Compressor Development Challenges in Energy Storage Applications

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July 2025

Evolution of the Energy Market

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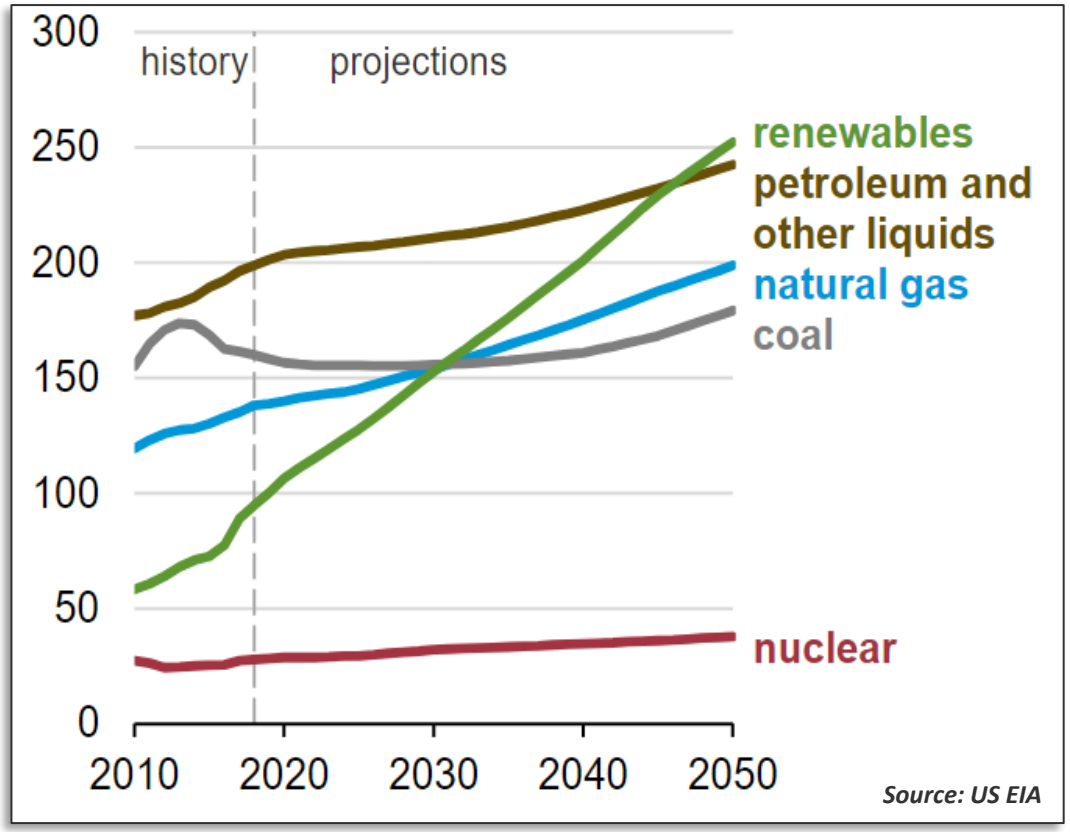
Global Energy Consumption by Source



Source: US EIA

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

Renewables Must Manage Transients and Integrate with Grid Demand Variation

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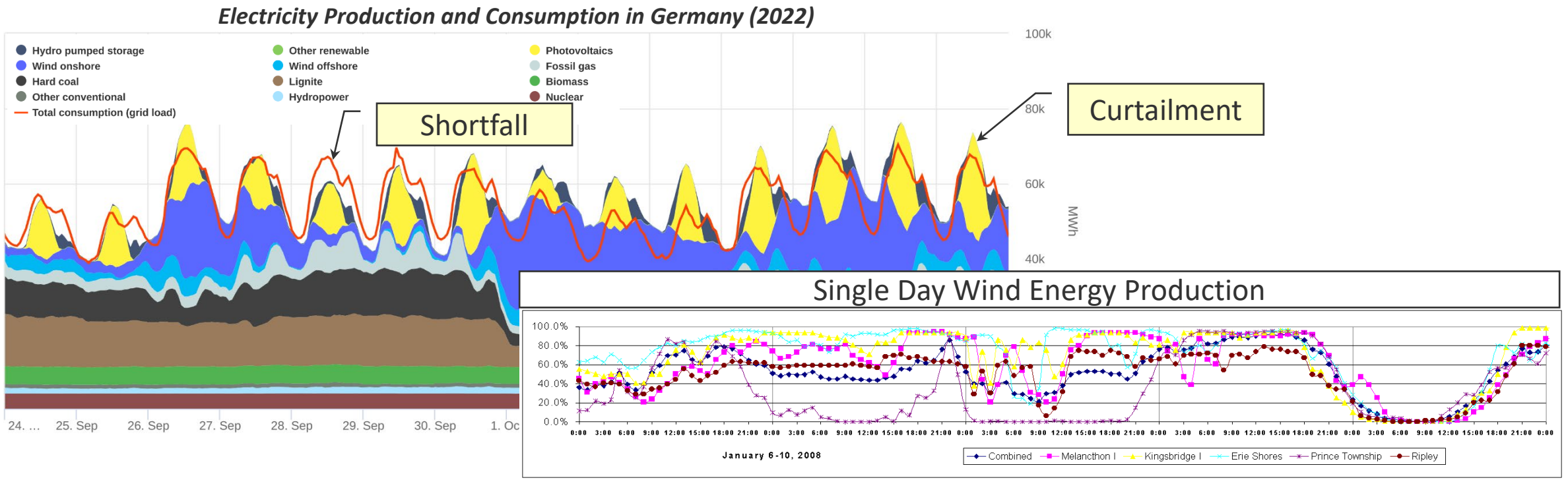

https://en.wikipedia.org/wiki/Variable_renewable_energy

- Energy demands are variable
- Integration of renewables further complicates the situation since their capacity is transient and unpredictable.
- ***Energy storage helps better match production to grid demands***

Compressor Operational Requirements

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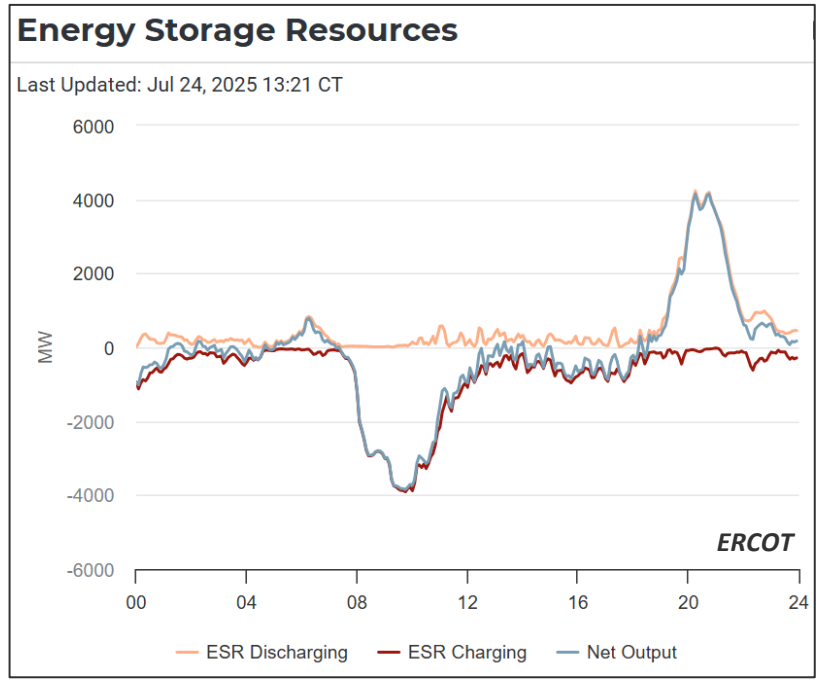
- Compressors in the established energy markets have had fairly stable operating requirements and minimal start and stops
- Compressors designed for the energy storage market must integrate with significant process fluctuations
  - ❑ Accommodate fast ramp rates
  - ❑ Manage frequent start-stops
  - ❑ Handle broad operating conditions
  - ❑ Operate at high temperatures
  - ❑ Designed for a wide range of process gases

- ➢ Storage demand has large fluctuation day/night
- ➢ Rapid smaller fluctuations through the data

Single Day Texas Grid Storage Performance



Compressor Applications in Energy Storage

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Thermal

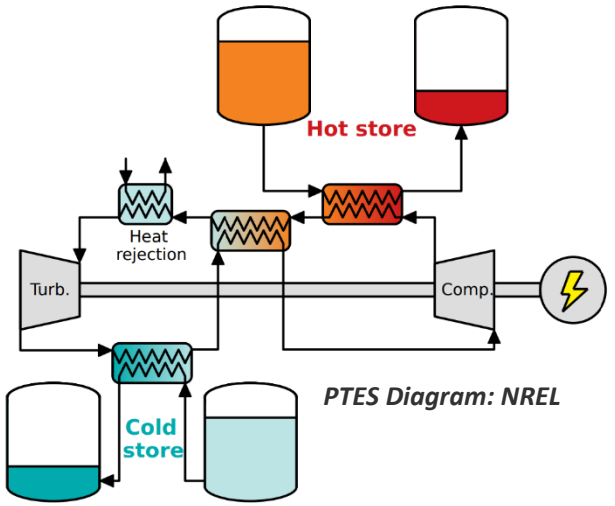
- Pumped Thermal Energy Storage
- Solid media storage

Chemical

- Pipeline
- Production and distribution compressors
- Oxyfuel Combustion
- Hydrogen Electrolosis

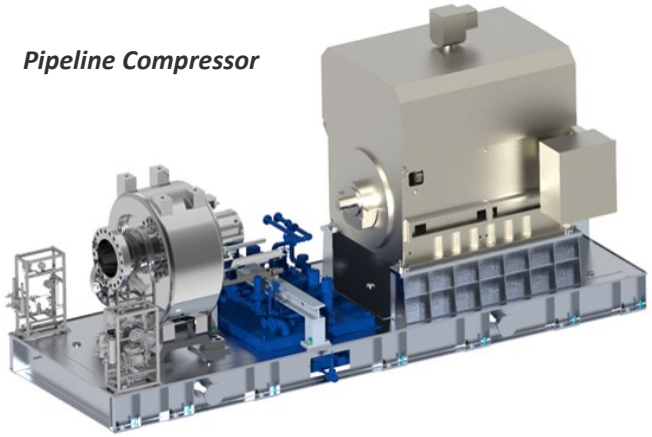
Mechanical

- Compressed Gas (Air, CO2, etc.)

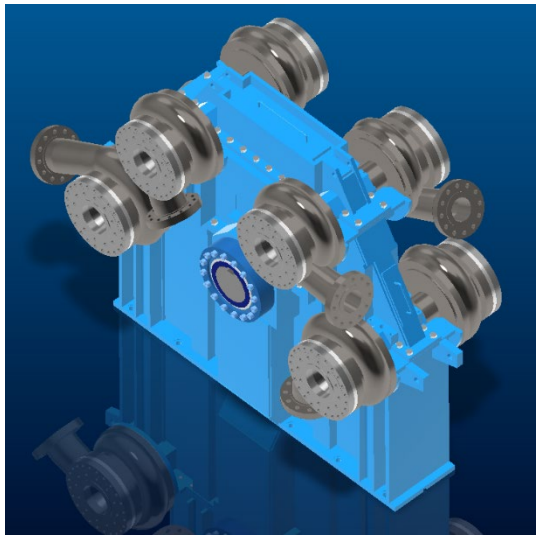


PTES Diagram: NREL

Pipeline Compressor



IG Compressor



Design for Transients

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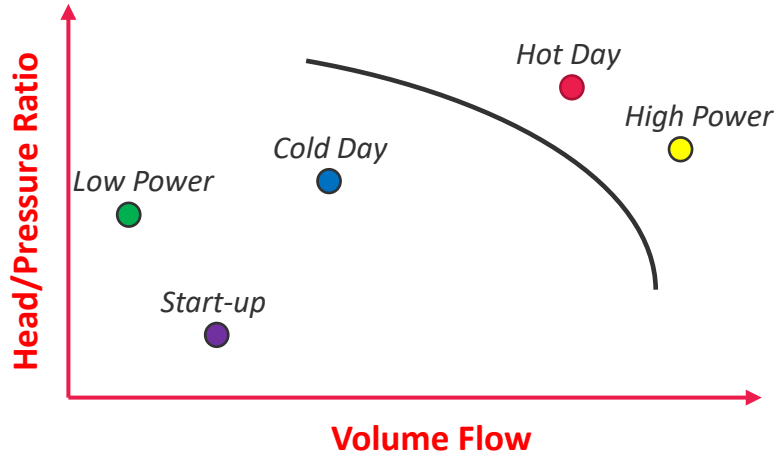
- Centrifugal compressors deliver a fixed amount of head rise for a given volume flow
- Actual process requirements change with the process gas supply temperature, available cooling, process load
- Fixed geometry machines typically cannot cover all the operating points
- Compressor operating range can be extended by:
  - ✓ Controlling speed
  - ✓ Adding variable geometry



Variable Compressor Geometry Enhances Range

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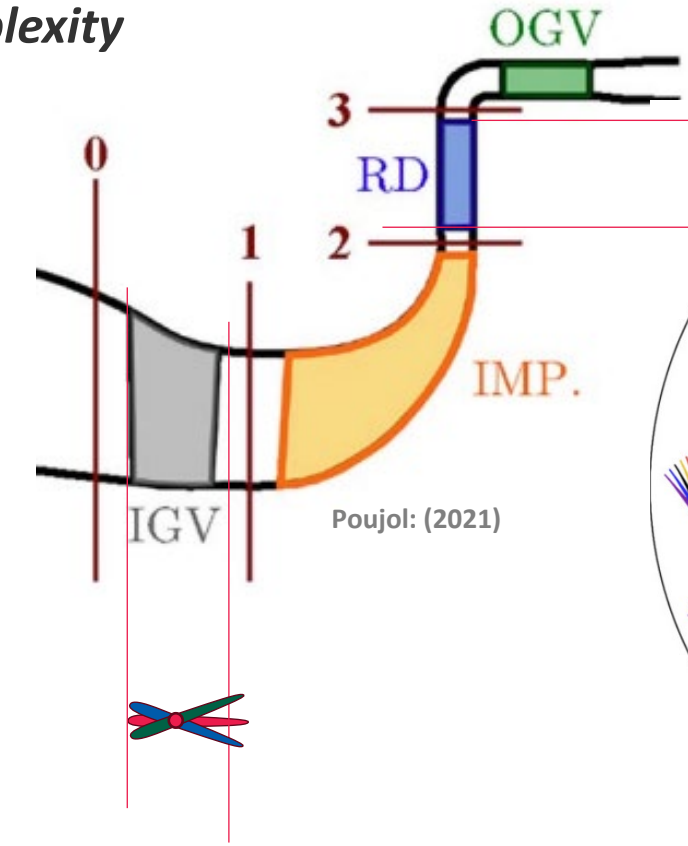
- Many methods to extend compressor range have been proposed
- Including adjustable vanes is well proven to increase compressor

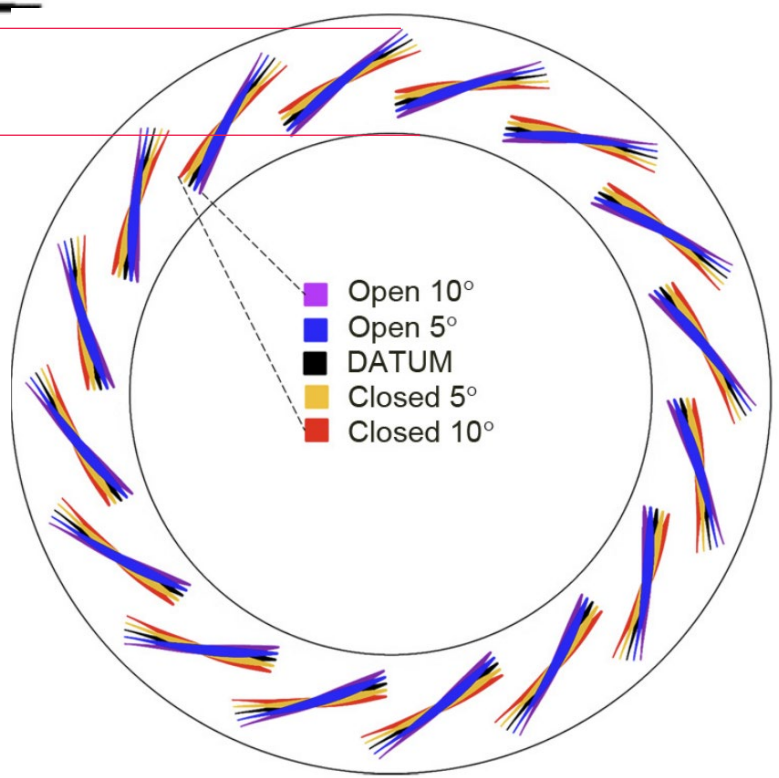
✓ ***They add cost and complexity***

Variable Inlet Guide Vanes

Tan, (2011)



Poujol: (2021)



Variable Diffuser Vanes

Enhanced Operability

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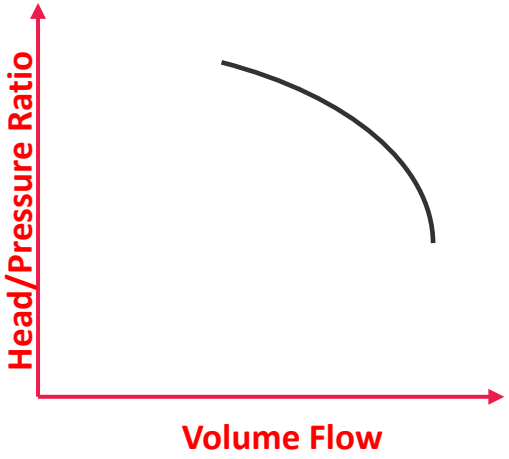
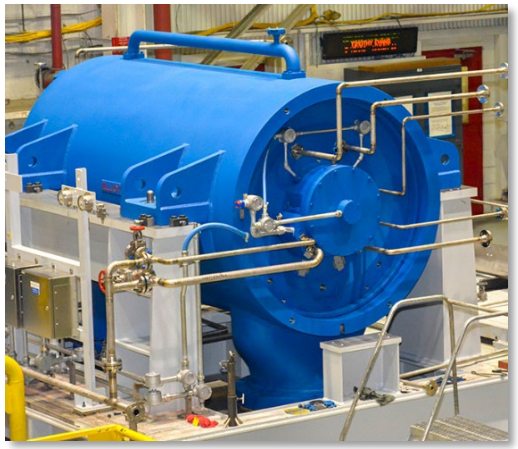
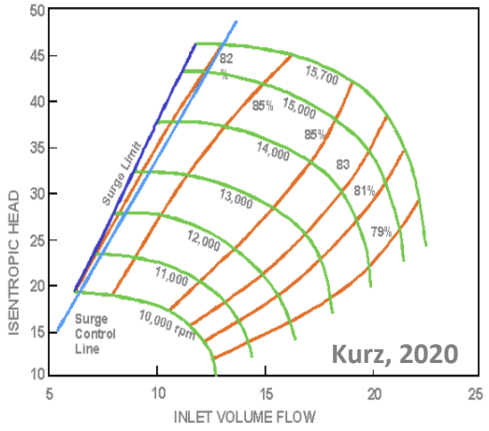
Fix Geometry



Variable Speed Drive





Variable Inlet Guide Vanes

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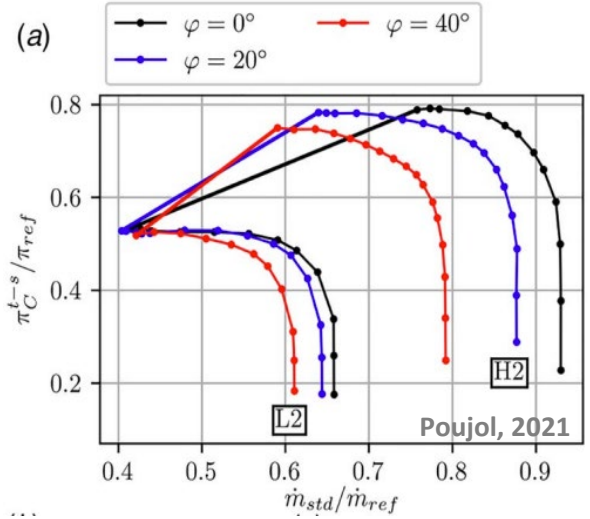
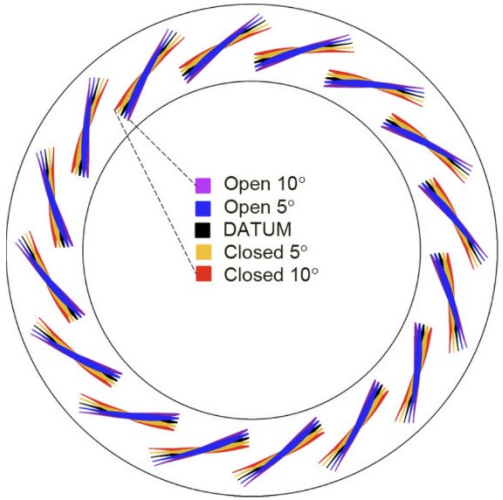
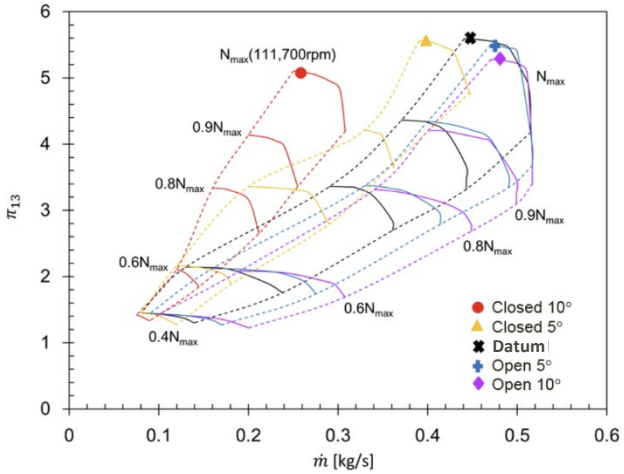


Variable Diffuser Vanes





Hot Gas Compression

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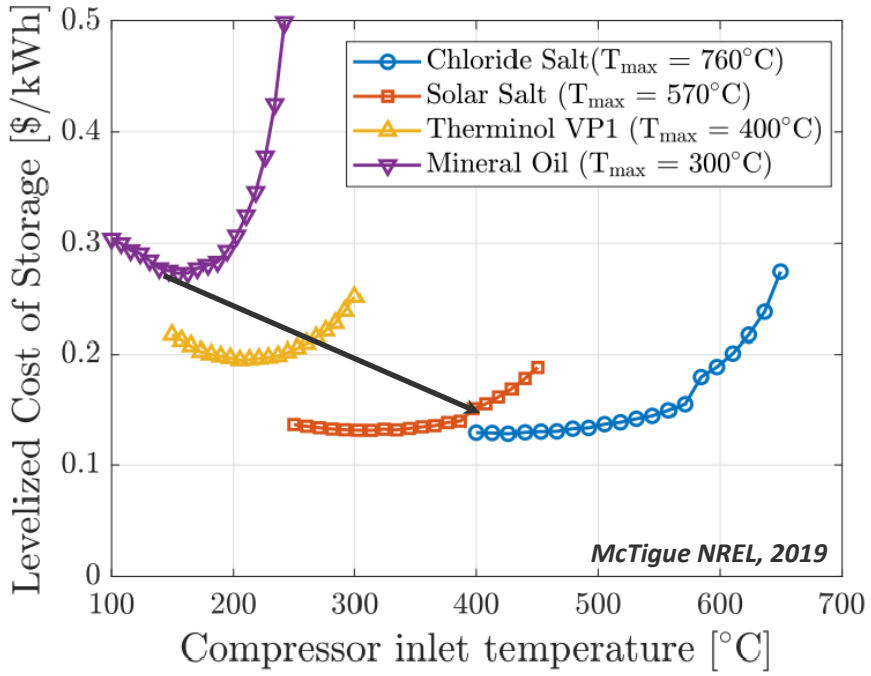
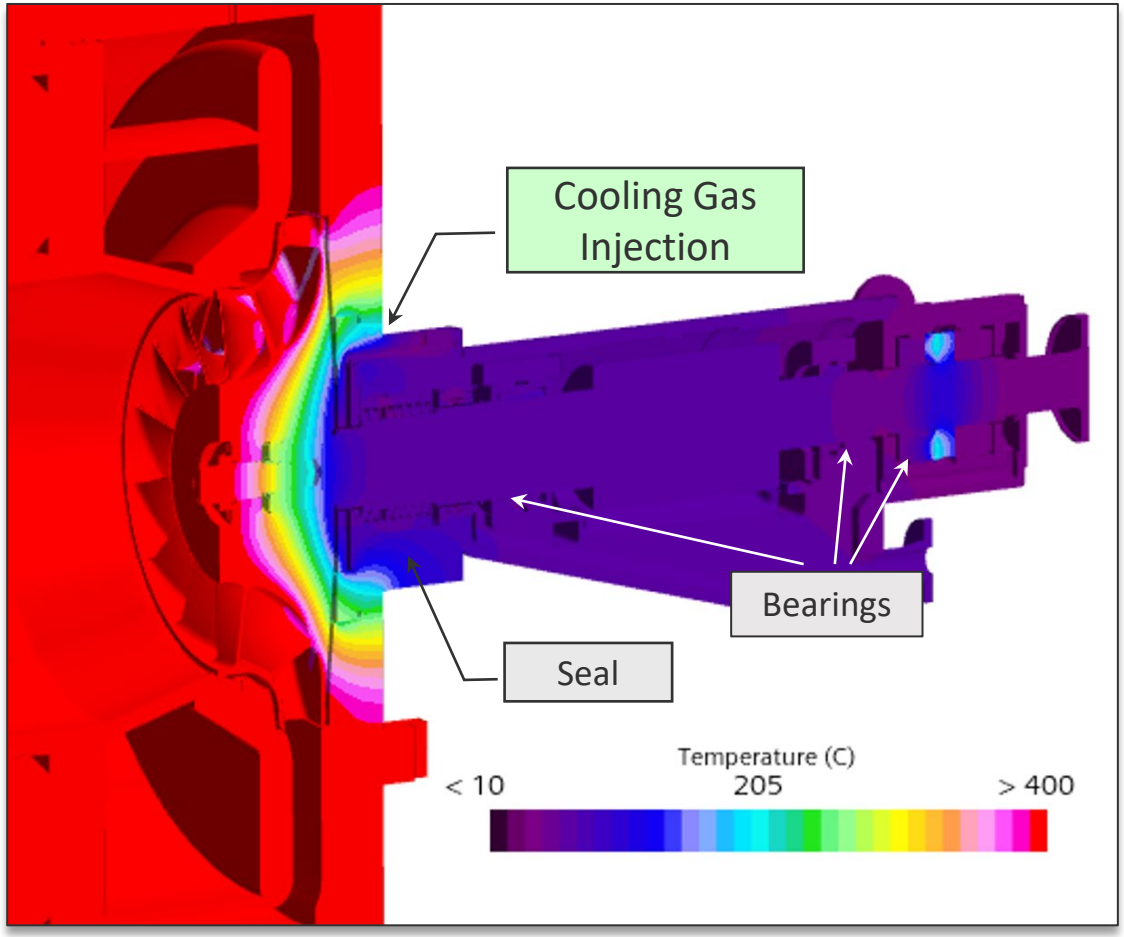
- Many thermal storage applications (heat pumps, PTES) require compression at high temperature
- Appropriate materials must be selected
- Bearing and seals must be isolated from the heat
- Active cooling may be required

Costs Assessment of PTES System Configurations





Conjugate Aero Thermal Analysis of a Hot Gas Compressor

Impact of Process Gas on Compressor Design

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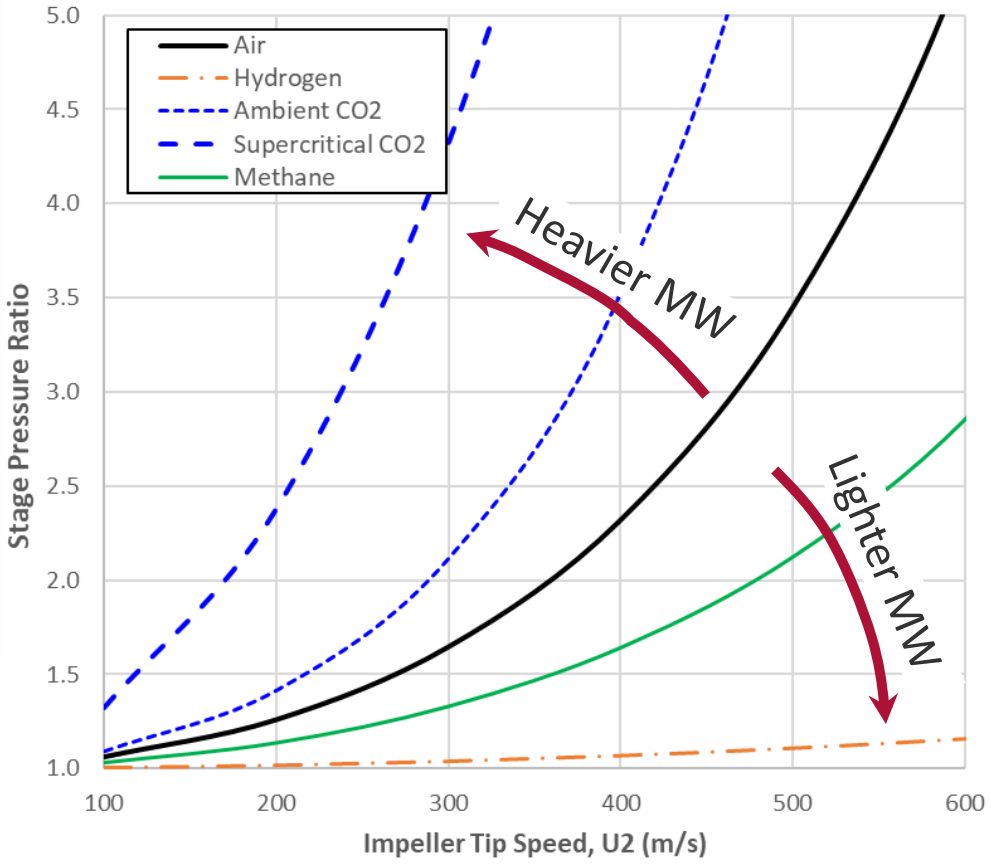
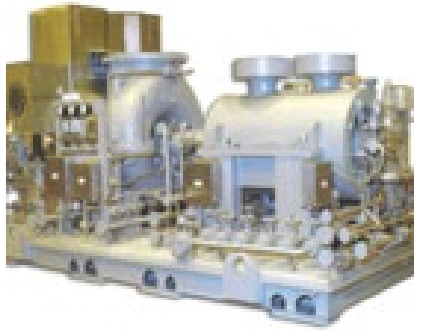
- With heavier MW gasses high pressure ratio can be achieved in fewer stages
- Temperature rise in each stage is significant
- Stages must be designed to manage greater thermal gradients
- Intercooling between stages is critical
- Supercritical CO2 is very power dense





- Low MW gases like Hydrogen are hard to compress
- Even at very high speeds relatively little pressure rise is achieved.
- Hydrogen compression applications will require more stages than traditional applications and run at high relative speeds
- Stress and service intervals may need to increase

Hydrogen Compressor Design Challenges

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Stage Design

- Design for higher head rise per stage
- Operate at high tip speeds
- Flat performance curve
- Reduced efficiency potential

Machine Configuration

- Increase number of compression stages
- Keep bore size small to reduce stress
- Select materials to avoid hydrogen embrittlement

Safety

- Hydrogen embrittlement
- Explosivity, wide flammability range,
- Dispersion and impact radius
- Facility leak detection

Dibella: DOE Hydrogen and Fuel Cells Program

Hydrogen Compressor Train

Materials Considerations For Hydrogen

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Embrittlement

- Diffusion of hydrogen into grain boundaries causes a significant loss of ductility
- API limits material yield strength to 120 ksi (827MPa) per API to avoid hydrogen embrittlement.

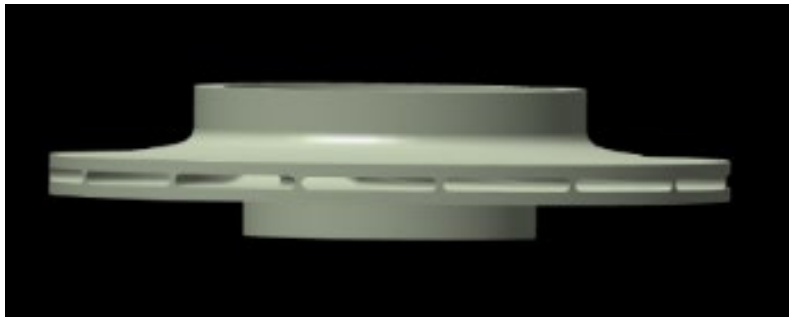
Coatings

- Limit hydrogen embrittlement
- Improve erosion and corrosion resistance
- …but all coatings will eventually be worn away, spalled, or dis-bonded

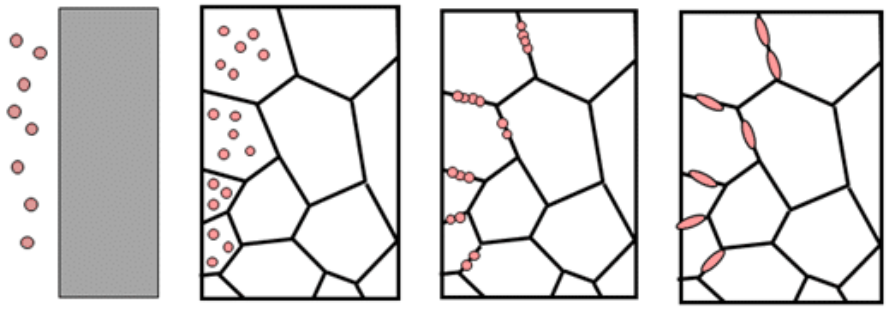
Impellers

- Aluminum Impellers
- Ceramic matrix impeller

Coated Impeller

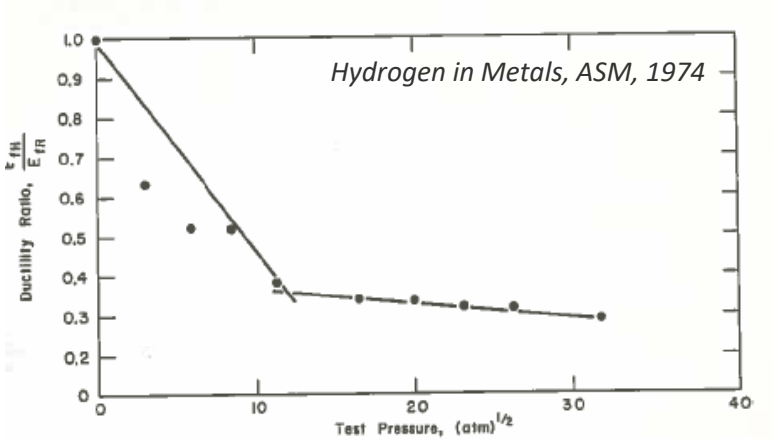


Advanced Ceramic Matrix Composites



Diffusion of Atomic Hydrogen to Grain Boundaries Within Steel

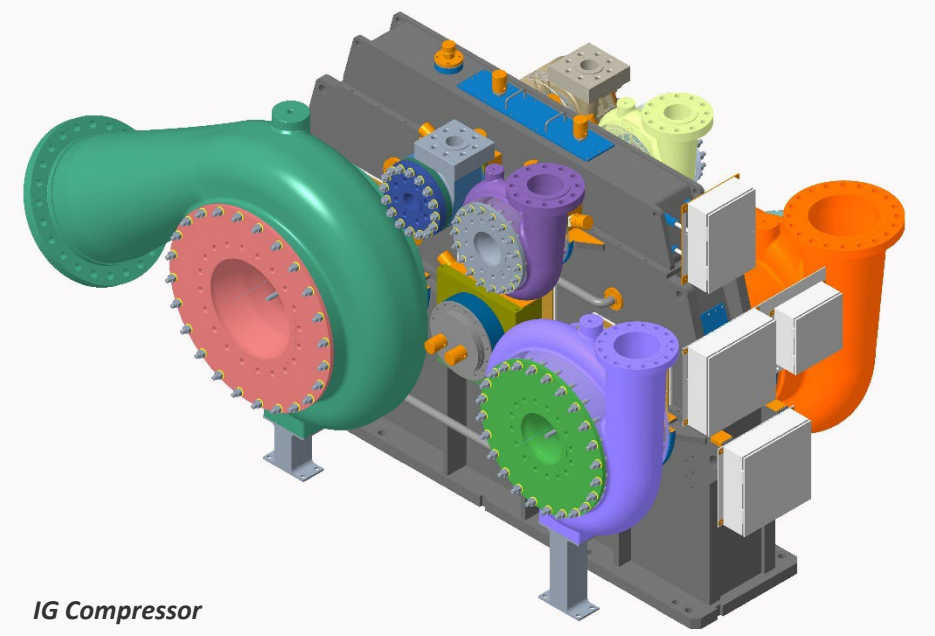
www.imetllc.com



Effect of Hydrogen Pressure on Ductility of 304L Stainless Steel Tested to Fracture in Hydrogen Gas at Room Temperature

sCO2 Compressor Design Conscideration

- Large pressure and temperature rise per stage
  - Need for intercooling
- Substantial volume reduction
  - Power Density
- Gas properties vary rapidly near the critical point
- Well suited for IGC configuration



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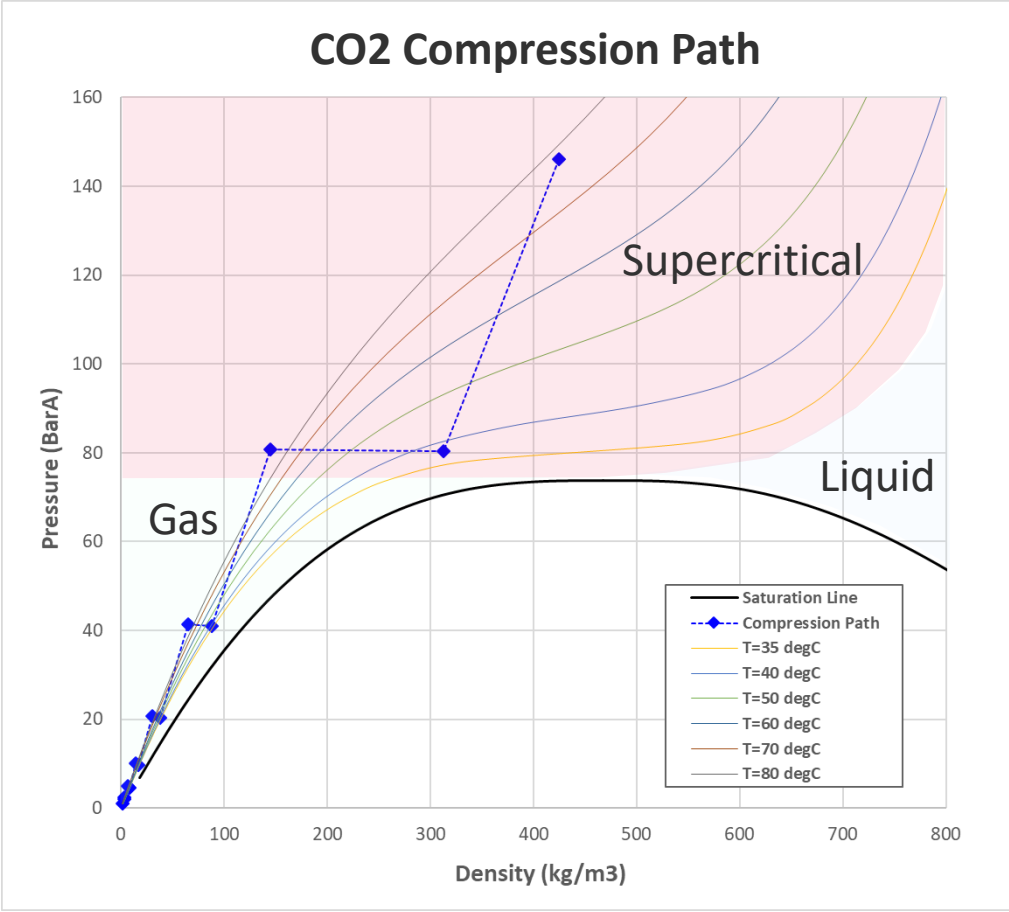

Aerodynamic Design Challenges of sCO2

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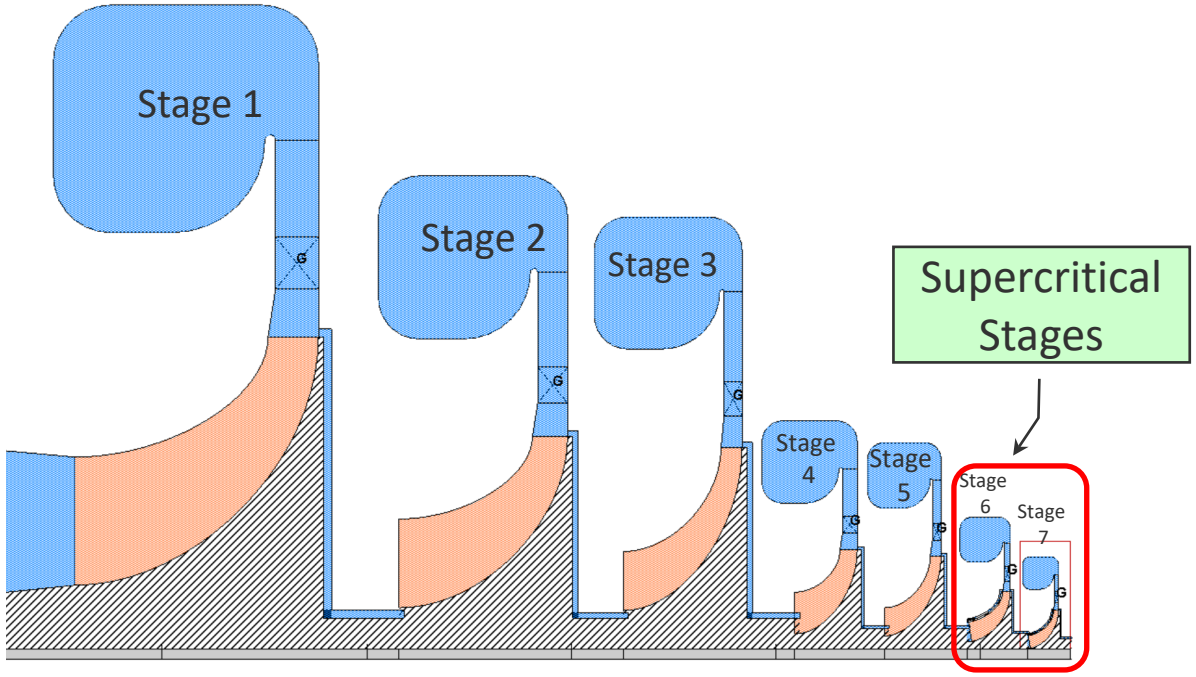
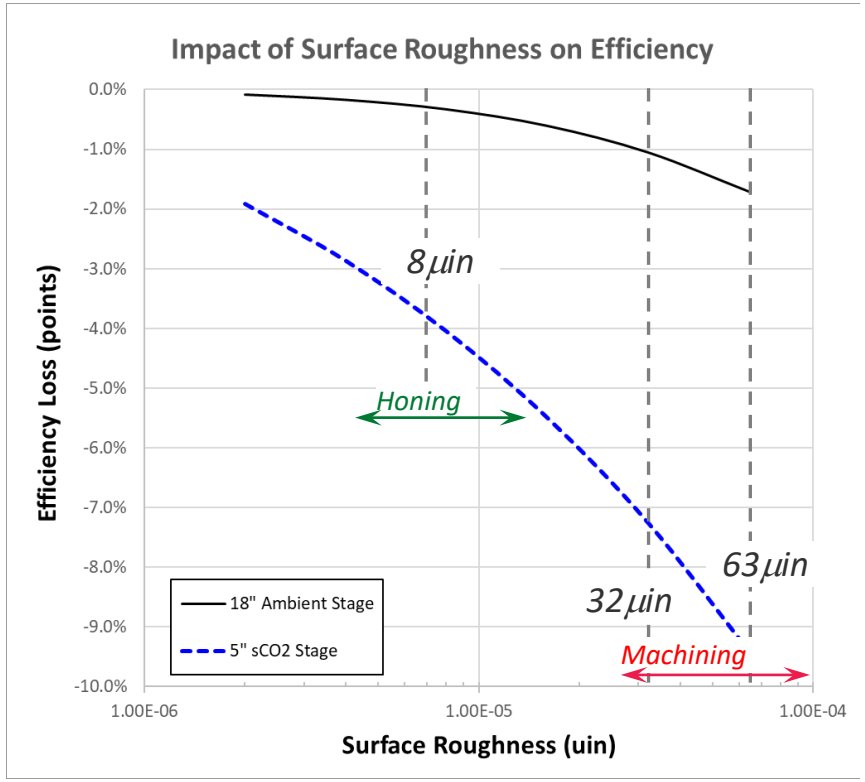
- Supercritical stages are small, even in high power applications
- Can be difficult to maintain tolerances necessary for good performance
- May need to run below optimum speed due to mechanical limits





Materials Considerations For CO_2

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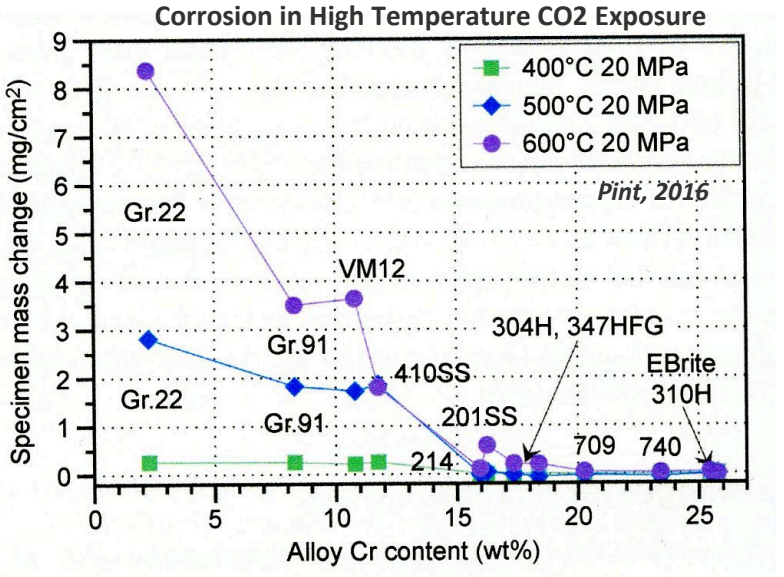
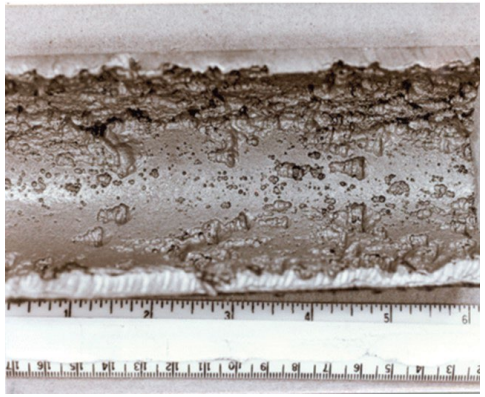
- Mostly inert with gases
- Forms carbonic acid when mixed with water
- High rates of corrosion in steel at high temperature
- Increased Cr content yields increased resistance to corrosion at high temperature
- Cladding can be applied for high temp compressor casings



$$CO_2 + H_2O \leftrightarrows H_2CO_3$$



Cladding Process

Compressor Casing

Product Impact

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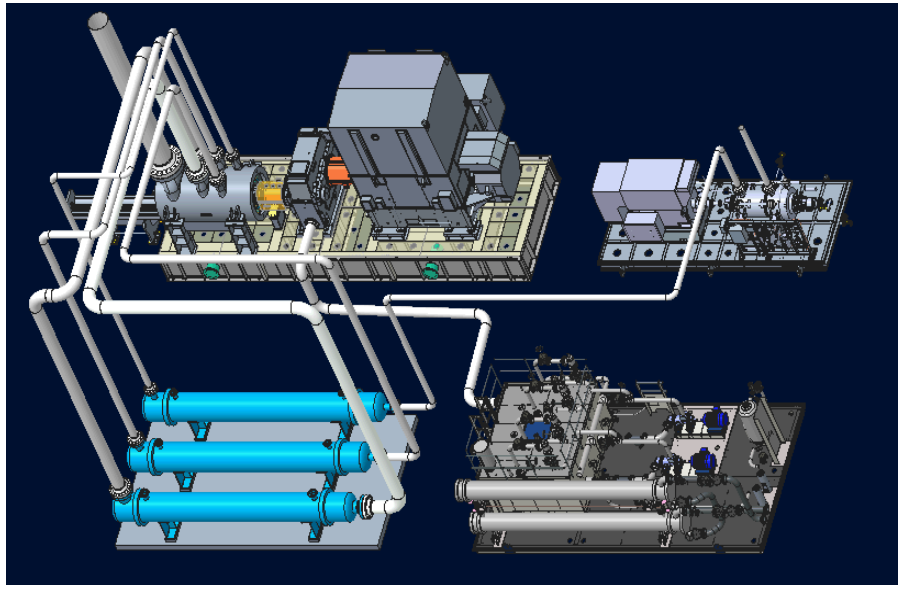
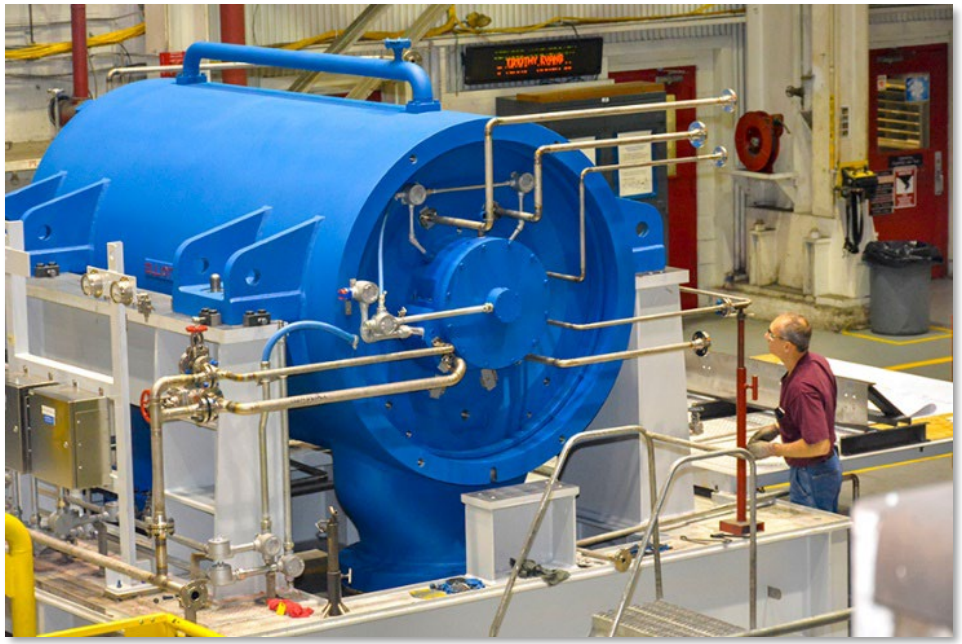
- Process specification have a significant impact on the compressor configuration, costs, and maintenance

CAPEX is impacted by:

- Process gas (stage count, materials)
- Range requirements (Variable geometry)
- Temperature (Material selection)
- Pressure (Casing thickness, seal type)





OPEX impacted by:

- Power consumption: Efficiency, intercooling
- Package complexity: Variable geometry
- Process gas: Corrosion
- Transients: Cyclic loading, fatigue, etc.