Ramgen Power Systems

Workshop on Future
Large CO2 Compression Systems

DOE Office of Clean Energy Systems, EPRI, and NIST

National Institute of Standards and Technology (NIST) Headquarters, Gaithersburg, MD 20899

March 30-31, 2009

Forward Looking Statement

Some of the information contained in this document contains "forward-looking statements". In many cases you can identify forward-looking statements by terminology such as "may," "will," "should," "expects," "plans," "anticipates," "estimates," "predicts," "potential," or "continue," or the negative of such terms and other comparable terminology. Forward-looking statements are only predictions and as such inherently include risks and uncertainties. Actual events or results may differ materially as a result of risks facing Ramgen Power Systems, LLC ("Ramgen") or actual results differing from the assumptions underlying such statements. These forward-looking statements are made only as of the date of this presentation, and Ramgen undertakes no obligation to update or revise the forward-looking statements, whether as a result of new information, future events or otherwise. Your decision to remain and receive the information about to be presented to you shall constitute your unconditional acceptance to the foregoing.

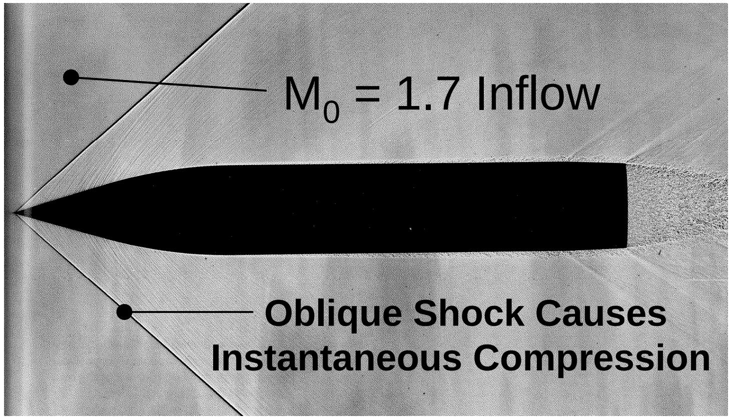
Company

- Privately-held R&D company founded in 1992
- Focused on unique applications of proven supersonic aircraft technology
- Primary technology innovations
  - Supersonic stationary air & gas compressors
  - High velocity combustor
  - Supersonic expander
- Product embodiments
  - Two-stage 100:1 Pr CO2 Compressor
  - 30:1; 42% LHV ASCE Engine
  - Airborne APU
  - H_2 fuel combustor

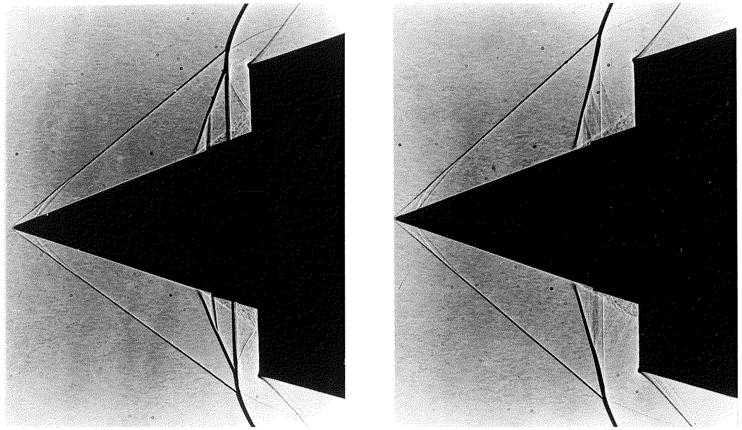
US Army Corps of Engineers

Ramgen Compressor Technology

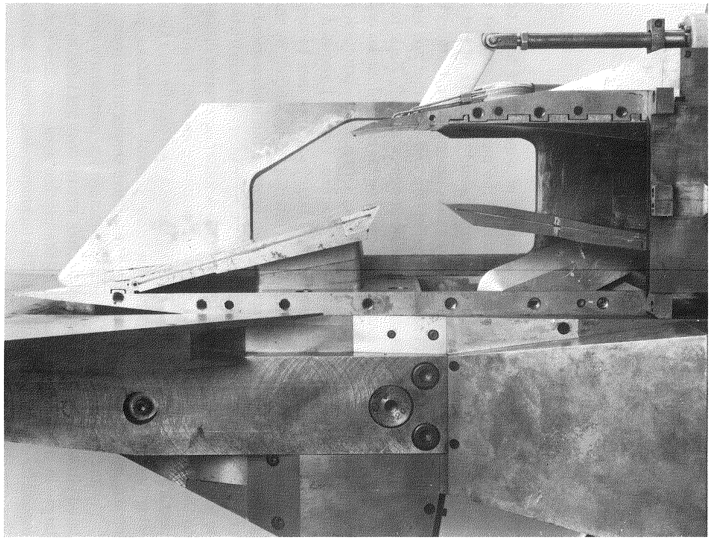
Shock Waves to Supersonic Inlets



Schlieren Photo of Projectile with Shocks



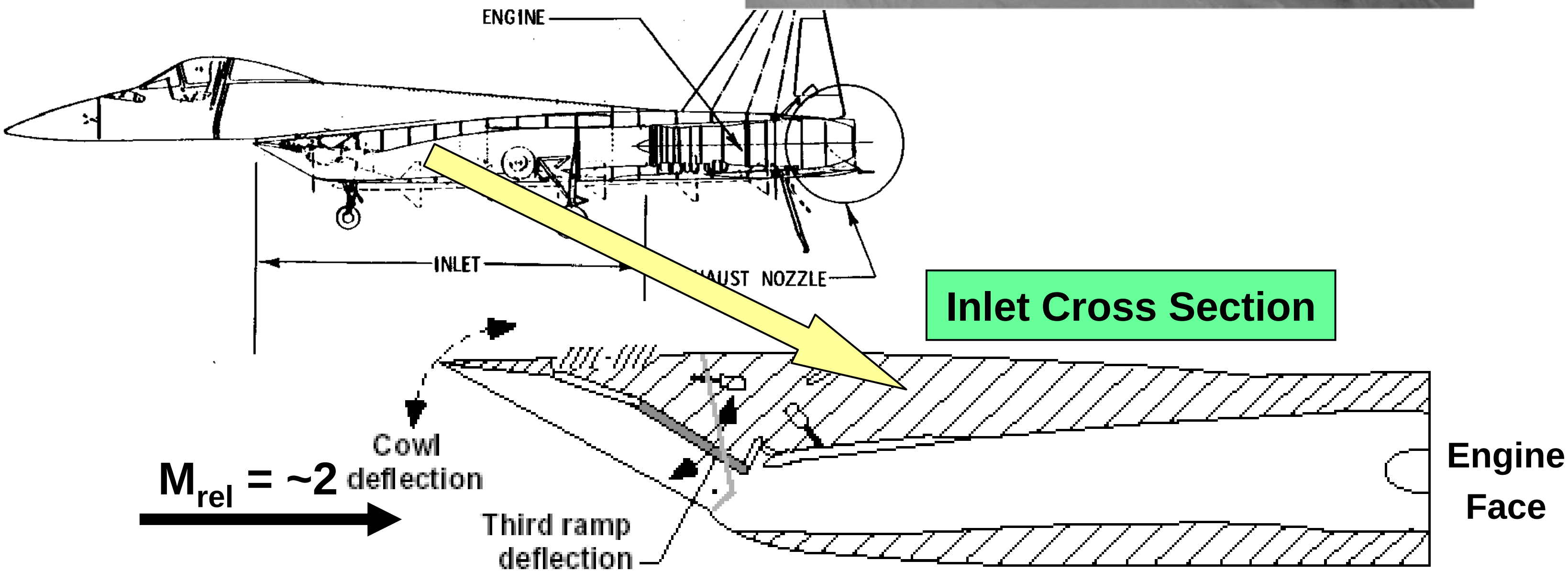
Schlieren Photo of Inlet Center-body and Cowl with Shocks



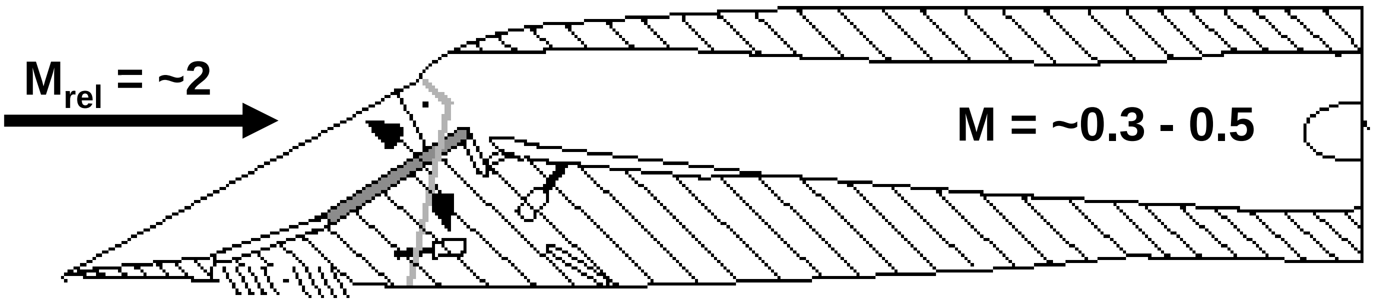
2-D Mixed Compression Inlet Model

- Initial External Shock System Followed by Internal Shock System
- Throat Bleed Slot For Inlet Starting
- Side Window For Schlieren Photography

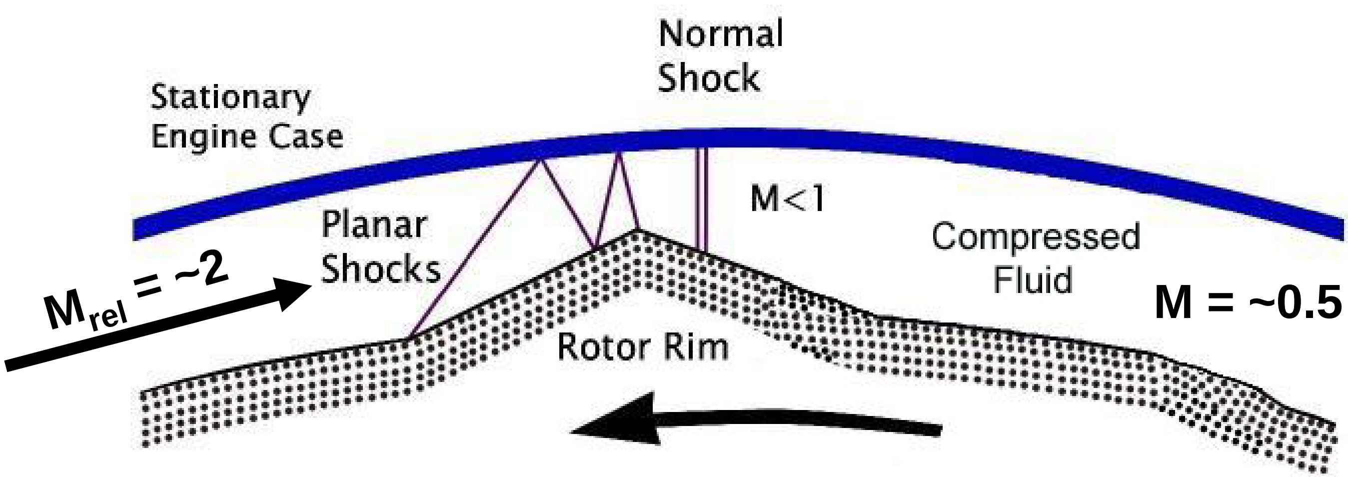
F-15 2-D Planar Supersonic Inlet



Rampressor Rotor Development

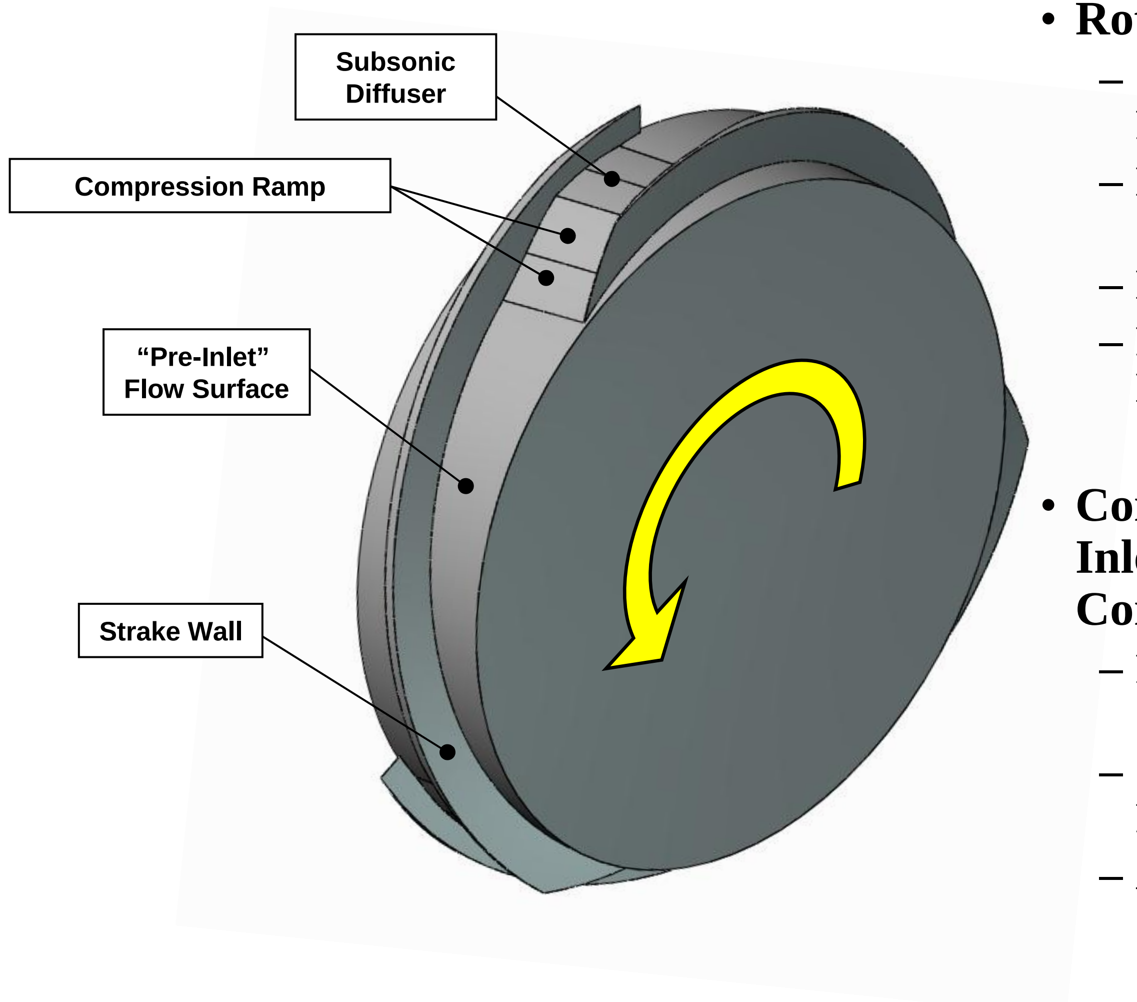


Supersonic F-15 Inlet



Rampressor Rotor

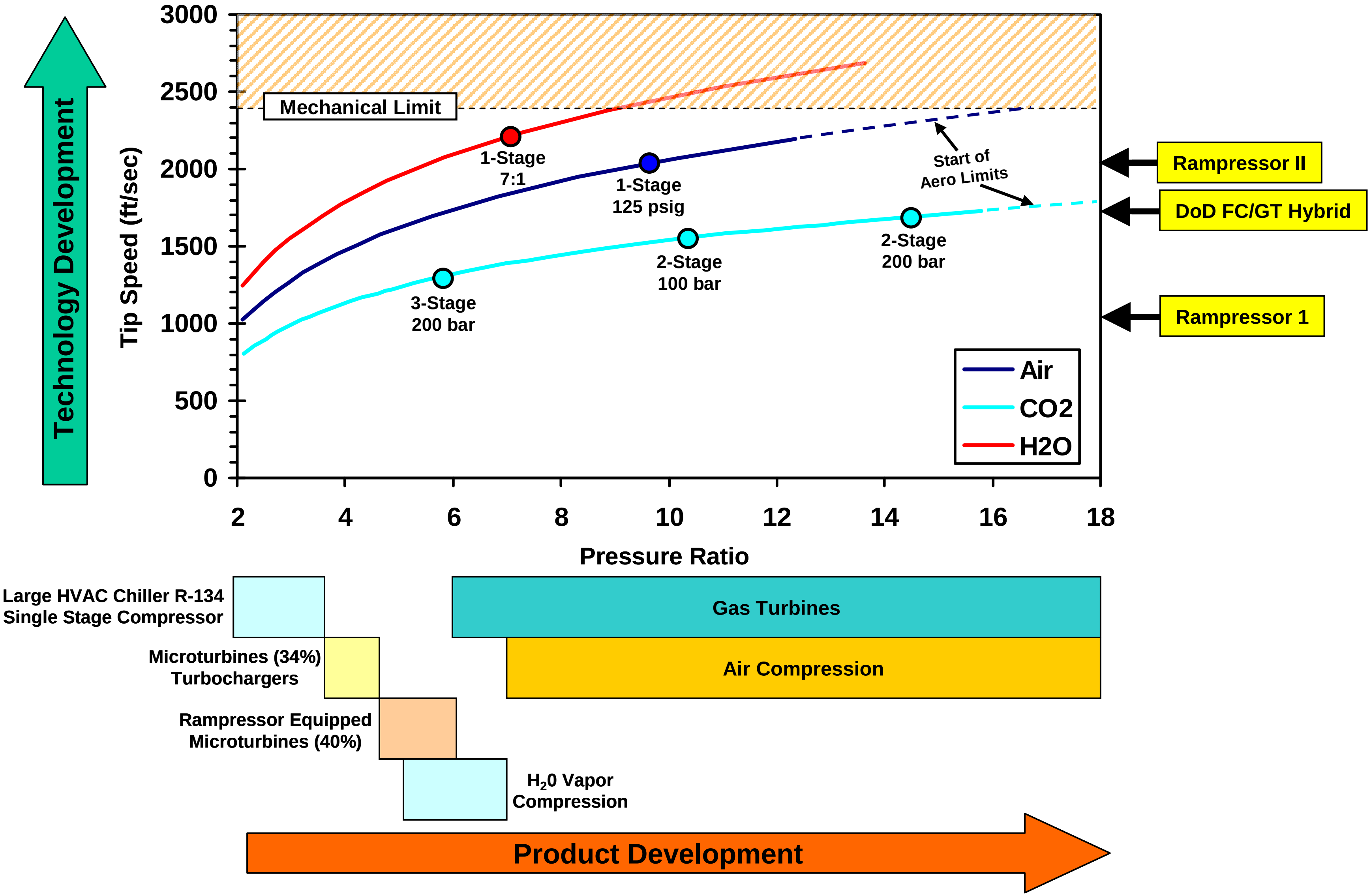
Typical Rotating Supersonic Flow Path



- **Rotor Flow Path:**
  - **3 Supersonic Compression Inlet Flow Paths On Disk Rim**
  - **High Efficiency, Compact Compression**
  - **Minimal Number of Leading Edges**
  - **Flow Path Geometry Similar For Different Pressure Ratios**

- **Combination of Supersonic Flight Inlet & Conventional Axial Flow Compressor Aerodynamics:**
  - **Rotor Rim Radius Change Produces Compression**
  - **3 “Blades” (Strakes) Do Minimal Flow Work**
  - **Axial Inflow/Outflow**

Compression Applications vs. Pr/Tip Speed



Enter Dresser-Rand

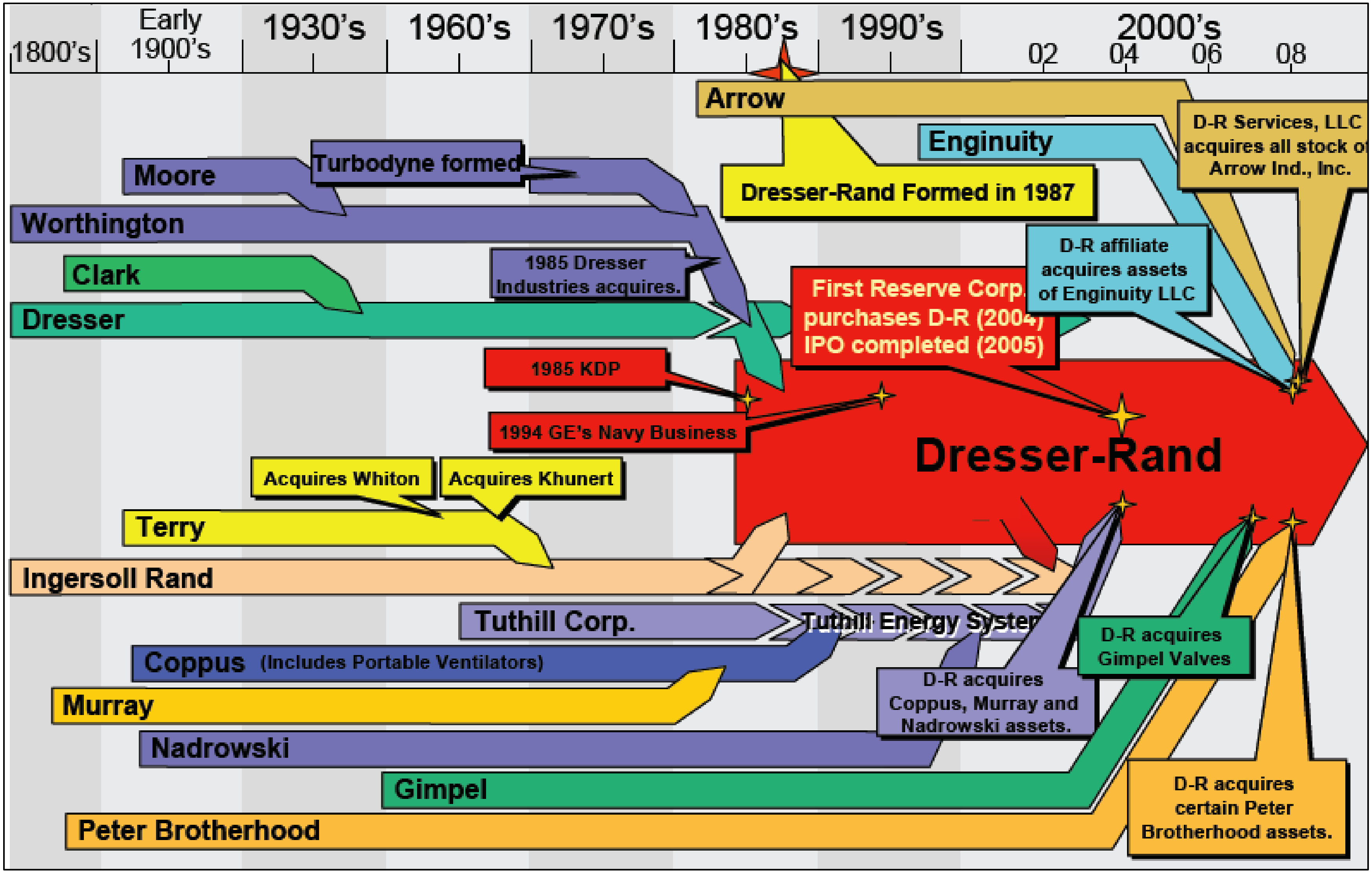
Dresser-Rand Invests in Ramgen

- Dresser-Rand invests in Ramgen's "game-changing technology"
  - Support on-going CO_2 compressor development
  - Satisfy DOE matching funds requirement
  - Consistent with strategy to be technology leader in our industry
  - Extend served market into Electric Utility industry
  - Invest up to $49 million
    - Fund development & demonstration
    - Obtain an option to purchase assets

Dresser-Rand is consistently ranked among top three manufacturers in its served markets

  - Turbomachinery
  - Reciprocating compressors
  - Steam turbines
- #1 in North America
- Leading supplier of CO_2 compressors
- Global sales & service presence
- Strong products & brands
- Established customer base

Dresser-Rand Historical Overview

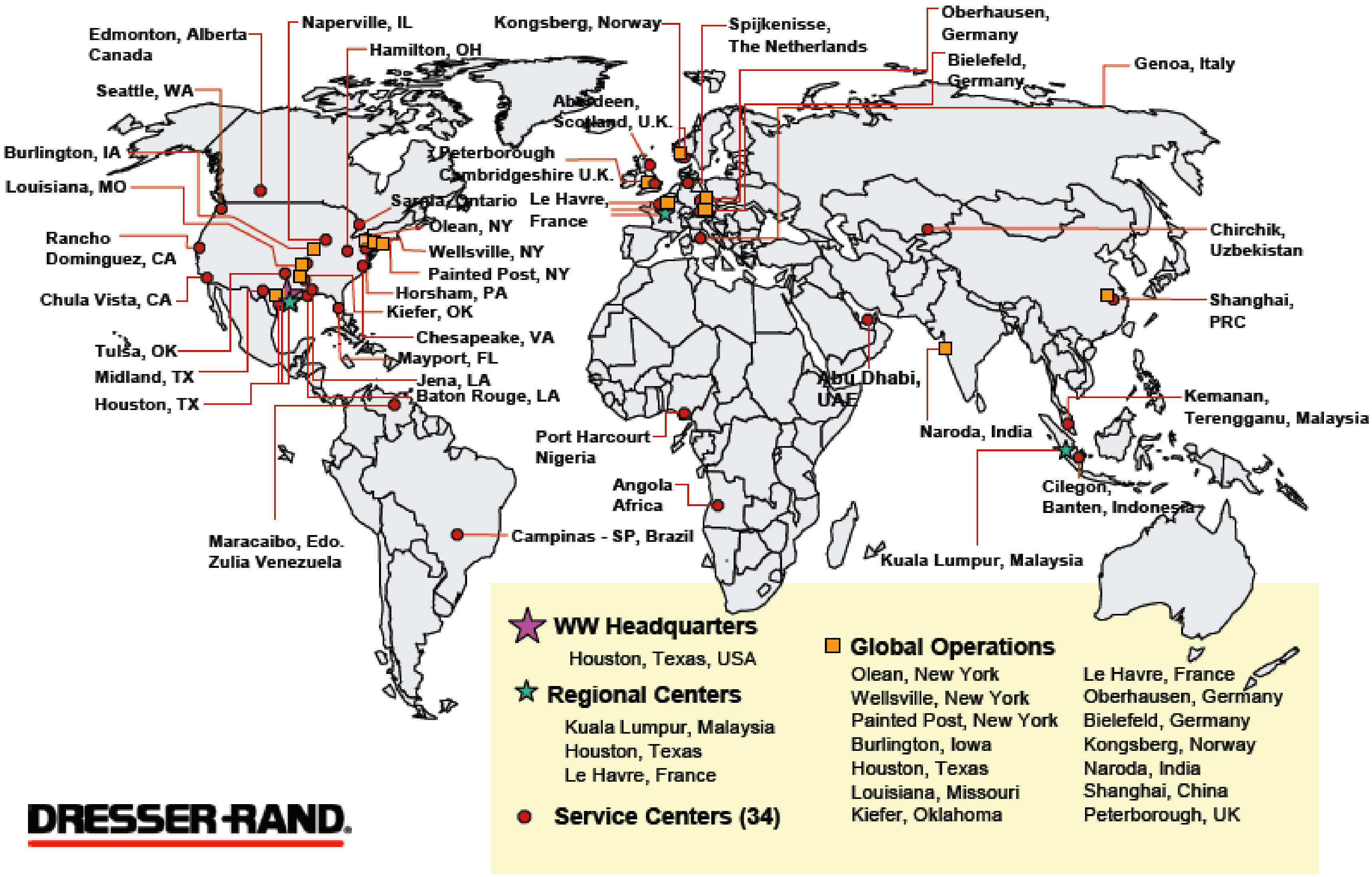


Dresser-Rand Heritage

DRESSER-RAND

Serving the energy markets since 1840

Dresser-Rand's Global Presence



Dresser-Rand Key Clients

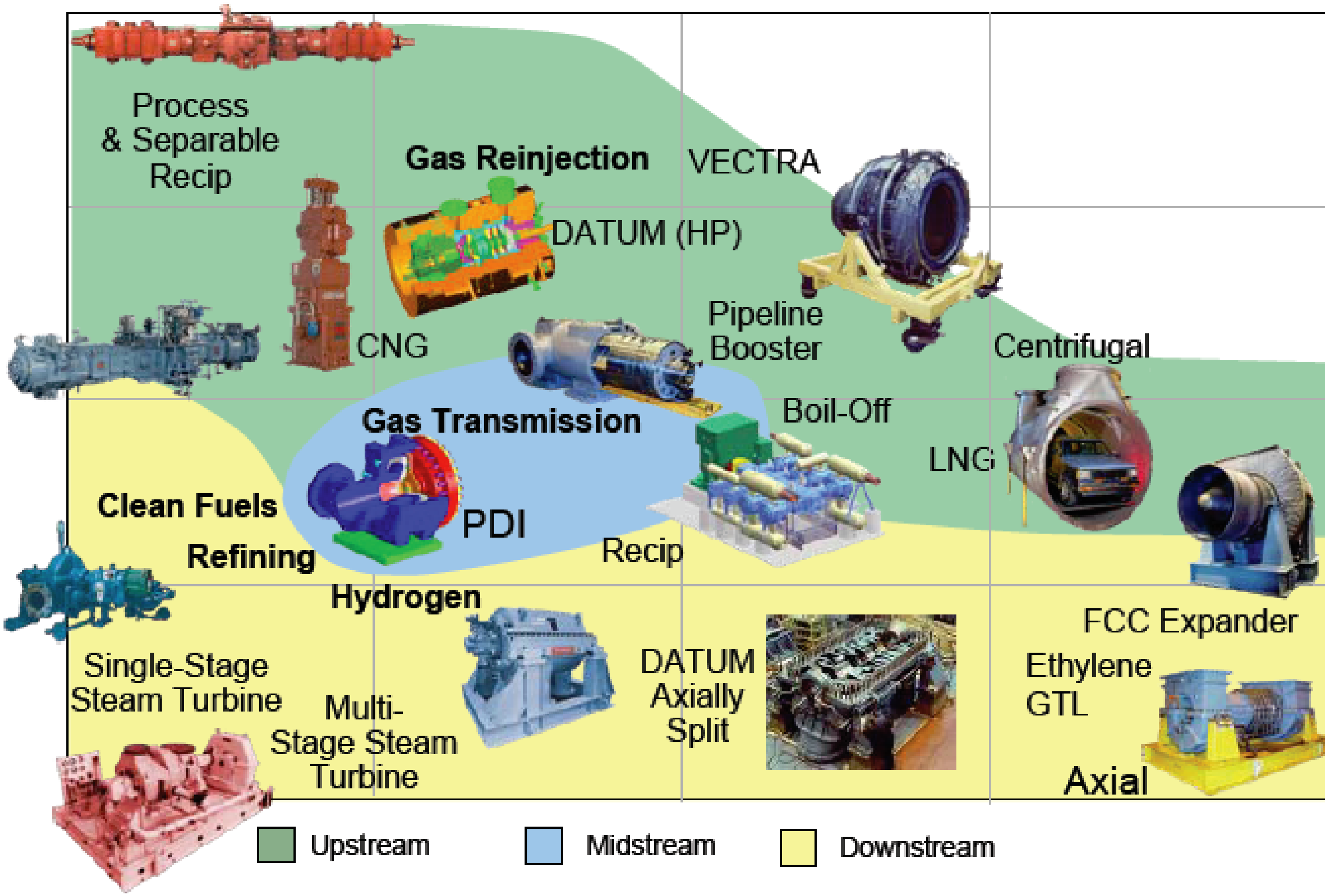
RAMGEN POWER SYSTEMS™

- Shell
- STATOIL
- Marathon Oil Corporation
- bp
- PEMEX
- HESS
- ConocoPhillips
- Chevron
- W
- PETROBRAS
- Chevron Phillips Chemical Company LLC
- REPSOL YPF
- ExxonMobil
- ENEX
- KINDER MORGAN
- PRAXAIR
- PDVSA
- VALERO ENERGY
- PT Badak NGL
- DOW
- FLUOR
- HOVENSA
- LYONDELL
- TEXAS GAS TRANSMISSION, LLC
- OXY
- Flint Hills Resources
- EQUISTAR
- Transco
- Panhandle Energy
- WOODSIDE
- TARGA
- elpaso
- dcp Midstream Partners

DRESSER-RAND

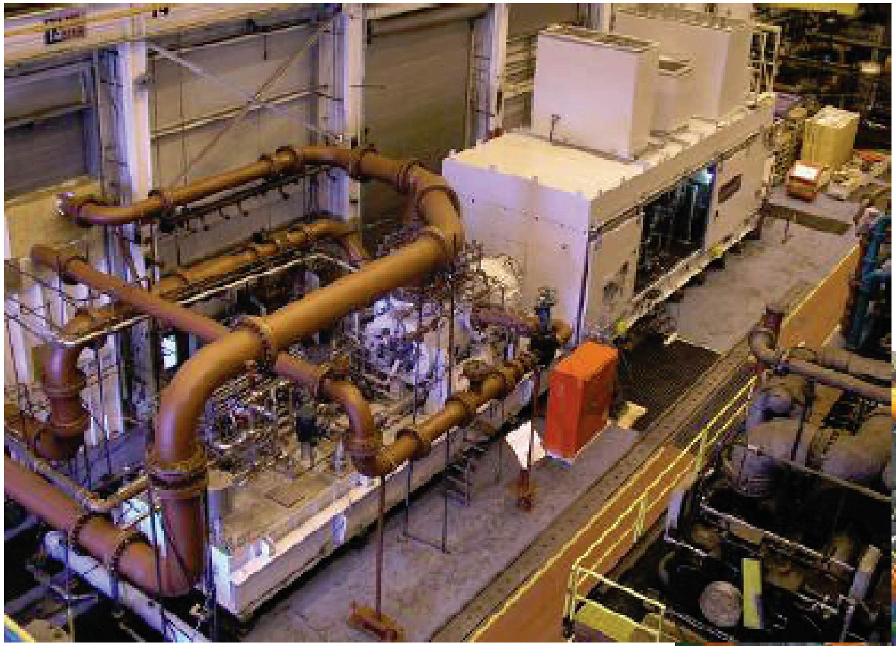
Note: Partial list as of December 2007.

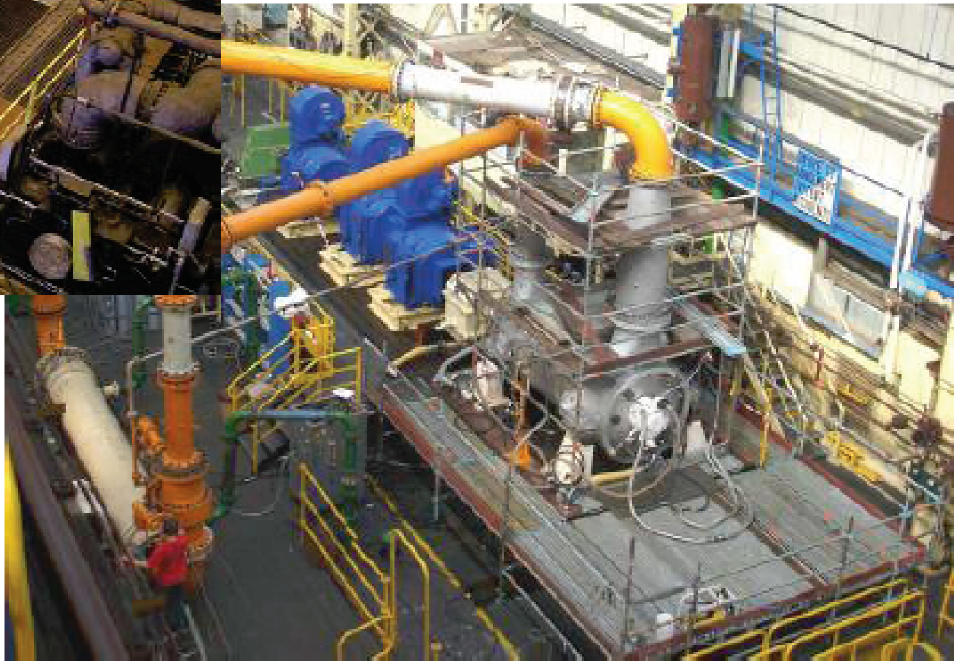
Products for All Served Markets



DRESSER-RAND

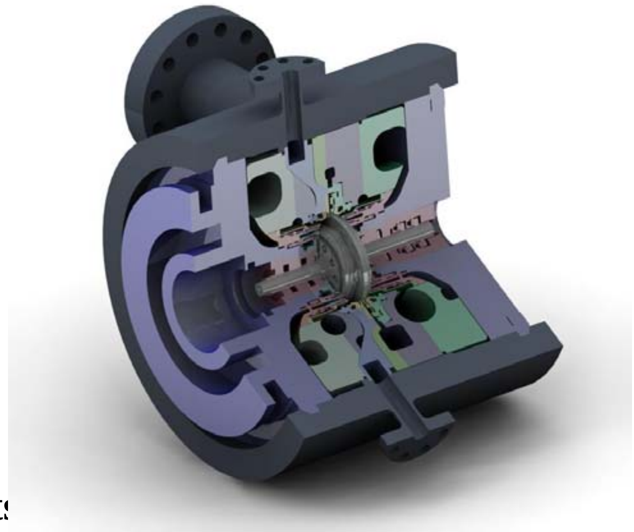
World Class Test Facilities



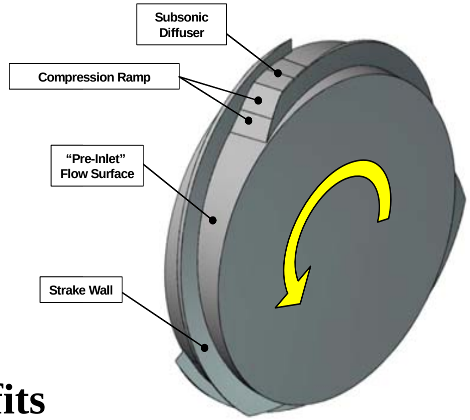


Ramgen CO_2 Compressor Product

- **100:1 CO2 compressor ⇨ 2-casings/2-stages/Intercooled**
  - **No aero Mach# limit**
  - **10+:1 pressure ratio; 400°F temperature rise**
  - **1400 fps tip speeds; Shrouded rotor design**
- **Single-stage, discrete-drive**
  - **Single stage per drive optimizes specific speed match**
  - **Simple single-step external gearbox or high speed direct drive**
  - **Lower mechanical losses**
- **Variable speed option**
  - **Match MW and temperature changes with speed changes**
- **Configuration adapts easily to match process requirements**
  - **Mismatched thru-flow**
  - **Side stream additions**
- **Active IGV Flow control on each stage**
  - **Match CO2 capture system constant pressure requirement**
- **Heat exchangers**
  - **Inter/aftercooler can be the CCS or power plant**
  - **"Compressor" heat exchanger cost can be eliminated**
  - **Eliminate or substantially reduce cooling tower requirement**
  - **Eliminate or substantially reduce cooling tower make-up water**
  - **3x LMTD ⇨ heat exchangers with 1/3 the surface area**
- **1/10th the physical size – facilitate space constrained retrofits**
- **1/2 the installation cost**



Ramgen Discrete Drive HP Stage



Ramgen Compressor Rotor

Compressed Air & Gas Handbook

can be handled with sufficient accuracy for most purposes when the unit is a typical single-stage air compressor. A little more discretion must be used on multistage compressors handling heavy gases, however, because fan-law deviation can become quite significant for speed changes as small as 10 per cent.

Choke Effect

The basic slope of the head flow curve has been discussed at some length, but the choke or stonewall effect that occurs at flows higher than design flow and which must be superimposed upon the basic slope (Fig. 11.19) has not yet been discussed.

Just as basic slope is controlled by impeller-tip vector geometry, the stonewall effect is normally controlled by impeller-inlet vector geometry. In Fig. 11.24, vector U_1 may be drawn to represent the tangential velocity of the leading edge of the blade similar to ... of the inl ... radially (... relative t ... V. At des ... shown.

…it is conventional practice to limit the Mach# to 0.85 or 0.90 at design flow.

Mach Number Considerations

The magnitude of V_{rel} compared to the speed of sound at the inlet pressure and temperature is called the relative inlet Mach number. It is the magnitude of this ratio that indicates stonewall effect in a conventional stage. While true stonewall effect should theoretically not be reached until the relative inlet Mach number is unity, it is conventional practice to limit the Mach number to 0.85 or 0.90 at design flow.

It is evident from Fig. 11.24 that, for a given rpm, the magnitude of V_{rel} will diminish with decreasing flow, since V is proportional to flow. If V_{rel} decreases, then relative inlet Mach number decreases, so the stonewall effect is normally not a factor at flows below design flow. It is also evident that at low flows the direction of V_{rel} is such that the gas impinges on the leading side of the blade, resulting in positive

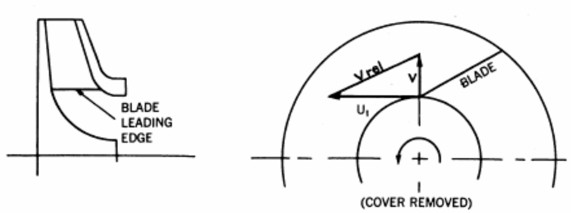


Figure 11.24 Impeller inlet geometry and velocity diagram.

$$c = \sqrt{\frac{kg\bar{R}T}{MW}}$$

incidence, a facto ... gh values of positive incide ...

Let us now ... , so also does V_{rel} and relati ... e trailing side of the blade, ... rved that high degrees of negative incidence tend to contribute to the stonewall problem as Mach number 1.00 is approached, presumably because of boundary layer separation and reduction of effective flow area in the blade pack.

Significance of Gas Weight

Since values of U_1 are typically in the 500-fps (152.4-m/second) range and values of V in the 250-fps (76.2 m/second) range, it is obvious that, since the speed of sound for air at 80 deg. F (26.7 deg. C) is 1140 fps (348 m/second), lighter gases suffer no true impeller stonewall problems as described, even at high overloads. Some head loss below the basic slope will be observed, however, in even the lightest gases, due in part to increased frictional losses throughout the entire stage and in part to the extreme negative incidence at high overloads.

The lightest common gas handled by conventional centrifugal compressors for which stonewall effect can be a definite factor is propylene with a sonic speed of 740 fps (225.7 m/second) at −40 deg. F (−40 deg. C). In order of increasing severity are propane at 718 fps (219 m/second) at −40 deg. F (−40 deg. C), butane at 630 fps (192.1 m/second) at −20 deg. F (−29 deg. C), chlorine, and the various Freons. The traditional method of handling such gases is to use an impeller of larger than normal flow area to reduce V, and run it at lower than normal rpm to reduce U_1, thus keeping the value of V_{rel} abnormally low. This procedure requires the use of more than the usual number of stages for a given head requirement and sometimes even requires the use of an abnormally large frame for the flow handled.

Inducer Impeller Increases Head Output

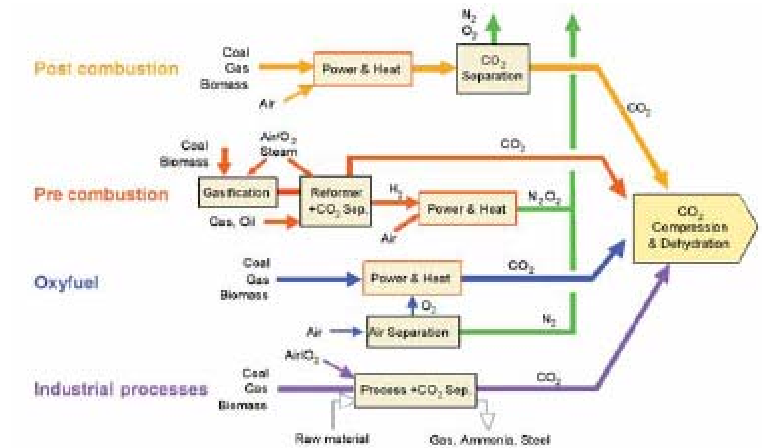
Much development work has been done in recent years toward the goal of running impellers at normal speeds on heavy gases in order to reduce hardware costs to those incurred in the compression of light gases. One approach has been to use inducer impellers (Fig. 11.25). The blades on this impeller extend down around the hub radius so that the gas first encounters the blade pack while flowing axially. Figure 11.25 shows the vector analysis at the inducer outer radius. Assuming that the inducer radius is the same as the leading edge radius of the conventional radial inlet impeller, the vector geometries of the two are identical.

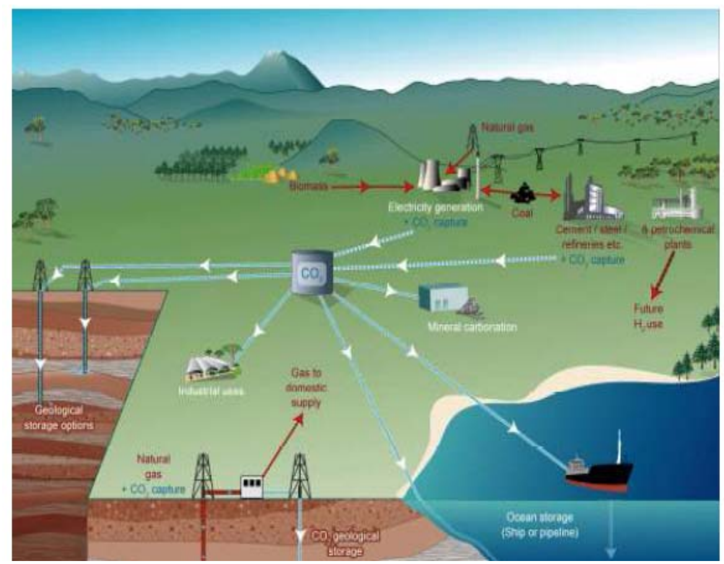
The advantage of the inducer lies in the fact that, as we move radially inward along the blade leading edge, the value of U_1, and therefore of V_{rel} and Mach number, decreases. As we move along the leading edge of the conventional impeller, the vector geometry remains essentially constant. It can be seen, therefore, that while maximum Mach number for the two styles is the same, the average Mach number for the inducer

Technology Development Needs & Direction

Fossil Fuel Power Plant – CC&S

- All fossil fuel power plants produce some level of CO2
- CO2 compressor power
  - Advanced pulverize coal – 8-12%
    - 600MW ⇨70MW ⇨93,000 hp
  - IGCC - 5%
    - 600MW ⇨30MW ⇨40,000 hp
  - CCGT – 8%
    - 400MW ⇨32MW ⇨43,000 hp
- 100 new power plants annually
  - $1.5 billion annual compressor market
- Retrofit opportunity
  - $0.7 billion annual compressor market





Over $2 Billion annual market opportunity

CCS Technologies

- Amine systems
  - Suction pressures – 15; 22; 25; 30 psia
  - Regeneration heat required
    - Conventional amines – 1550 Btu/lbm-CO_2
    - Advanced amines – 1200 Btu/lbm-CO_2
    - Really advanced amines – 800 Btu/lbm-CO_2
  - 8% parasitic power
  - Post combustion - New & Retrofit
- Ammonia-based systems
  - Suction pressures – ~ 30-300 psia
  - Regeneration heat required
    - Aqueous ammonia – 493 Btu/lbm-CO_2
    - Chilled ammonia – TBD
  - 4% parasitic power
  - Post combustion - New & Retrofit
- Chemical Looping
  - Suction pressure atmospheric
- Selexol/Rectisol
  - Suction pressures 50, 150 & 300 psia with sidestreams
  - Regeneration heat required for the Claus Plant
  - 5% parasitic power
  - IGCC (new) only
- Oxy-fuel systems
  - Raw gas feed – 15 to 500 psia
  - Twin purified suction streams – ~150 & 300 psia
  - 12-13% parasitic power
  - New plants only
- Membrane Separation & Enzyme Processes
  - Suction pressures from <3.0-14.7 psia
- Discharge pressures – 1200;1600; 2000; 2215; 2500; 2700; 2900 psia

Baseline Case for Comparison

Data Provided

- Case 3 ASME TurboExpo Berlin - June 2008
- Case 12 in the Baseline Cost & Performance Study – May 2007
- Compressor 6-stage integrally geared design
- 84% isentropic efficiency all stages
- Inlet conditions 23.52 psia; 69°F inlet temperature; 92.4% RH
- Discharge conditions 2215 psia
- Cooling water 60°F
- Stage pressures
- 1,259,600 lbm/hr
- 2 units

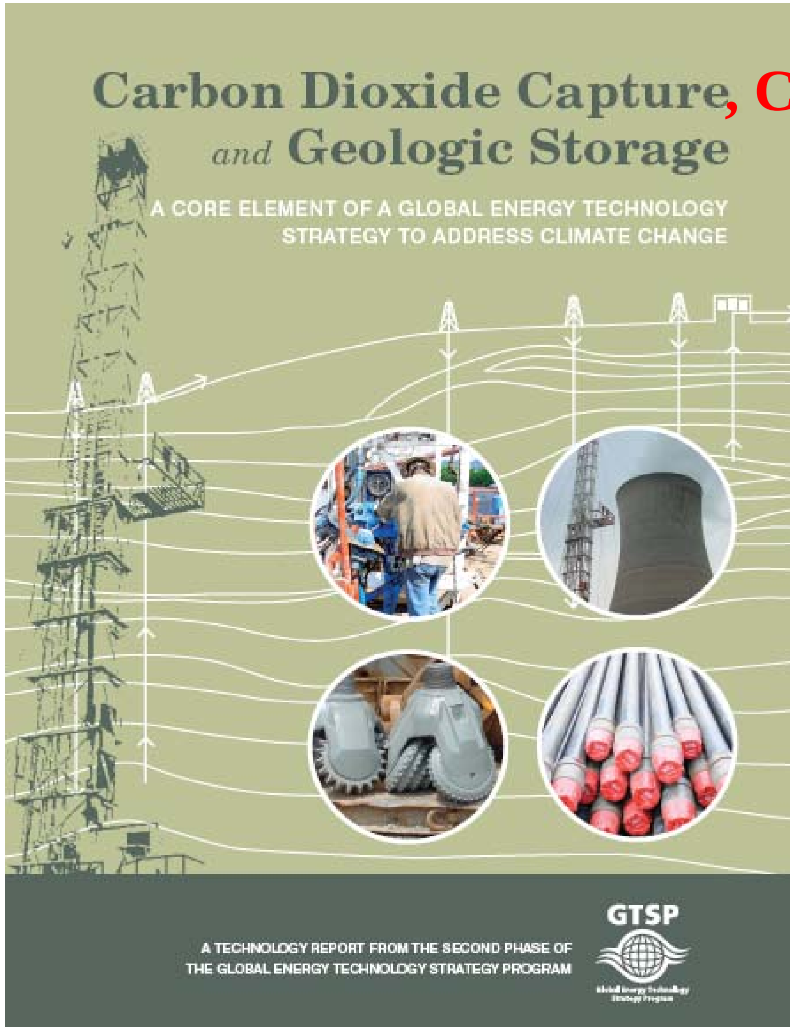
Assumptions

- Intercooler approach temperature 9°F
- Interstage pressure drop DP = (P2^0.7)/10 ; but not greater than 5 psi
- Mechanical loss 1.5%
- Drying between stages 3 & 4
- Partial cooling between stages 5 & 6
- 46,900kW Published (2 unit total)
- 46,898kW Calculated with these assumptions

	Stage					
	1	2	3	4	5	6
P1 - psia	23.52	52.00	113.01	248.00	545.00	1200.00
T1 - °F	69	69	69	69	69	100
P2 - psia	53.65	115.80	253.00	550.00	1205.00	2219.99
Pr	2.23	2.28	2.24	2.22	2.21	1.85

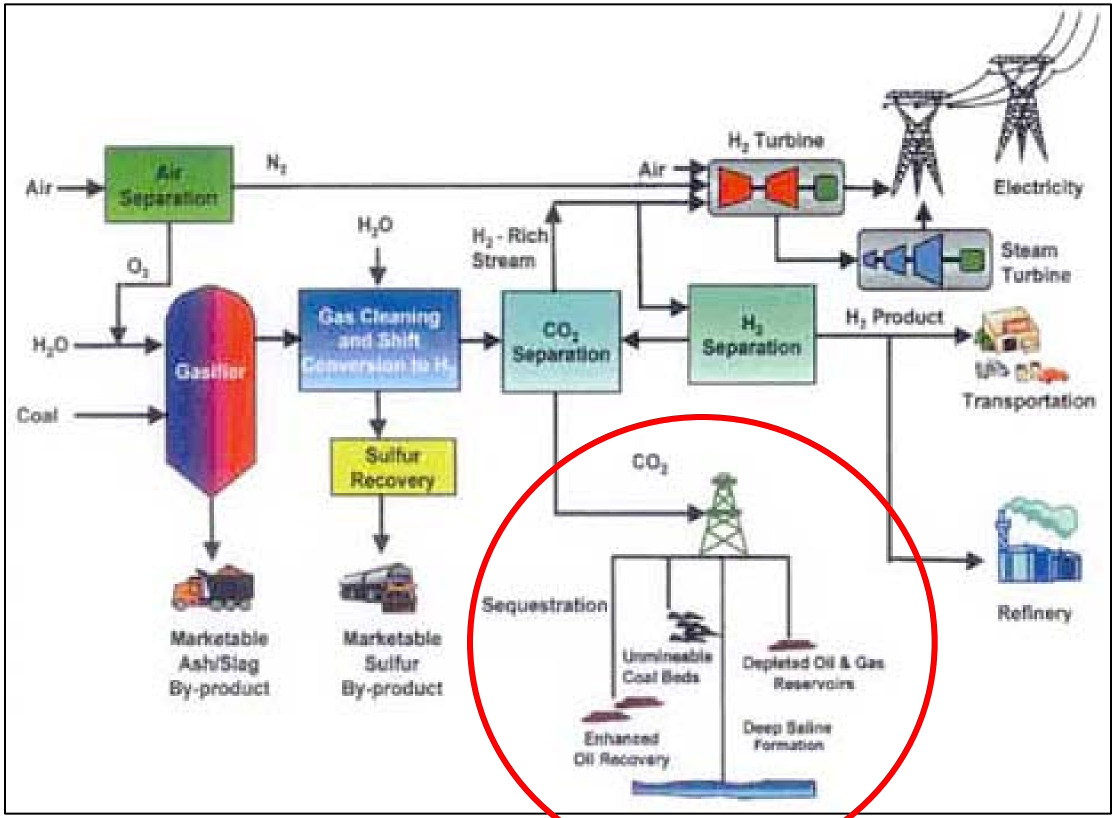
Baseline case needs realistic assumptions

It’s No Fun Being Overlooked!



, Compression

Immaculate Compression

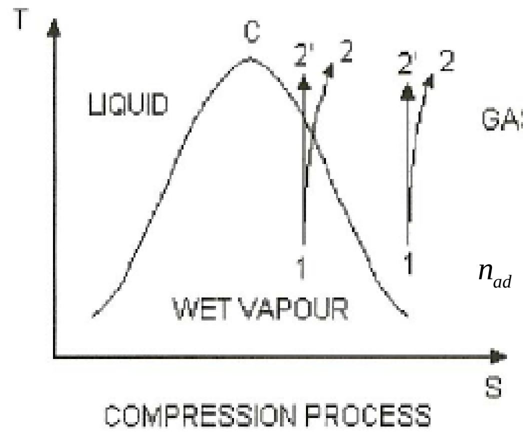


Sequestration

Compressor Power & Things That Affect It

- The basic inputs
  - Gas composition, including moisture content
  - Mass flow
  - Inlet pressure
  - Inlet temperature
  - Discharge pressure
- Often forgotten
  - Cooling media & temperature
    - Air
    - Water-cooled
    - Process cooled
  - Interstage assumptions
    - Pressure drop
    - Design practice
    - Fluor estimate ΔP = P2^0.7/10; not to exceed 5 psi
    - Intercooler/heat exchanger approach temperature or Cold Temperature Difference – CTD
    - 15°F CTD normal approach temperature
  - Mechanical losses
    - Compressor
    - Gearbox
  - Sparing philosophy (i.e., 2 x 50% + 1)

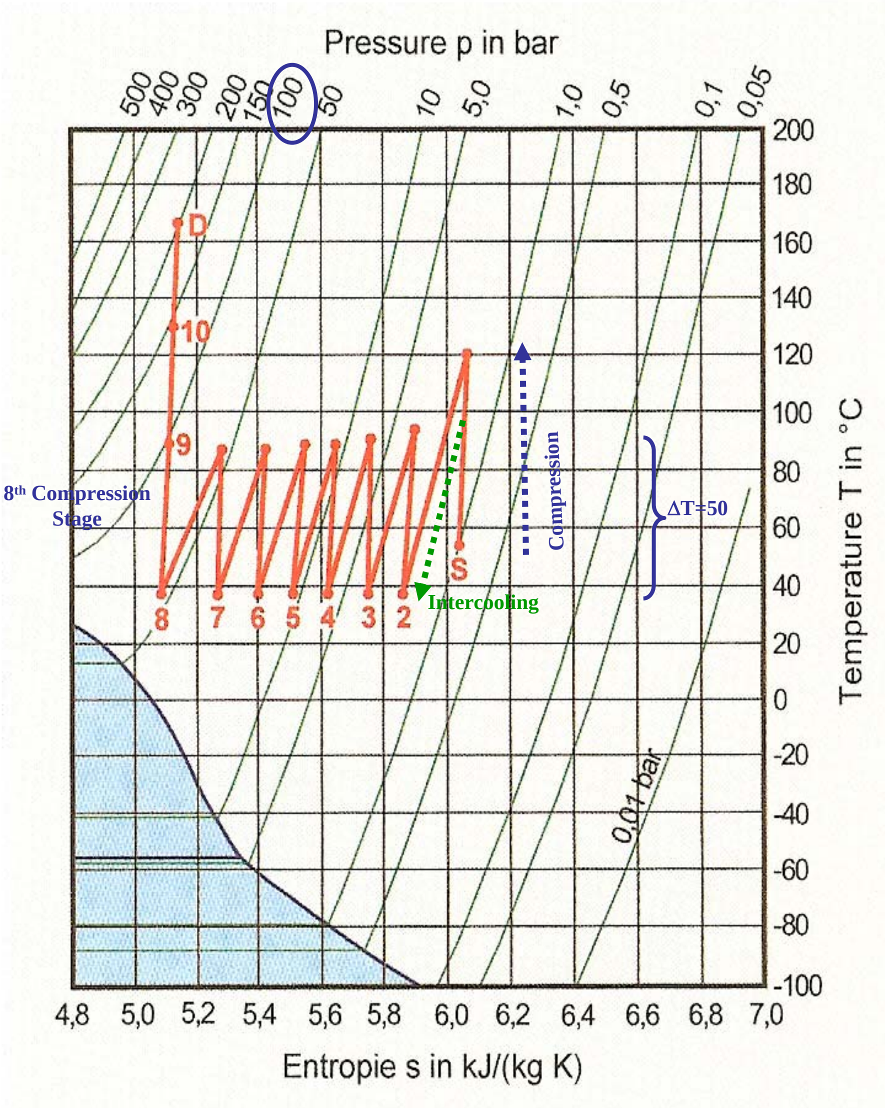
Only the first stage is affected by the inlet conditions…..all the other stages are affected by interstage assumptions.



$$n_{ad} = \frac{h_{2'} - h_1}{h_2 - h_1}$$

- CCS Application Specific Issues
  - Capture system flash levels & control requirements
    - Pressure
    - Mass flow additions
  - Water knockout
    - Process location (i.e., pressure)
    - Method – Glycol/Molecular sieve/PSA
  - CO2 compressor inlet pressure
  - Heat integration
  - Materials of construction
    - Heat exchangers
    - Piping
  - Discharge pressure

Heat Exchangers are a Big Deal!



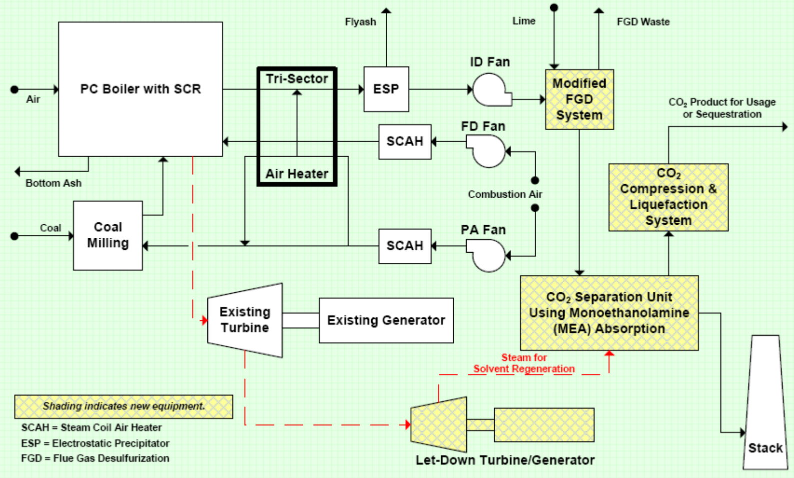
Retrofit Capture Cost Assumptions

- **“Carbon Dioxide Capture from Existing Coal-Fired Power Plants”**
  - DOE/NETL 401/110907 – Revised November 2007
  - AEP/Alstom Conesville Unit #5
  - Base line & Case 1
- **Process Conditions**
  - P1 19 psia
  - T1 115 F
  - P2 2015 psia
  - Illinois #6 @ 1.80/mmBtu
  - 90% capture
  - 85% capacity factor
- **Financial Assumptions**
  - Make-up power 6.4 cents/kWh
  - Burden rate 2.28
- **Baseline Compressor Horsepower**

– CO2 compressor	31,262
– Propane refrigeration	23,321
– CO2 product pump	2,932
Total	57,515 hp
– Compressor only equivalent	56,800
– Analysis	56,800 hp

Description of Plant Retrofit for Incorporating Carbon Capture Technology

A simplified process flow diagram for the study unit, modified with the addition of the post-combustion amine-based capture system, is shown in below. This simplified diagram is applicable to each of the CO_2 capture cases included in this study. The operation and performance of the existing boiler, air heater, and electrostatic precipitator (ESP) systems are identical to the Base Case for all the capture cases investigated and are not affected by the addition of the post-combustion amine-(MEA)-based CO_2 recovery systems.



Simplified Process Flow Diagram for Power Plant Modified with the Addition of an Advanced Amine Based CO_2 Capture System

The flue gas desulfurization (FGD) system is modified identically for each of the cases with the addition of a secondary absorber to reduce the SO_2 content of the flue gas entering the new amine system to below 10 ppmv. Recovery of less than 90% CO_2 (Cases 2, 3, and 4 with 70%, 50%, and 30% recovery respectively) is accomplished by bypassing a fraction of the total flue gas stream around the new CO_2 absorber. Flue gas bypass was determined to be the least costly way to obtain lower CO_2 recovery levels.

Conventional CO_2 Compression

- CO2 compressor power
  - Advanced pulverize coal – 9.1%
  - 463MW ⇨42MW ⇨56,800 hp
- Capital Cost for 56,800 hp
  - 2 x 50% operating units @ $1000/hp — 57
  - 1 x 50% spare — 28
  - Burdened Installation cost — <u>109</u>
  - Total Cost — $194M
  - $194M/303MW = — $640/kW
- Cost of Electricity (COE)
  - Baseline w/o CCS — 6.07
  - Capture system — 4.74
  - Compressor — <u>2.70</u>
  - Total cents/kWh — 13.51
  - Increase in COE for CCS — 122%
- Cost per tonne
  - Capture system — 41
  - Compressor — <u>23</u>
  - Total — $64

Compression Costs are 36% of Total Cost/Mt of CO2

- Heat recovery – Btu/lbm-CO2
  - Regeneration Heat — 1548
  - Heat recovery — <u>0</u>
  - Net Btu/lbm-CO2 — 1548
- Plant output
  - Original rating — 463
  - De-rating @ 1548 Btu/lbm — <u>160</u>
  - Net — 303 MW
  - Value @ 6.4 cents/kWh — $62M/year

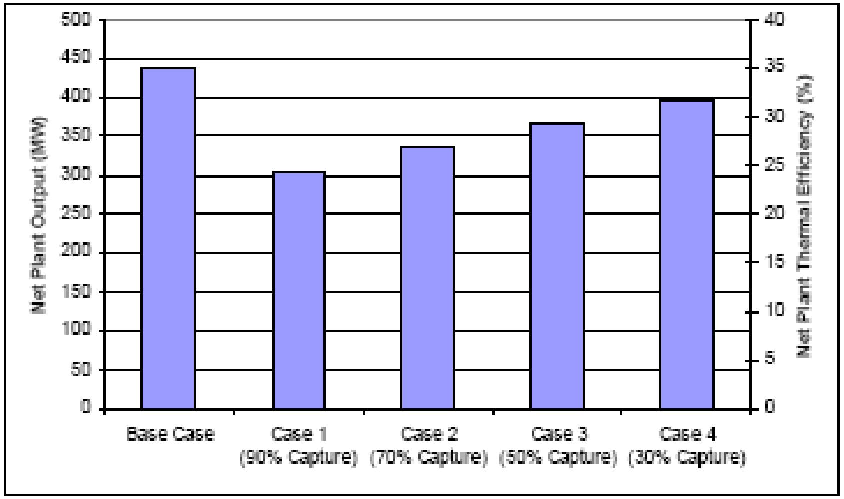
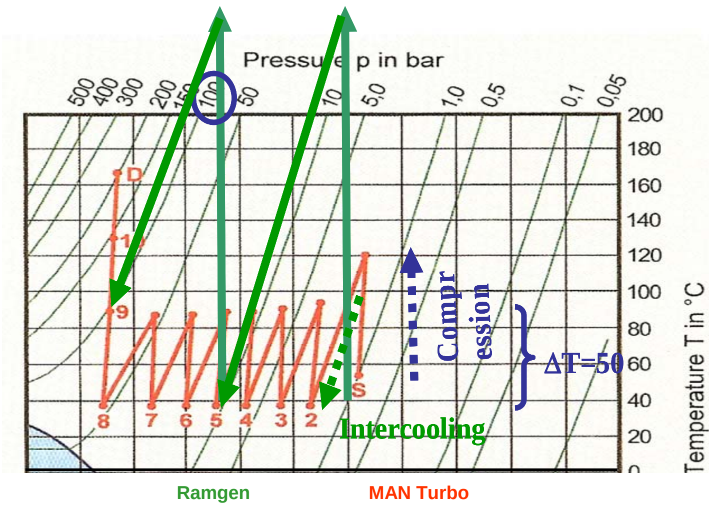


Figure ES-3: Plant Performance Impact of Retrofitting a Pulverized Coal-Fired Plant at Various Levels of Carbon Capture

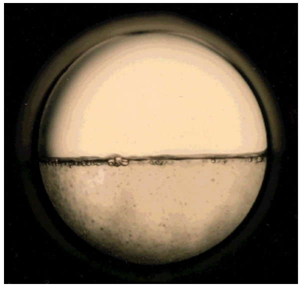
Ramgen CO_2 Compression w/Advanced CCS

- CO2 compressor power
  - Advanced pulverize coal – 4.2%
  - 463MW ⇨20MW ⇨26,000 hp
- Capital Cost for 26,000 hp
  - 2 x 50% operating units @ $400/hp — 11
  - 1 x 50% spare — 5
  - Installation cost — 20
  - Total Cost — $36M
  - $36M/388MW = — $93/kW
- Cost of Electricity (COE)
  - Baseline w/o CCS — 6.07
  - Capture system — 2.02
  - Compressor — 0.47
  - Total cents/kWh — 8.56
  - Increase in COE for CCS — 41%
- Cost per tonne
  - Capture system — 22
  - Compressor — 5
  - Total — $28
- Heat recovery – Btu/lbm-CO2
  - Regeneration Heat — 450
  - Heat recovery @ 230F — 93
  - Net Btu/lbm-CO2 — 357
  - HR potential @ 100F — 87
- Plant output
  - Original rating — 463
  - De-rating @ 450 Btu/lbm — 75
  - Net — 388 MW
  - Value @ 6.4 cents/kWh — $22M/year

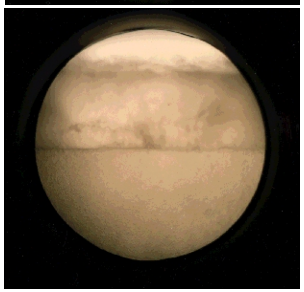


CC&S cost can be reduced by 56% from $64 to $28/tonne CO_2

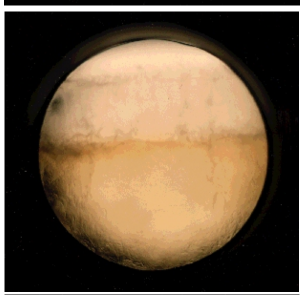
PT Diagram & Supercritical Phase



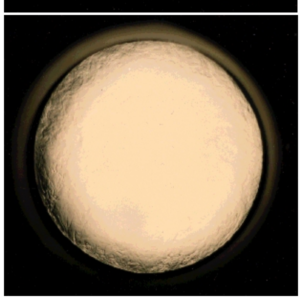
Separate Phases Visible- Meniscus Clearly Observed



Increase in Temperature- Diminished Meniscus

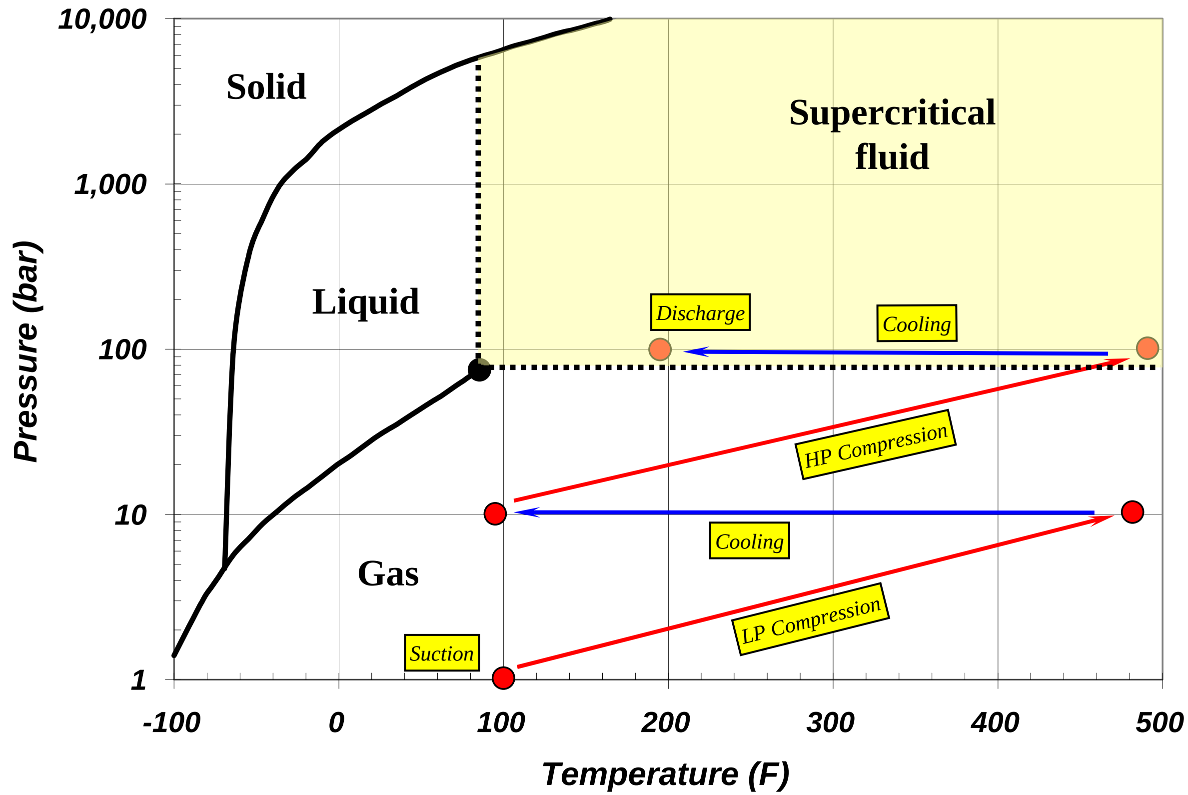


Further Increase in Temperature- Gas & Liquid Densities more Similar



At Critical P & T- Distinct Gas & Liquid Phases no Longer Visible "Supercritical Fluid" with Properties of Both Liquids & Gases

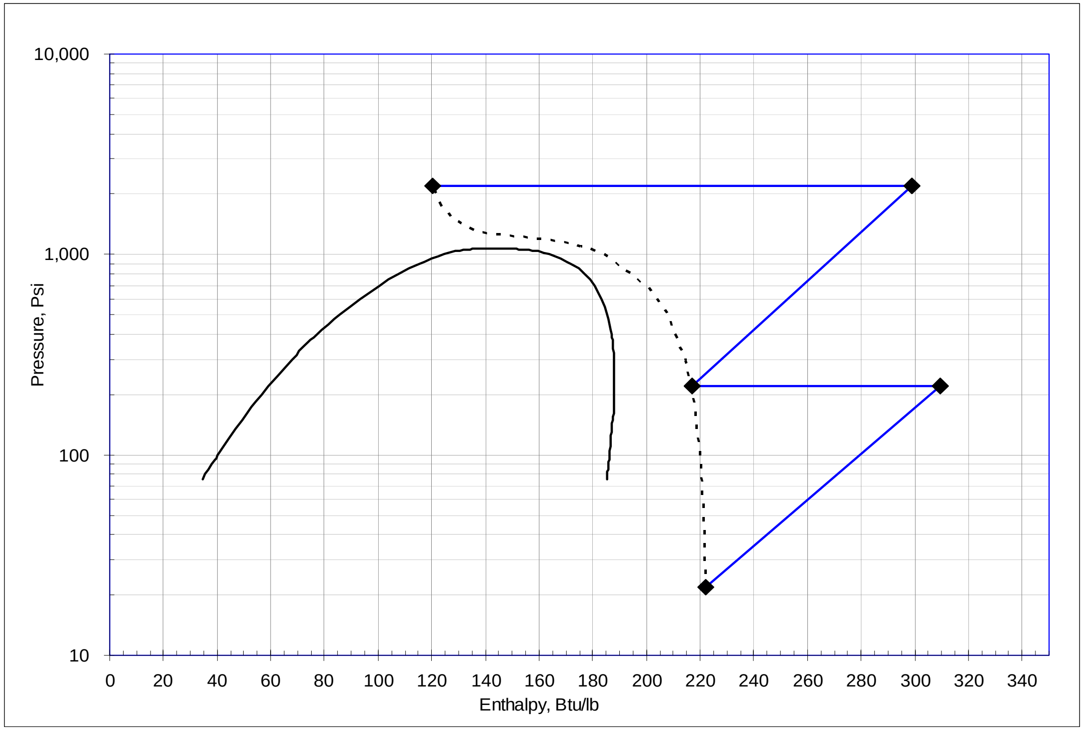
- **Compression process transitions from superheated to supercritical phases**
- **Avoids liquid (sub-cooled) phase**



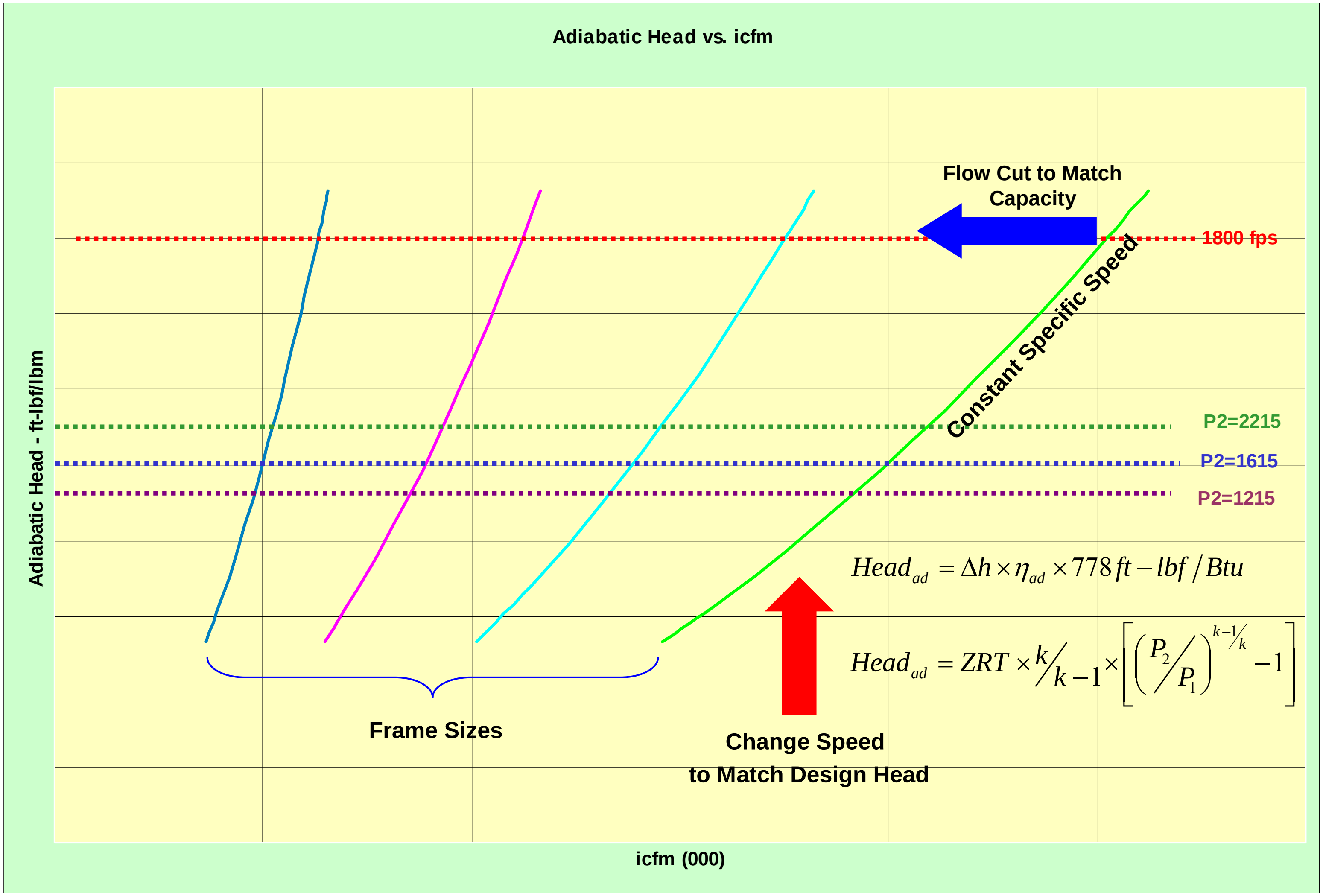
Ramgen Heat Recovery

	Low Pressure Stage 22 - 220 psia	High Pressure Stage 220 - 2200 psia
Compressor Shaft Input Work	90.6 Btu/lbm	87.0 Btu/lbm
Discharge Temperature	489 °F	509 °F
Lower Recovery Temperature	100 °F	100 °F
Recovered Heat	92.4 Btu/lbm	178.8 Btu/lbm
Recovered Heat/Compression Work	102%	205%

- **Heat available in the HP hot discharge CO_2 is more than double the compressor shaft work**
- **153% of the combined LP + HP shaft work is available as heat in the discharge CO_2**



Optimizing Compressor Selection



$$Head_{ad} = \Delta h \times \eta_{ad} \times 778\, ft - lbf / Btu$$

$$Head_{ad} = ZRT \times {k}/{k-1} \times \left[\left({P_2}/{P_1} \right)^{{k-1}/{k}} - 1 \right]$$

“The Convenient Half-Truth”

	PC		SCPC		IGCC*		NGCC	
	w/out	with	w/out	with	w/out	with	w/out	with
Gross Power	583,315	679,923	580,260	663,445	770,350	744,960	570,200	520,090
Net Power	550,445	549,613	550,150	545,995	640,250	555,675	560,360	481,890
Coal Flowrate - lbm/hr	437,699	646,589	411,282	586,627	489,634	500,379	-	-
Natural Gas Flowrate - lbm/hr	-	-	-	-	-	-	165,182	165,182
Net Plant Heat Rate - Btu/kW-hr	9276	13724	8721	12534	8922	10505	6719	7813
Net Plant Efficiency - HHV%	36.8%	24.9%	39.1%	27.2%	38.2%	32.5%	50.8%	43.7%
Carbon Factor - lbm-CO2/mmBtu	203.3	203.3	203.3	203.3	196.7	196.7	118.5	118.5
Capacity Factor	85.0%	85.0%	85.0%	85.0%	80.0%	80.0%	85.0%	85.0%
Capture %	0.0%	90.0%	0.0%	90.0%	0.0%	90.0%	0.0%	90.0%
Capital Cost - $/kW	$1,549	$2,895	$1,575	$2,870	$1,813	$2,390	$554	$1,172
LCOE - $/kW-hr	$ 0.0640	$ 0.1188	$ 0.0633	$ 0.1148	$ 0.0780	$ 0.1029	$ 0.0684	$ 0.0974
CO2 lbm/MW-hr Net Output	1886	278	1773	254	1755	206	797	93

Capture % to Achieve 797 or 278 lbm/MW-hr	57.7%	71.4%	55.0%	68.7%	54.6%	61.4%	0.0%	70.0%
	797	797	797	797	797	797	797	278

Note: Baseline Report Cases 1 & 2

$$tons/year = \left(power_{net} \times 8760 \times capacity\ \ factor \times heat\ rate_{net} \times carbon\ \ factor\right)/10^6$$

$$CO_2\, lbm / MWh_{net} = heat\ rate_{net} \times carbon\ \ factor \times \left(1 - capture\%\right)/10^3$$

NETL Cost & Performance Baseline
NETL May 2007

Technology Development Needs

Compressor System

- Compressor
- Drives
  - High power 2-pole motor
  - High power VFD's
  - Steam turbine drives & control
- Gearboxes
  - Industry capacity
  - Auxiliary drive
- Coolers - conventional service
  - Air-cooled
  - Water-cooled
- Heat Recovery Coolers
  - Boiler feedwater
  - Solvent regeneration
  - Coal drying
  - Air pre-heater
  - Flue gas re-heating

Capture System

- Improved solvents
  - Higher loading
  - Reduced regeneration heat
  - Improved thermal stability
  - Lower regeneration temperatures
  - Lower cost
  - Faster reaction kinetics
  - High pressure CO_2

Design & Analysis Tools

- NIST REFPROP CO2 Mixtures with:
  - Water
  - CO
  - Argon
  - Oxygen
  - Ammonia
  - Hydrogen
- Heat exchangers for supercritical fluids
- Impurities & phase change models
- Generic capture system modeling capabilities – (Excel & ASPEN)
- Installed first cost & operating cost models
- Materials selection guidance

Questions?

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