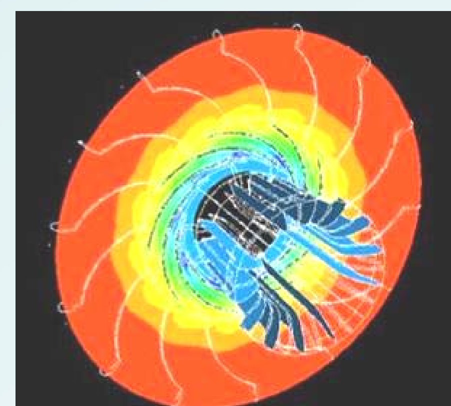

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Who Is SOUTHWEST RESEARCH INSTITUTE?

<u>11 Divisions</u>

- **Engine Emissions**
- **Fuels & Lubricants**
- **Automation**
- **Aerospace Electronics**
- **Space Science**
- **Nuclear Waste**
- **Applied Physics**
- **Training, Simulation**
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- **1200 Acres**
- **2 million Ft^2**

- **3300 Employees**
- **1300 Engineers**
- **170 Buildings**

CO_2 R&D Needs

- Reduce the power penalty associated with CCS
- Compression must be integrated and optimized with various capture schemes
  - Amine solvents
  - Chemical looping
  - Membranes
- Reliability of the equipment important
- Beneficial to leverage existing compression technology
- Equation of state near critical point and with mixtures

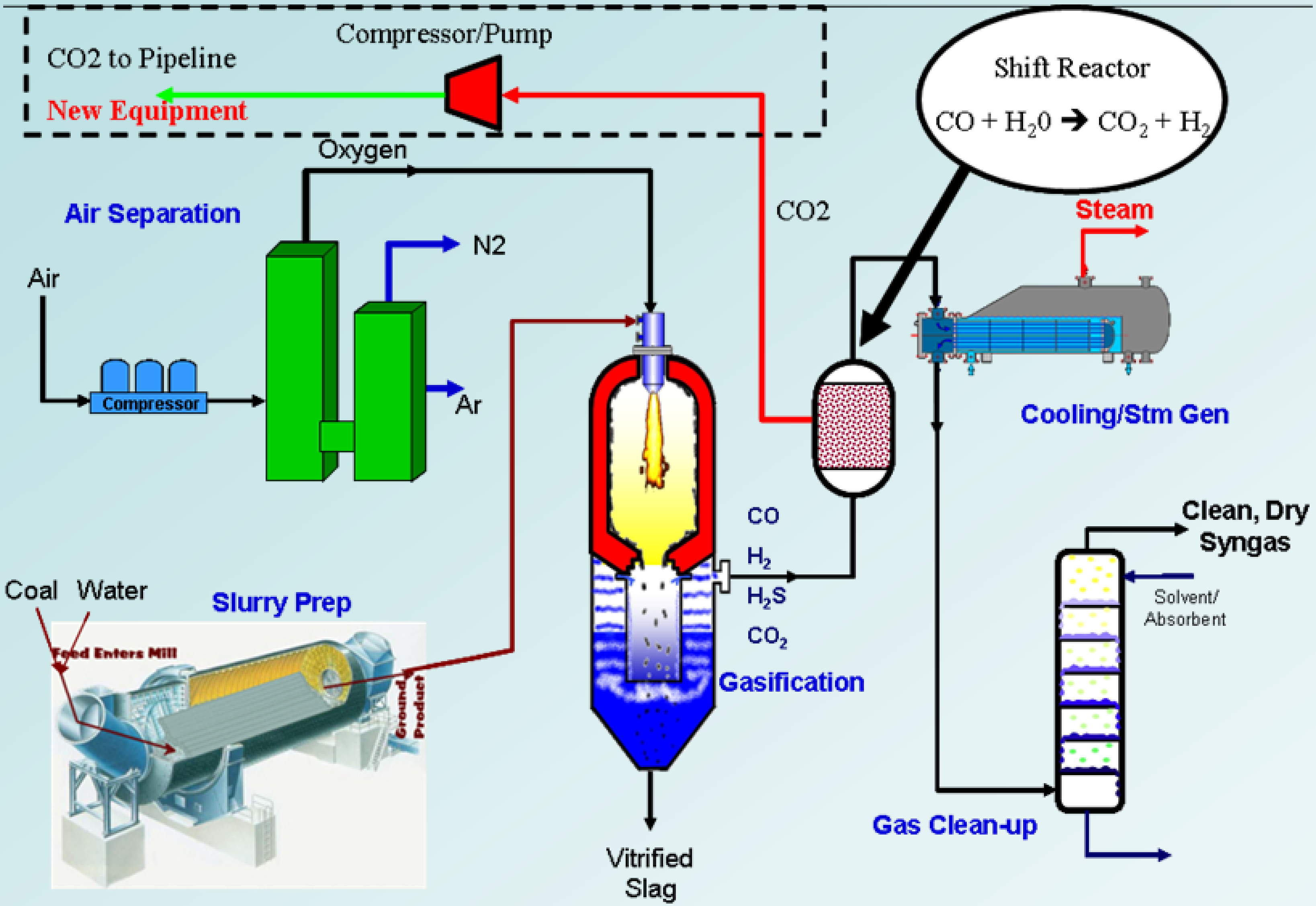
Motivation of Current Project

- CO_2 capture has a significant compression penalty
- Final pressure around 1,500 to 2,200 psia for pipeline transport or re-injection.
- Based on a 400 MW 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.
- Research applicable to PC, Oxy-Fuel,IGCC & NGCC

General Comments

- The type of compressor is highly dependent on the starting pressure
  - Approximately 20 to 500 psia for CO_2 scrubbing of the fuel stream (for IGCC).
  - Approximately 15 psia from PC and Oxy-Fuel.
- High pressure ratio results in significant heat of compression.
- Various compressor types have been considered.
- Isothermal compression - one concept considered to reduce the power of compression.
- Liquefaction of CO_2 has also been studied.

IGCC Process with Carbon Capture



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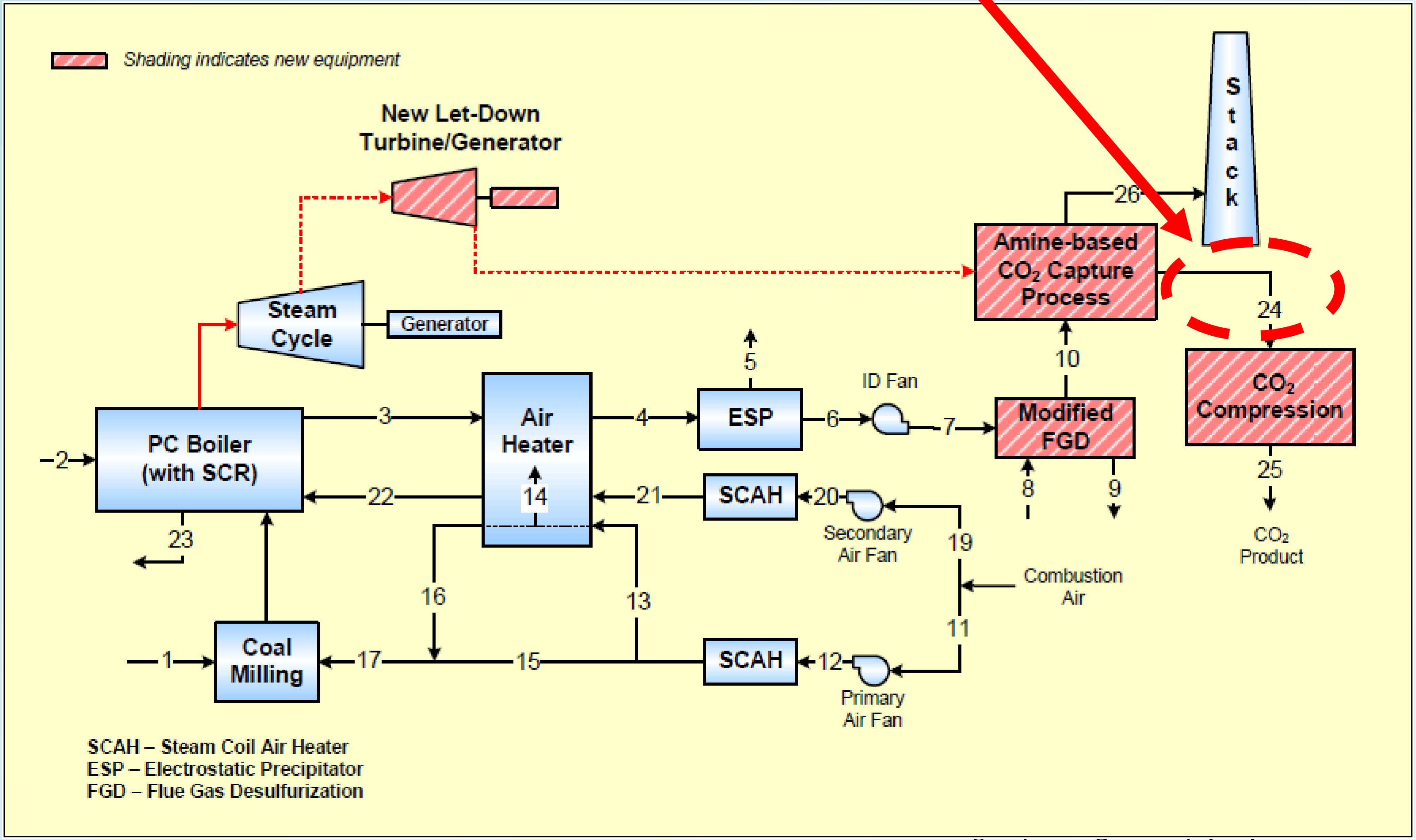
DOE PC Reference Case

- Only CO_2 stream considered

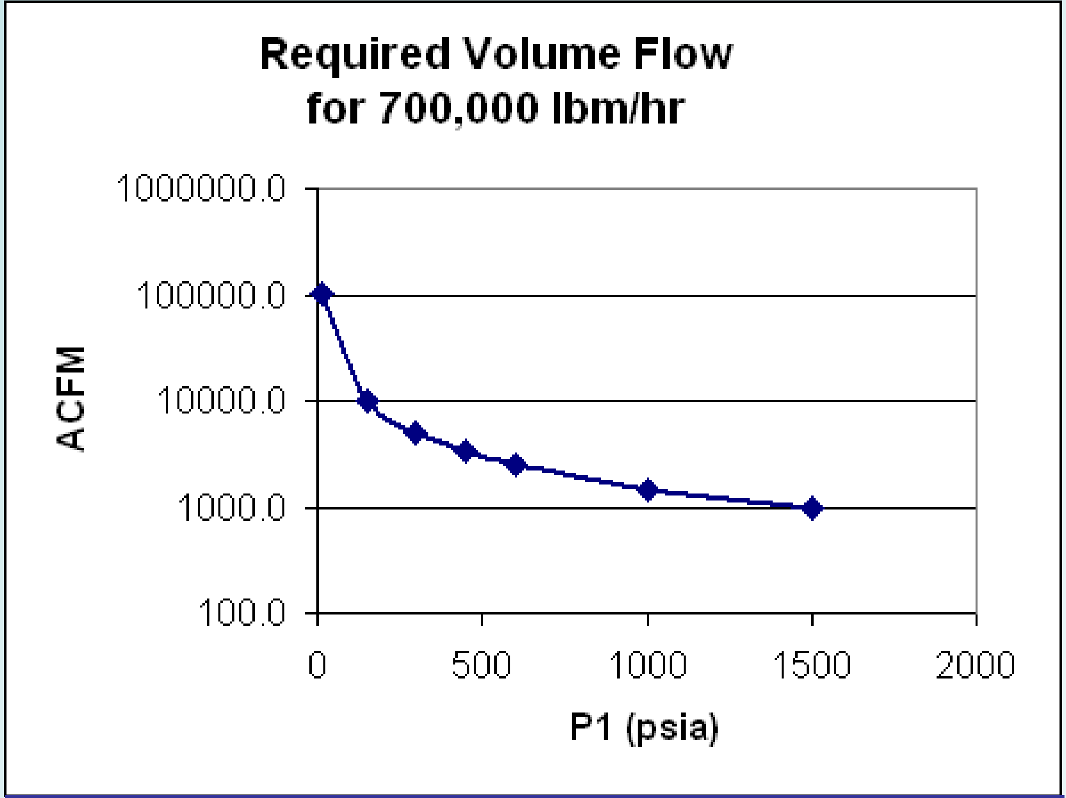


DOE/NETL report 401/110907

Challenges: Volume Reduction

Mass Flow Rate = 700,000 lbm / hr = 144.89 MMSCFD

Pressure (psia)	Volume Flow (acfm)
14.7	100,595.2
150	9,858.3
300	4,929.2
450	3,286.1
600	2,464.6
1,000	1,478.8
1,500	985.8



High volume flow reduction adds to challenge in compressor selection

Challenges: Multiple Streams

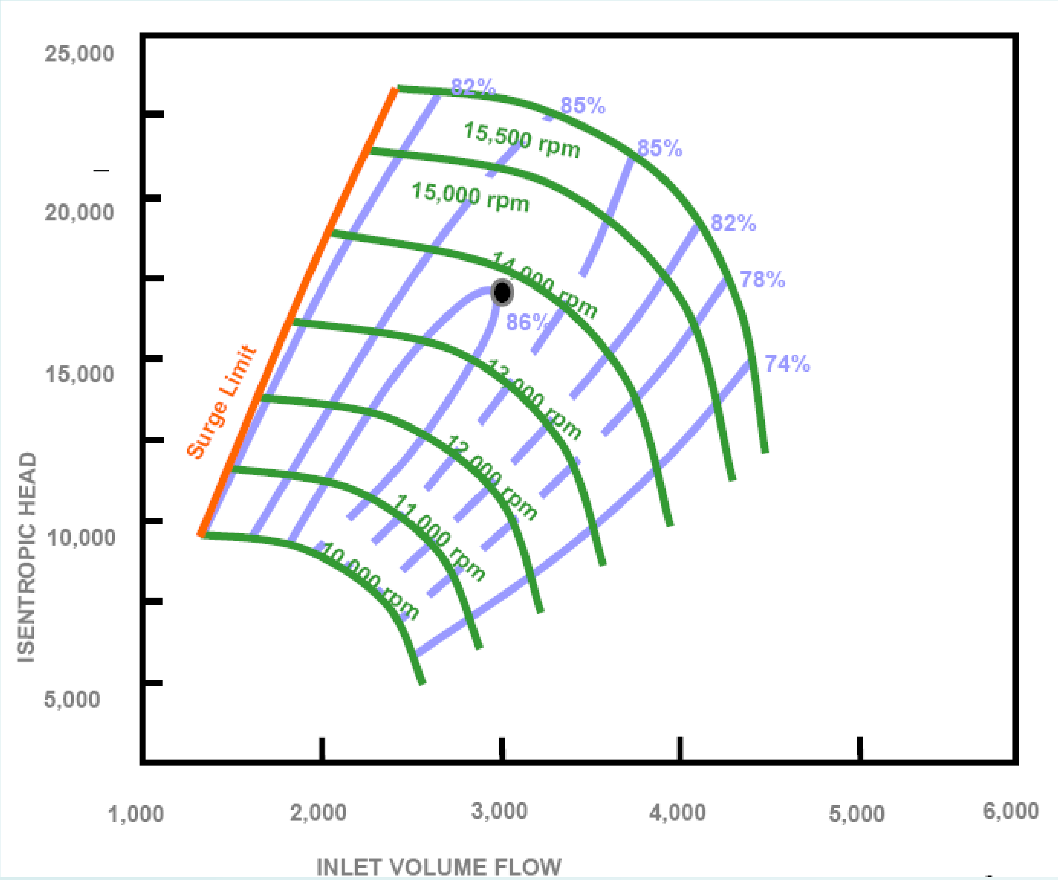
- Uncompressed CO_2 streams in a typical IGCC plant with a physical absorption separation method using Selexol solvent.

CO_2 Gas Streams	LP	MP	HP 1	HP 2
Pressure (psia)	21.9	160.0	250.0	299.0
Temperature (°F)	51.0	68.0	90.0	75.0
Density (lbm/ft^3)	0.177	1.3	1.87	2.088
Flow Rate (acfm)	33,257	2,158	3,374	1,073

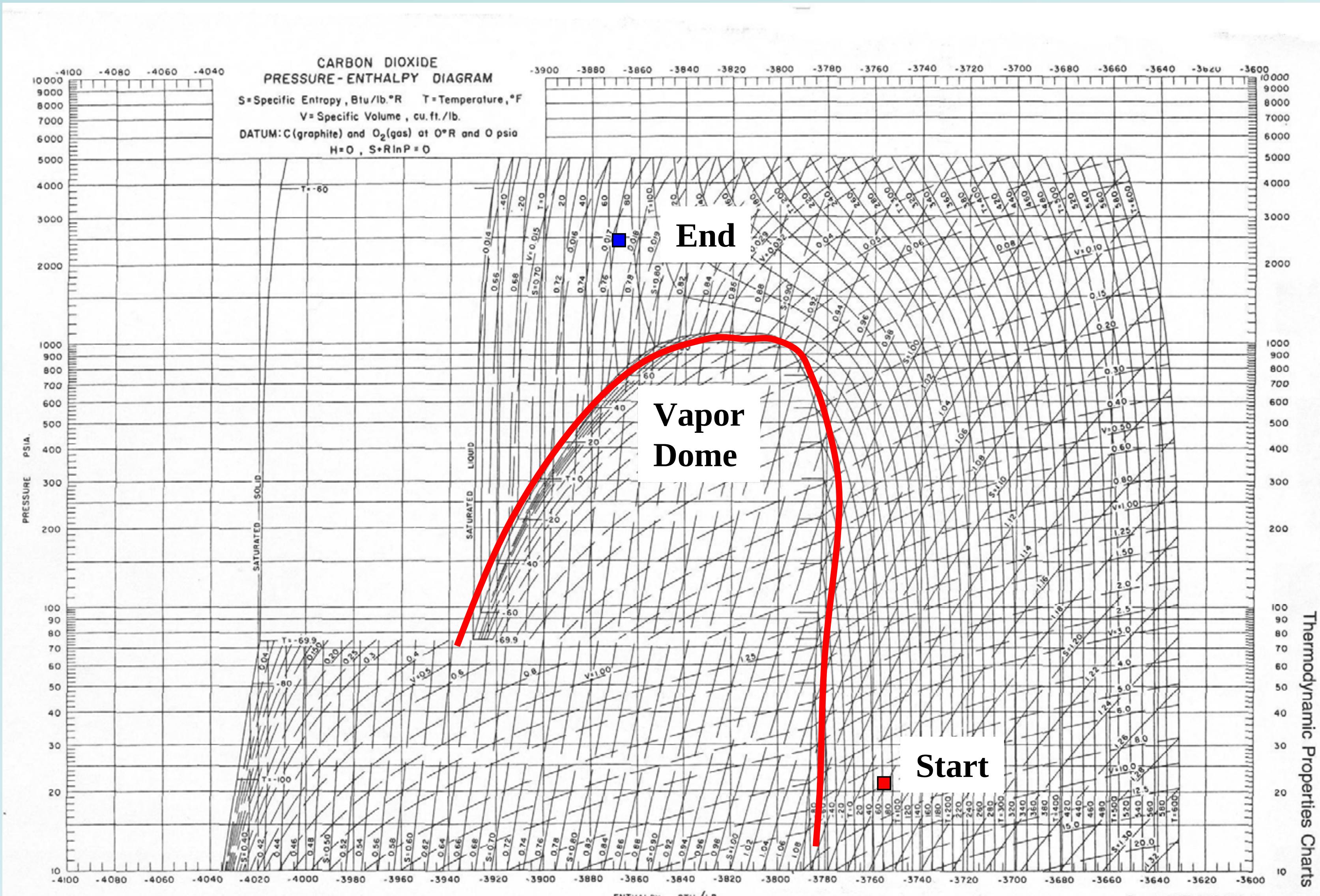
Higher pressure separation streams help reduce volume reduction. This allows a more uniform frame size in compressor selection.

Challenges: Wide flow range required

- CO_2 mass flow proportional to power plant Output (e.g. 50-100%)

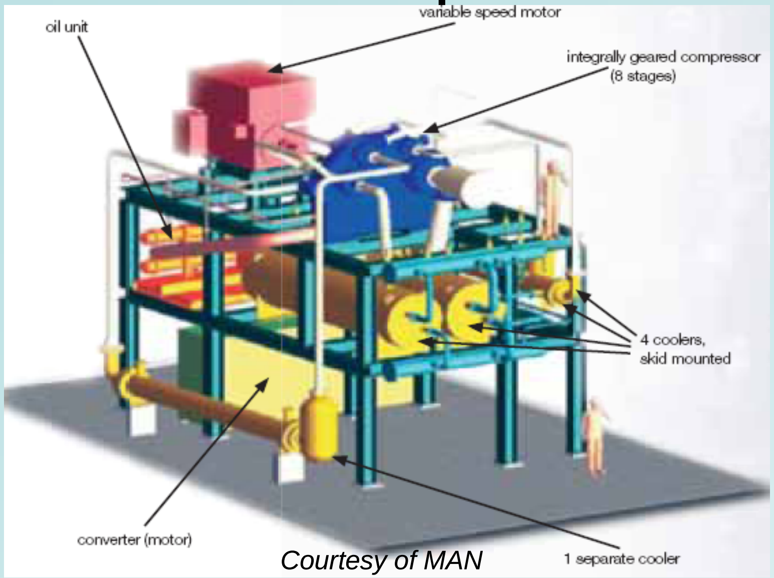


Challenges: High Mole Weight



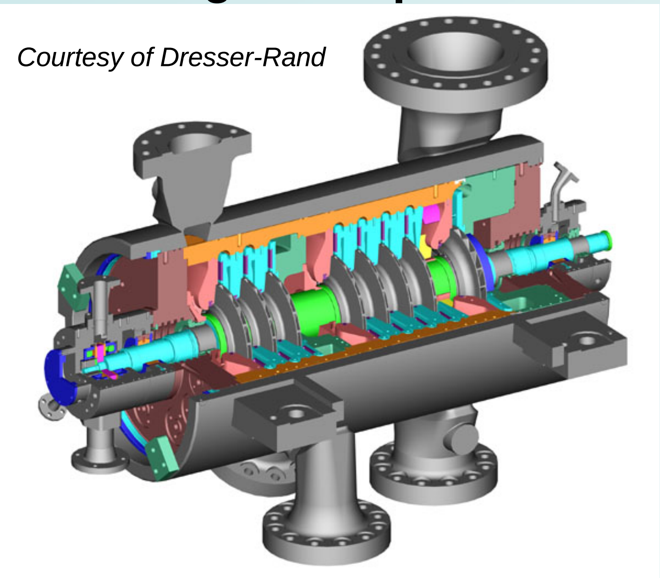
Challenges: High Reliability

Integrally Geared Isothermal Compressor



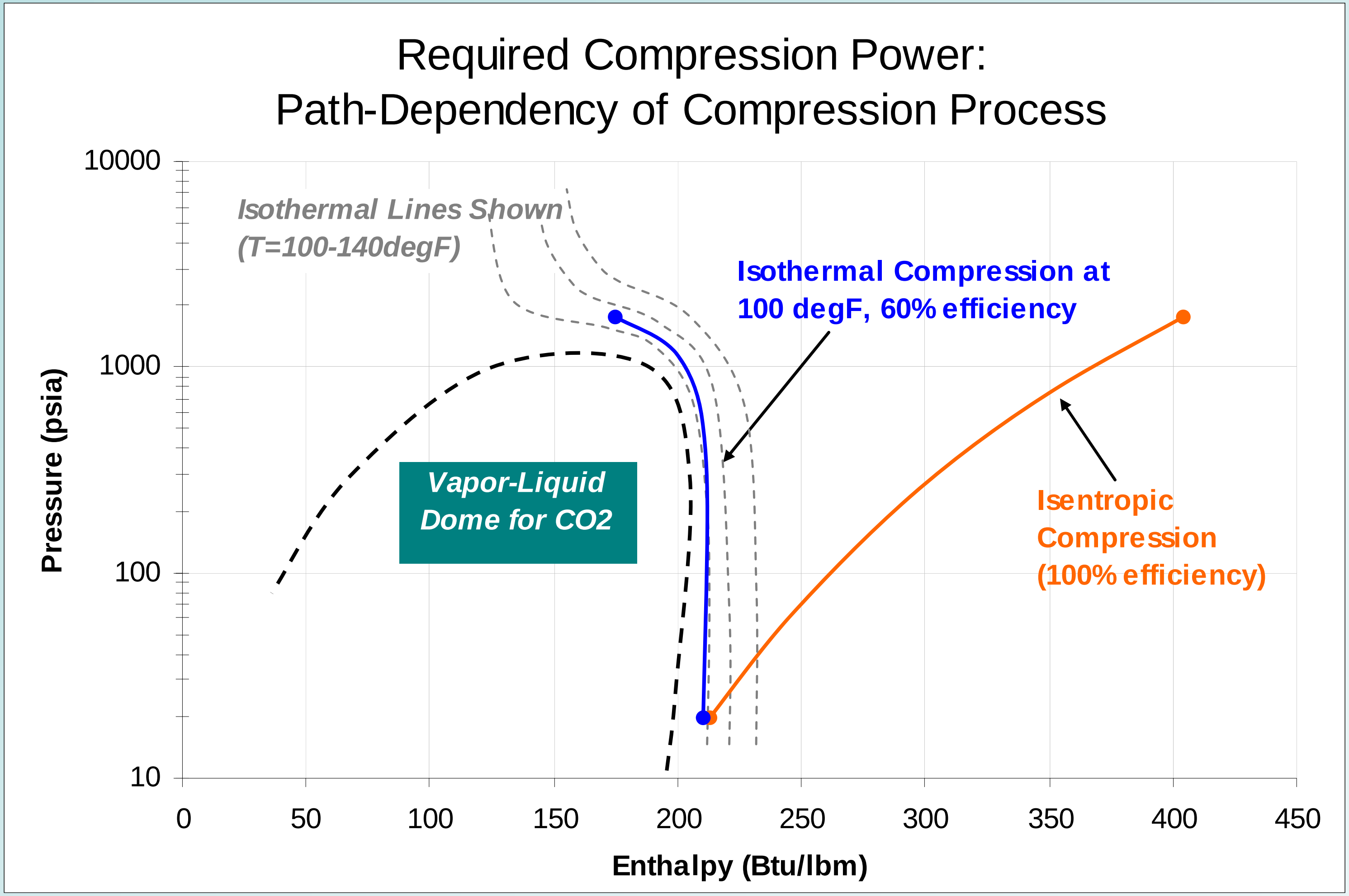
- Integrally geared can achieve near isothermal compression
- Can contain up to 12 bearings, 10 gas seals plus gearbox
- Typically driven by electric motor
- Impellers spin at different rates
  - Maintain optimum flow coef.

Single-Shaft Multi-stage Centrifugal Compressor



- 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

Path Dependent Process Comparison



Comparing a 60% isothermal compressor to a 100% efficient isentropic compressor…Which is better???

Isentropic vs. Isothermal Compression

Isentropic Compression Calculations for 20-2200 psia										
									Mdot (lb/hr)=	**200000**
P1	P2	T1	T2	h1	h2	rho1 (lbm/ft3)	rho2 (lbm/ft3)	**Polytropic Efficiency**	W/mdot (Btu/lbm)	**BHP**
20	220	70	415	216.05	290.92	0.156	1.0446	**0.99**	74.870	**5879.6**
									Mdot (lb/hr)=	**200000**
220	2200	415	875	290.92	404.12	1.0446	6.6665	**1.00**	113.200	**8889.6**
									Total BHP =	**14769.2**

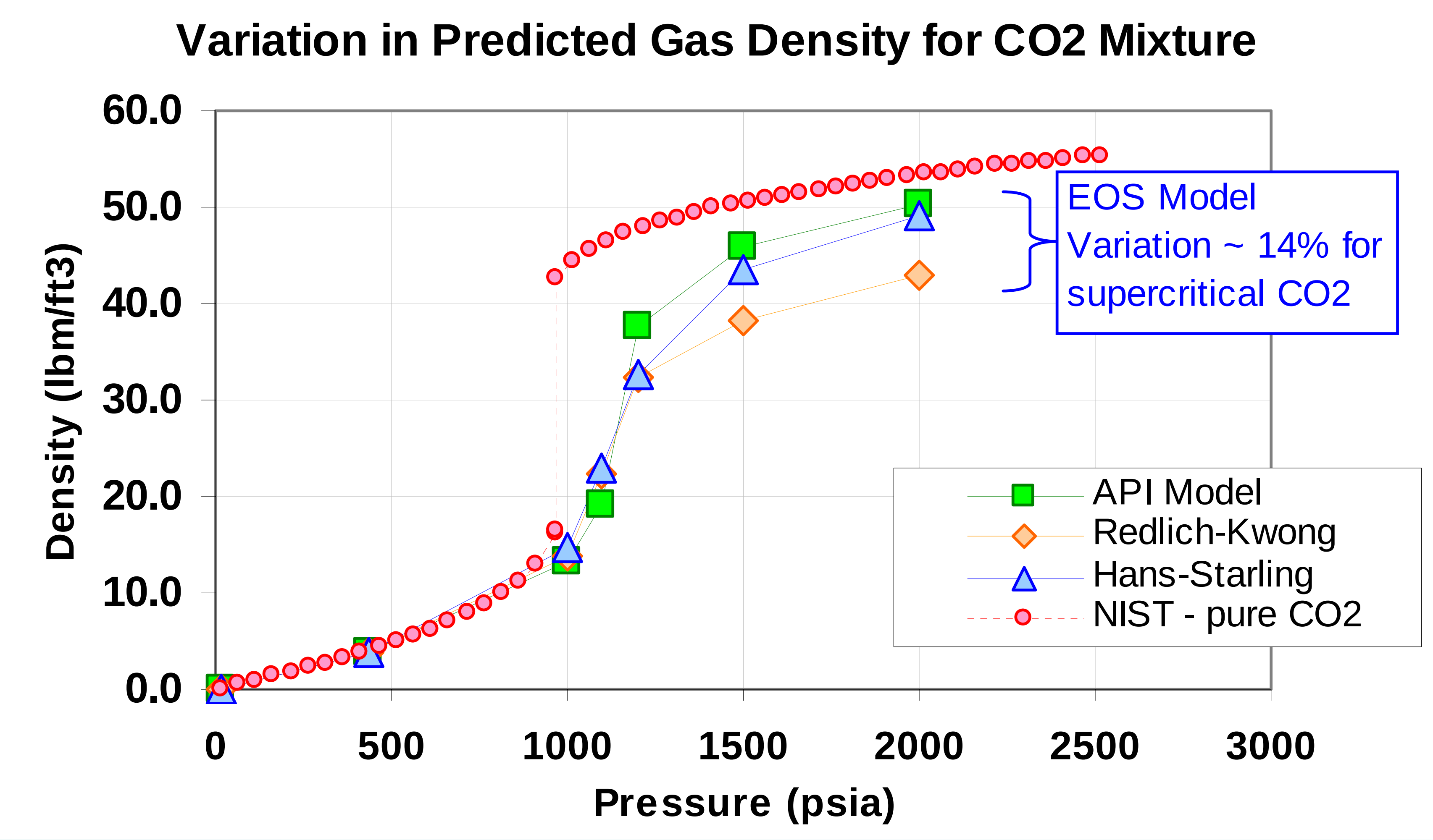
Isothermal Compression Calculations at 100 degF and 60% efficiency								
Low Pressure							**Mdot (lb/hr)=**	**200000**
P1	P2	To	P2/P1	ln (P2/P1)	Ideal W/mdot (Btu/lbm)	Assumed Efficiency	Actual W/mdot (Btu/lbm)	**BHP**
20	100	100	5.00	1.61	37.62	0.600	62.705	**4924.2**
Side Stream + Medium Pressure							**Mdot (lb/hr)=**	**200000**
P1	P2	To	P2/P1	ln (P2/P1)	Ideal W/mdot (Btu/lbm)	Assumed Efficiency	Actual W/mdot (Btu/lbm)	**BHP**
100	260	100	2.60	0.96	21.28	0.600	35.461	2784.8
							Mdot (lb/hr)=	**200000**
170	260	100	1.53	0.42	9.32	0.600	15.541	1220.4
High Pressure							**Mdot (lb/hr)=**	**200000**
P1	P2	To	P2/P1	ln (P2/P1)	Ideal W/mdot (Btu/lbm)	Assumed Efficiency	Actual W/mdot (Btu/lbm)	**BHP**
260	600	70	2.31	0.84	16.41	0.600	27.344	**2147.3**
600	1097	70	1.83	0.60	6.50	0.600	10.841	**851.4**
							Mdot (lb/hr)=	**200000**
1097	2200	70	2.01	0.70	3.92	0.600	6.536	**513.3**
							Total BHP =	**12441.4**

Isentropic Compression (100% efficiency) = 14,769 BHP

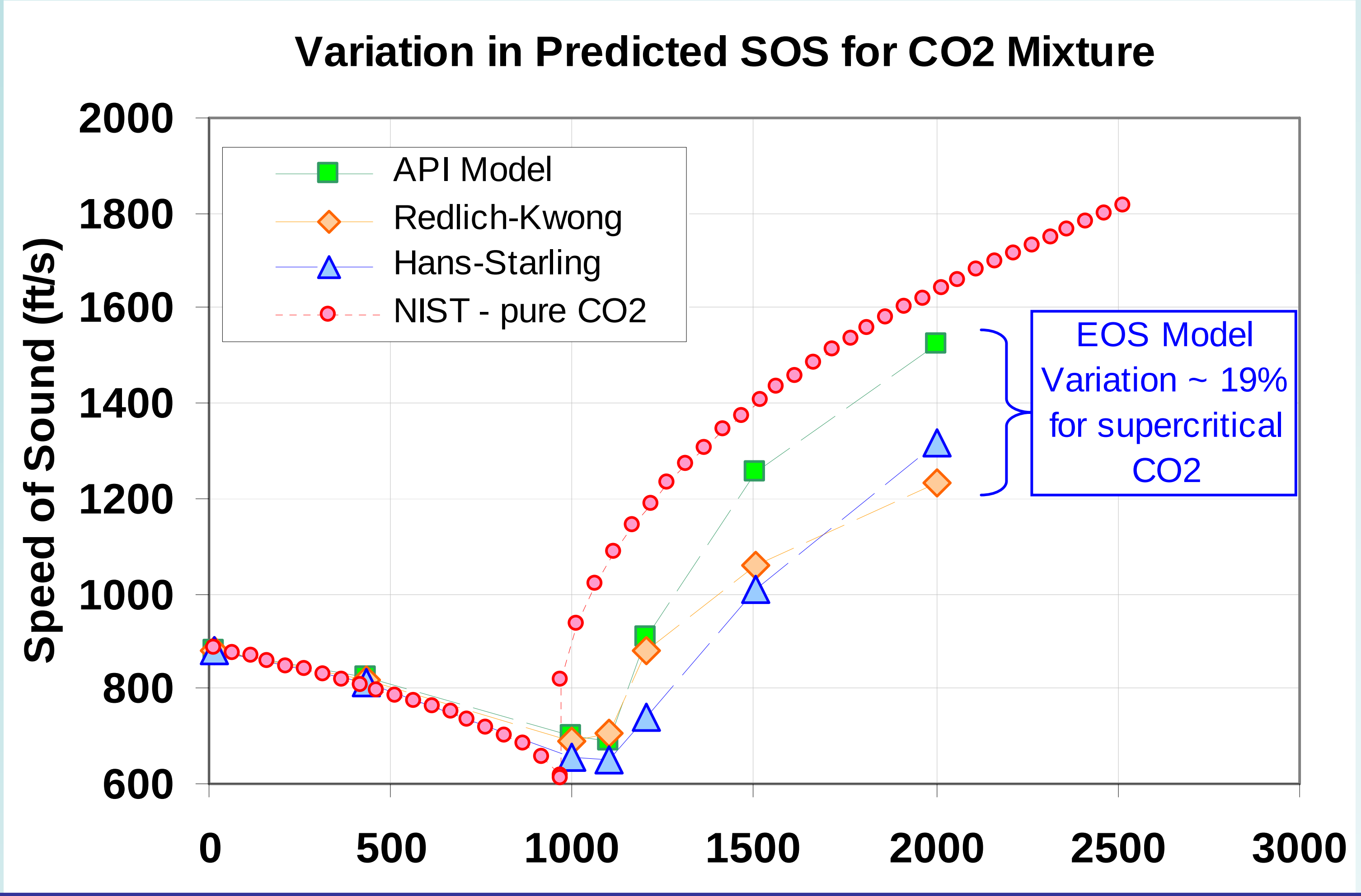
Isothermal Compression (60% efficiency) = 12,441 BHP

The 60% efficient isothermal compressor is preferred.

Deviation in Models for CO_2 Mixtures



Deviation in Models for CO_2 Mixtures



Large differences exist in gas properties predicted by standard equation of state models (API, RKS, HANS) and pure CO_2 correlation models from 1000-2000 psia.

Gas Properties Testing

- Gas properties testing for acid gas at SwRI
- Molecular weight and speed of sound

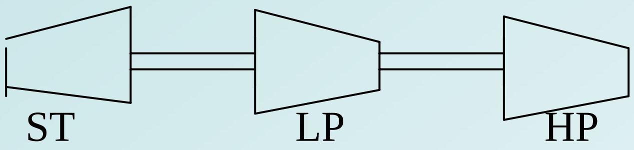
Back to Current Project

Project Overview

- Phase I (Completed)
  - Perform thermodynamic study to identify optimal compression schemes
- Phase II (Complete in 2010)
  - Pilot testing of two concepts:
    - Isothermal compression
    - Liquid CO_2 pumping
  - Total Project Amount $1.5 million

D-R Selection Using Conventional Centrifugal Compressors (Baseline)

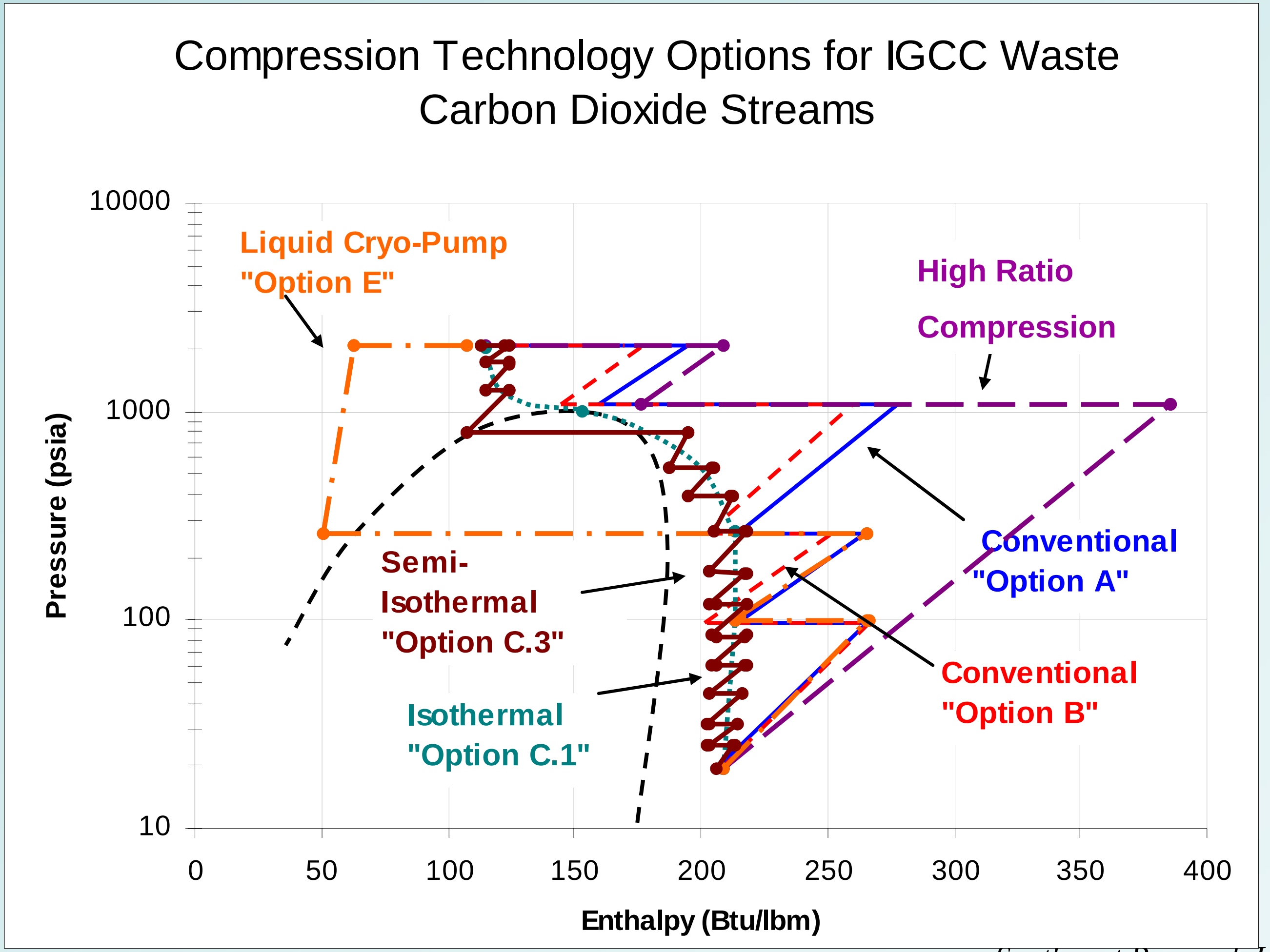
- Requires two parallel trains
- Intercooling between each section



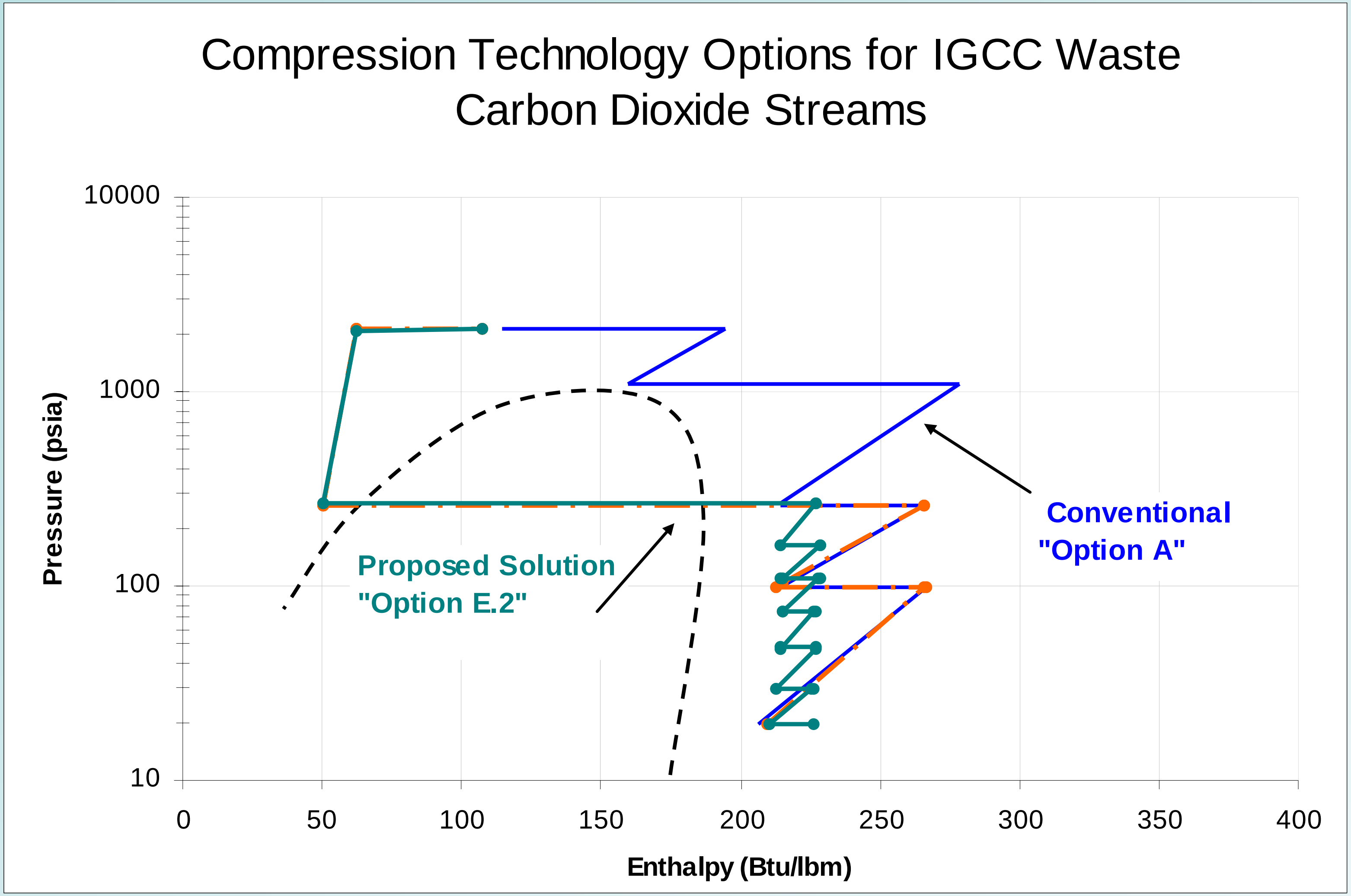
9		**OPERATING CONDITIONS**					
10							
11		(ALL DATA ON PER UNIT BASIS)	Base				
12			D18R7B			D16R9B	
13			SEC #1	SS In	SEC #2	SEC #1	SEC #2
14	●	GAS HANDLED (ALSO SEE PAGE)	LP	MP		Blend	
17	●	WEIGHT FLOW, (Lb/Hr) (WET)	176,649	168,445	260,872	517,475	517,475
18		**INLET CONDITION**					
19	●	PRESSURE (PSIA)	21.90	170.0	96.58	248.0	1,087
20	●	TEMPERATURE (°F)	51.00	68.00	90.21	100.00	100.0
22	●	MOLECULAR WEIGHT	43.88	43.13	43.63	41.61	41.61
25	■	INLET VOLUME, (ACFM)(WET)	16,634		5,908	4,694	745.0
26		**DISCHARGE CONDITI**					
27	●	PRESSURE (PSIA)	106.6		258.0	1,097	2,215
28	■	TEMPERATURE (°F)	299.3		258.1	369.8	231.4
29	■	Cp/Cv(Kavg)	1.271		1.272	1.274	1.230
30	■	COMPRESSIBILITY (ZAvg)	0.9910		0.9685	0.9334	0.6919
36							
37	■	GHP REQUIRED (HP)	3,684		3,656	12,126	5,180
40	■	SPEED (RPM)	5,166				

Total Power = 49,292 HP (37 MW, 5.2% of 700 MW Output)

Summary of Thermodynamic Analysis



Proposed Solution for Optimal Efficiency



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

Summary of Thermodynamic Analysis

Option	Compression Technology	Power Requirements	% Diff from Option A	Cooling Technology
A	Conventional Dresser-Rand Centrifugal 10-stage Compression	23,251 BHP	0.00%	Air-cool streams between separate stages
B	Conventional Dresser-Rand Centrifugal 10-stage Compression with additional cooling	21,522 BHP	-7.44%	Air-cool streams between separate stages using ASU cool N2 stream
C.1	Isothermal compression at 70 degF and 80% efficiency	14,840 BHP	-36.17%	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)	-26.78%	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)	-22.67%	Tc = 100degF in between each stage.

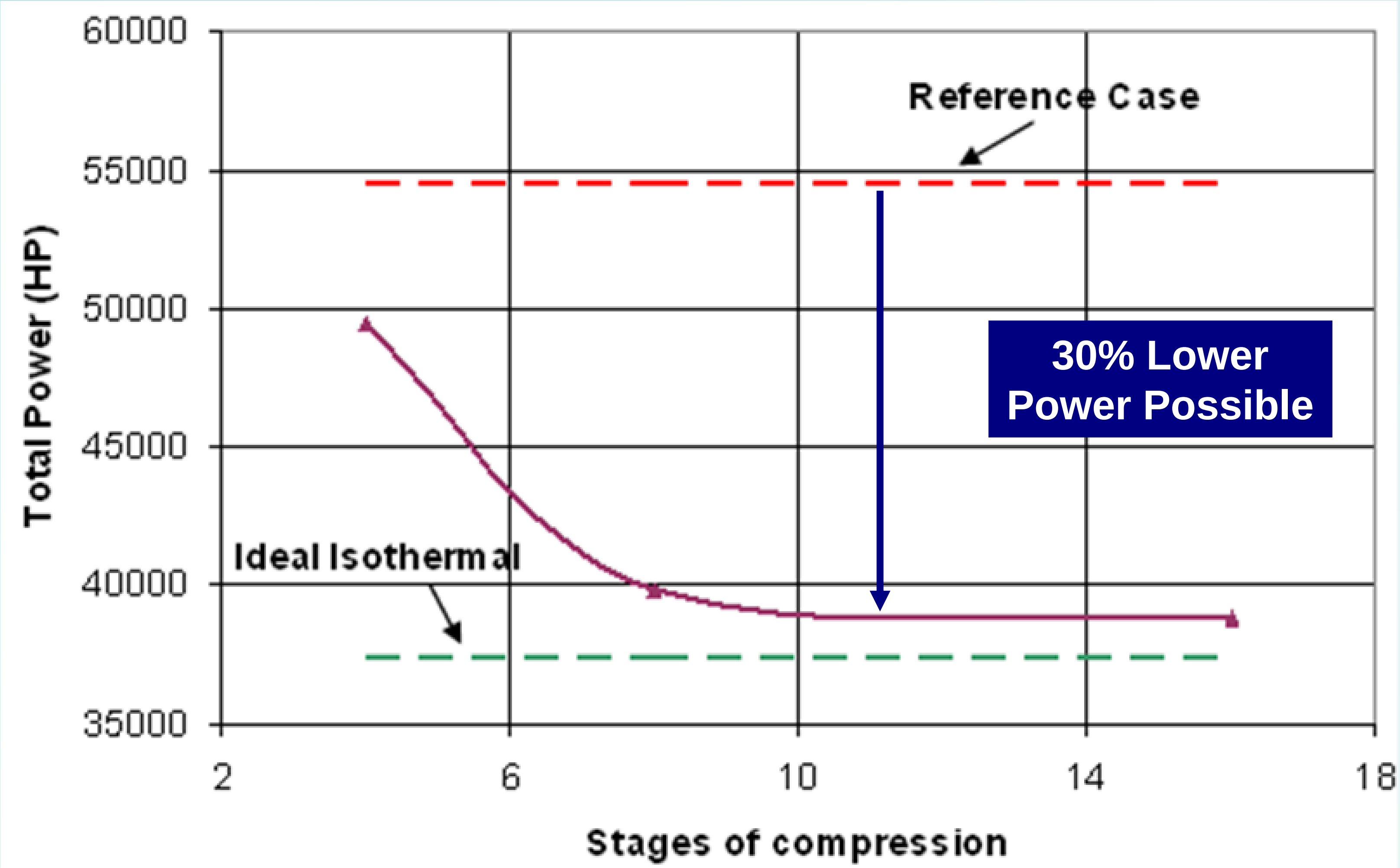
Summary of Thermodynamic Analysis

Option	Compression Technology	Power Requirements	% Diff from Option A	Cooling Technology
D.3	High ratio compression at 90% efficiency - no inter-stage cooling	34,192 BHP	47.06%	Air cool at 2215 psia only
D.4	High ratio compression at 90% efficiency - intercooling on final compression stage	24,730 BHP	6.36%	Air cool at 220 and 2215 psia
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.

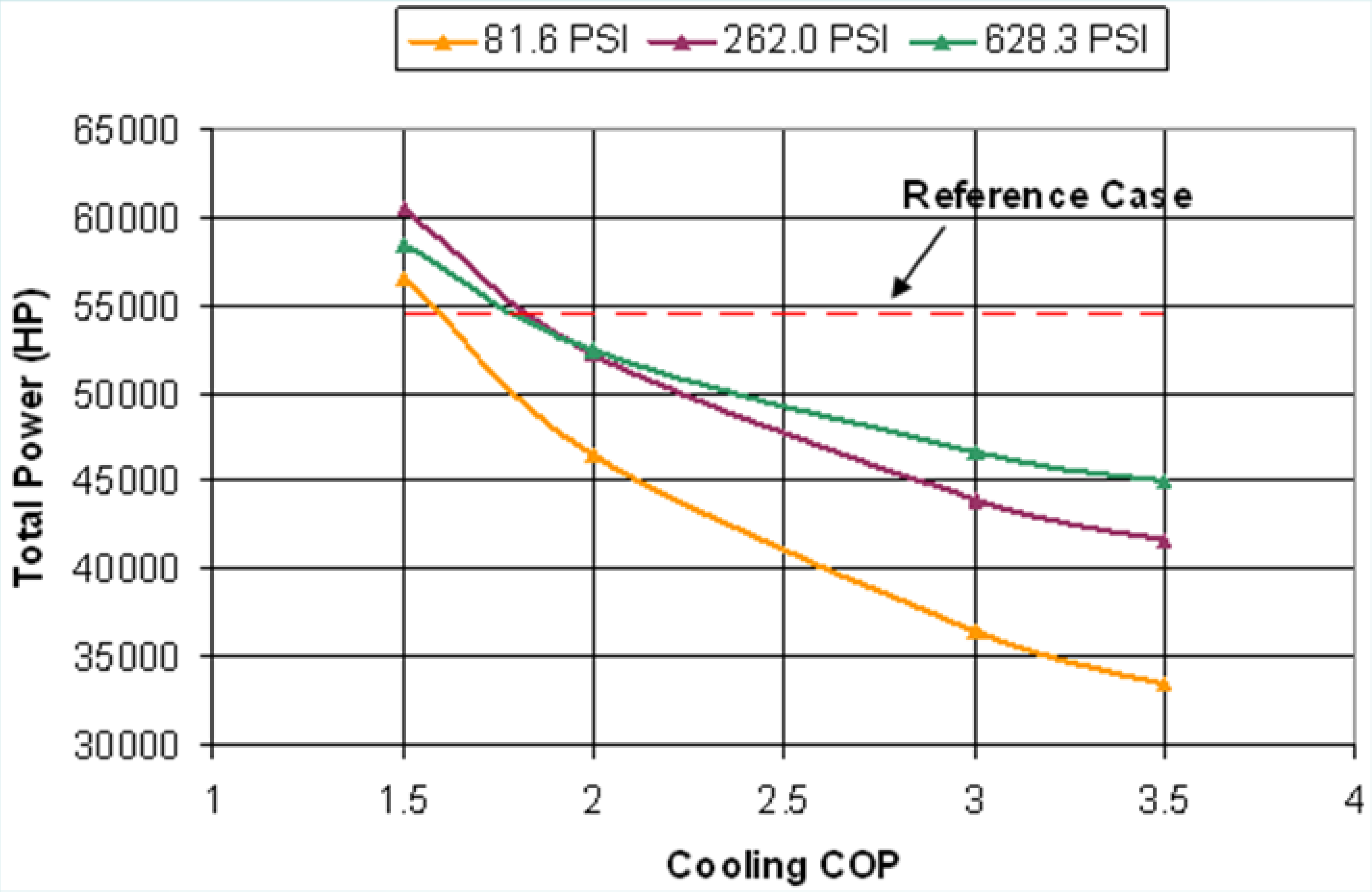
Compression Power for PC Plant

Isothermal Compression



Compression Power for PC Plant

Liquefaction/Pumping Compression



Project Goals

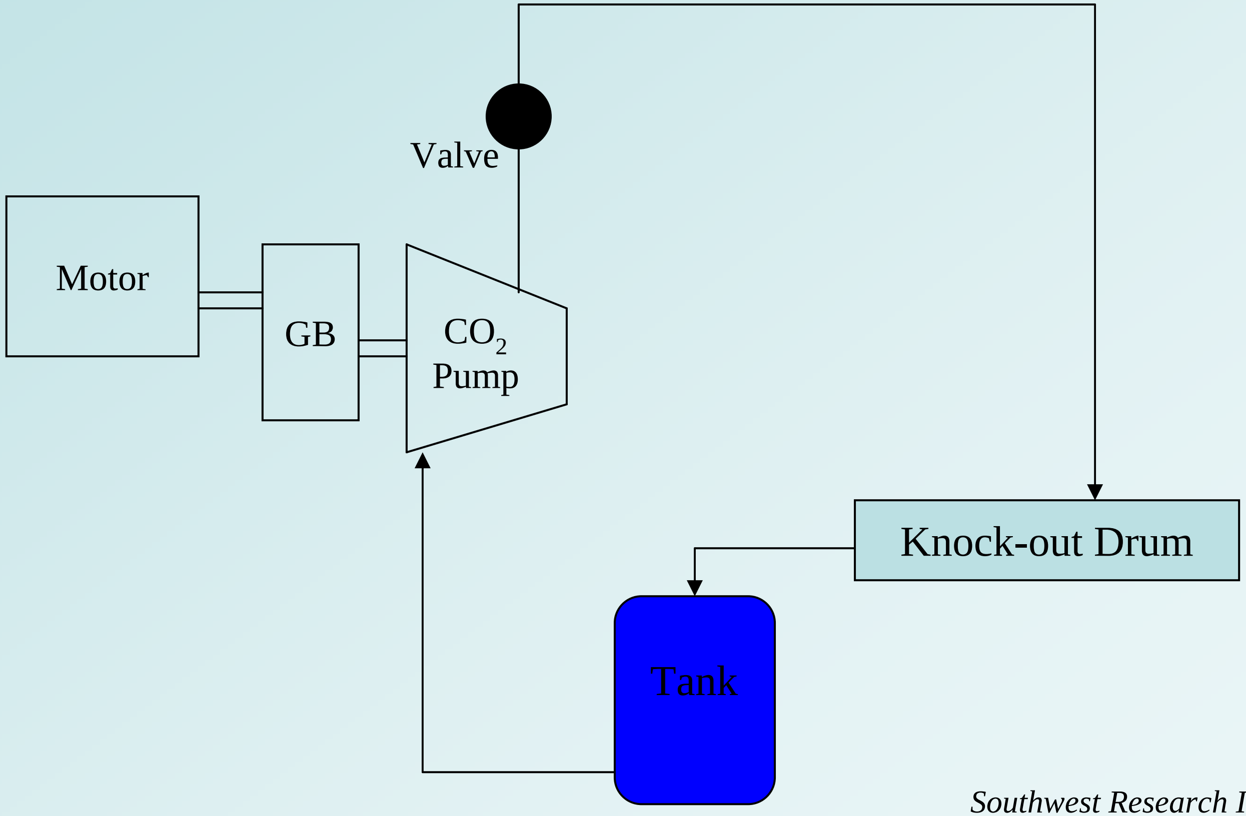
- Develop internally cooled compressor stage that:
  - Provides performance of an integrally geared compressor
  - Has the reliability of a in-line centrifugal compressor
  - Reduces the overall footprint of the package
  - Has less pressure drop than a external intercooler
- Perform qualification testing of a refrigerated liquid CO_2 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.

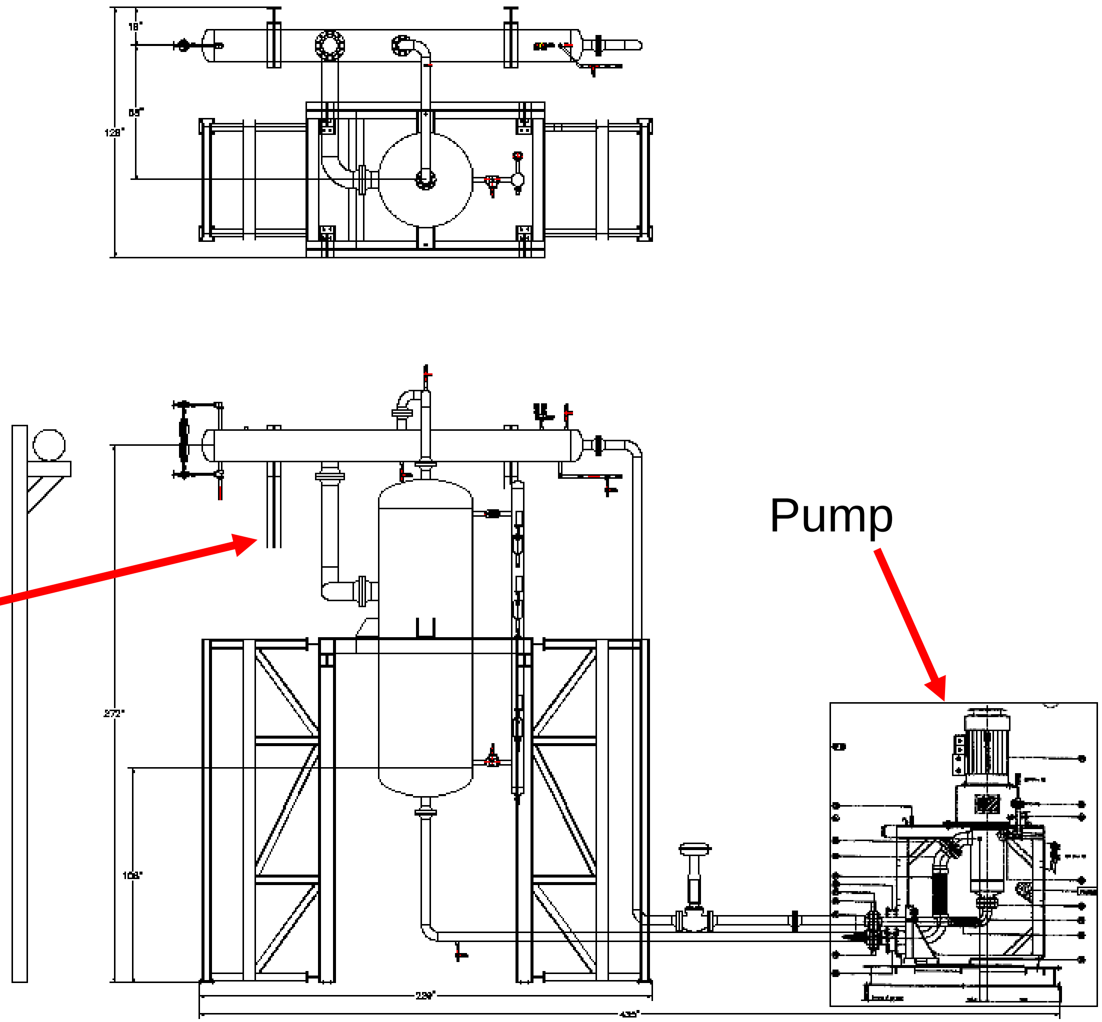
Liquid CO_2 Pumping Loop Testing

- Testing will measure pump efficiency
- Validate pump design
- Measure NPSH requirements looking for signs of cavitation
- Investigate gas entrainment effects
- Cryostar will supply the pump (250 KW, 100 gpm)



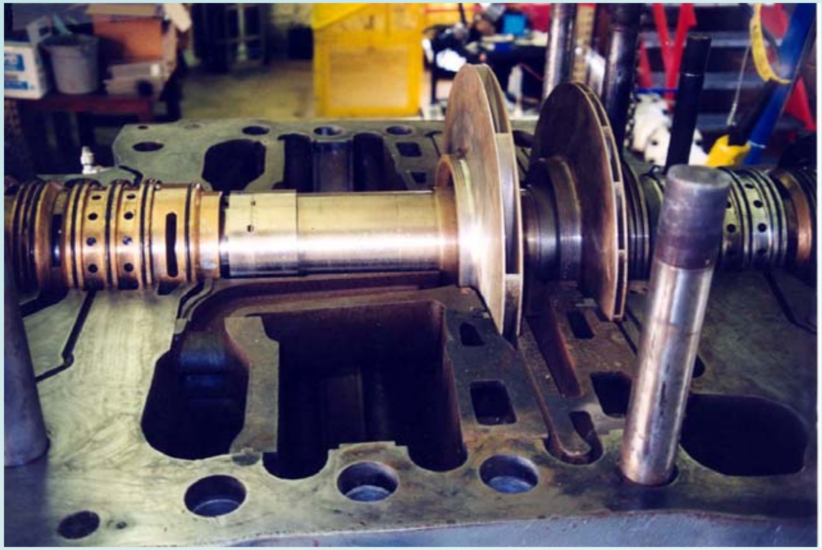
Liquid CO2 Loop

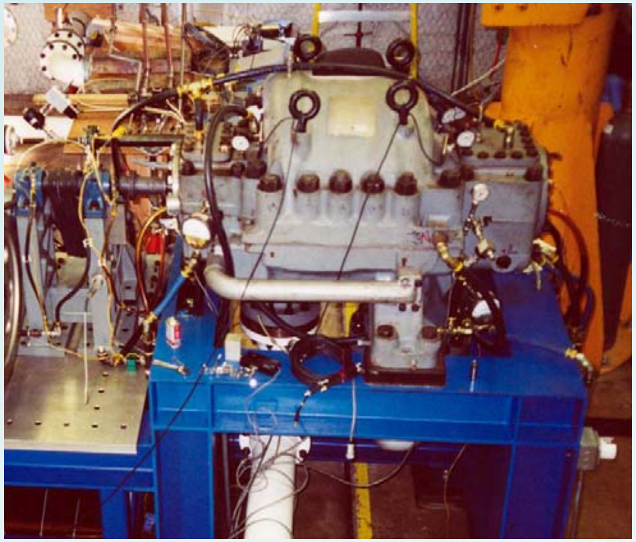
- Vessel layout showing elevated reservoir and knock-out drum
- Pump will be mounted at ground level.
- Orifice run will be located between pump and control valve (in supercritical regime)
- Knock-out drum structural support completed



Internally Cooled Compressor Testing

- Goal: To measure effectiveness of internally cooled diaphragm
- Existing Multi-Stage Test Rig will be utilized using CO_2
- New impeller and internals will be manufactured and tested
- Diaphragms will contain optimized flow path and cooling jacket design
- Stage performance will be measured (P1, T1, P2, P2, Q)
- Both ambient and chilled cooling water will be employed
- Heat transfer enhancement devices employed





Program Benefits

- Provide enabling technology to compress CO_2 from a PC, Oxy-Fuel, or IGCC power plant, cost-effectively minimizing the financial impact of CO_2 sequestration.
- This program identified up to 35% power savings over a conventional CO_2 compression solution.
- Technology applicable to all power plant types plants
- The thermodynamic process is more important than compressor efficiency.
- The internally-cooled compressor concept should result in significant capital savings over an integrally geared compressor
- Liquefaction and pumping equipment will add some additional capital expense, but some is offset by lower cost pump compared to high-pressure compressor.
  – A 35% power reduction will save a utility $4.2 million per year, based on 4¢ / kwh, which will provide a fast return on investment.
- Testing will be complete 1st Qtr 2010

Areas Needing Further Research

- Further work to reduce the power penalty associated with CCS and utilize waste heat
- Compression must be integrated and optimized with various capture schemes
- Perform optimum driver study
  - i.e. gas turbine, motor, steam turbine
- Develop more reliable compression designs
- Perform more gas properties measurements of CO_2 mixtures
- Refine equation of state near critical point and with mixtures
- Perform optimization of pipeline booster stations
  - Station spacing, liquid vs. gas, driver selection
- Improve reliability of recip EOR recycle compressors
  - i.e. valve reliability
  - Variable speed of sound pulsation models (real gas effects)
- Perform further corrosion studies on the effects of moisture on pipeline corrosion

Questions???

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