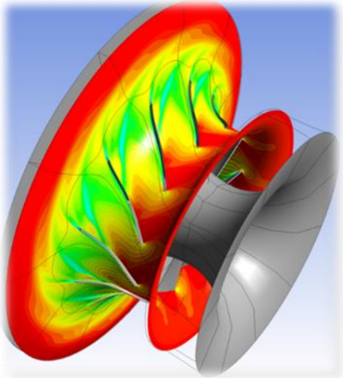
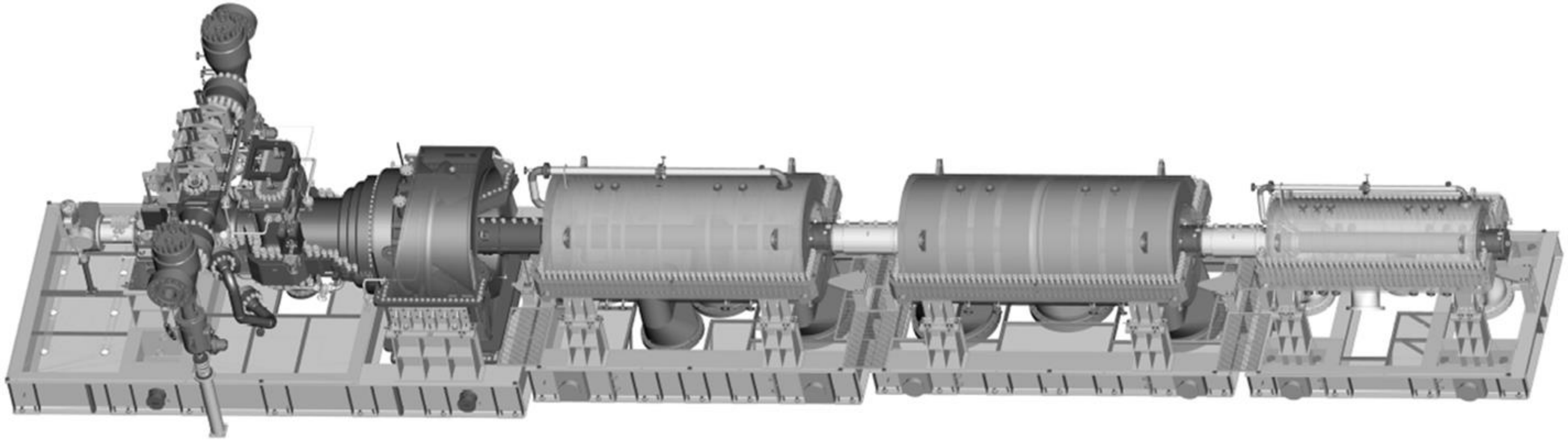


Carbon Dioxide Compression

Klaus Brun, Ph.D.
Karl Wygant, Ph.D.
Ebara Elliott Group



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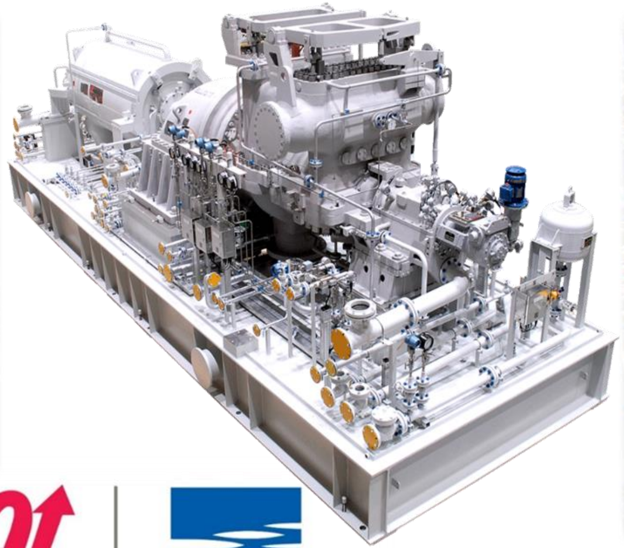
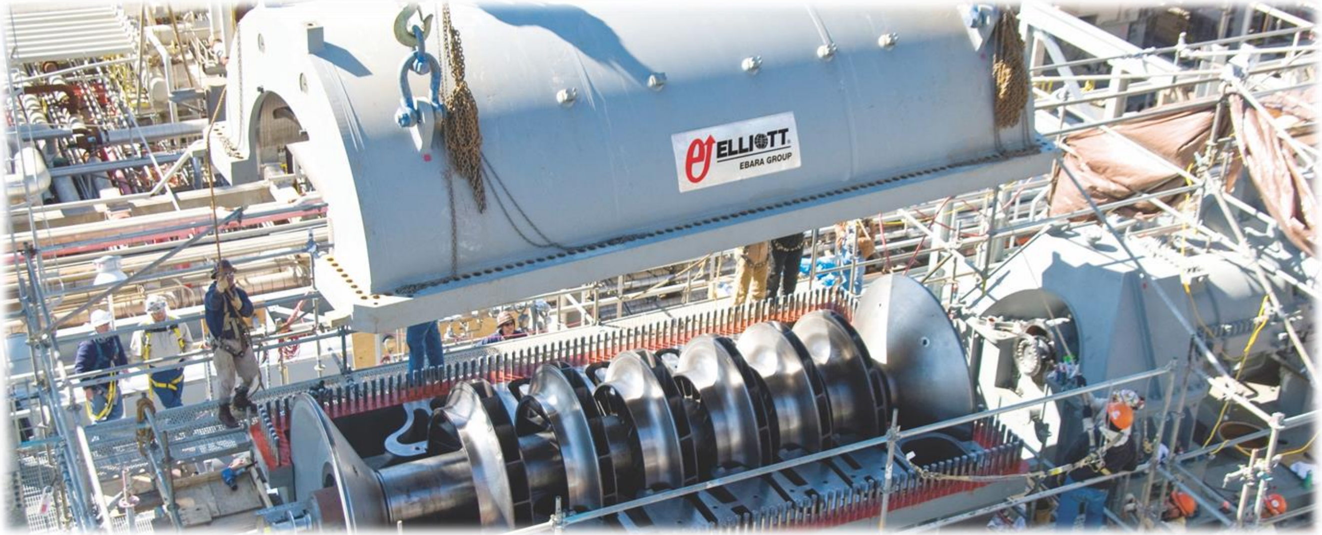
EBARA ELLIOTT ENERGY

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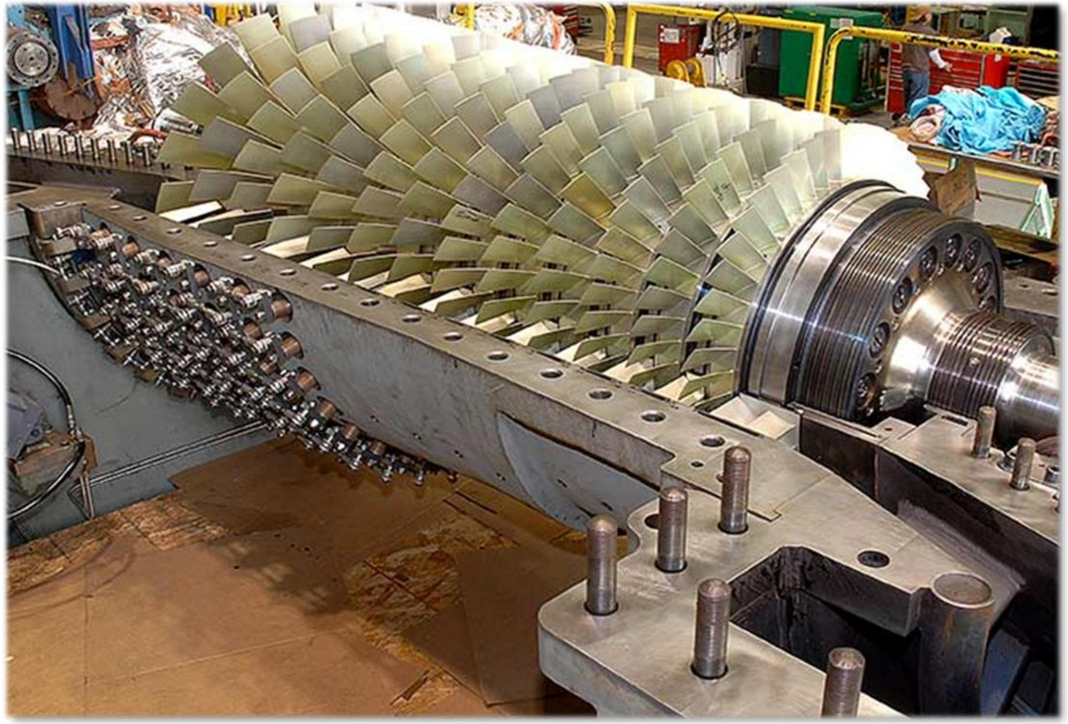


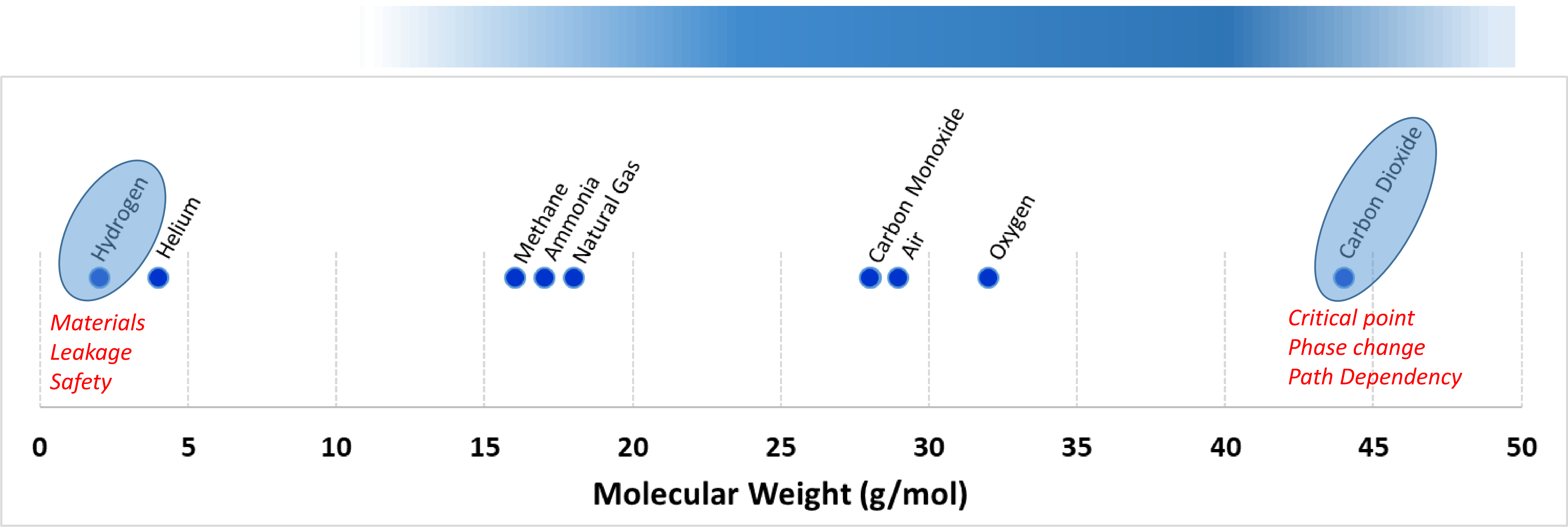
Challenges Associated with Turbomachinery Design

Higher Tip Speeds

- Stress Management
- Gas Leakage Control
- Rotordynamics

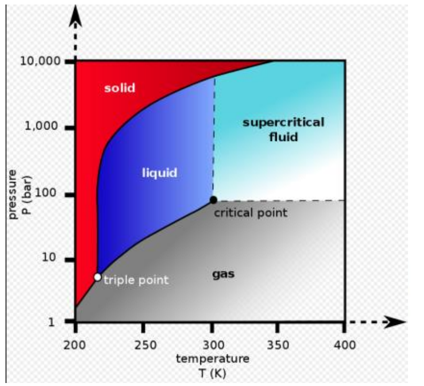
Higher Loading

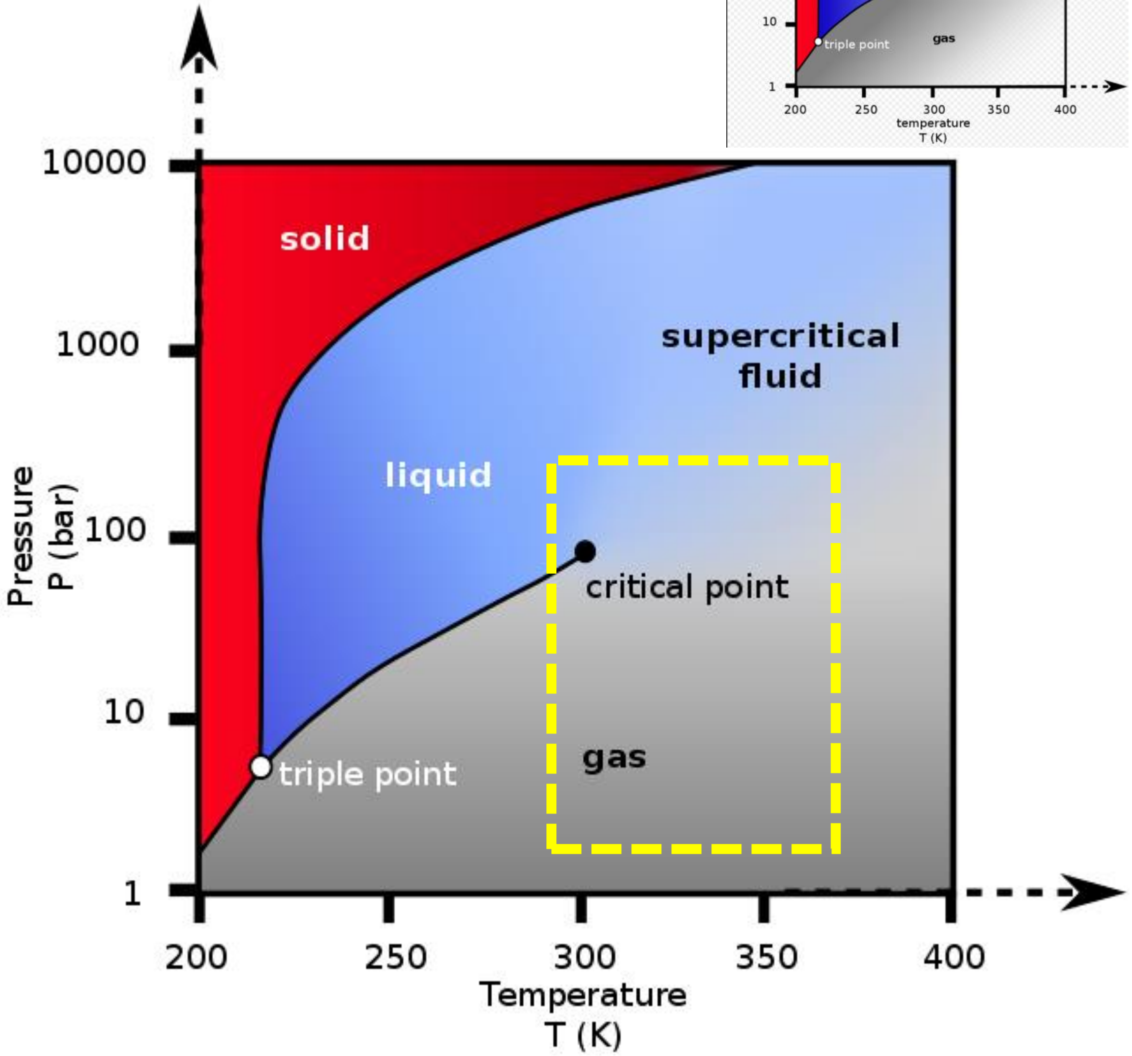
- Gear Life
- Bearing Loads
- Axial Force Management



CO_2 Compression Operating Conditions

- Injection compression from near atmospheric
- Maintain dense phase operation
  - High density and low viscosity
  - Temperatures above 88˚F (30.9˚C)
  - Pressures above 1200 psi (73.3 bar), likely 1800-2300 psi
  - For pure CO_2
- Impurities alter speed of sound, vapor pressure, critical point, and compressibility factor
- <u>2100 psi is a typical pipeline pressure</u>
- Recompression is basically pumping

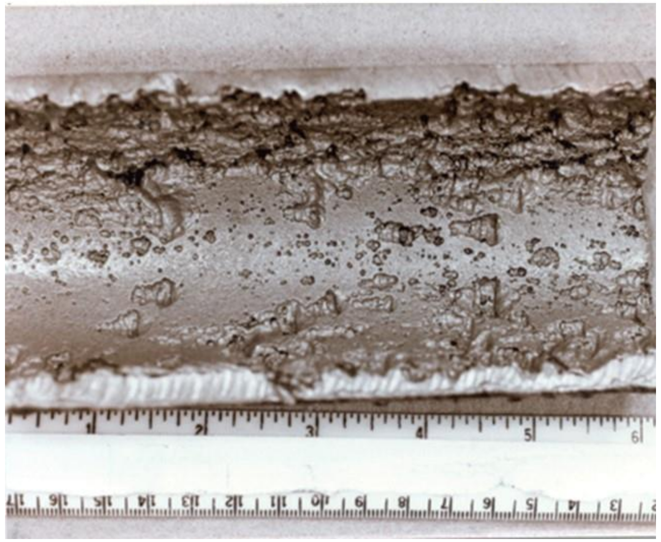


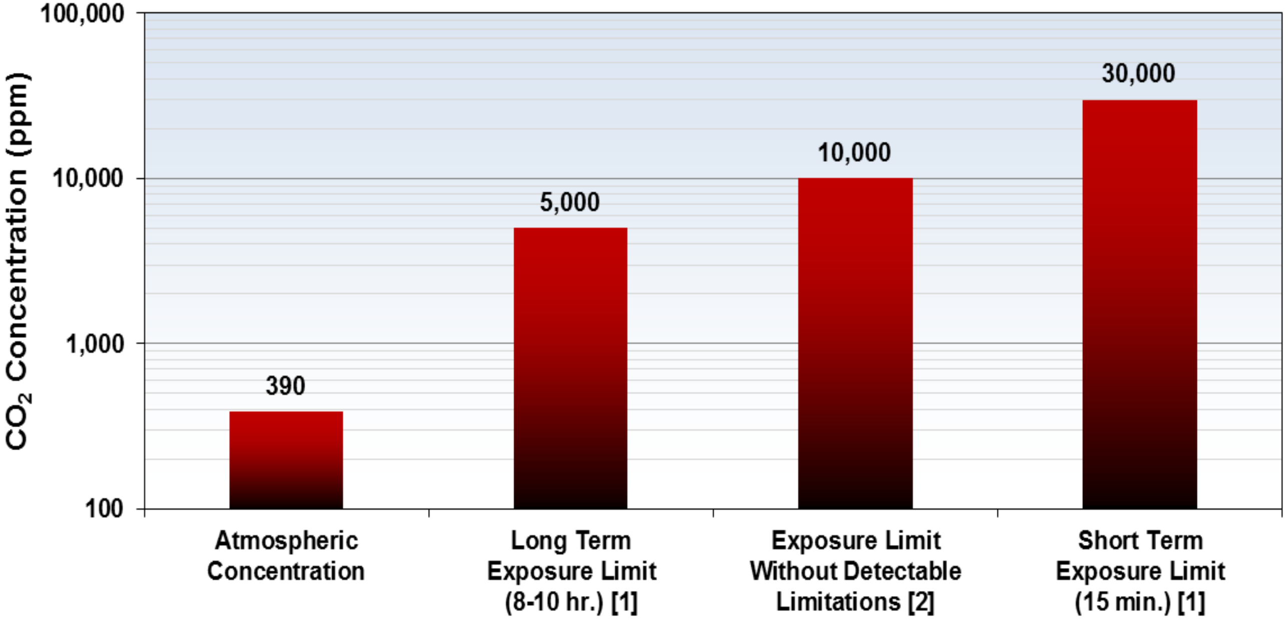


Characteristics of CO_2

- Naturally occurring (0.04% of air)
- Odorless and colorless
- Mostly inert with gases
- Forms carbonic acid when mixed with water
- Non-toxic
- Asphyxiant
  - Sleepy at 1%, fatal over 7 to 10% concentration

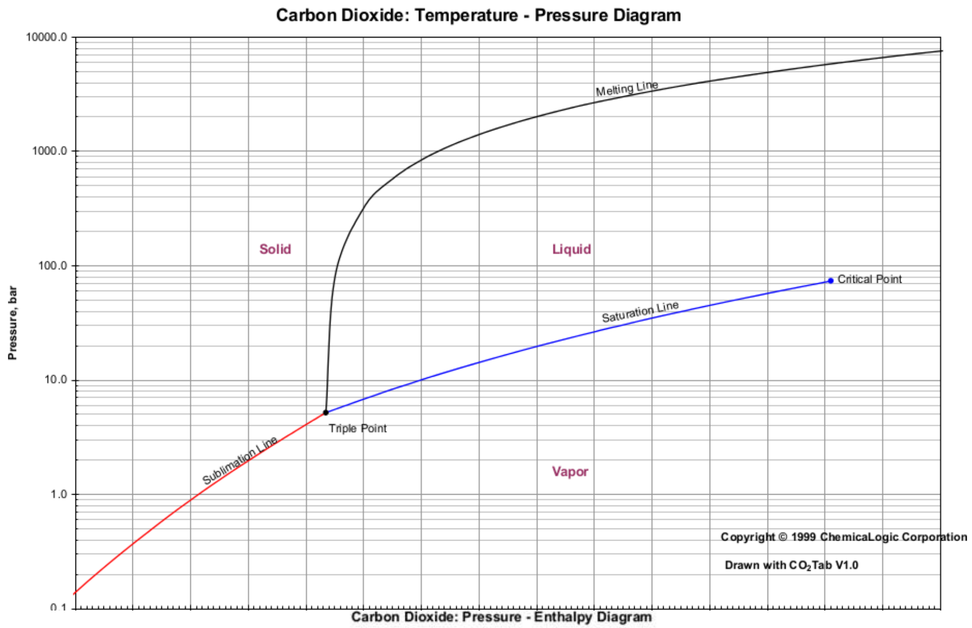
$$CO_2 + H_2O \leftrightarrows H_2CO_3$$

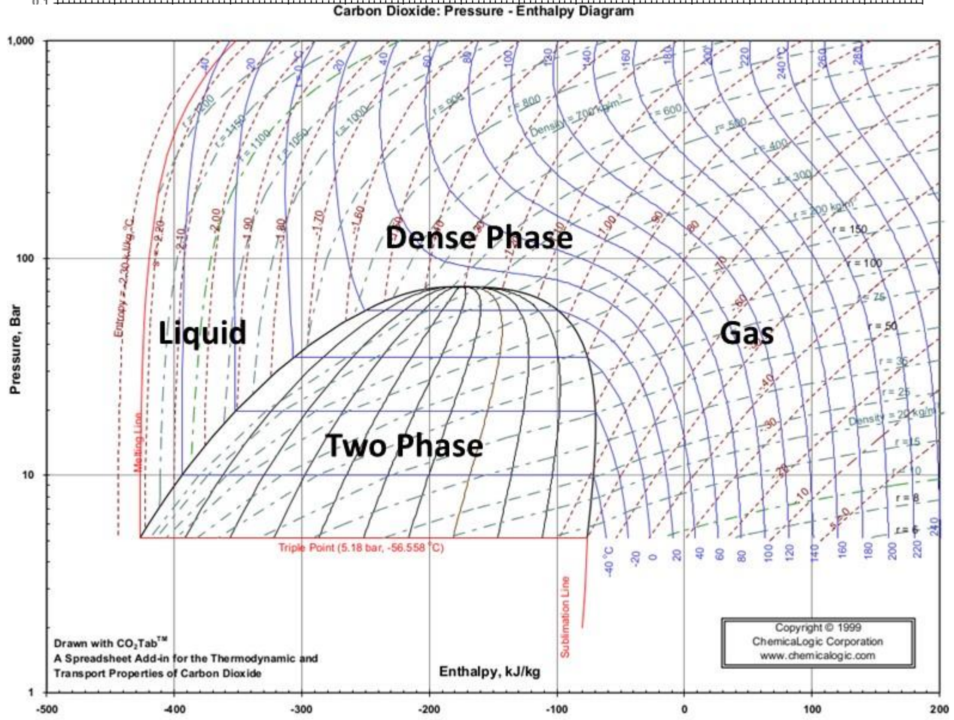




Supercritical CO_2

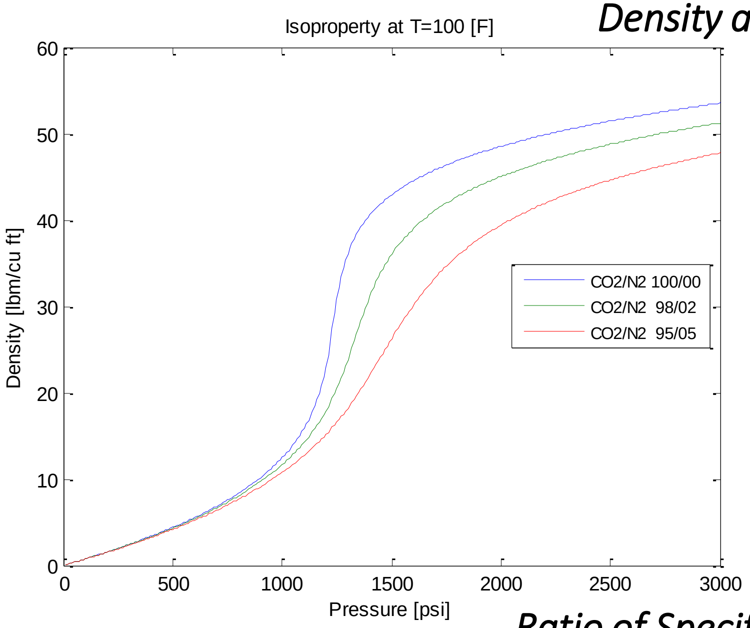
- Above 88˚F and 1080 psi (30.9˚C and 73.3 bar) for pure CO_2
- Quote "Density of liquid but fills voids like gas" *(wrong)*
- Density of liquid phase
  - At 2100 psi similar to liquid water
  - Low volumetric flow at high mass flow
- Viscosity of gaseous phase
  - Less friction loss at higher flow velocity
- Hydrophobic solvent
  - Dissolve nonpolar or light molecules
  - Organic compounds act as co-solvents that increase solubility and polarity
  - Dissolves light oils and aromatics

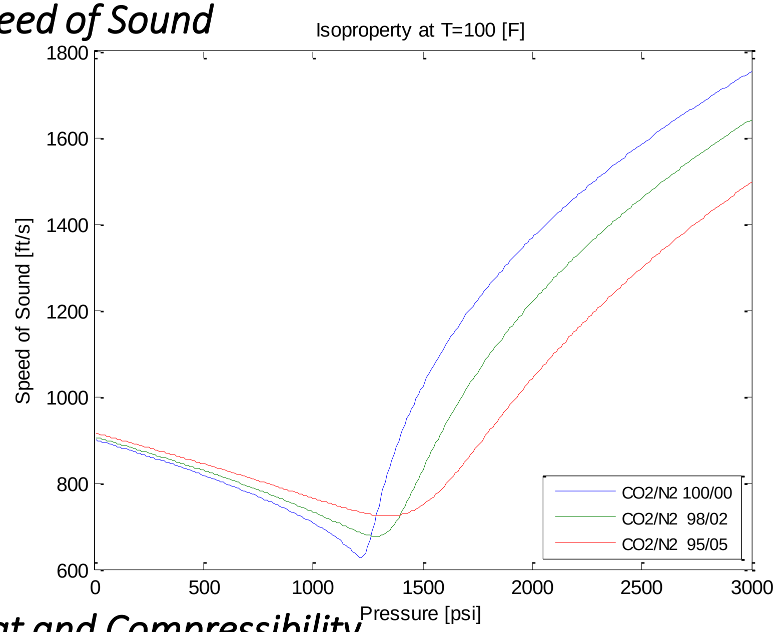




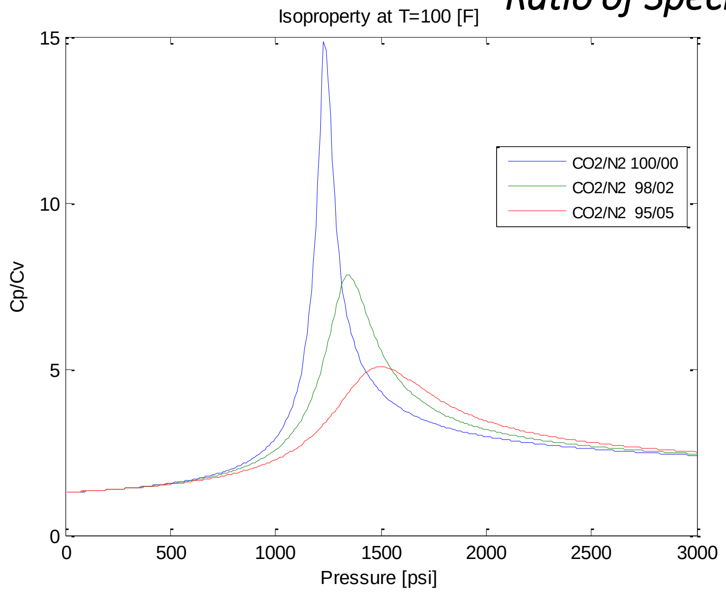
CO_2 Physical Property Variation Near Critical Point

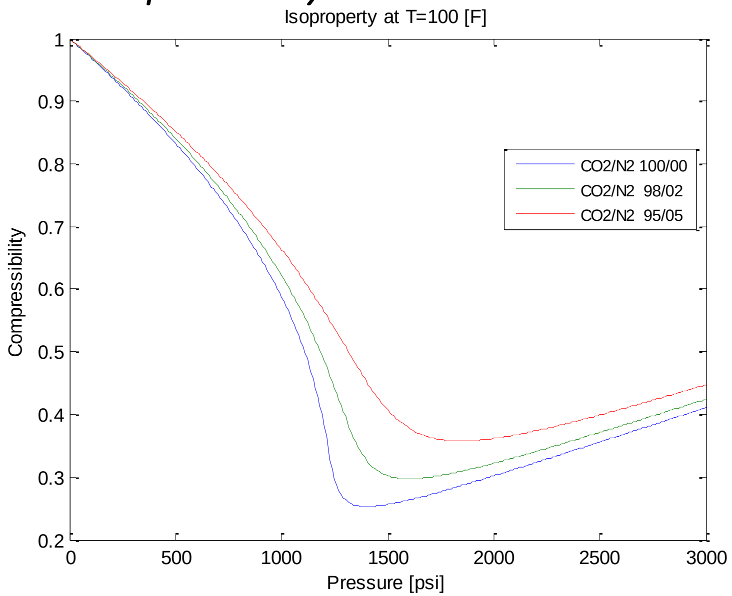
Density and Speed of Sound





Ratio of Specific Heat and Compressibility





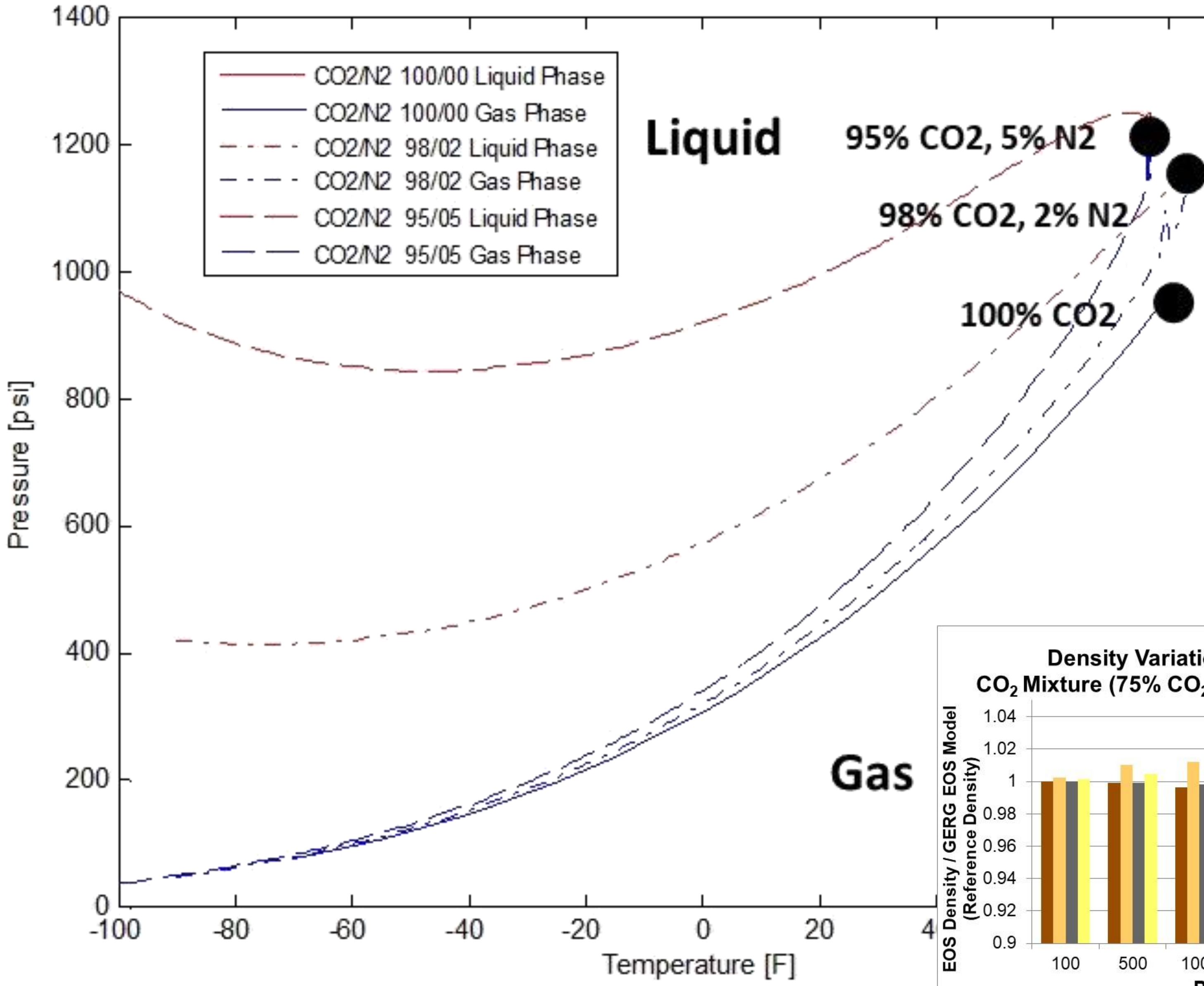
<u>Near Critical Point</u>:

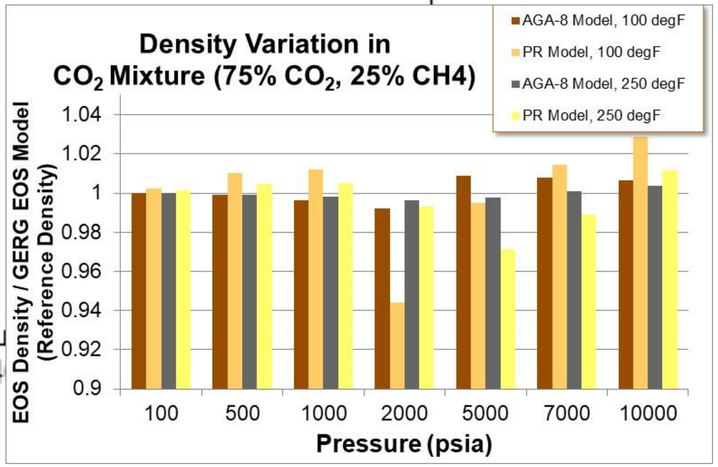
- Enhanced thermal conductivity
- Sharp density decrease
- Increased thermal conductivity
- High ratio of specific heats

<u>Above Critical Point</u>:

- Small density increase (i.e., small volume decrease) with P
- Drastic speed of sound increase with P

Change in Critical Point with Mixture



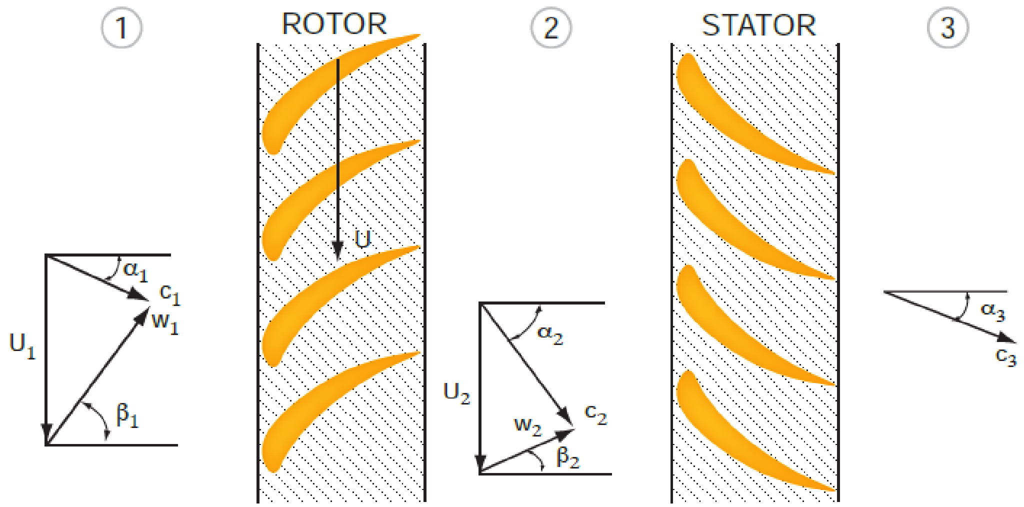


Typically trace impurities:

- H_2O – Water
- H_2S – Hydrogen Sulfide
- CO – Carbon Monoxide
- O_2 – Oxygen
- CH_4 – Methane
- N_2 – Nitrogen
- NH_3 – Ammonia
- Ar – Argon
- H_2 – Hydrogen
- SO_x – Sulfur Oxide/Dioxide
- NO_x – Nitrogen Oxide/Dioxide

+ EOS Uncertainties

Heavy Gas Compression



Head and efficiency is not significantly affected.

Head: $H = h_2 - h_1 = \frac{P}{W} = \omega \cdot (r_2 c_{u,2} - r_1 c_{u,1})$ $\eta_s = \frac{H_s}{H}$

Power: $P = \omega \cdot \Delta\tau = \omega \cdot W \cdot \Delta(r \cdot c_u) = \omega \cdot W \cdot (r_2 c_{u,2} - r_1 c_{u,1})$

P Ratio: $\frac{P_2}{P_1} = \left(1 + \frac{\eta}{c_p \cdot T_1} \cdot H\right)^{\frac{\gamma}{\gamma-1}}$

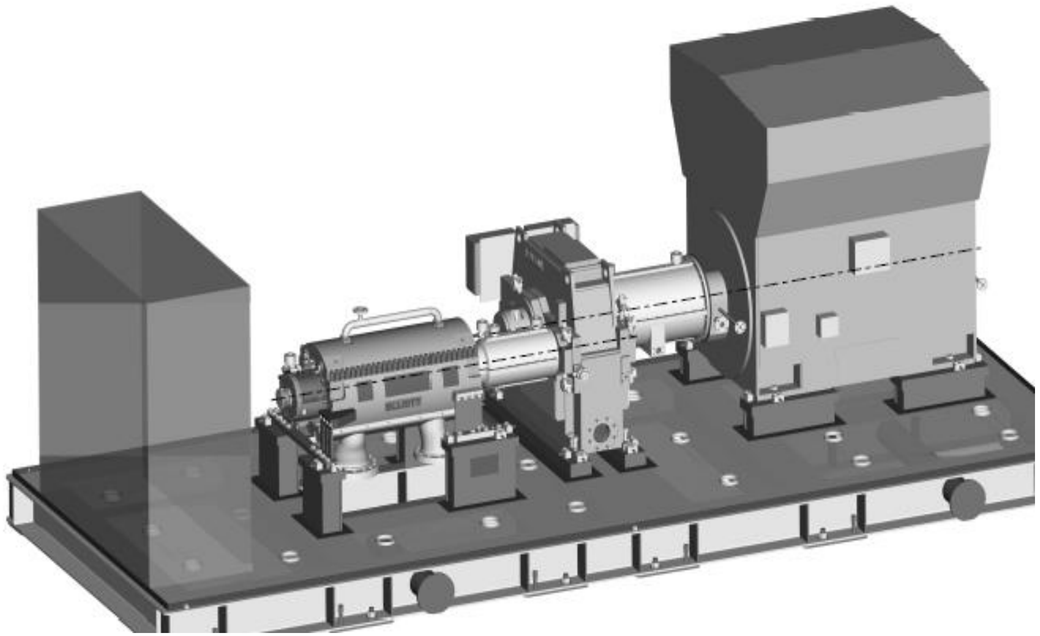
Specific Heat:
Natural gas – 2.3 kJ/kgK
Carbon Dioxide – 0.8 kJ/kgK

T Ratio: $\frac{T_{Cold}}{T_{Hot}} = \left(\frac{P_{Hot}}{P_{Cold}}\right)^{\frac{1-\gamma}{\gamma}}$

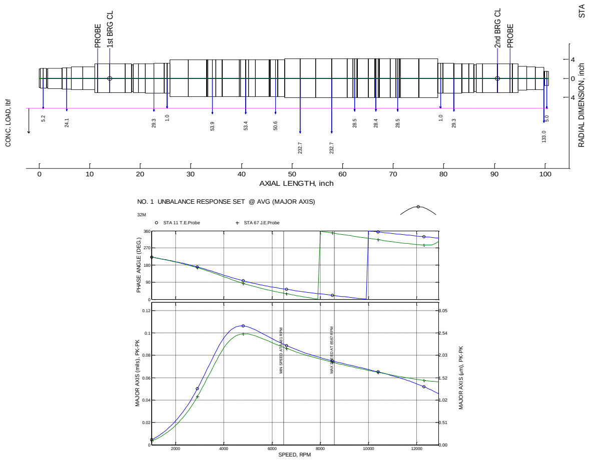
High Volume Reduction
High Temperature Rise

Per Stage

CO_2 Compressors



Elliott 15 MW CO2 Recycle Compressor



<u>Design Challenges</u>:

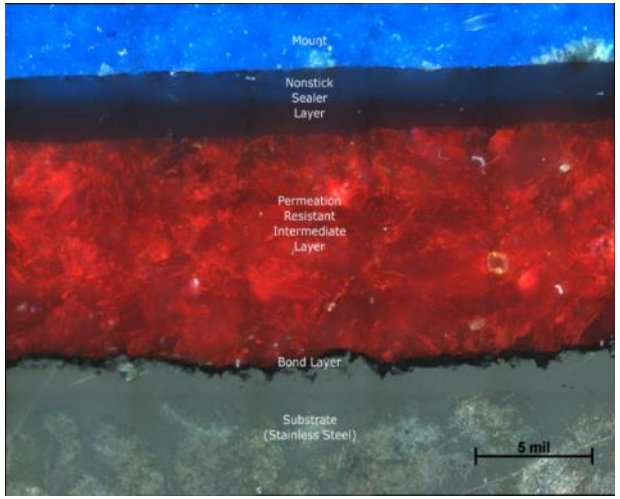
- High compression ratios (large volume changes, high temperature rise, gear boxes, intercooling, mechanical reliability)
- Wide required operating range (function of plant load)
- Low viscosity at high pressures
- Low sonic speed (higher shock losses and reduced operating range)
- Equation of state for CO_2 uncertainty (high pressure, high temperature, mixtures)
- High density (amplifies rotordynamic and impeller-dynamic forces)
- Thermodynamic path dependence (isentropic versus isothermal)
- Multi-phase behavior (pumping versus compression)
- Carbonic acid formation in presence of water (corrosion)
- Solubility in elastomeric materials (seals, flexible ducting, packings, valves)
- Liquid/ice formation when rapidly expanded (Joule-Thomson) at shaft seals
- Selectively leeches certain elements from common metals (materials, coatings)

Coatings

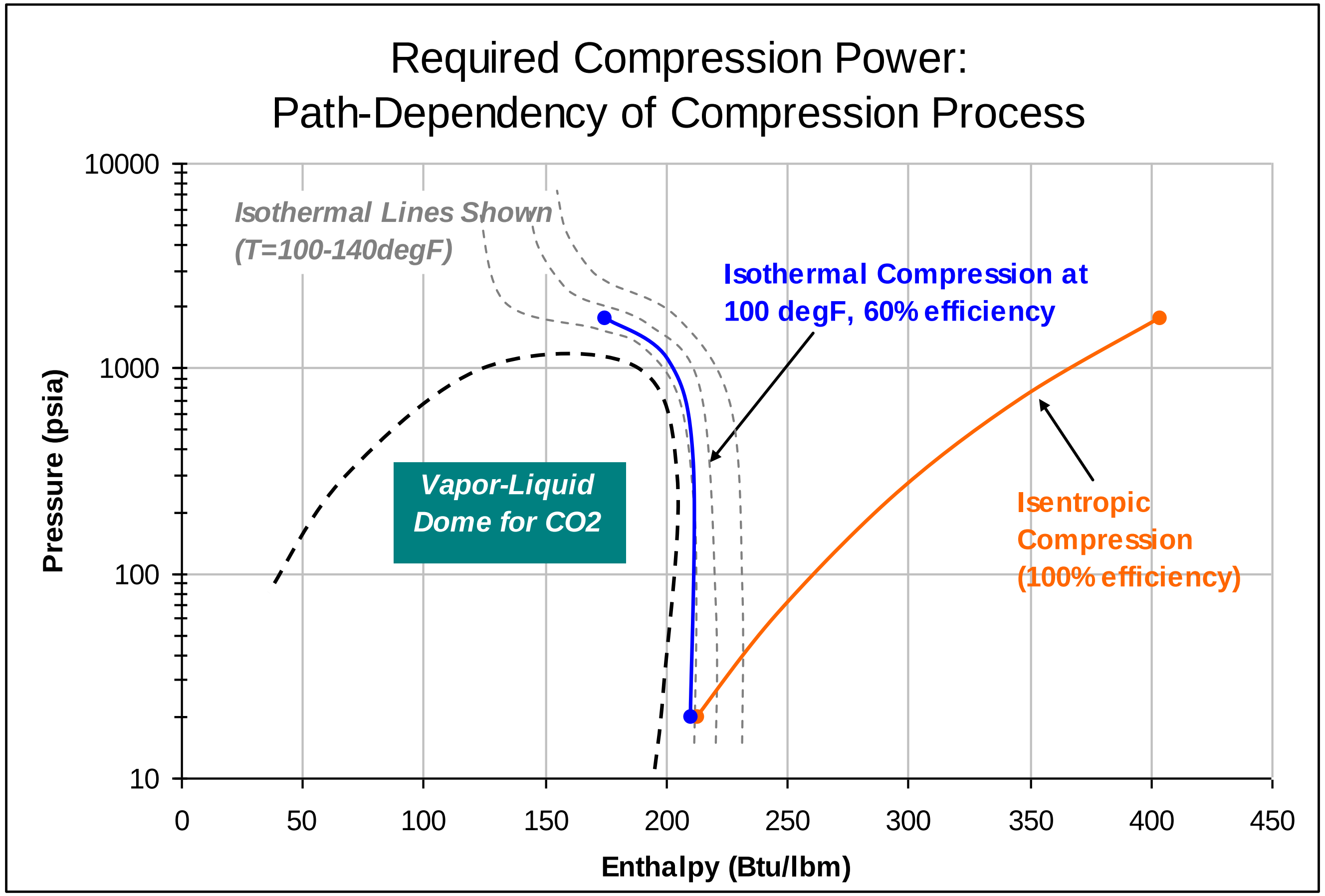
- Protects the base metal
- Improve erosion and corrosion resistance
- Anti-fouling

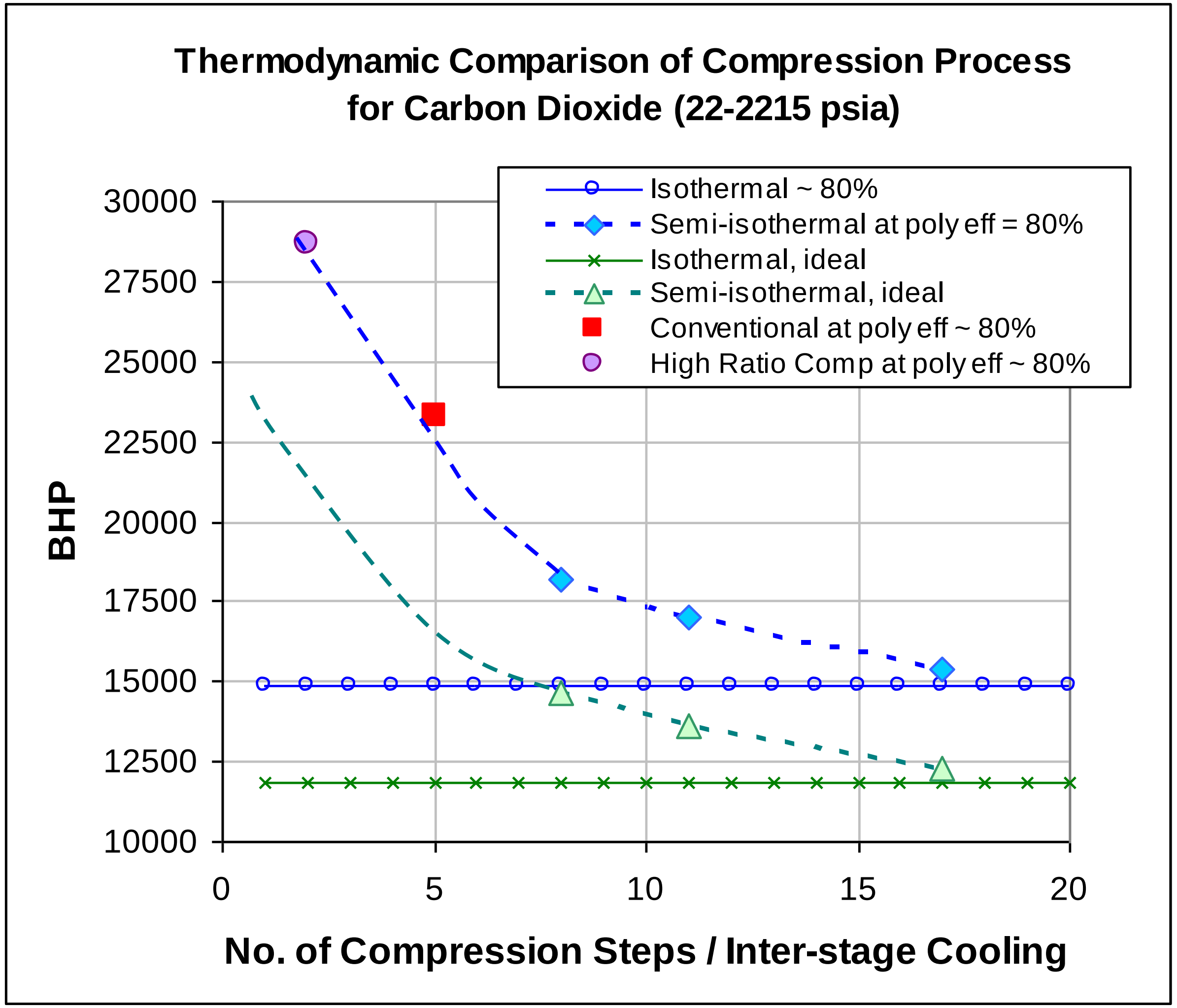
…but all coatings will eventually be worn away, spalled, or dis-bonded.

Cannot be used to increase material yield strength limits for long-term service applications.



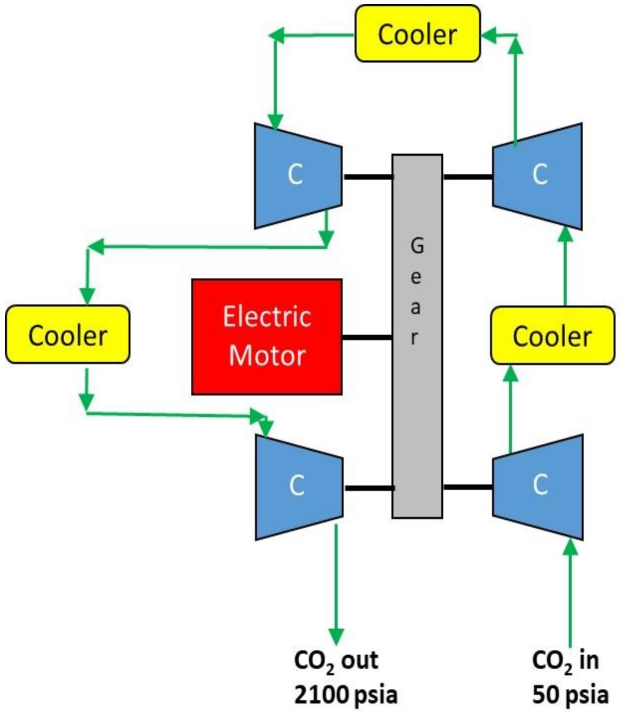
CO_2 Compression Path Dependence



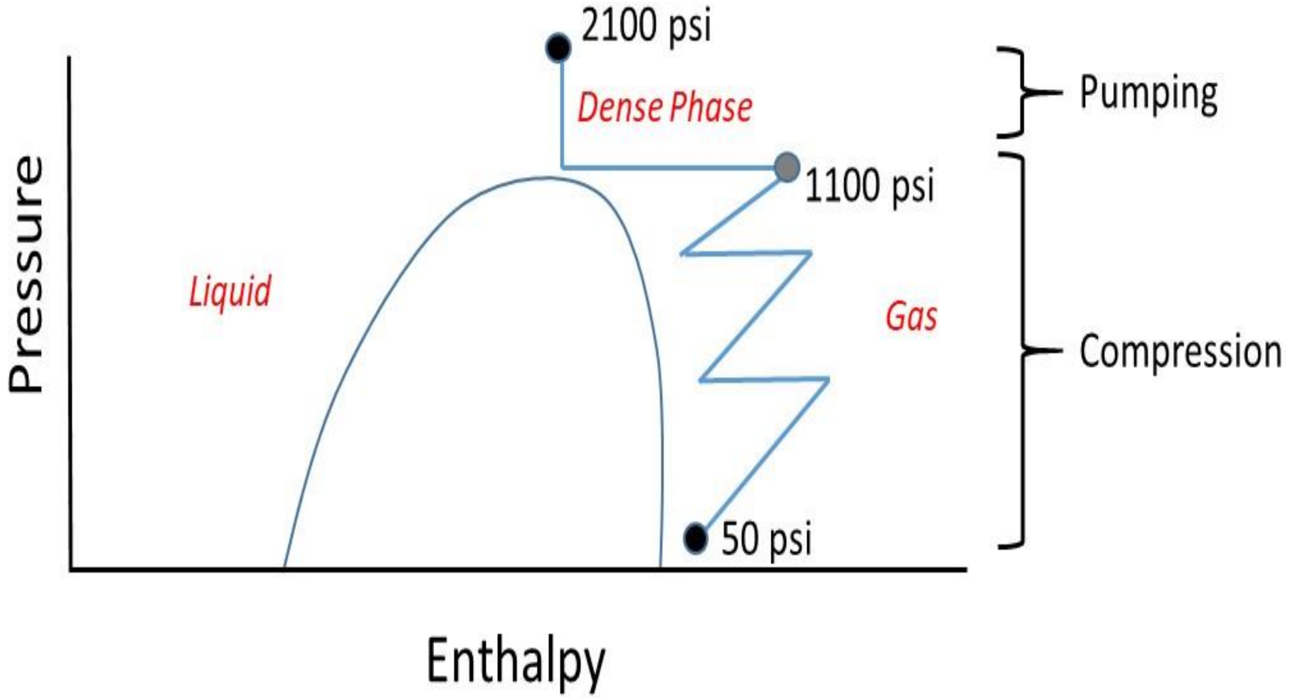


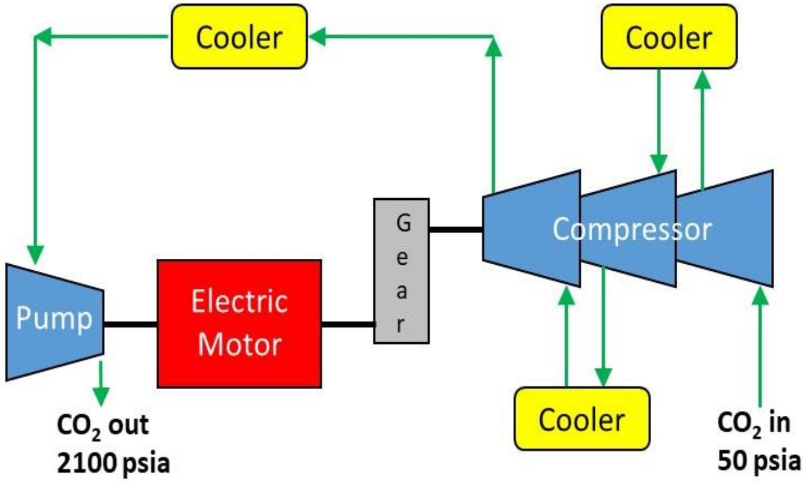
Courtesy SwRI and DOE [Moore et al.]

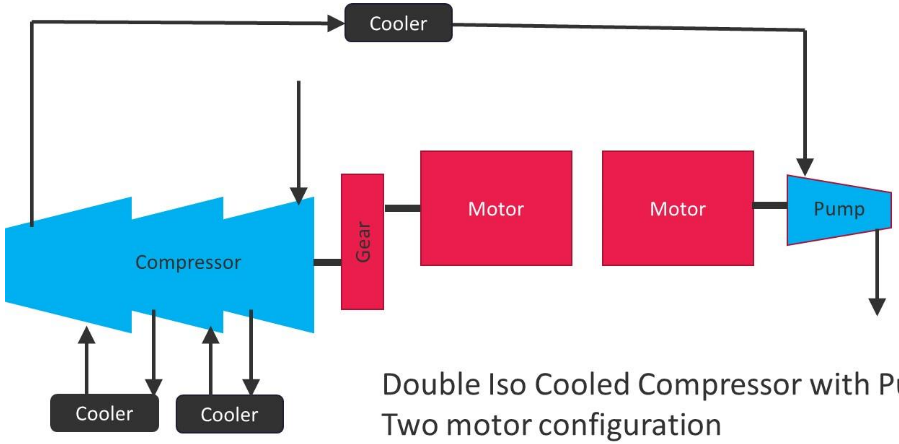
Compression Solutions



Integrally Geared Compressor







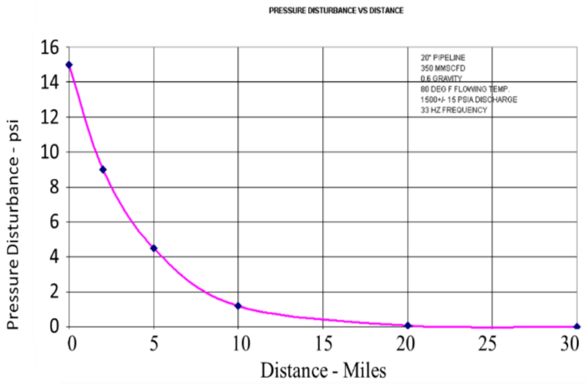
Double Iso Cooled Compressor with Pump
Two motor configuration

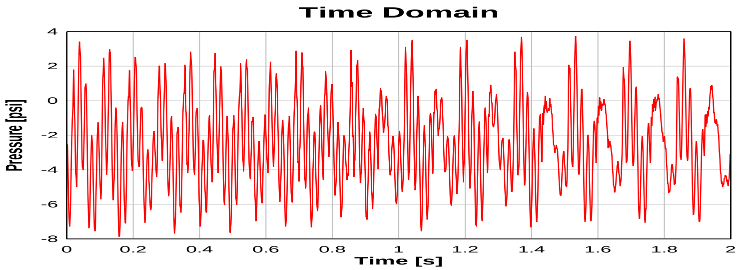
Hybrid Barrel-Pump

Aside: Reciprocating Compressors for sCO2

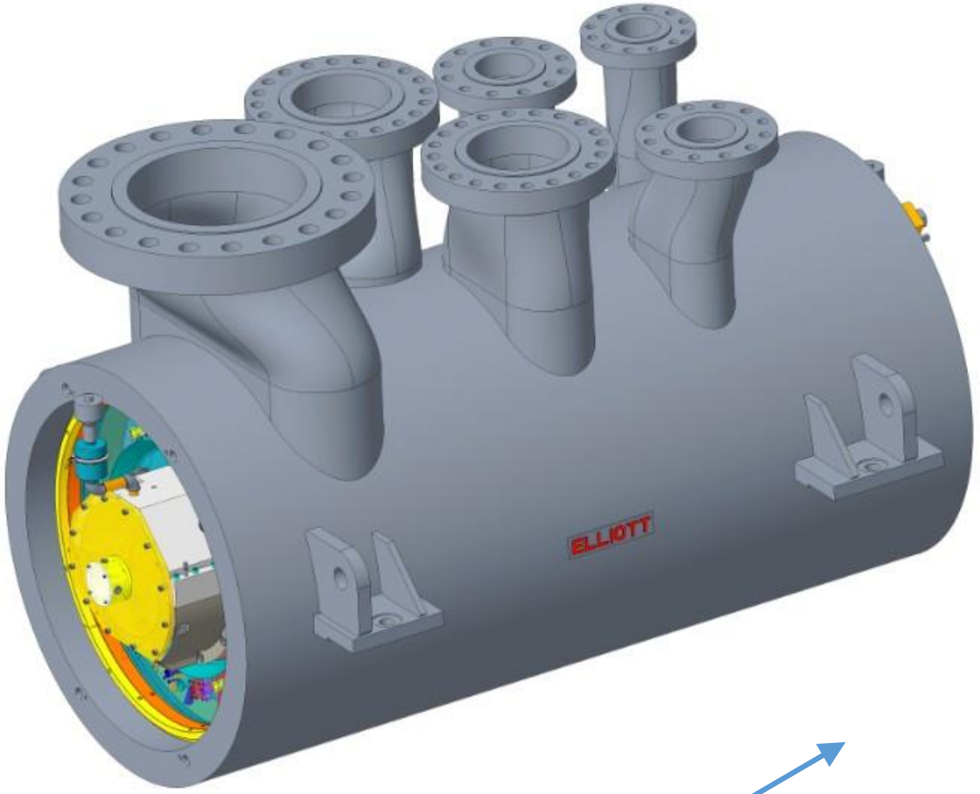
<u>Discussion</u>:

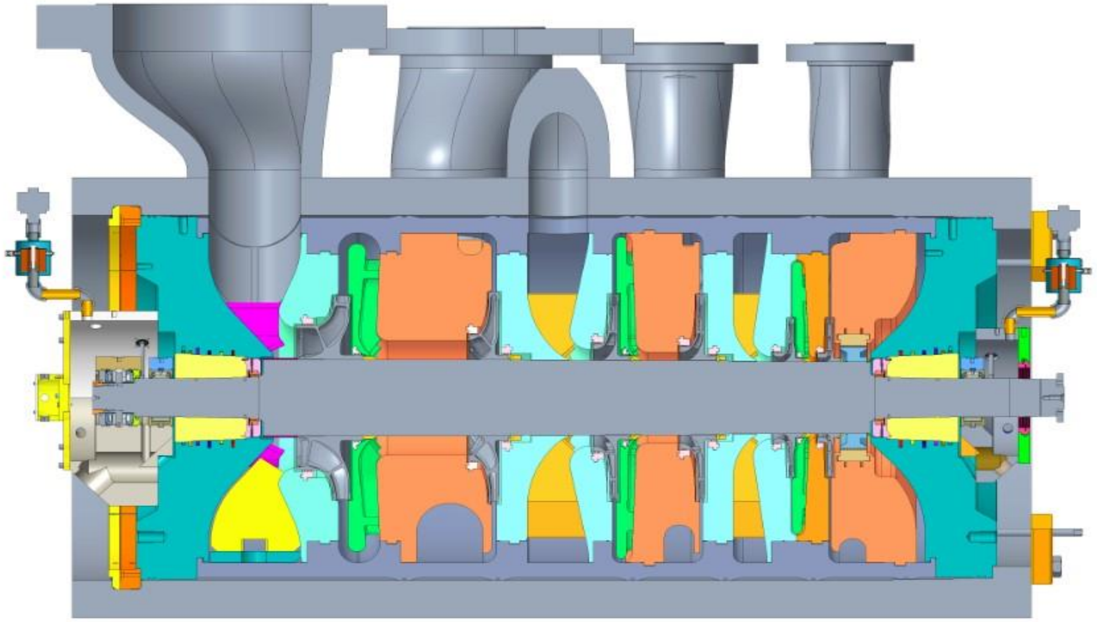
- Pulsation control
- Lube oil-gas contamination
- Leakage
- Flow Limited
- Reliability

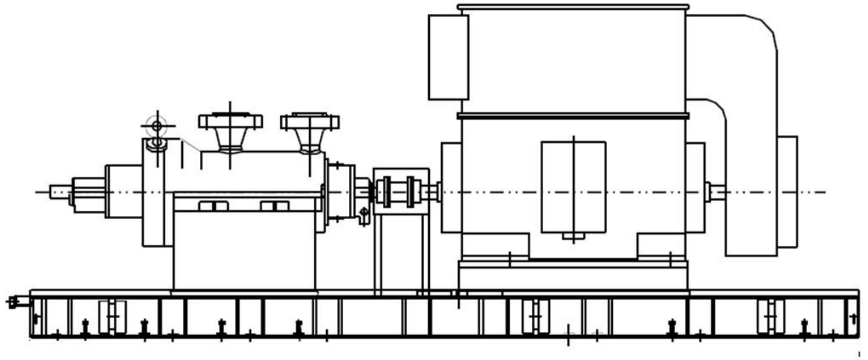




Hybrid CO_2 Compressor-Pump







<u>Below Critical Point</u>:

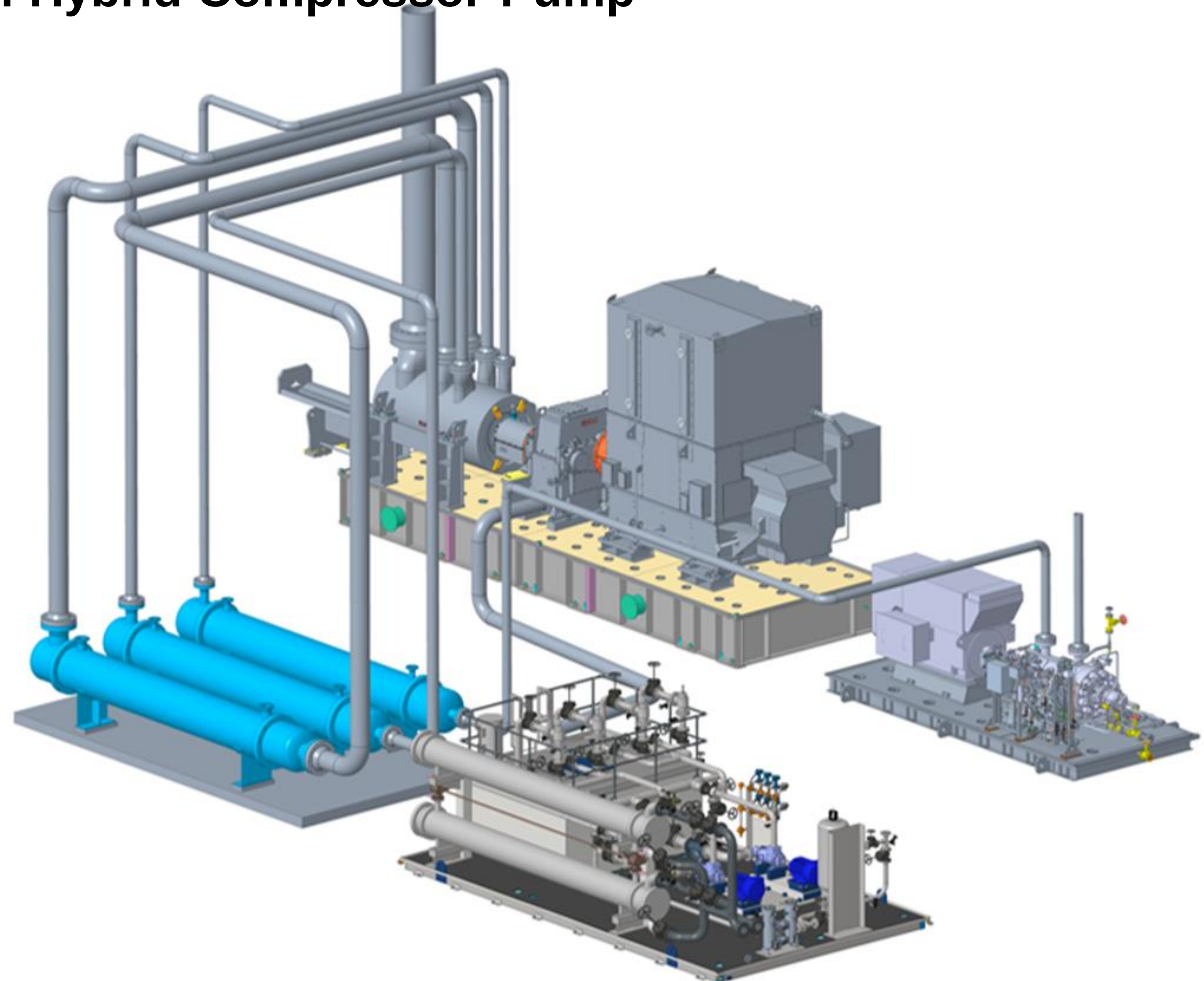
- Multistage barrel compressor with intercooling

<u>Above Critical Point</u>:

- Multistage sCO_2 Pump

Layout of Hybrid Compressor-Pump

***Multistage Compressor*:**
100% CO_2
20→1200 psia
30 kg/s
≈ 13,000 hp



***sCO_2 Pump*:**
1200→2200 psia
100% CO_2
30 kg/s
≈ 2,000 hp

***Intercoolers*:**
- ***Water***
- ***No.: 3***

***Ancillaries*:**
- ***Lube***
- ***Seals***

Compressor Test Stand – Upgrade

Expansion Currently Underway

- 2025 Completion

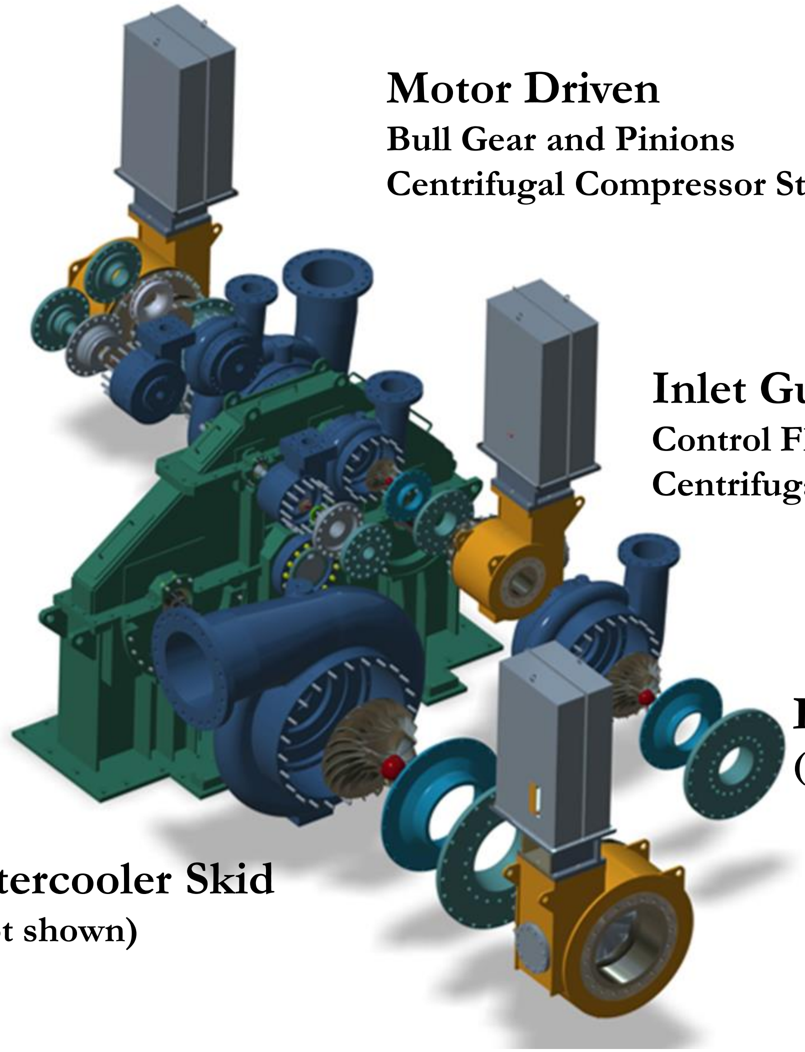
Power Supply Increased to 100 Mwe

- 138 kV Upgrade to Ebara Elliott Energy's Facility
- 34.5 kV to Test Stand

Increased Test Capacity

- 90 MW String Test
- CO_2 Full Load Full Power Test
- LNG
- Supports Electrification of Petro-chemical Industry

Integrally Geared Compressor for CO_2 Sequestration



Motor Driven
Bull Gear and Pinions
Centrifugal Compressor Stages are Overhung

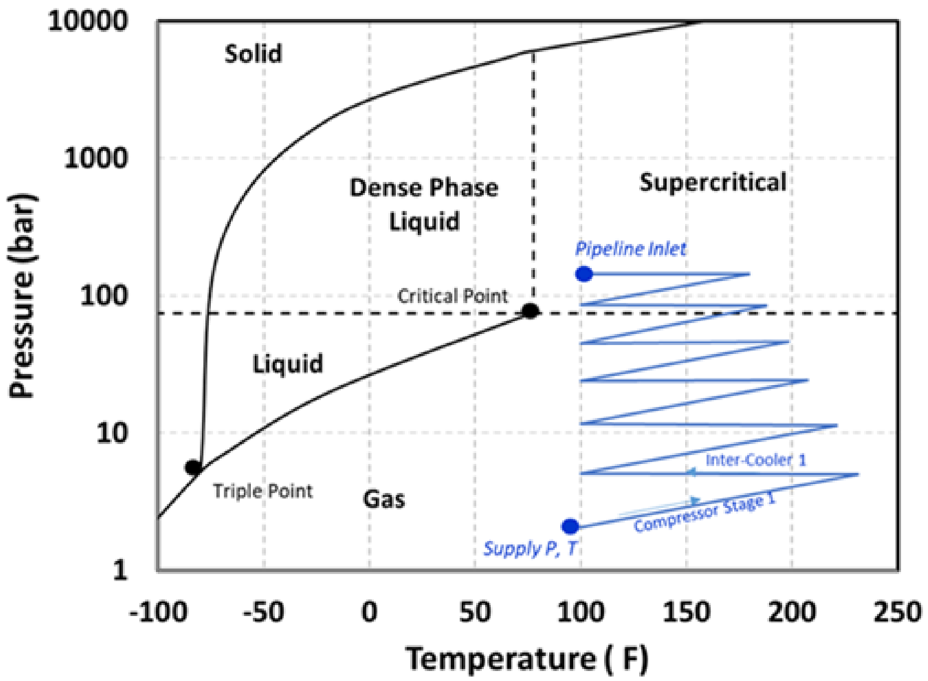
Inlet Guide Vanes
Control Flow Rate
Centrifugal pump

Lubrication System
(not shown)

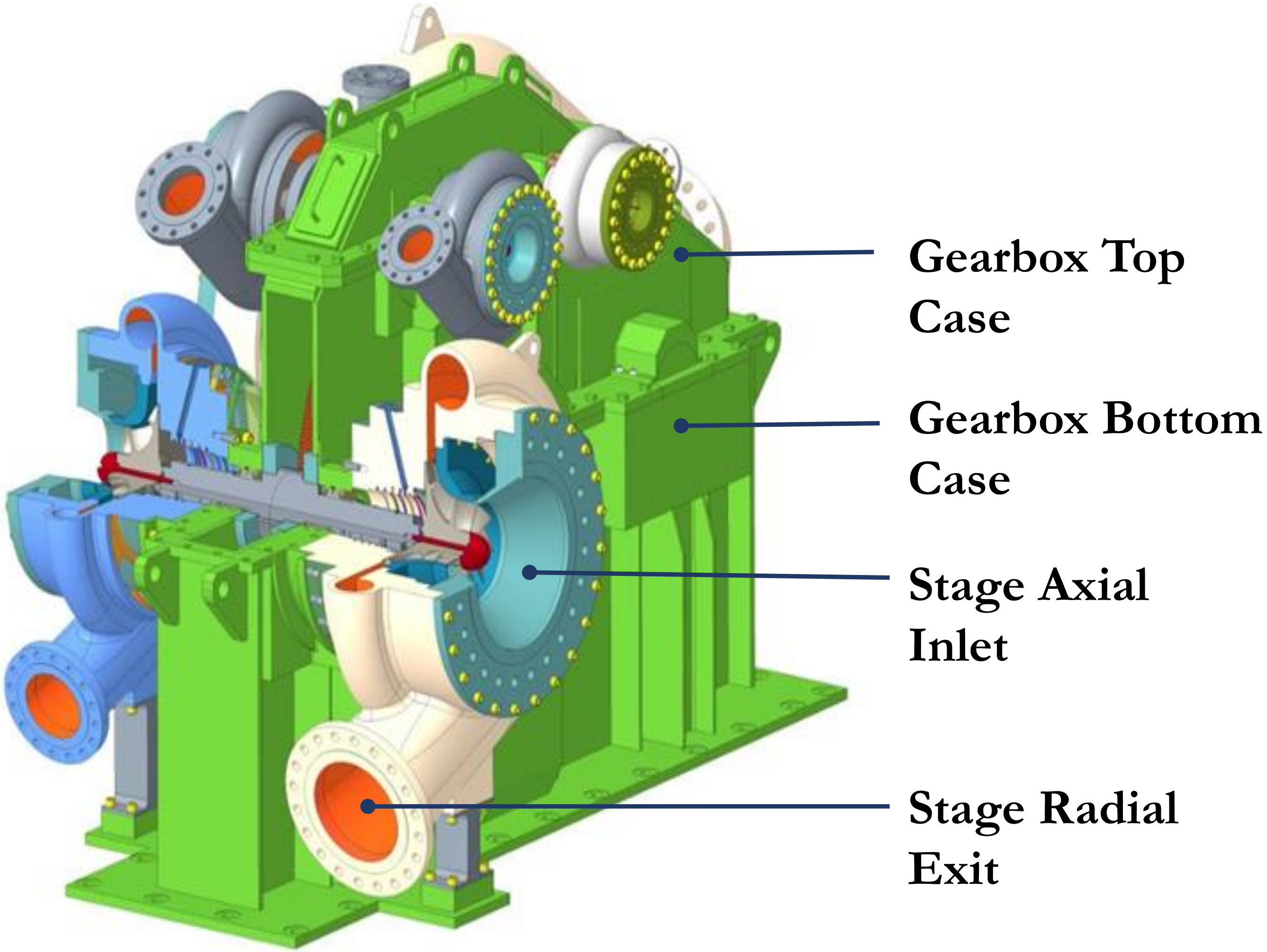
Intercooler Skid
(not shown)

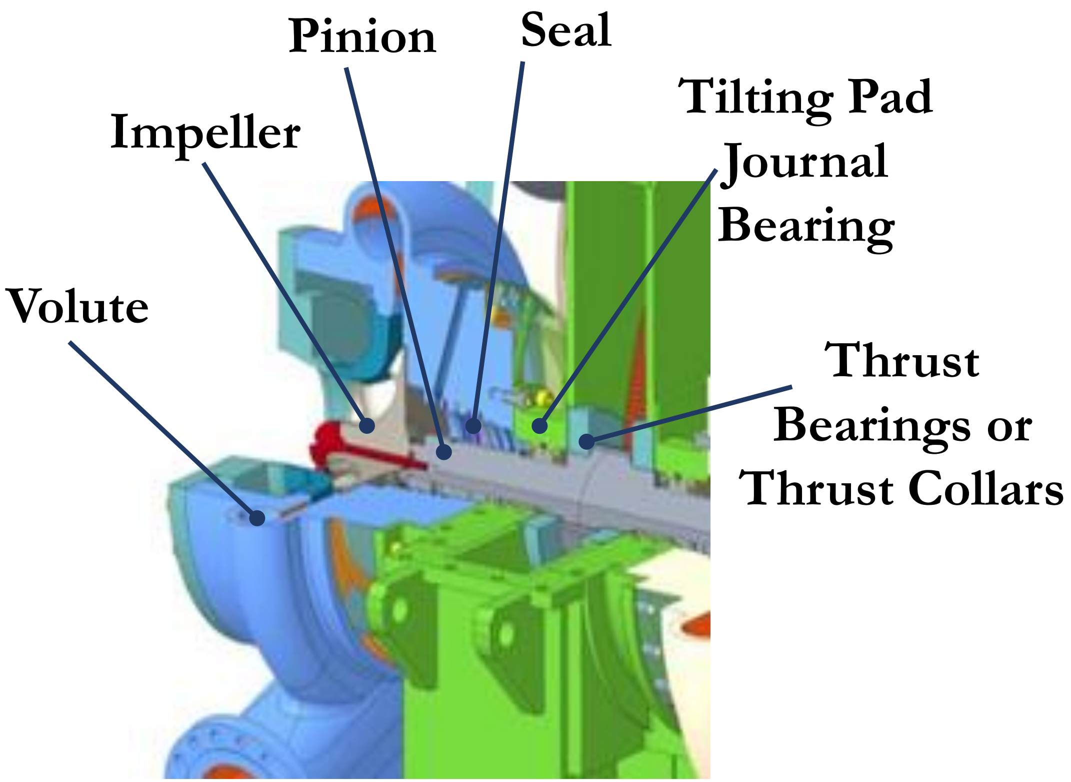
CO_2 Sequestration

- Integrally geared compressor offers efficient method of raising pressure from atmospheric pressure to pipeline conditions.
- Inter-cooling stages reduced the power consumption of the overall package.



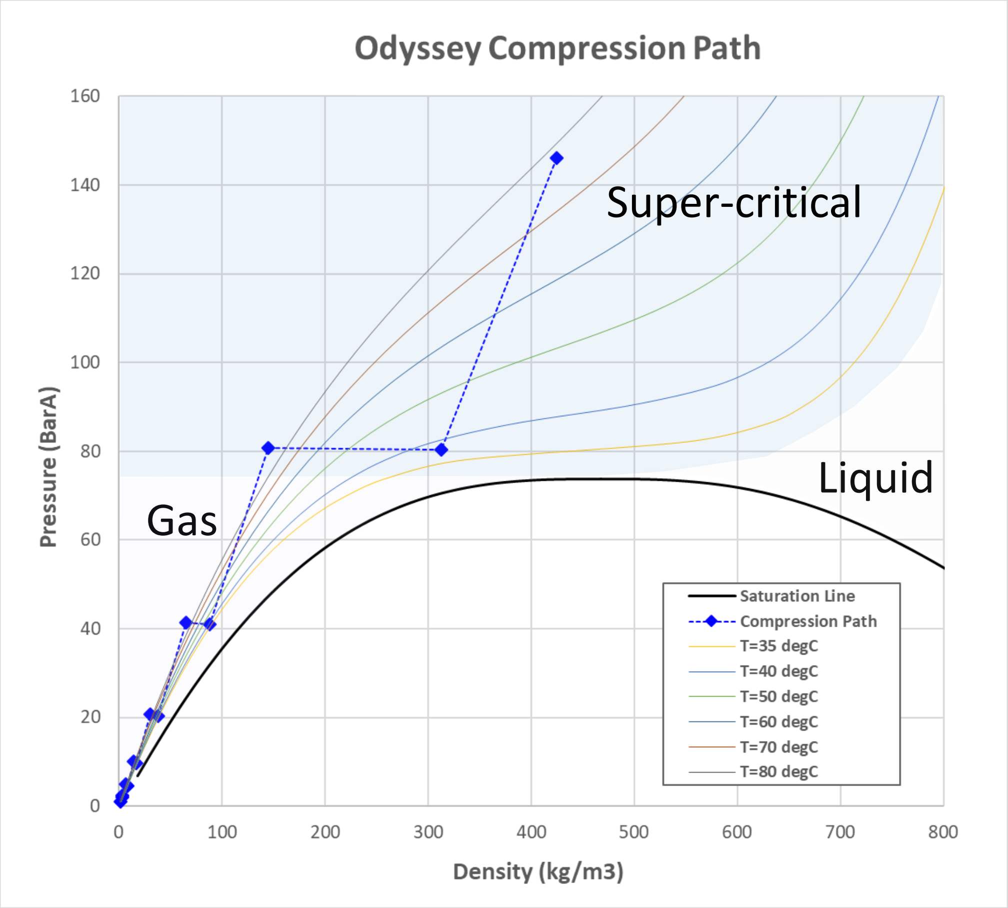
Integrally Geared Compressor





IG CO_2 – Technical Challenges

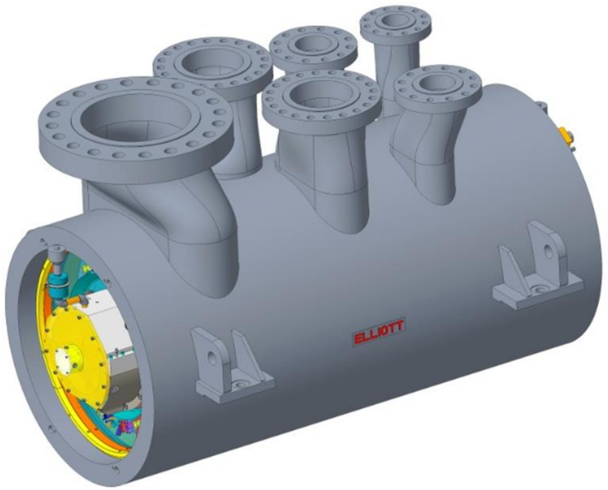
Compression Process Overview



- Compressors achieve a **pressure ratio of 145:1** in 7 stages.
- **250x increase in gas density** across the machine
  - The first 5 stages operate sub-critical in the gas region
  - The last 2 stages operate at super-critical pressure and real gas effects are pronounced and strongly impact performance
- Substantial reduction in stage size though the machine.
  - *Stage 1 = 31"dia → Stage 7 = 4.75" diameter*
  - *Stage matching is very dependent on intercooling.*
- **Extreme levels of power density** are generated in the super-critical stages.
  - 7,000kJ of energy added to ever cubic meter of flow in the 7th stage compared to just 100kJ/m3 for the first stage
  - Aero and mechanical design work must be closely coupled

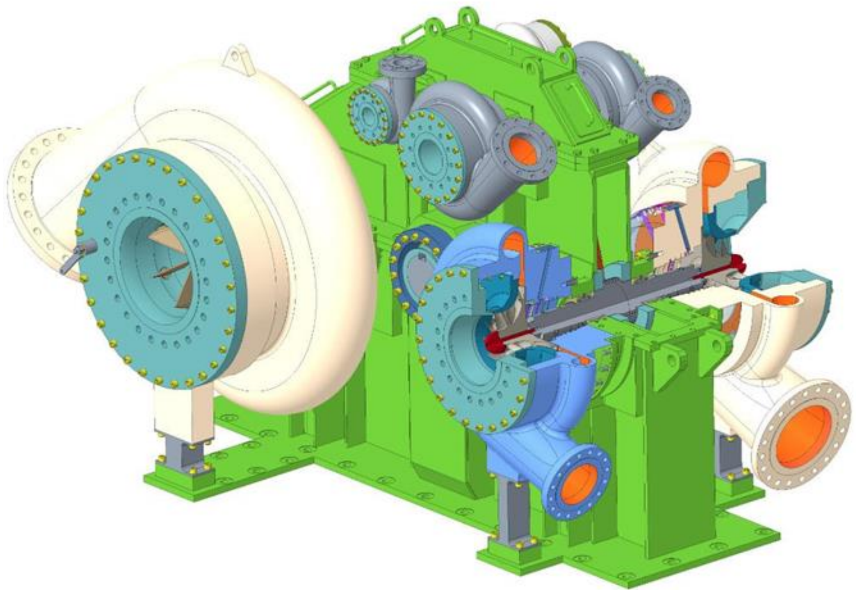
Impact of Cooling Between Stages (Inter-Cooling)

LP Section



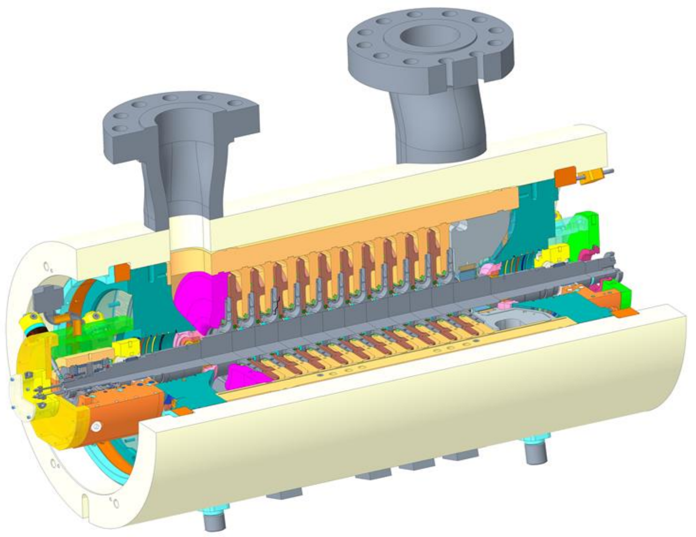
HP Section

<u>2 Beam Style Compressors (or Pump)</u>
2 Gearbox
3 inter-coolers
4 Gas Seals / 4 Journal Bearings
Drive Power = 12,863 kW

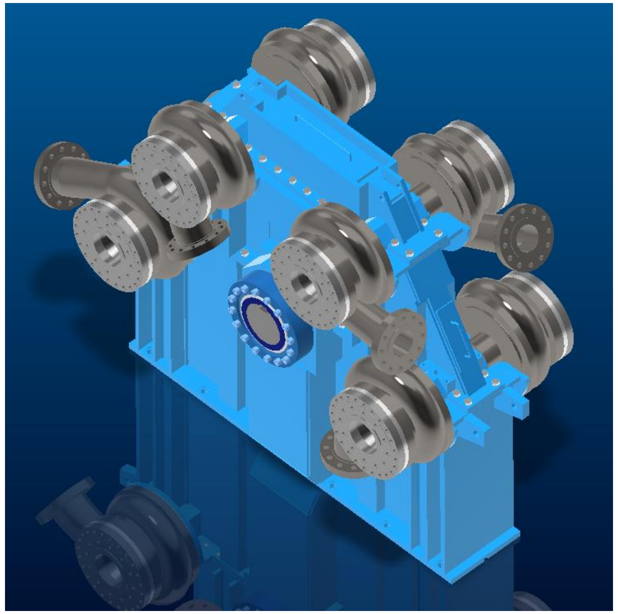


<u>IG Compressors</u>
7 Stages
6 Inter-coolers
7 Gas Seals / 16 Journal Bearings
Drive Power = 10,925 kW

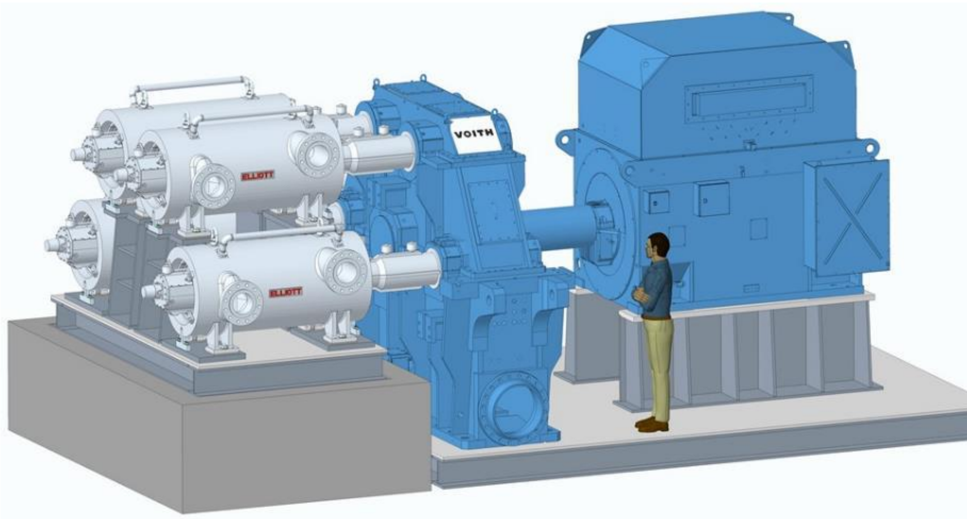
CO_2 Compression Technology Options



Conventional High Speed
In-Line Centrifugal Compressors



Integrally Geared Conventional and
High Speed Centrifugal Compressors



Multi-Body Centrifugal
Compressor/Pumps

Pressure Ratio: *1.2* *1.5* *4.0* *30* *90* *120* *200* *300* *500* *700*

Application:

Blower ***Pipeline Transport*** ***Pipeline Header*** ***Production*** ***Storage***

Elliott-Ebara Turbomachines for Decarbonization of Energy Streams

- Centrifugal Compressors (API)
  - Barrel/Horizontal Split
  - Inline/Back-To-Back
- Axial Compressors (API)
- Multi Valve Steam Turbines (API)
- Single Valve Steam Turbines
- Gas Expanders
- Cryo Pumps
- Cryo Single Phase and Multi Phase Expanders
- Custom Pumps (hydrocarbons, sCO2, ammonia, liquid hydrogen, etc.)

Elliott Centrifugal Compressor Train

Thanks a lot! Questions?

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