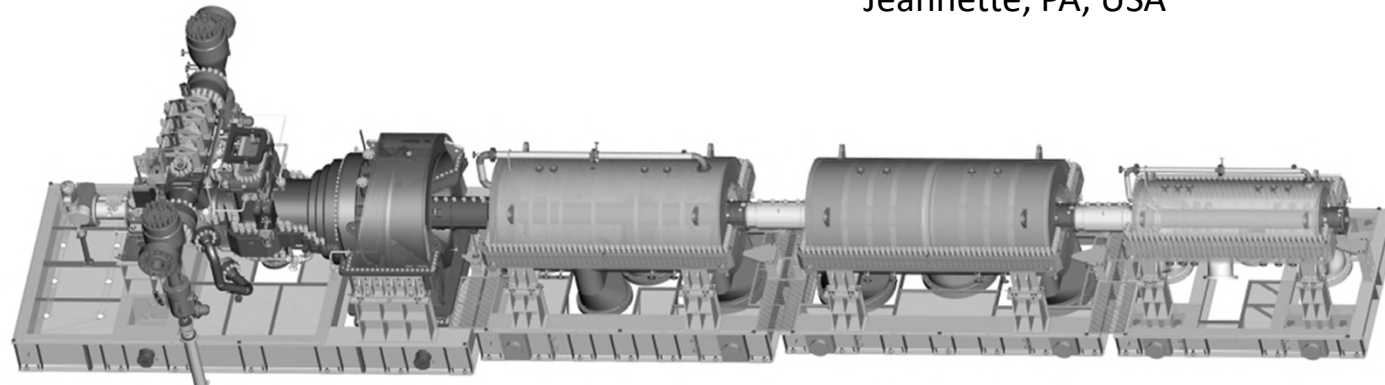


# Compression Options for Carbon Capture and Sequestration

**Klaus Brun, Ph.D.**  
Vice President Products & Technology  
Ebara Elliott Energy  
Jeannette, PA, USA

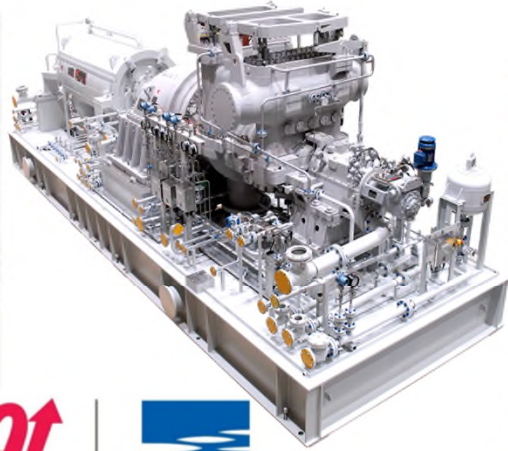


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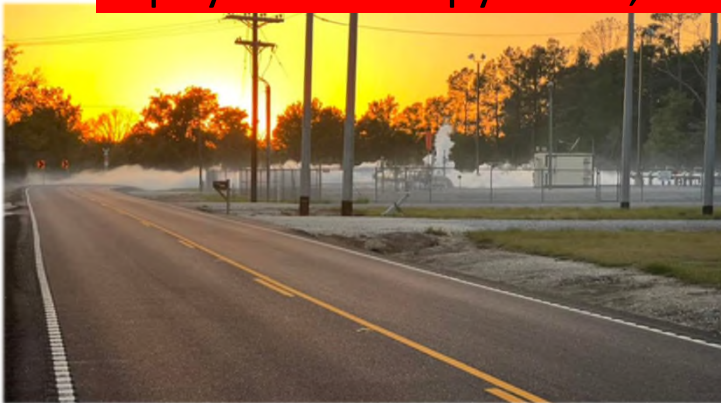
EBARA ELLIOTT ENERGY



# Not what you want...



Asphyxiant: Sleepy at 1%, fatal over 7 to 10% concentration



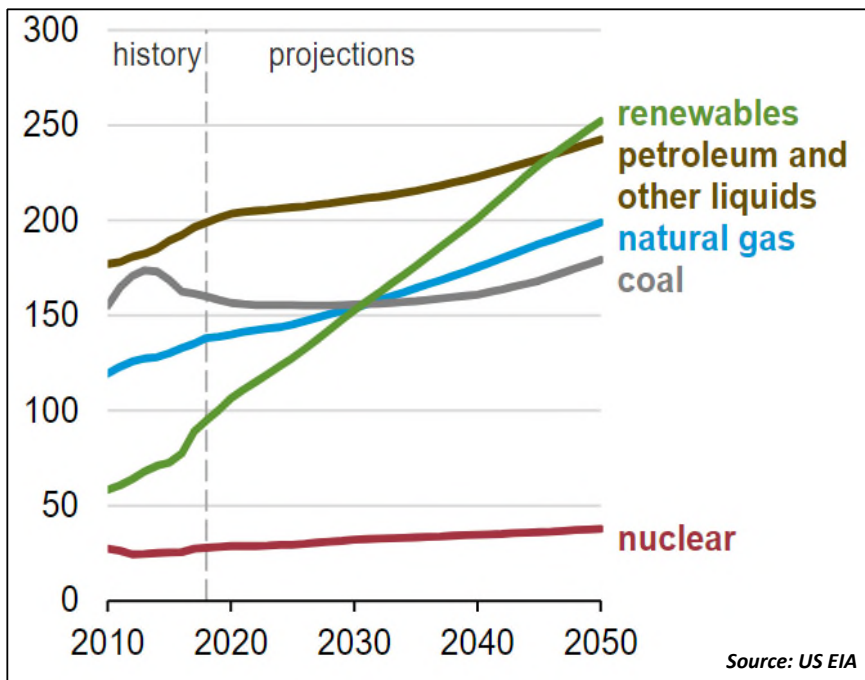
Making the right technology decisions early is critical

# The Case for Carbon Capture



# Changes to the Energy Market

Global Energy Consumption by Source



Thorntonbank Wind Farm



Andasol solar power station



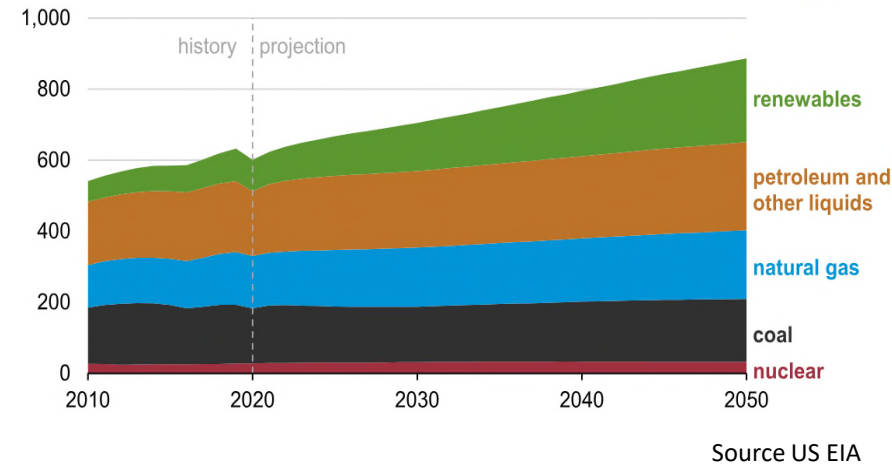
Source: Solar Paces

- ✓ Renewables are the fastest growing section of the energy market
- ✓ They are expected to be the single largest source of energy by 2050

# World of Sustainable Energy

- World Energy Consumption
  - Energy must be Reliable, Cheap, Clean
- Lots of Different Forecasts
  - US Energy Information Administration (EIA)
- Carbon Free Energy (Wind, Solar, Hydro, Nuclear)
  - Provide carbon free energy
  - Reliability, energy transport, and storage questions
- Decarbonize Existing Fossil Infrastructure
  - Transportation (Automotive, Marine, Aviation)
  - Electricity production (Coal, Natural Gas)
  - Fertilizer, chemical, cement, refinery, pharma

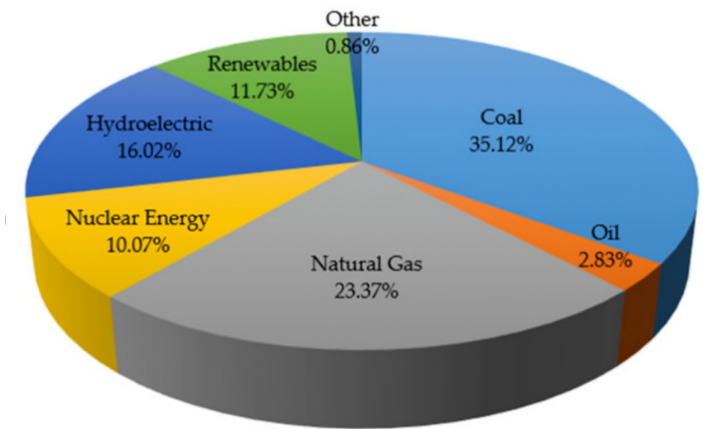
Global primary energy consumption by energy source (2010–2050)  
quadrillion British thermal units



***Carbon Free  
“Sustainable”***

# Low Hanging Fruits: Carbon-Free or Decarbonized Electricity Supply Pathways

- Green (wind/solar/hydro/geothermal/wave) and nuclear electricity direct
- Green and nuclear (red) hydrogen
- Fossil fuel (blue) hydrogen (mostly from natural gas)
- Fossil plant post combustion (flue gas) carbon capture
- Fossil fueled oxy cycle plants



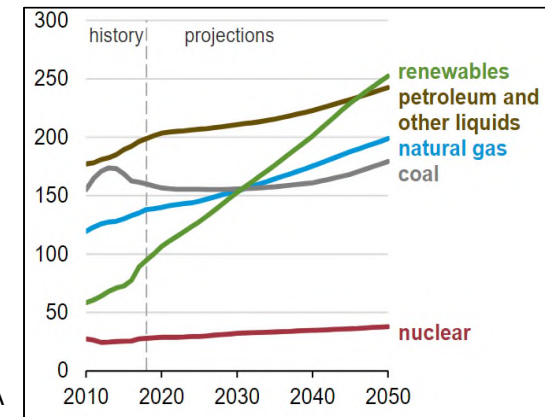
World Electricity Generation Mix

**Carbon  
Capture and  
Sequestration  
(CCS/CCUS)**

About 61% of Global Electricity Production Requires CCS

# World of Sustainable Energy

- Sustainable Energy Concerns
  - Socio Economic Impact (Cost, Impact on Life)
    - New Costly Infrastructure
    - Levelized Cost of Electricity (Energy) - Different for 50%, 70%, 99% reliable energy
  - Environmental Impact / Health
    - Other criteria pollutants (NO<sub>x</sub>, SO<sub>x</sub>, CO, PM, Heavy Metals, Hazardous Chemicals)
      - Air
      - Water
      - Soil
  - Safety
    - Hydrogen
    - Ammonia...and even CO<sub>2</sub>
  - Supply Chain
    - Who will provide this new infrastructure?
    - Existing supply chain is already at its limits



Source US EIA

# CO<sub>2</sub> Turbomachinery for Sustainable Energy

## Zero Carbon Energy Supply

- Wind turbines
- Concentrating solar power
- Geothermal (direct flash, binary)
- Hydro
- Nuclear

## Fossil Remediation

- Power Plant Source carbon capture (pre/post combustion)
- Direct Air Capture
- Carbon Dioxide sequestration, storage, and utilization (CCUS)
- Oxyfuel plants

## Energy Transport

- Hydrogen Production, Transport, and Distribution
- Ammonia and other hydrogen carriers

## Energy Storage

- Gas (compressed air, compressed CO<sub>2</sub>)
- Mechanical (flywheel, gravity)
- Thermal (pumped heat, direct heat)
- Chemical (hydrogen, ammonia)

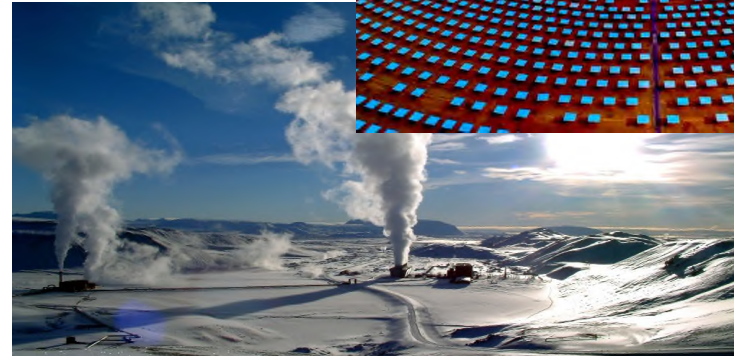
## Efficiency

- Heat Pumps
- sCO<sub>2</sub> and other advanced cycles

## Industrial Electrification

- Motor driven compressors, pumps
- Waste heat generation
- Distributed power

Source Solar Paces



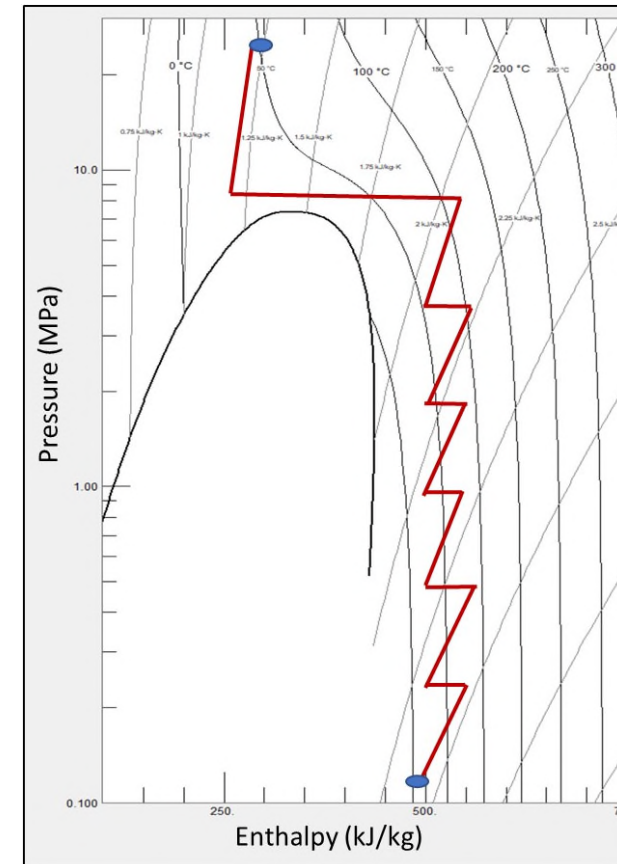
Source Krafla



Source DXP

# Key CO<sub>2</sub> Turbomachinery Applications

- Carbon Capture and Sequestration (and Utilization)
- Heat Pumps
- sCO<sub>2</sub> Power Cycles (CSP, WHR) and Oxyfuel Cycles (CCS)
- Energy Storage Applications (Pumped Heat and Geothermal)
- Enhanced Oil Recovery and Reinjection Compression (Acid and Sour Gas Injection)



*Similar Trans-Critical Compression Conditions*

# Turbomachinery Manufacturer's Challenges

- Engineering

- New machines, cycles
- Challenging Fluids
  - Carbon dioxide, hydrogen, ammonia, Methanol, Ethanol, Dimethyl Ether

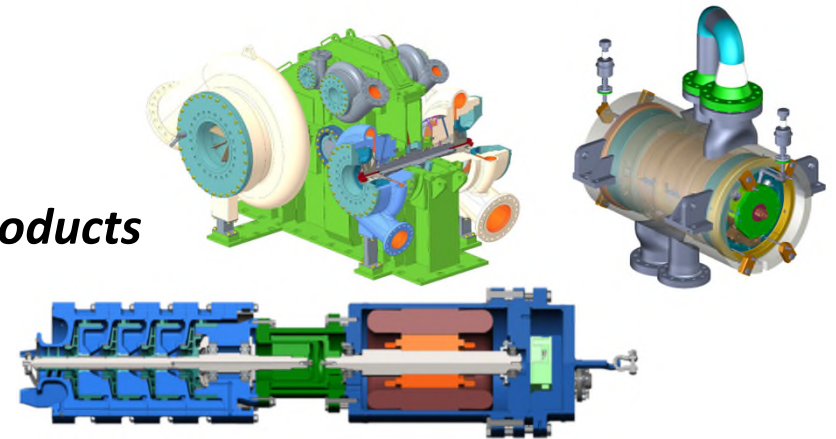
- Design

- Complex processes
- Lack of test data
- Uncertainty of specifications, codes, and standards

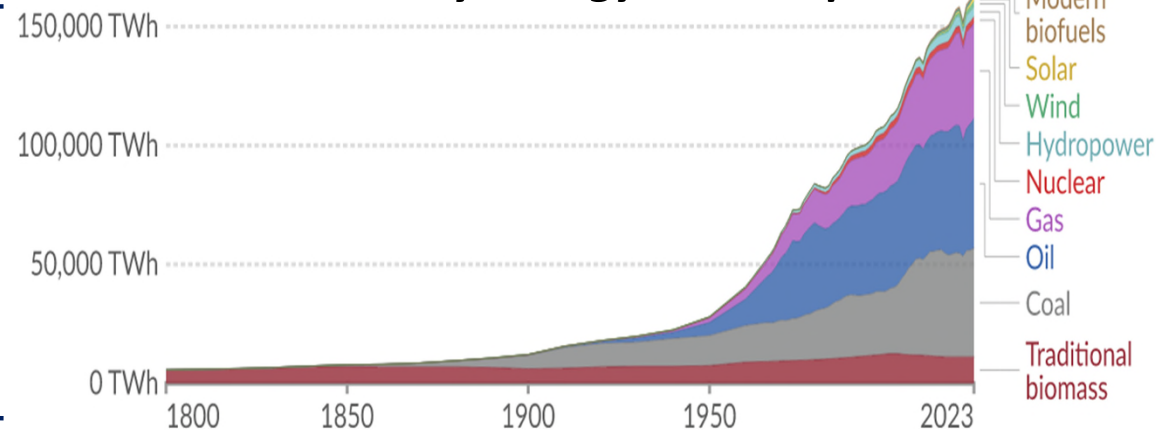
- Manufacturing and Supply Limits

- Limited production capacity
- Market uncertainty
- Investment uncertainty
  - Cost of:
    - Design, engineering
    - Manufacturing facilities
    - Test stands
    - Service facilities

## New Products

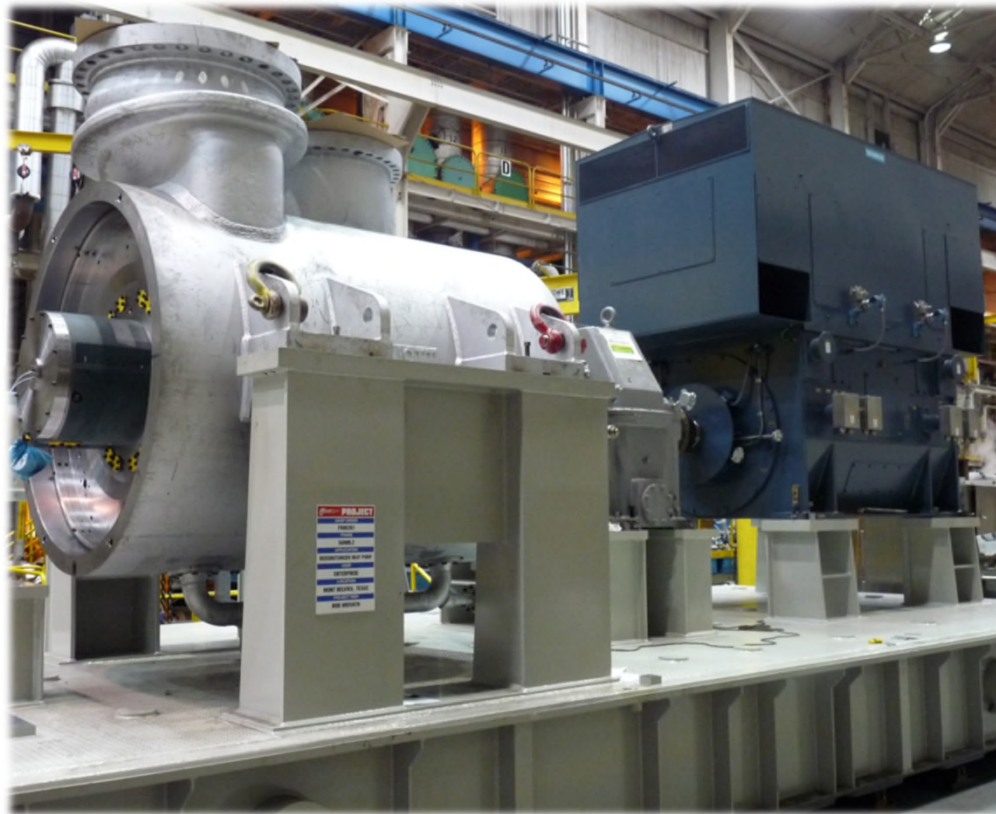


## Global Primary Energy Consumption



Source OurWorldInData

# Carbon Capture and Sequestration



# Industrial Sources of CO<sub>2</sub>

## Availability:

- From Natural Gas Power Plants:

- Steam Methane Reforming
- Gasification
- Oxyfuel Combustion
- Combined Cycle Flue Gas

P=20-100 psia

P=50-400 psia

P=500-2000 psia

P=15-20 psia

- From Coal Power Plants:

- Gasification Combined Cycle
- Stack Flue Gas Cleanup

P=100-500 psia

P=15-20 psia

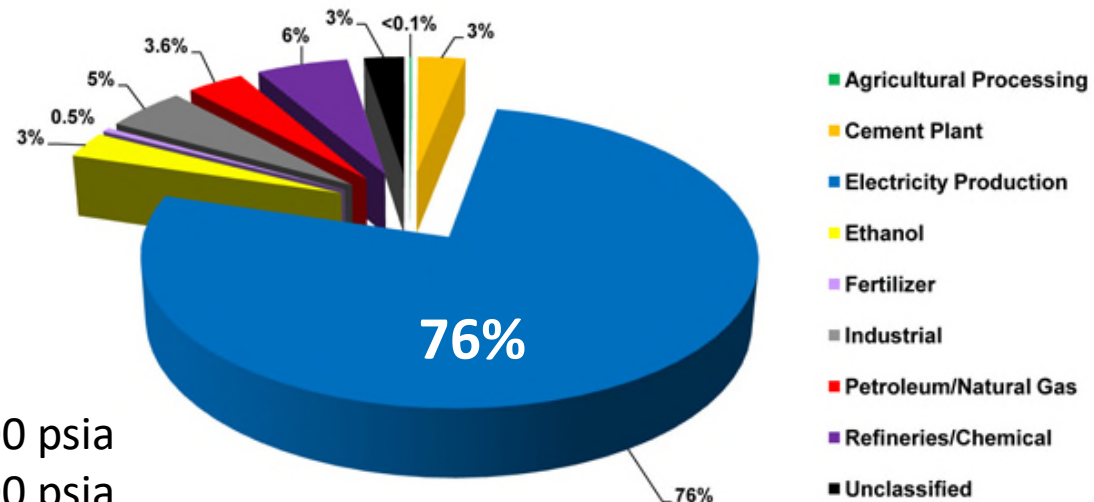
- From Oil & Gas Production

- Associated Gas Separation

P=15-700 psia

- Other Industrial Sources ?

CO<sub>2</sub> Stationary Source Emissions by Category

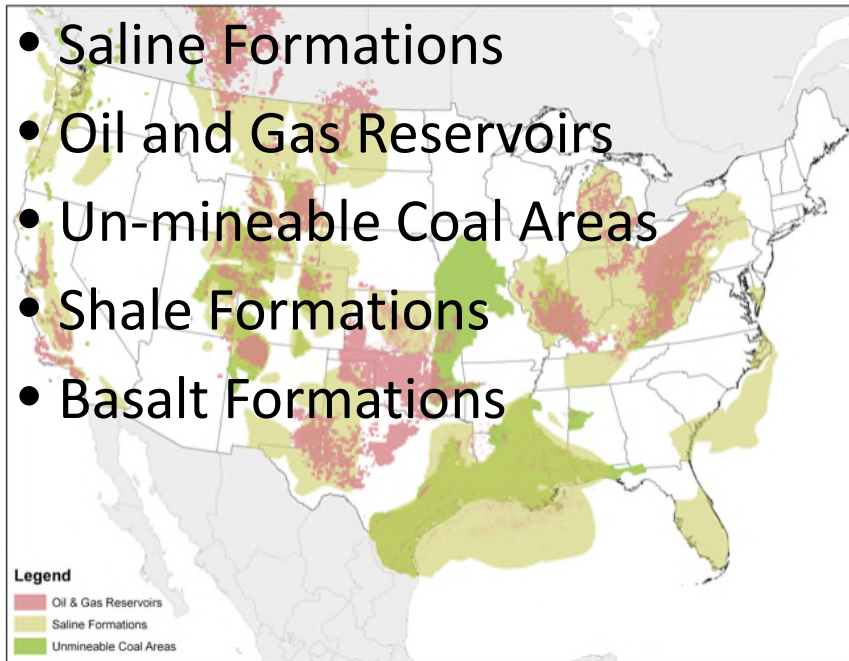


Source:  
DOE/NETL

**Wide Range of  
Source Pressures**

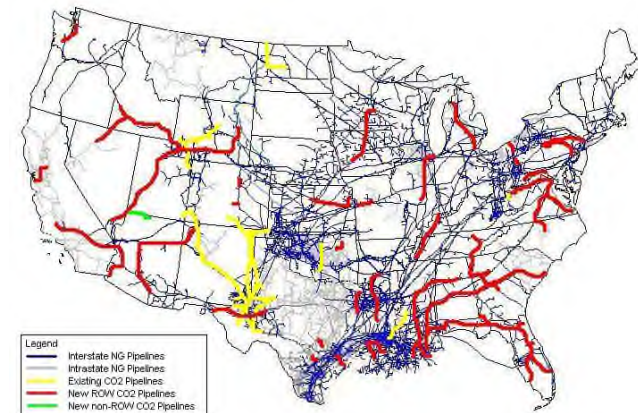
# Carbon Dioxide Storage Locations and CO<sub>2</sub> Pipelines

- Saline Formations
- Oil and Gas Reservoirs
- Un-mineable Coal Areas
- Shale Formations
- Basalt Formations

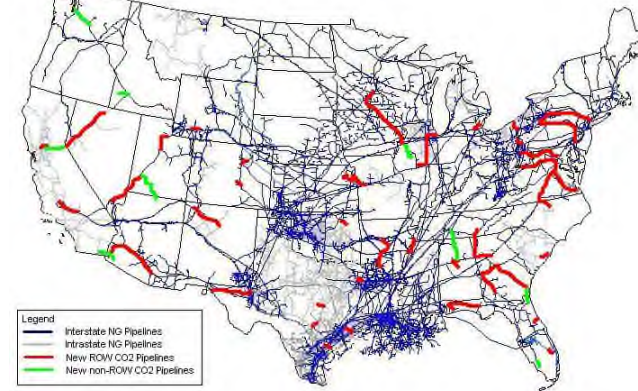


Source: National Carbon Sequestration Database and Geographic Information System

**Plenty of storage capacity and options, but do not align geographically with likely CO<sub>2</sub> production sites**



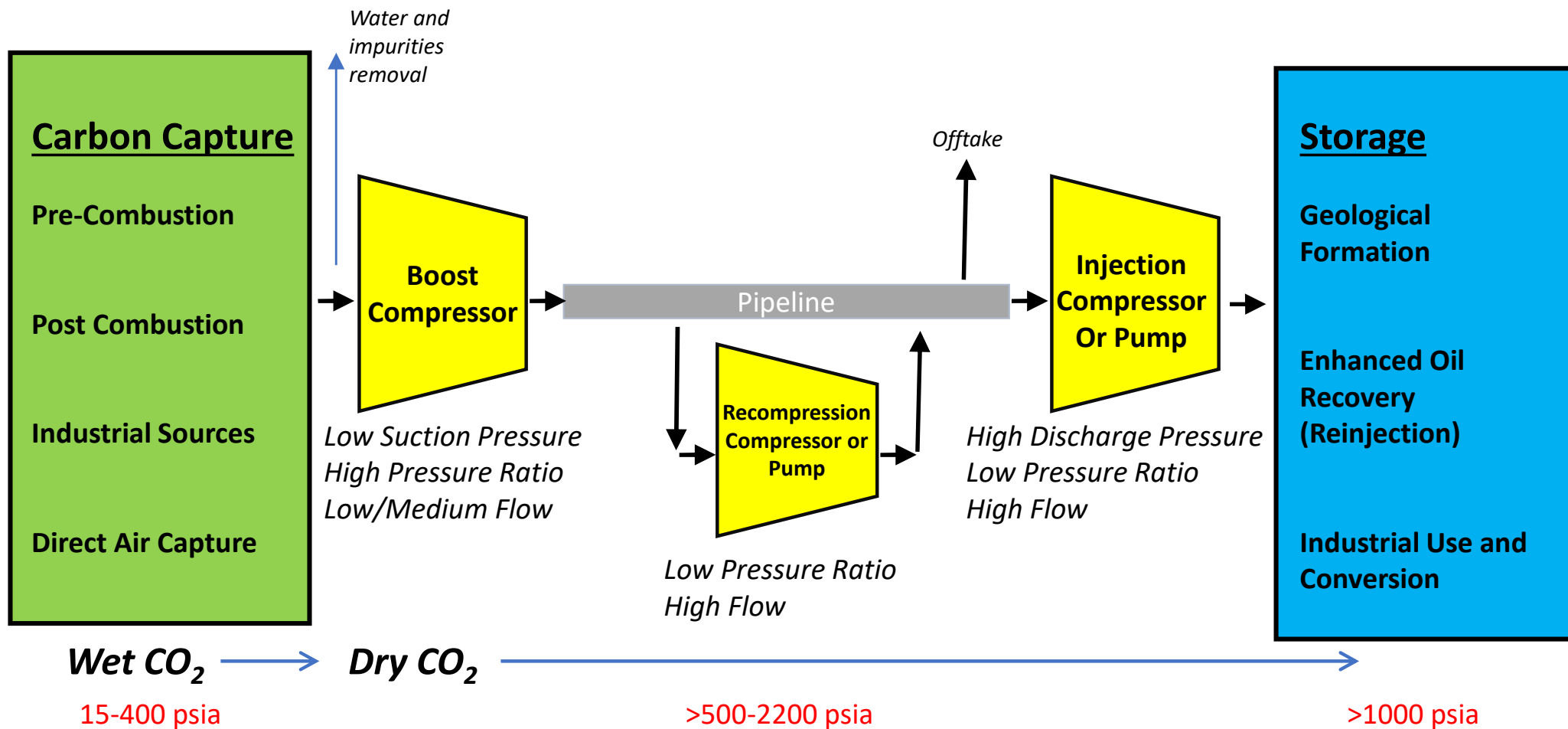
**Enhanced Oil Recovery**



**Saline Formations**

**Injection pressure is 1800 psi for every mile of depth**

# Carbon Capture and Sequestration Value Chain



# Carbon Dioxide Compression Challenges



# Challenges Associated with CO<sub>2</sub> Turbomachinery Design

## Higher Tip Speeds

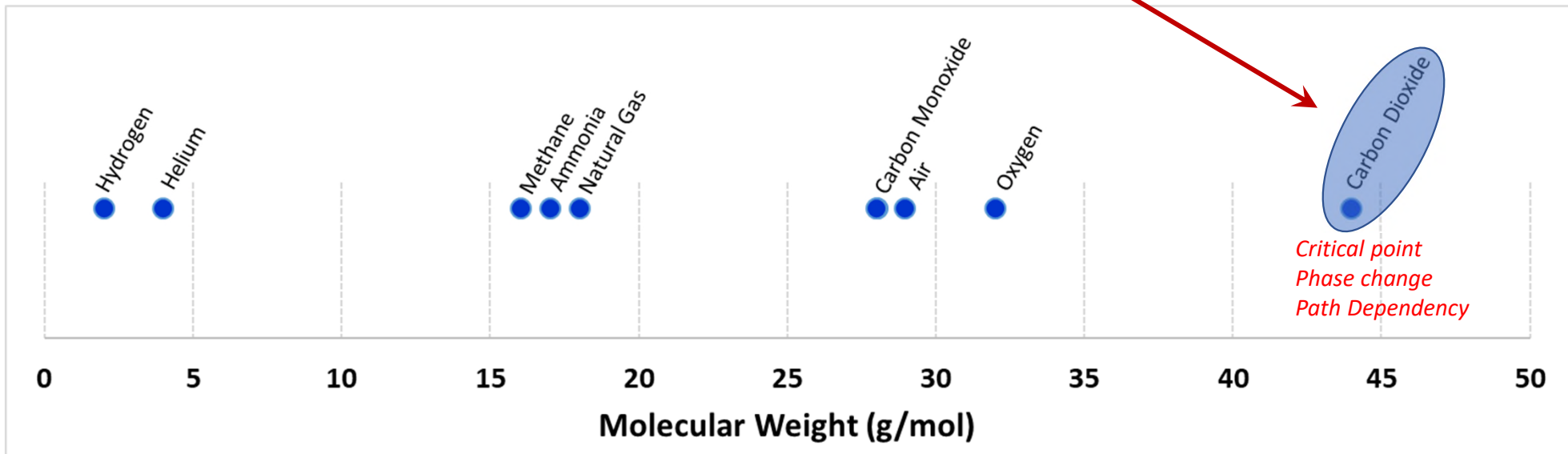
- Stress Management
- Gas Leakage Control
- Rotordynamics



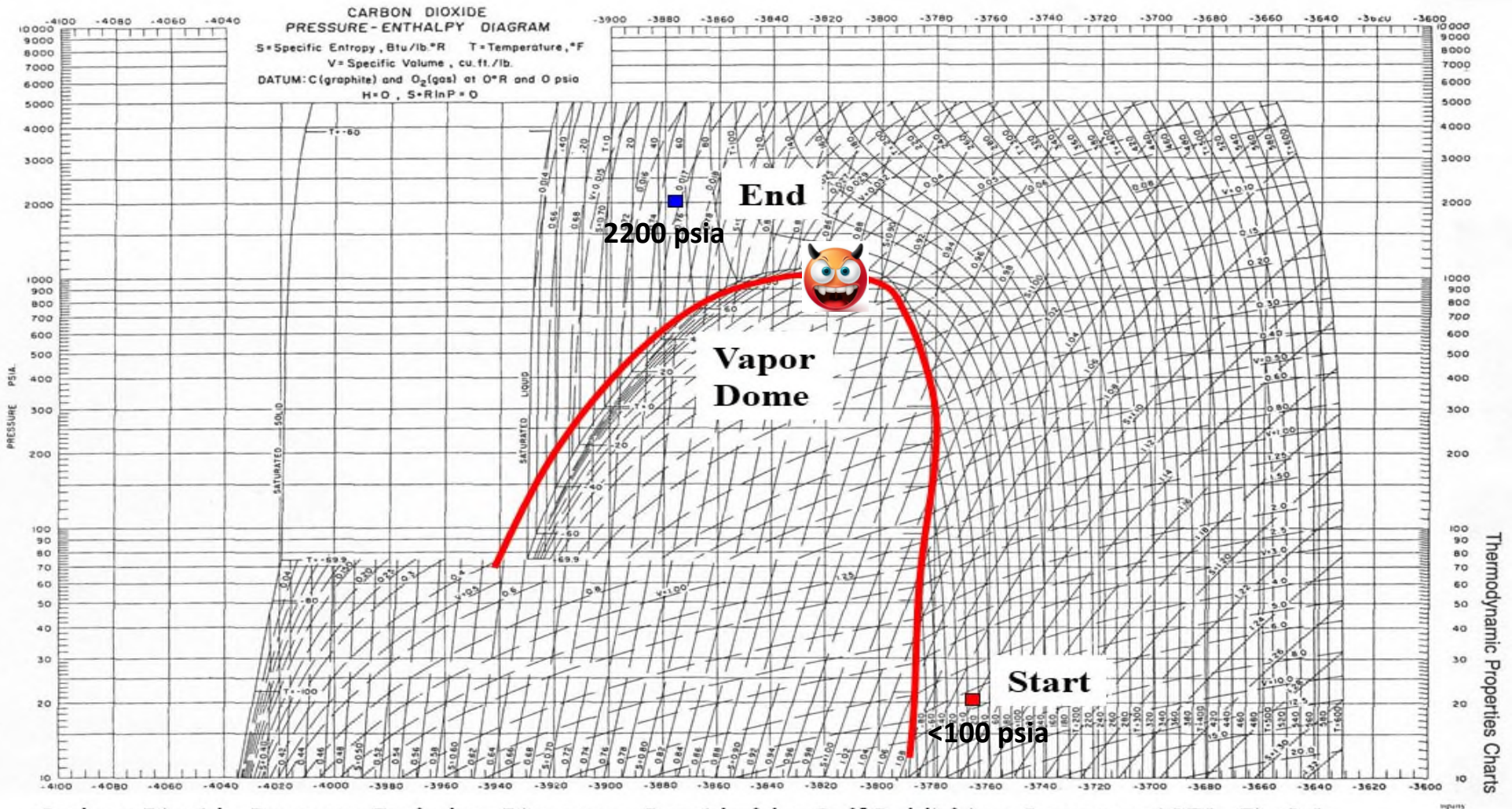
CO<sub>2</sub>

## Higher Loading

- Gear Life
- Bearing Loads
- Axial Force Management

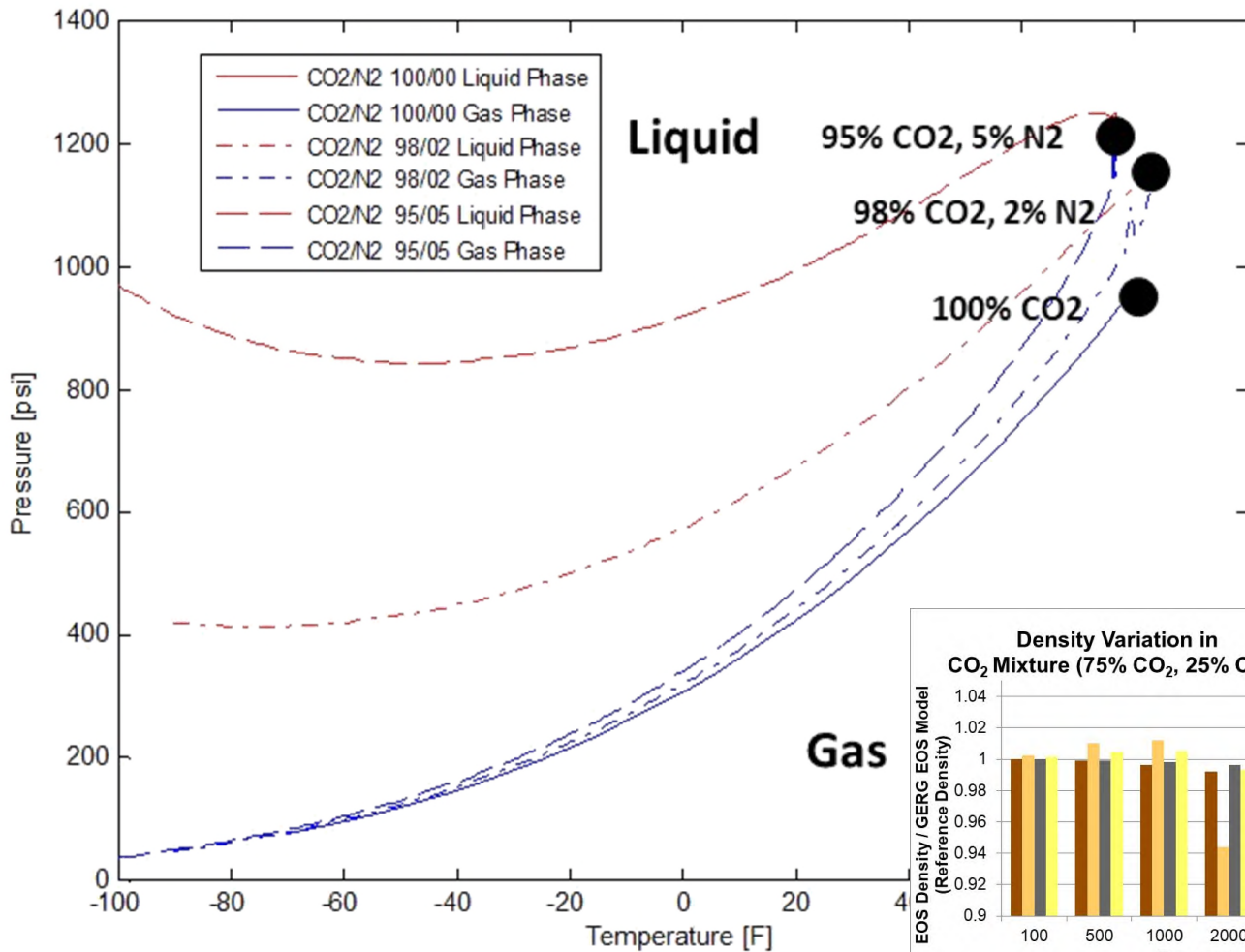


# Carbon Capture CO<sub>2</sub> Compression



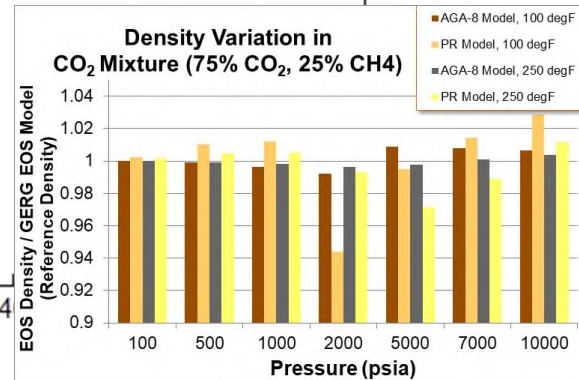
Carbon Dioxide Pressure-Enthalpy Diagram – Provided by Gulf Publishing Company-1972, Fig.8.2

# Change in Critical Point with Mixture



Typically trace impurities:

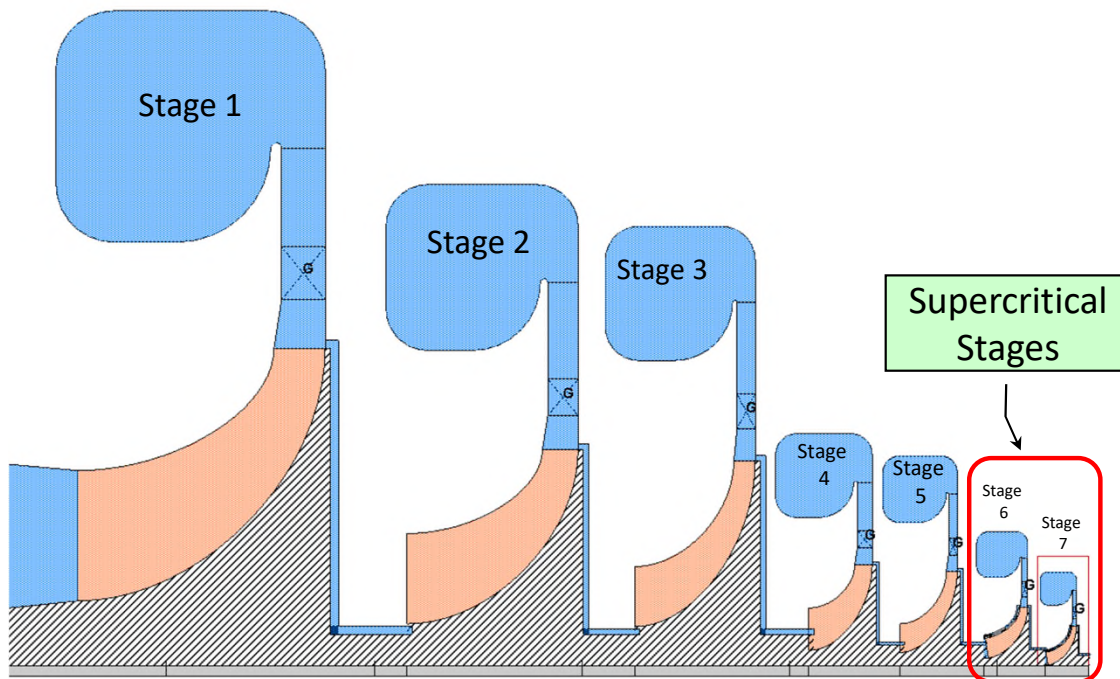
- H<sub>2</sub>O – Water
- H<sub>2</sub>S – Hydrogen Sulfide
- CO – Carbon Monoxide
- O<sub>2</sub> – Oxygen
- CH<sub>4</sub> – Methane
- N<sub>2</sub> – Nitrogen
- NH<sub>3</sub> – Ammonia
- Ar – Argon
- H<sub>2</sub> – Hydrogen
- SO<sub>x</sub> – Sulfur Oxide/Dioxide
- NO<sub>x</sub> – Nitrogen Oxide/Dioxide



**+ EOS Uncertainties**

# Aerodynamic Design Challenges of sCO<sub>2</sub>

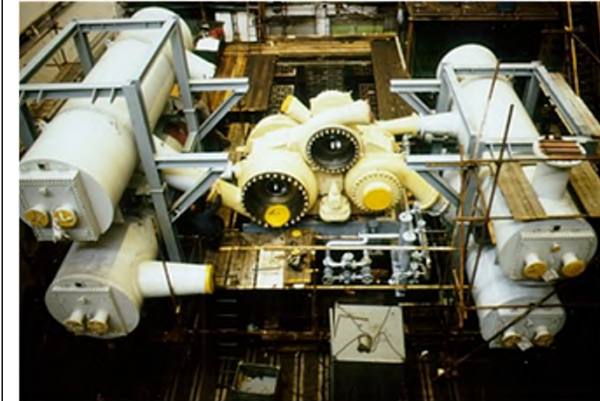
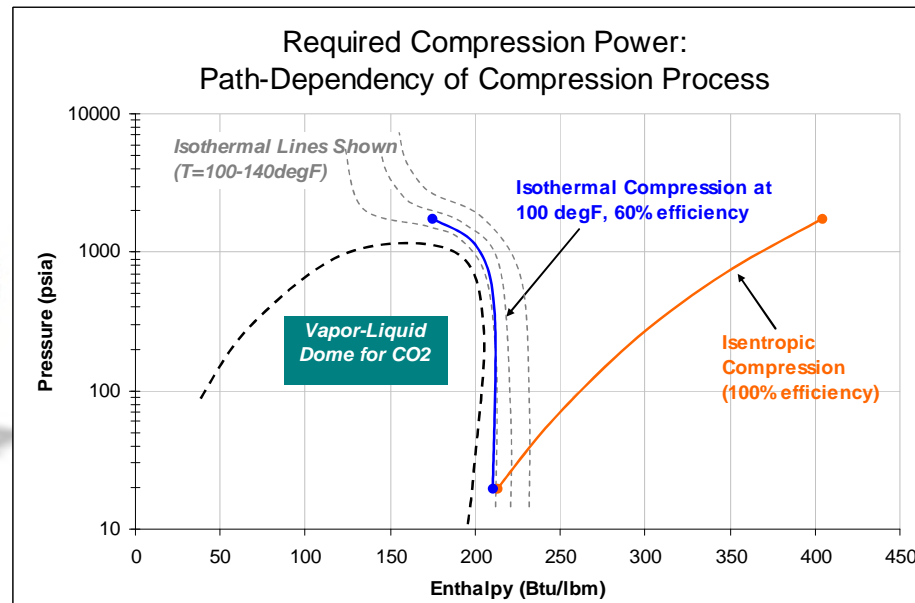
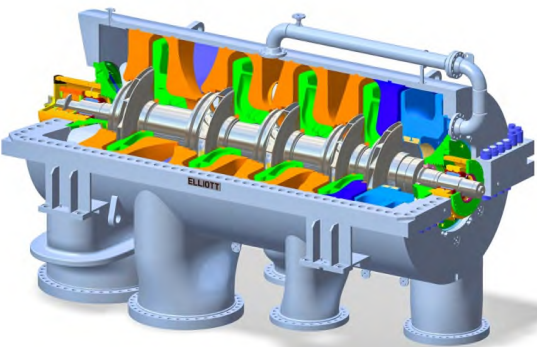
- Wide range of flow stages
- Supercritical stages are small, even in high power applications
- Can not be speed optimized on single shaft
- Difficult to maintain tolerances necessary for good performance
- May need to run below optimum speed due to mechanical limits



**High Pressure Ratio**  
**High Volume Reduction**  
**High Temperature Rise**

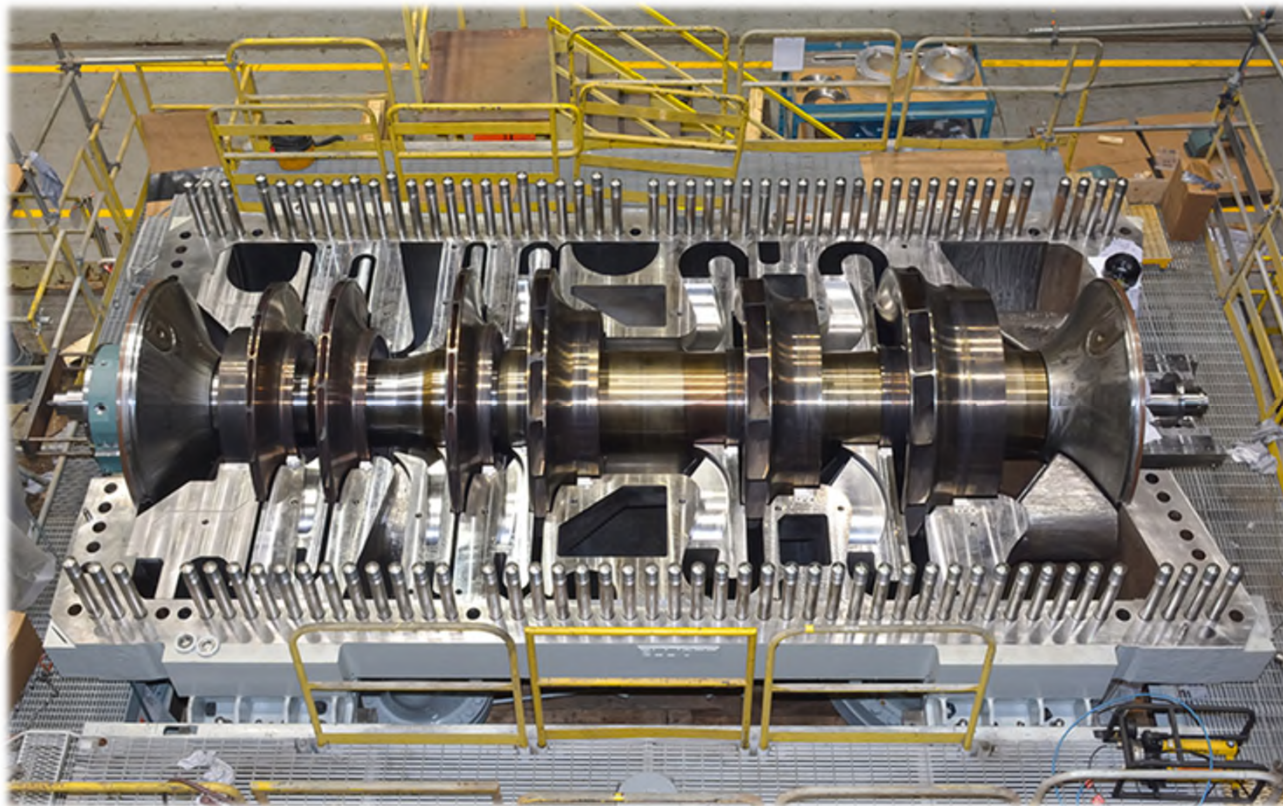
Per Stage

# Compressor Inter-Cooling

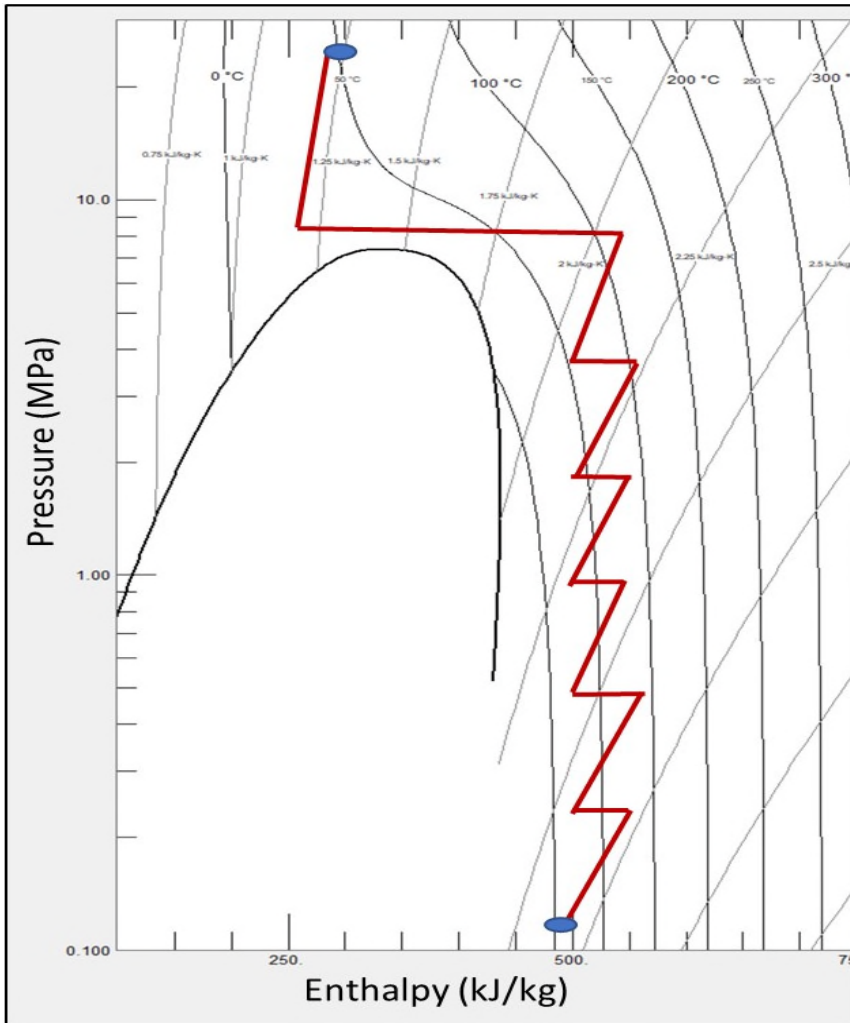


- **Improved Efficiency:** Intercooling helps to reduce the temperature of the compressed gas between stages, which in turn reduces the work required for subsequent compression stages. This leads to lower power consumption.
- **Increased Capacity:** Lowering the temperature of the compressed gas allows for higher pressure ratios and increased capacity without the risk of overheating the compressor.
- **Enhanced Reliability:** Intercooling can help to reduce the thermal stresses on compressor components, extending their operational life and improving overall reliability.
- **Flexibility in Operation:** Intercooling allows for greater flexibility in compressor operation, as it can help maintain performance under varying operating conditions, such as changes in ambient temperature or inlet conditions.

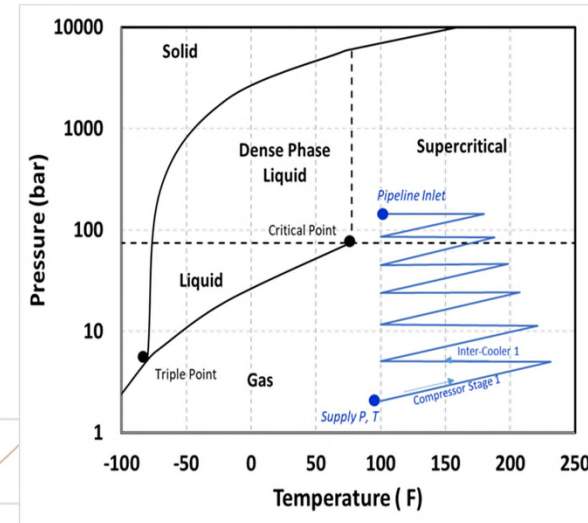
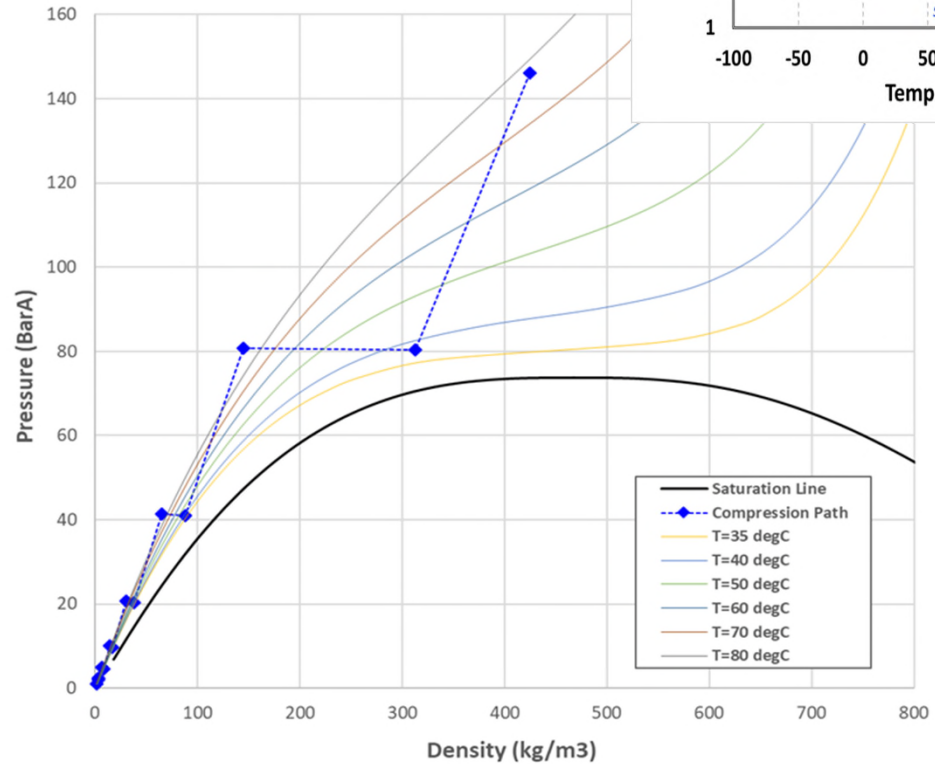
# Compression Option for CCUS



# Compression Path for Carbon Capture



50-2200 psia (3.5-152 bara)  
 7 compression stages  
 6 intercoolers

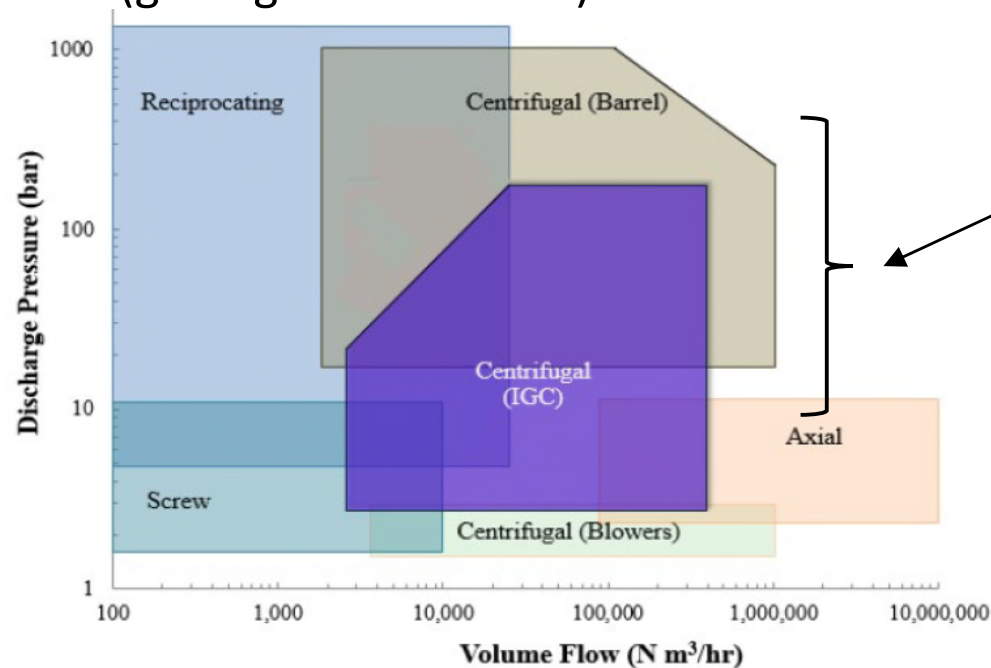


# Carbon Dioxide Compression

## Compression Applications:

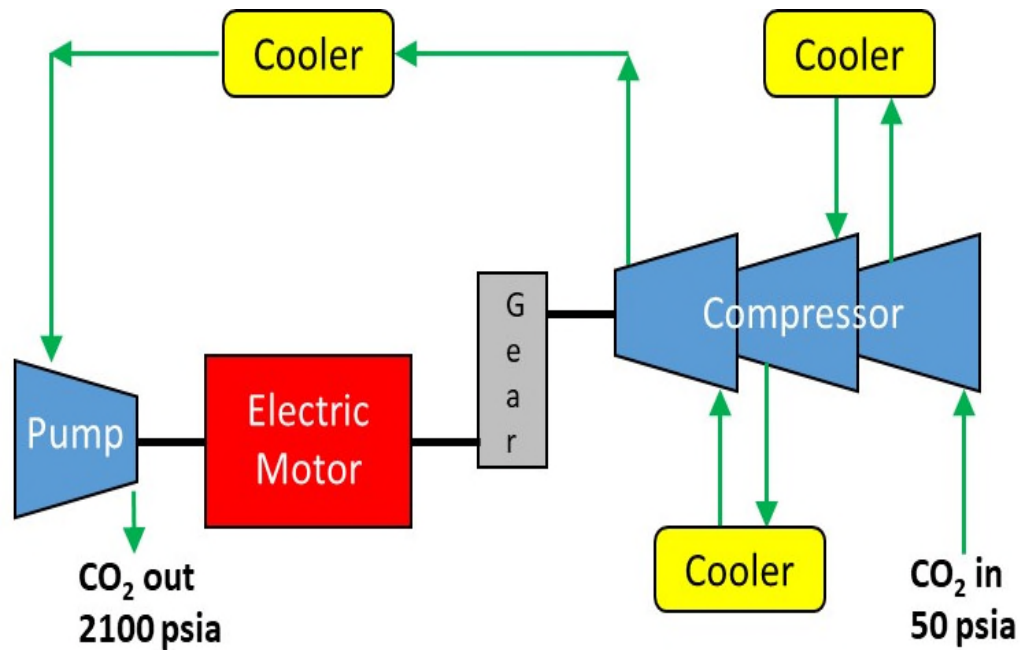
- Pipeline re-compression/re-pumping (2100 psi)
- Steam reformer to Pipeline Pressure (2100 psi)
- Gasifier to Pipeline Pressure
- Flue Gas to Pipeline Pressure
- Boost into sequestration (geological formation)

PR 1.2-1.5  
PR 40-70  
PR 5-20  
PR 120-300  
PR 1.2-300

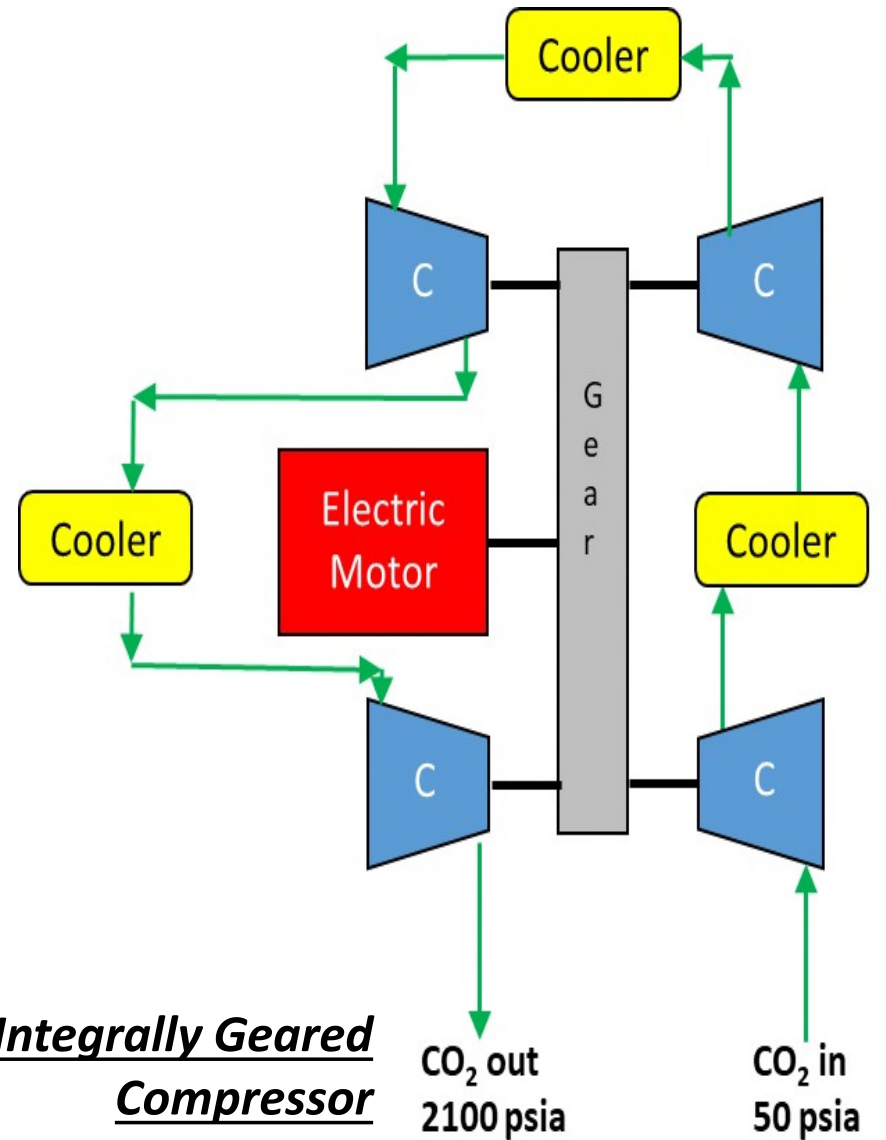


**Flows are too high  
for reciprocating  
compressors**

# Compressor Solutions



*Barrel Compressors  
and Pumps*



*Integrally Geared  
Compressor*