Compressor Development Challenges for Geothermal Applications

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Types of Compressors for Geothermal Applications

Pumps and ejectors meet most compression (pressure-rise) and Non-Condensable Gas (NCG) removal needs.

Compressors are still uncommon, used mainly in conventional dry-steam/flash-steam plants with high NCG.

Use of compressors is expected to grow due to:

- **Higher Performance Cycles:** Ongoing development efforts around cycles using CO_2 as a working fluid.
- **Regulatory Pressure:** Increasing regulations require Non-Condensable Gas (NCG) reinjection, particularly in high NCG-concentration plants.
- **System Standardization:** Development of standardized reinjection/abatement systems involving compressors.
- **Aging Reservoirs:** Declining reservoir pressure and temperature increase NCG content making reinjection crucial for well productivity maintenance.

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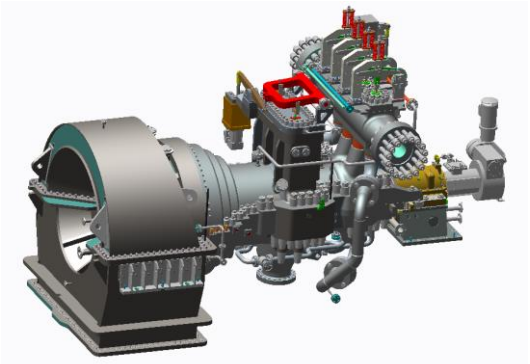
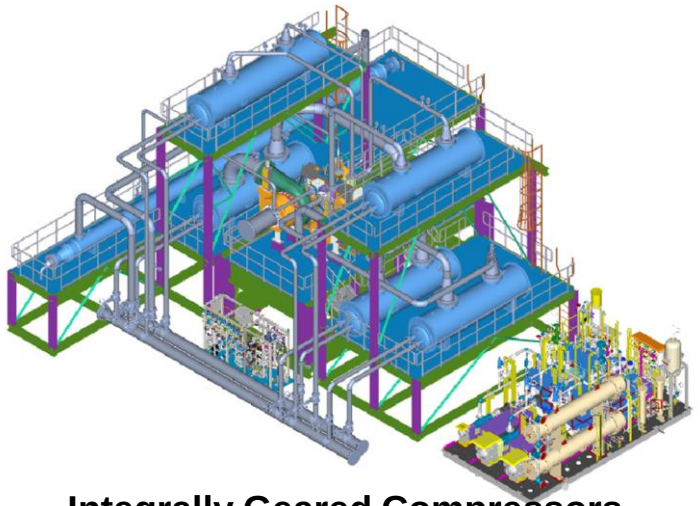
Ebara Elliott Energy Machinery Products



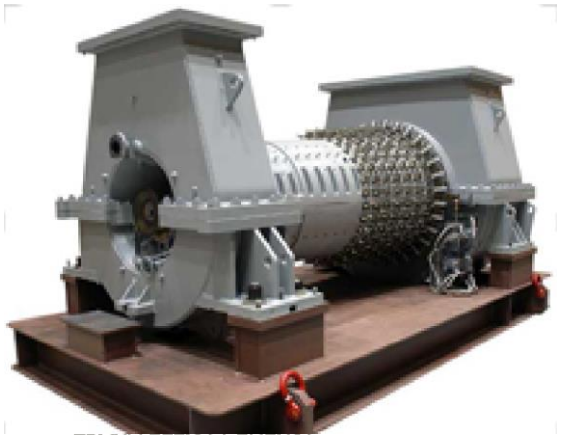
Steam Turbines

Cryogenic Expanders



Integrally Geared Compressors

Cryogenic Pumps



Axial Compressors

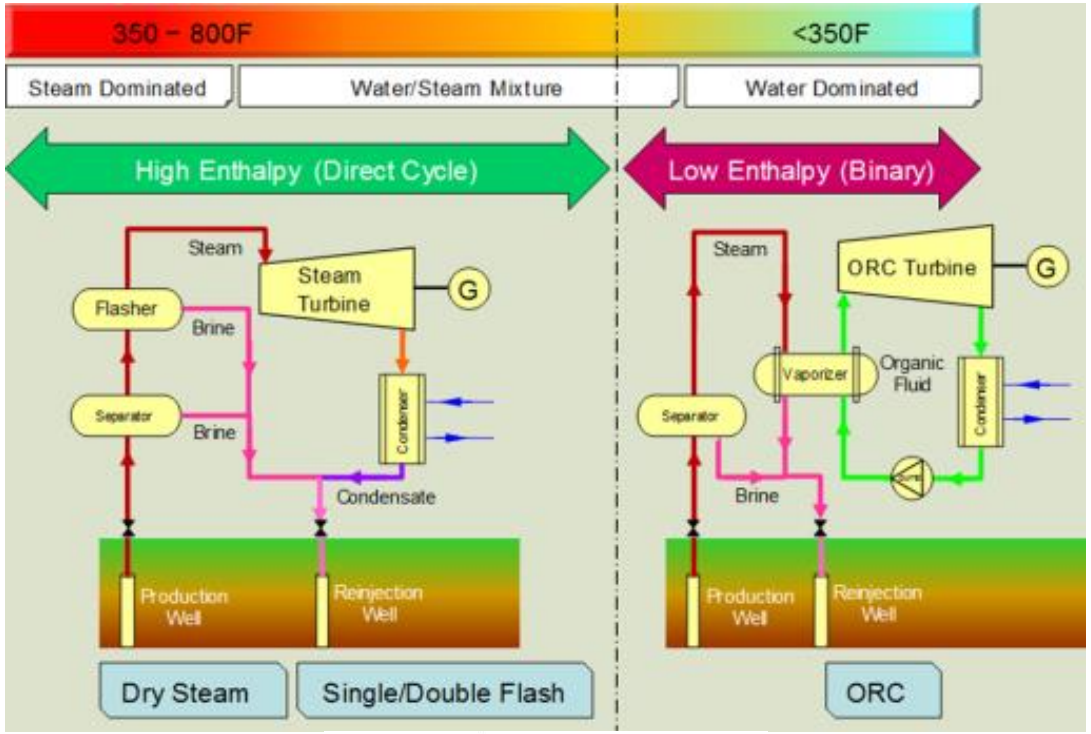
Inline Centrifugal Compressors

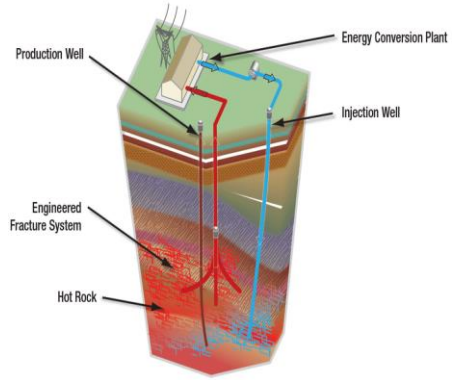
Single Stage Centrifugal Compressors

Renewable Energy – Geothermal

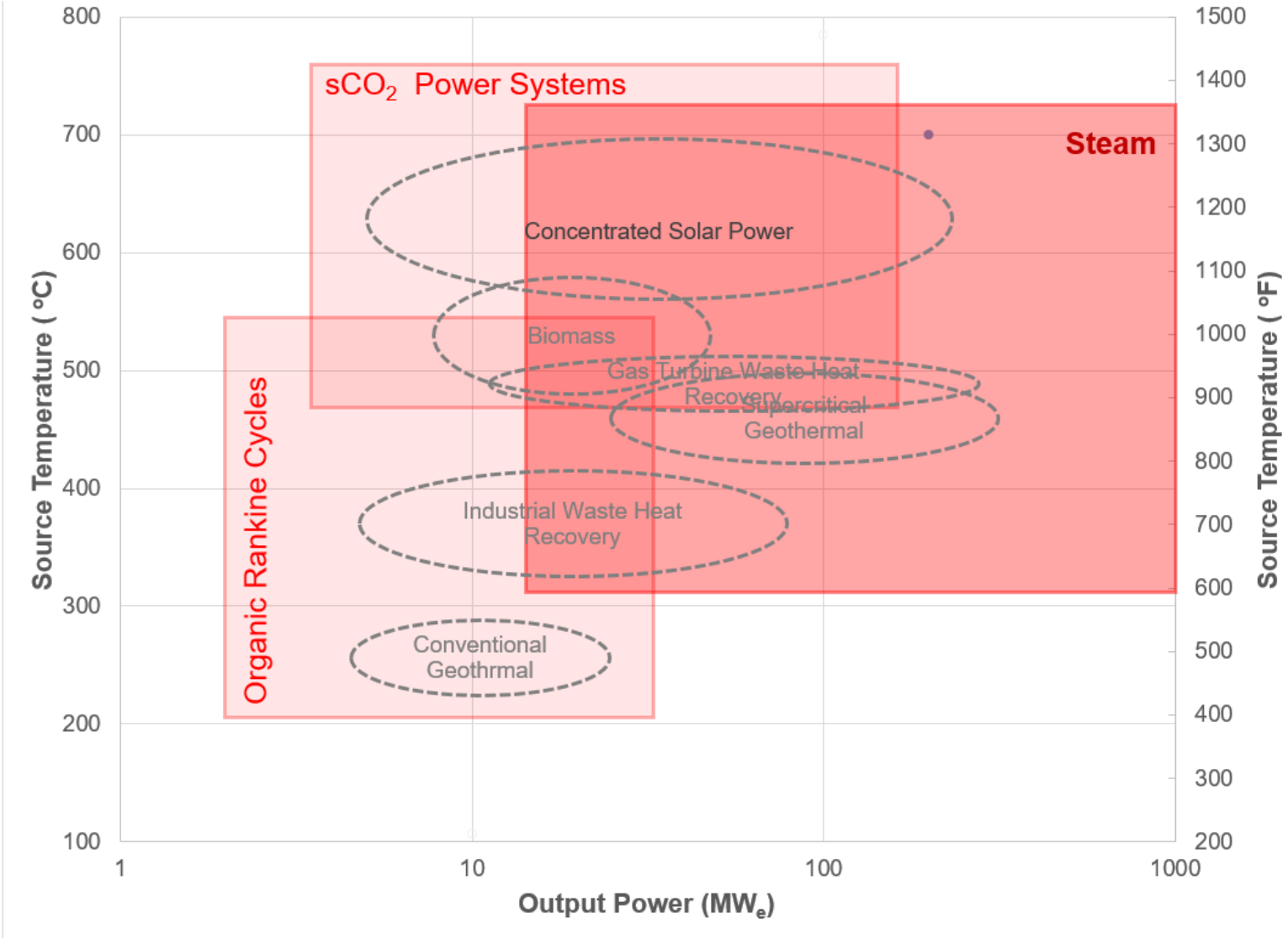
- Conventional:
  - Inlet Temperature 480ºF (250ºC)
  - Power range 2 MW – 30 MW
  - Shallow (<5km)

- Supercritical (sEGS):
  - Inlet Temperature 940ºF (500ºC)
  - Power range 30 MW – 150 MW
  - Ultra-deep (>10km)





Steam, ORC, and sCO_2 Cover a Wide Range of Applications



- No one technology covers all applications.
- Steam Turbines still cover a wide range of applications.
- Focus on improving our product ranges and performance to better meet the needs of renewable applications.

FOCUS ON CONVENTIONAL COMPRESSION CHALLENGES FOR GEOTHERMAL SYSTEMS

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Material Challenges in Conventional Geothermal Applications

- Temperature
  - Conventional Geothermal
    - T<300°C (572°F)
  - Future – Ultra High Temperature
    - T<600°C (1112°F)
- Corrosion
  - Varies by location, but many corrosive elements
  - Depends on the system design
- Erosion
  - Varies by location
  - Depends on the system design
- Coatings can be used to minimize effects

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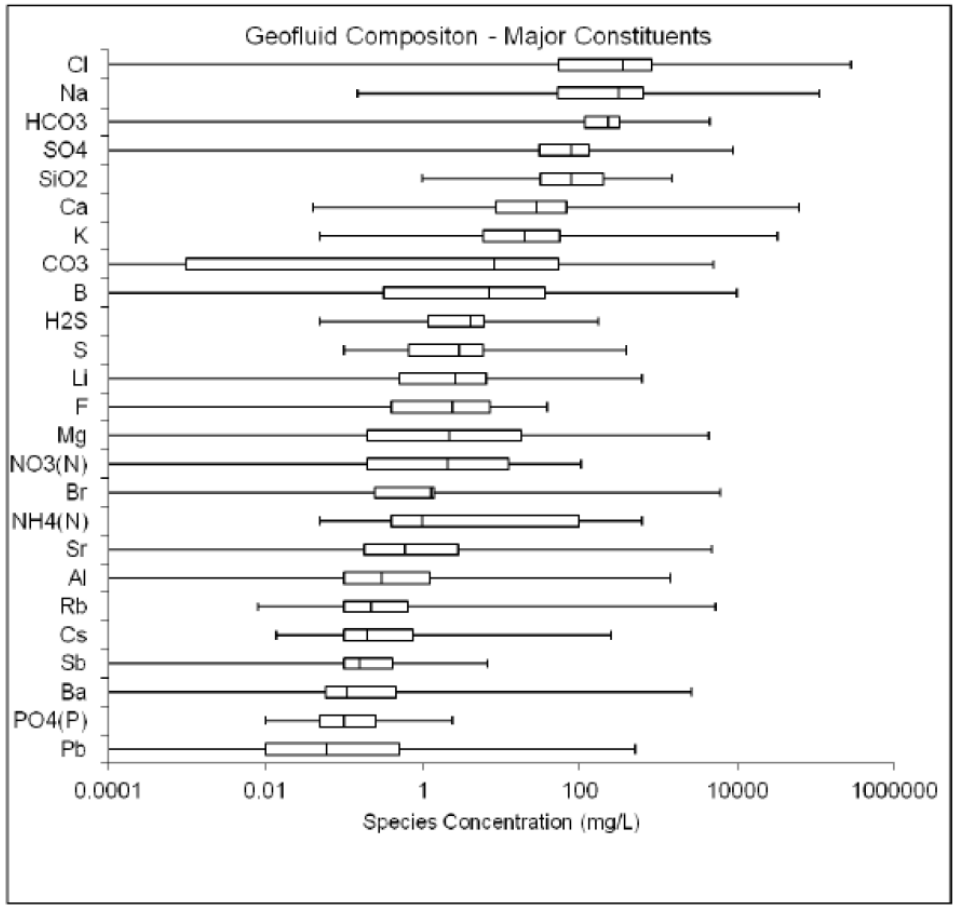
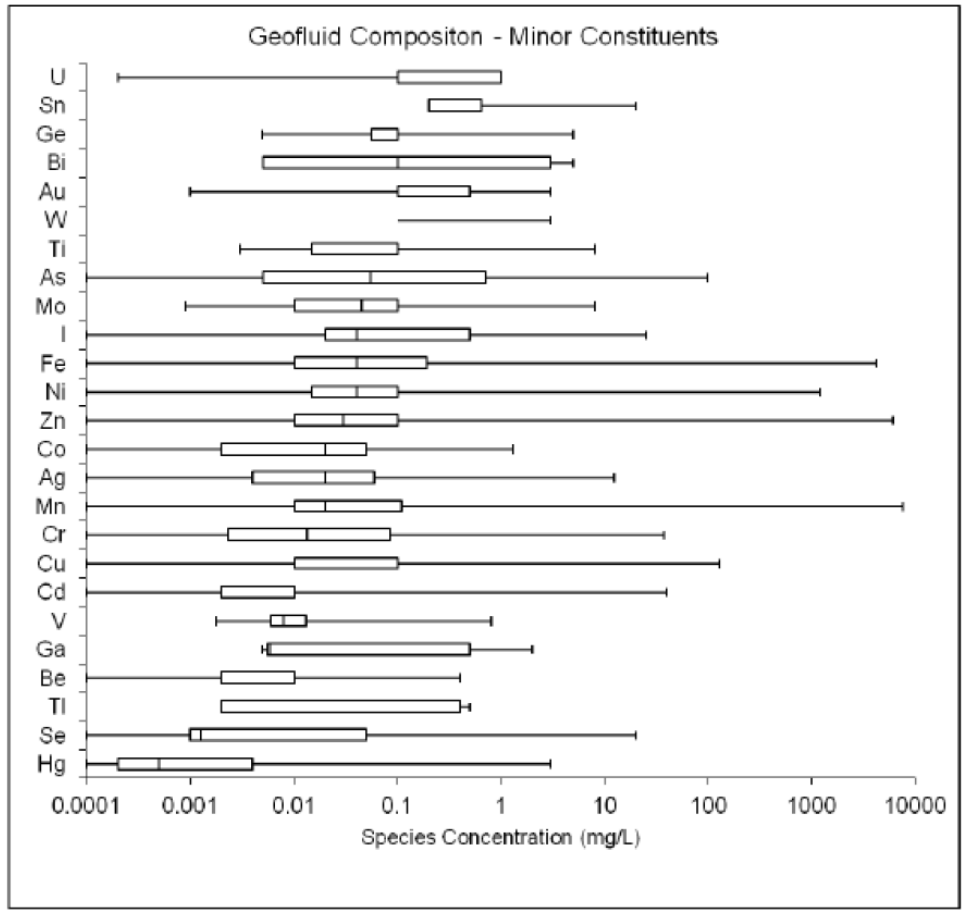
Possible Constituents in Geothermal Fluids





47 of 118 (40%) of the elements on the periodic table are listed

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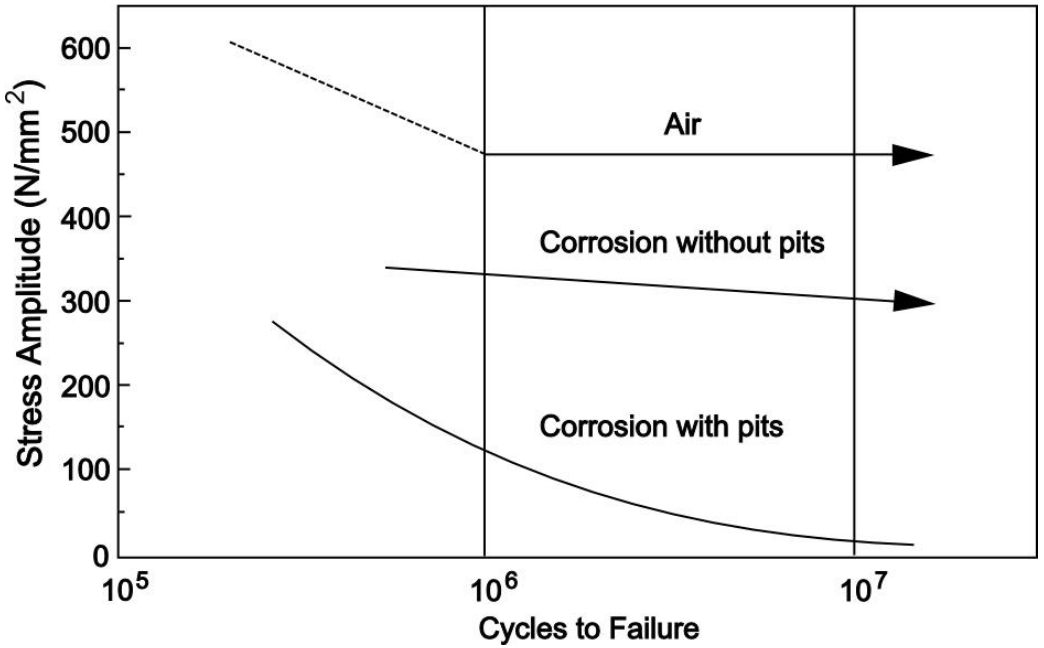
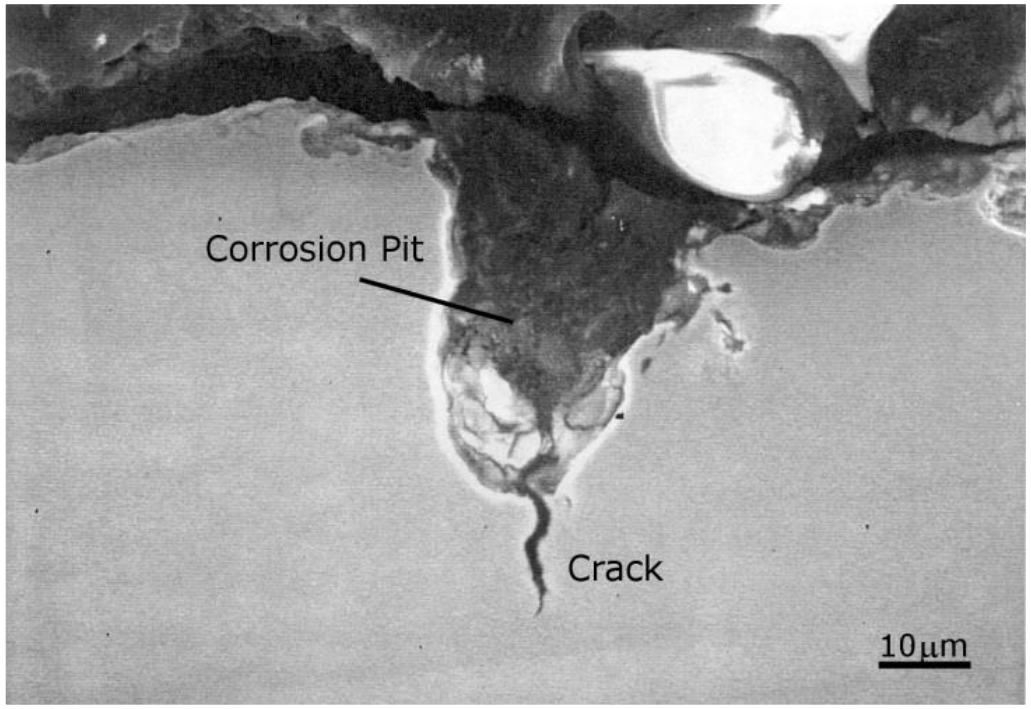
Pitting Corrosion and High Cycle Fatigue Cracking



Pitting corrosion can result in a 5x loss of fatigue endurance limit



Textbook image of a corrosion pit. Sharp cracking creates a localized stress riser that act as initiation sites for fatigue cracks

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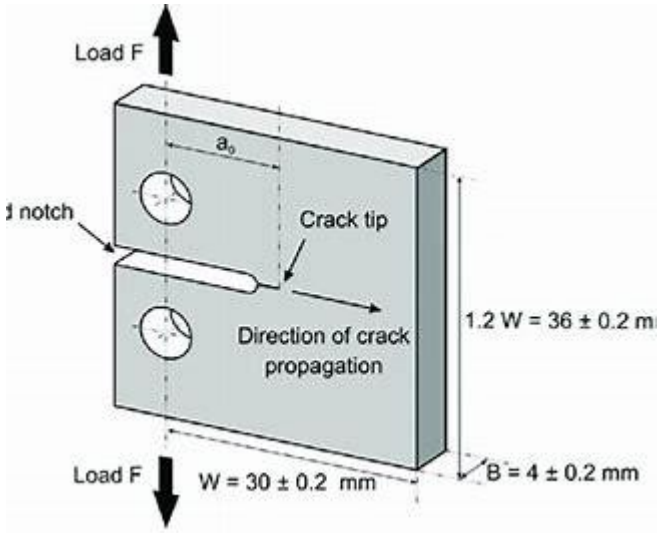
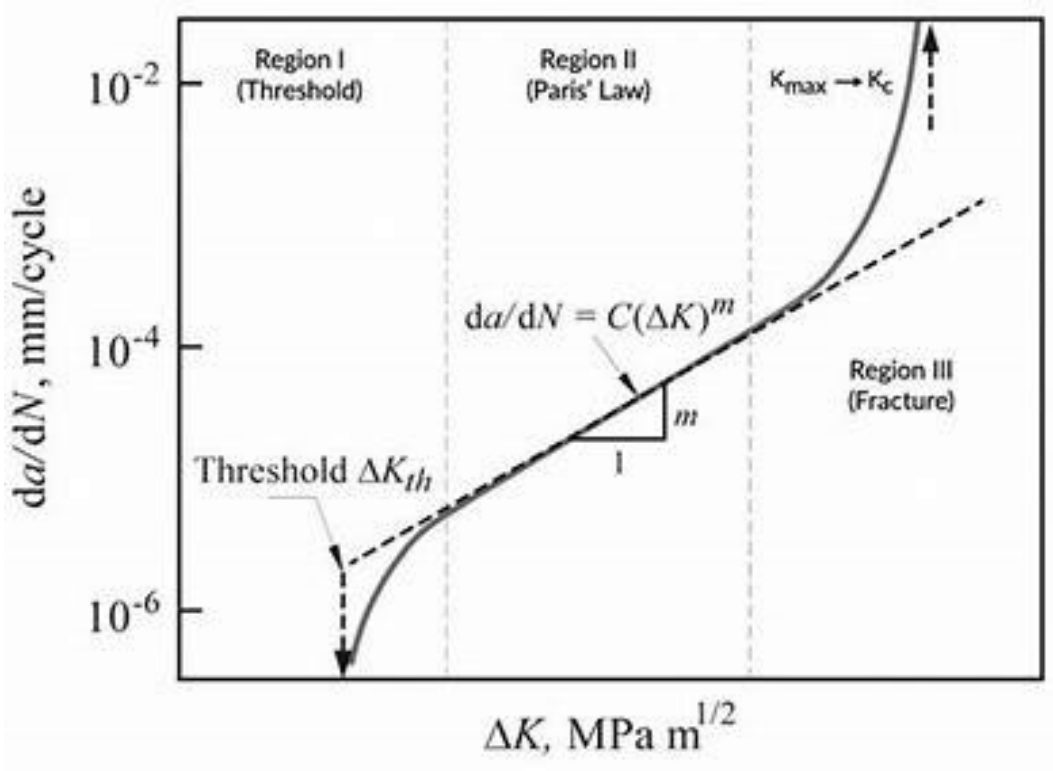
Fatigue Testing for Environmental Factors

ASTM E647 is Standard Method for Measurement of Fatigue Crack Growth Rates

- Used to determine crack growth rates, but also the threshold level for fatigue cracking





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Stress Corrosion Cracking (K_{1SCC}) per ASTM F1624

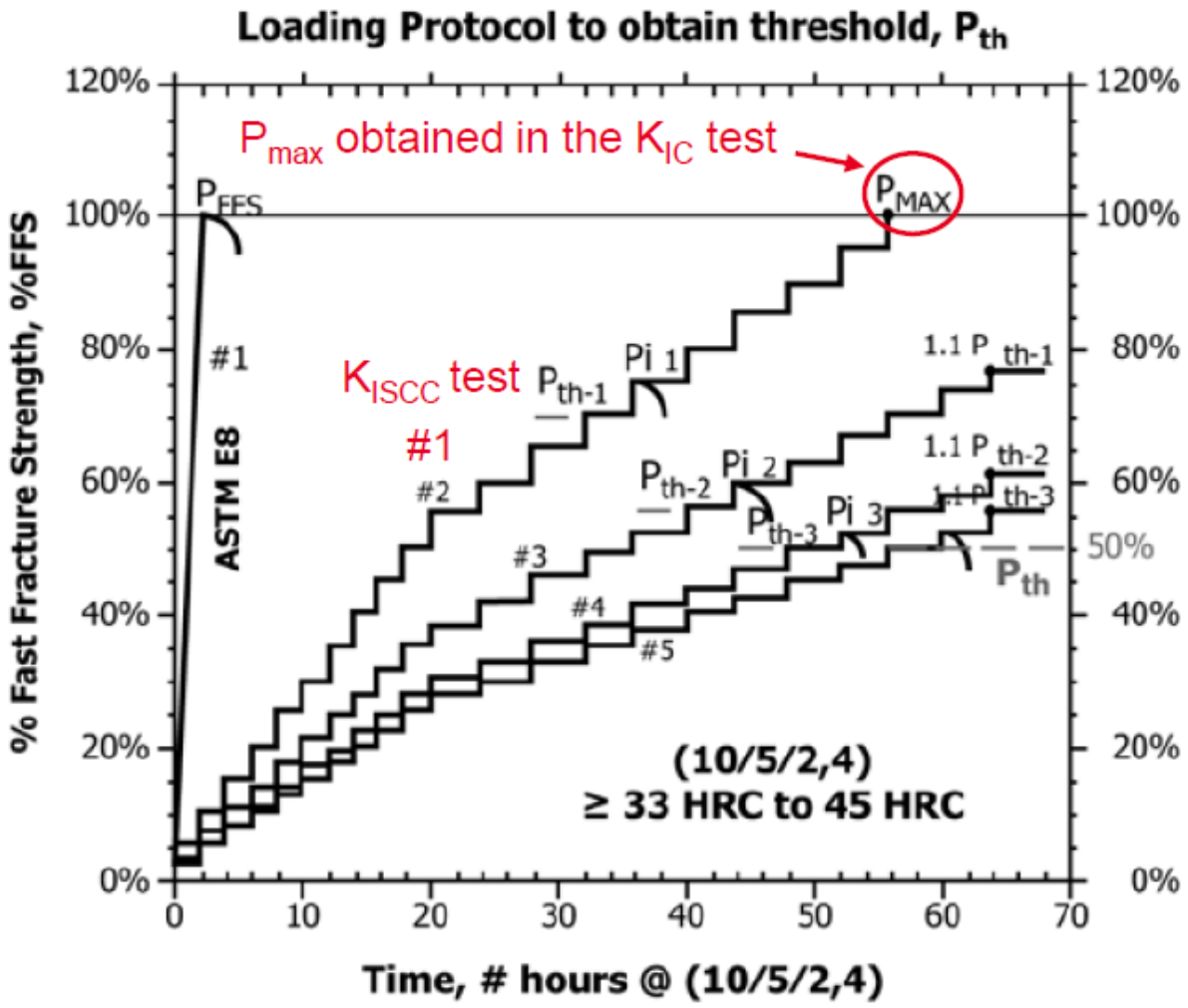
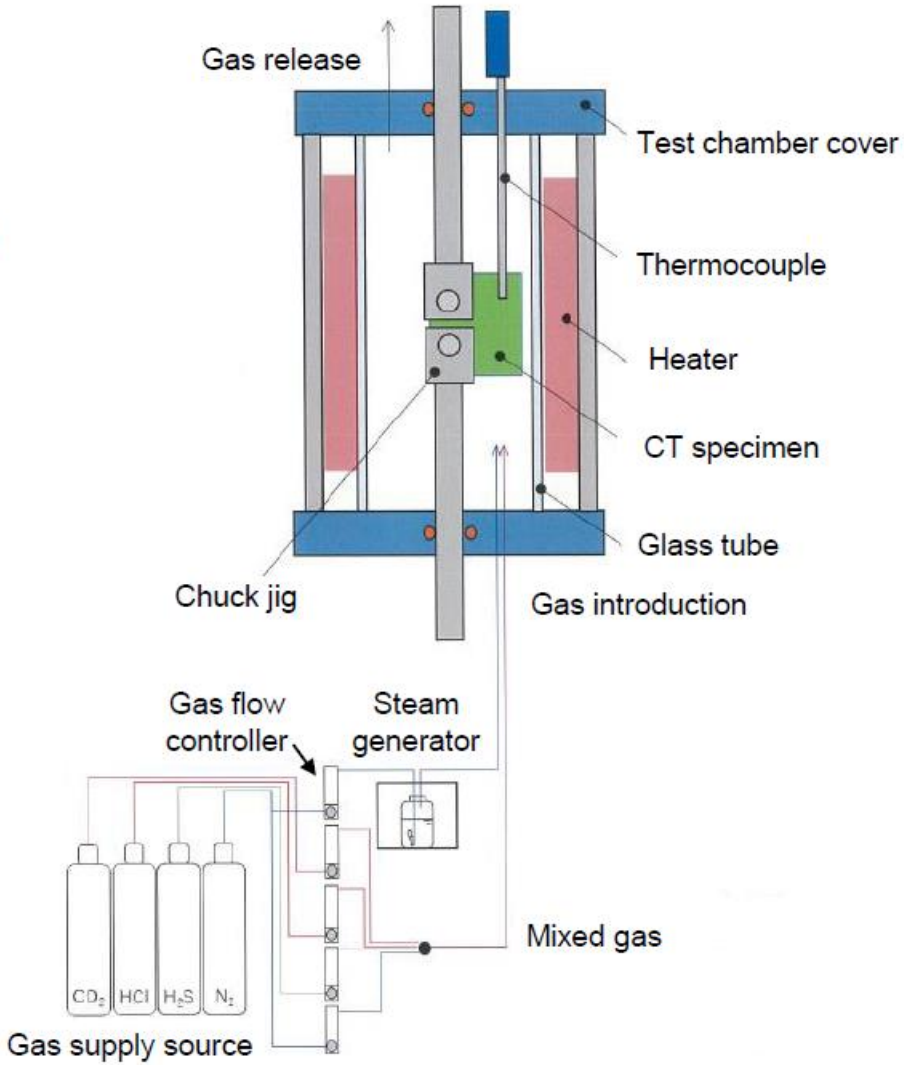


FIG. 3 Schematic of a (10/5/2,4) Step Loading Profile to Determine Threshold for the Hardness of Steel ≥ 33 HRC to 45 HRC



Schematic diagram of the K_{ISCC} test

FOCUS ON FUTURE COMPRESSION CHALLENGES FOR GEOTHERMAL SYSTEMS

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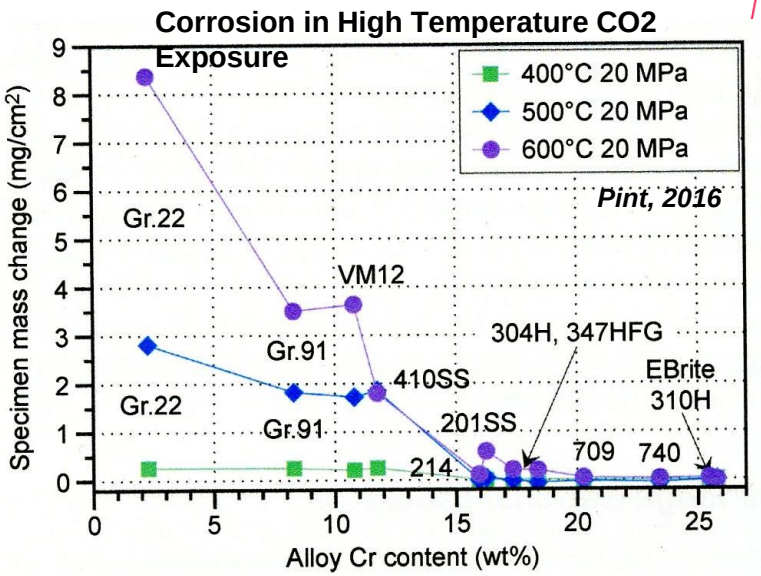
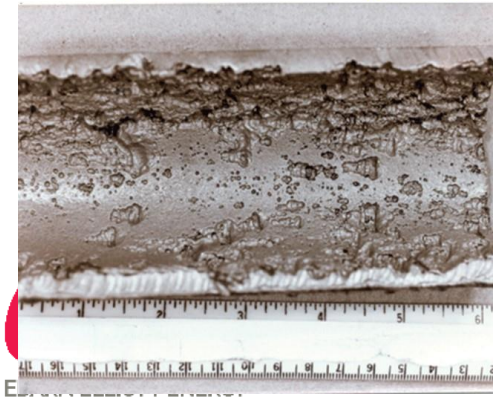
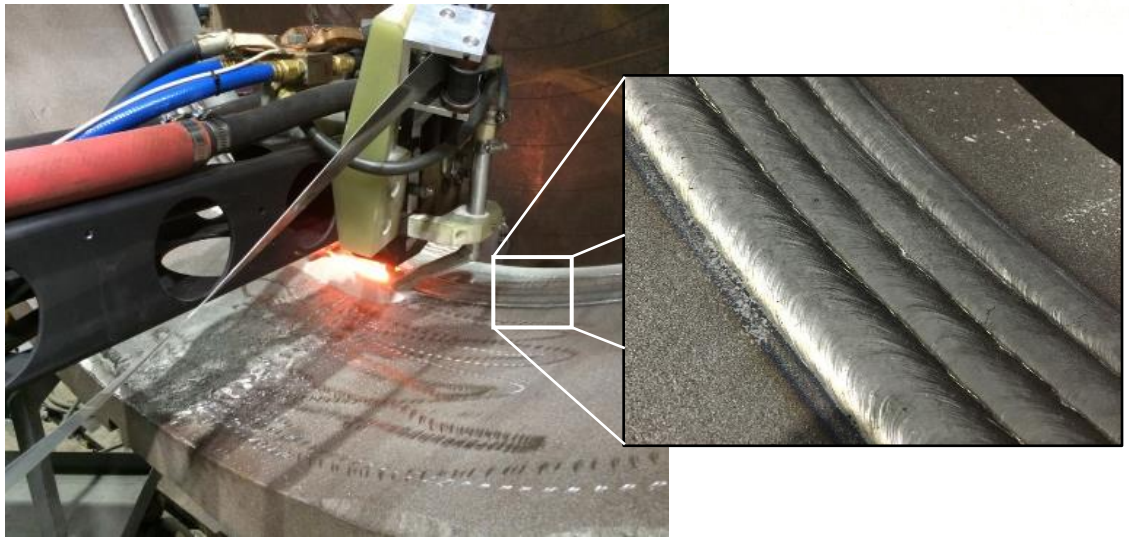
Materials Considerations For CO_2

- 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



$$CO_2 + H_2O \leftrightarrows H_2CO_3$$



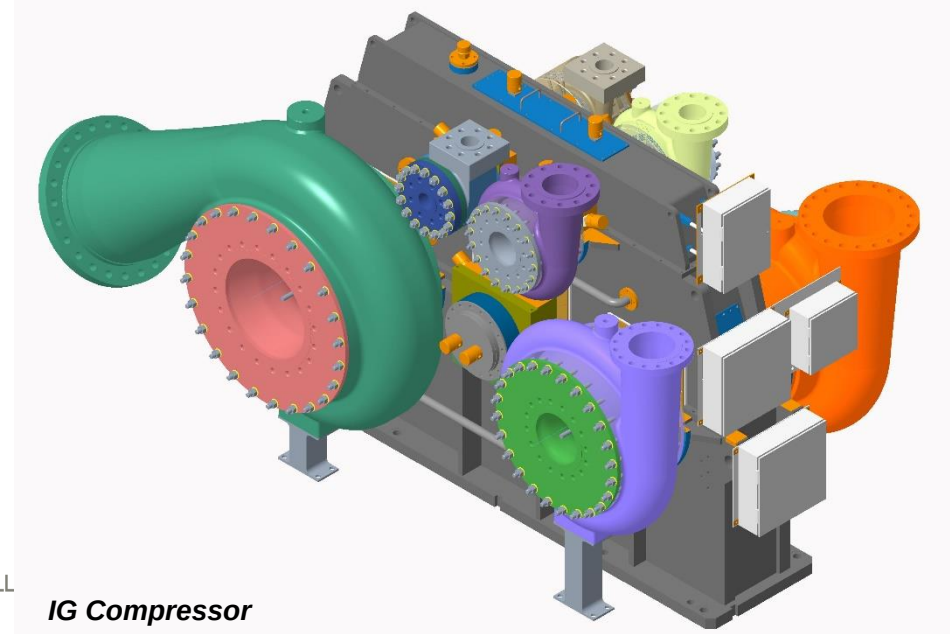


Cladding Process

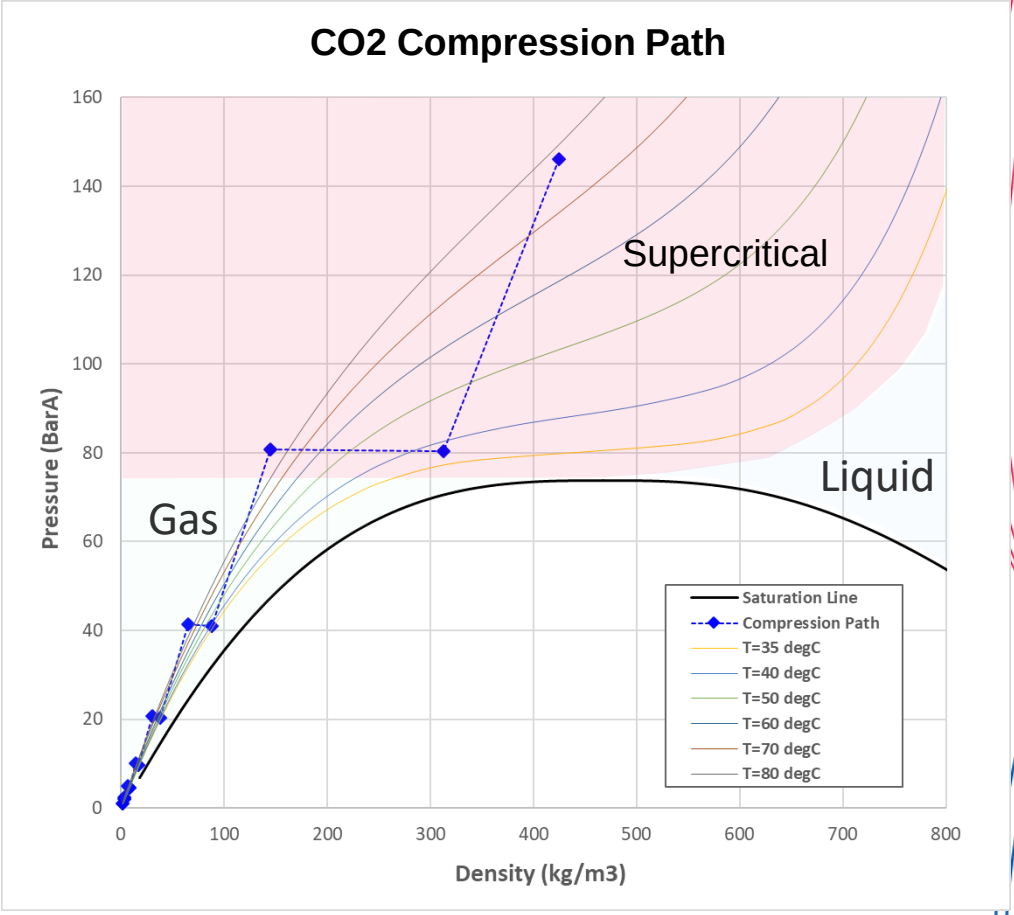
Compressor Casing

sCO_2 Compressor Design Considerations

- 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

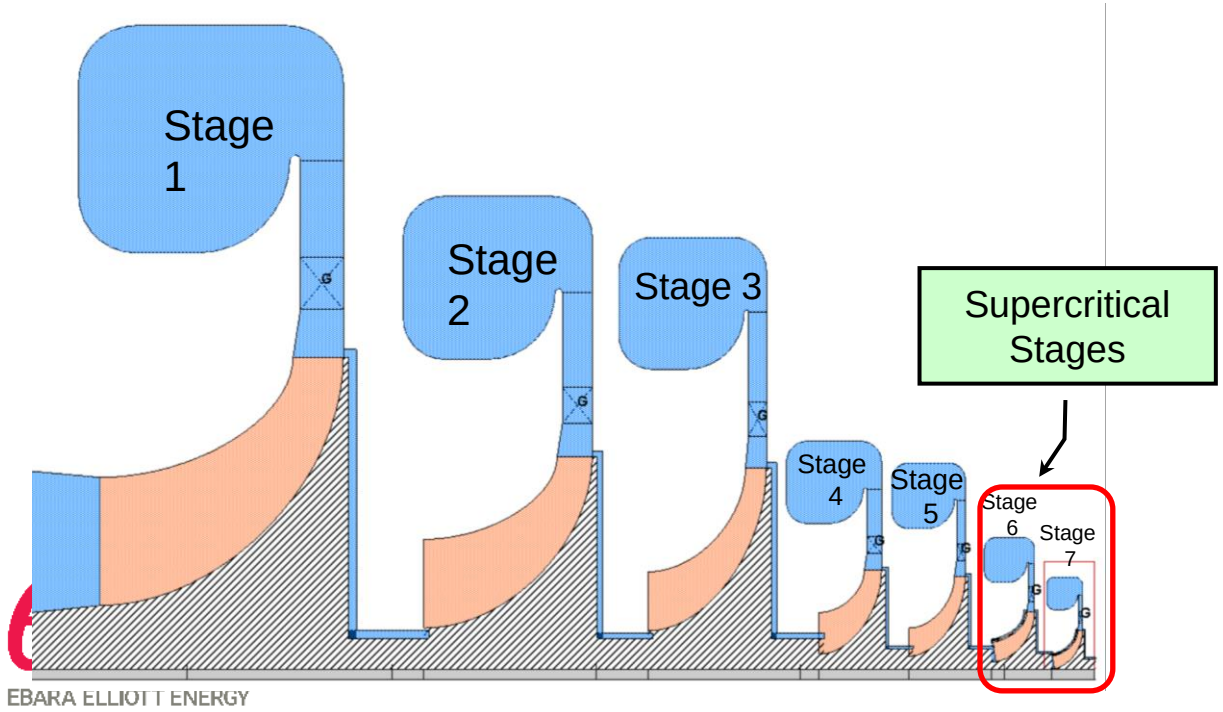


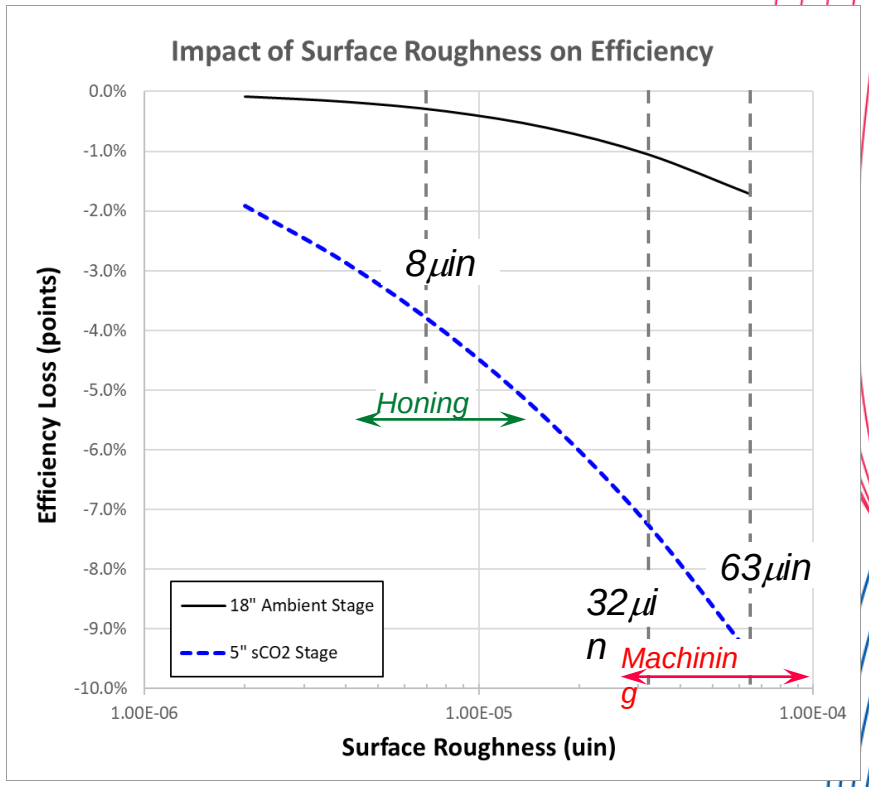
IG Compressor



Aerodynamic Design Challenges of sCO_2

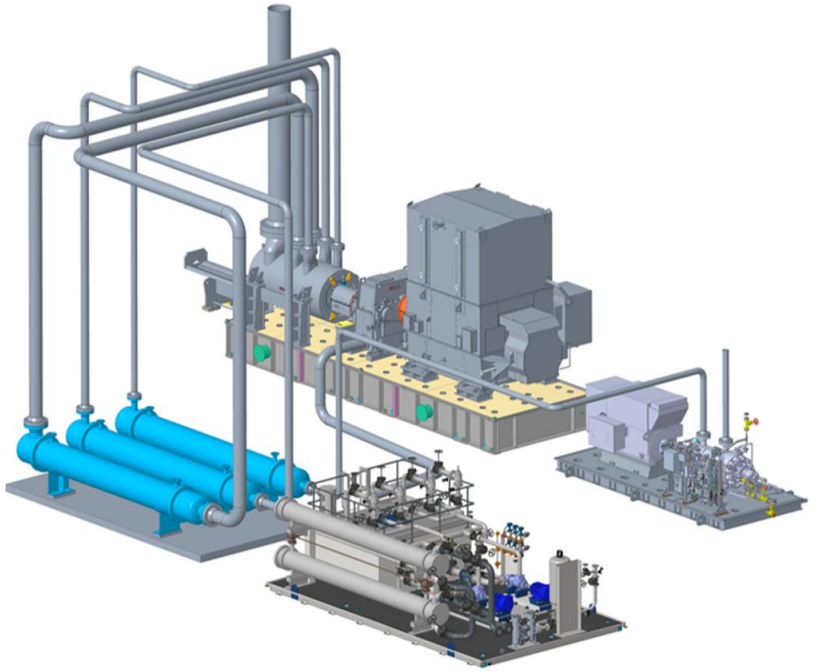
- Supercritical stages are small, even in high power applications
- Can be difficult to maintain tolerances necessary for good performance
- May need to run below optimum speed due to mechanical limits

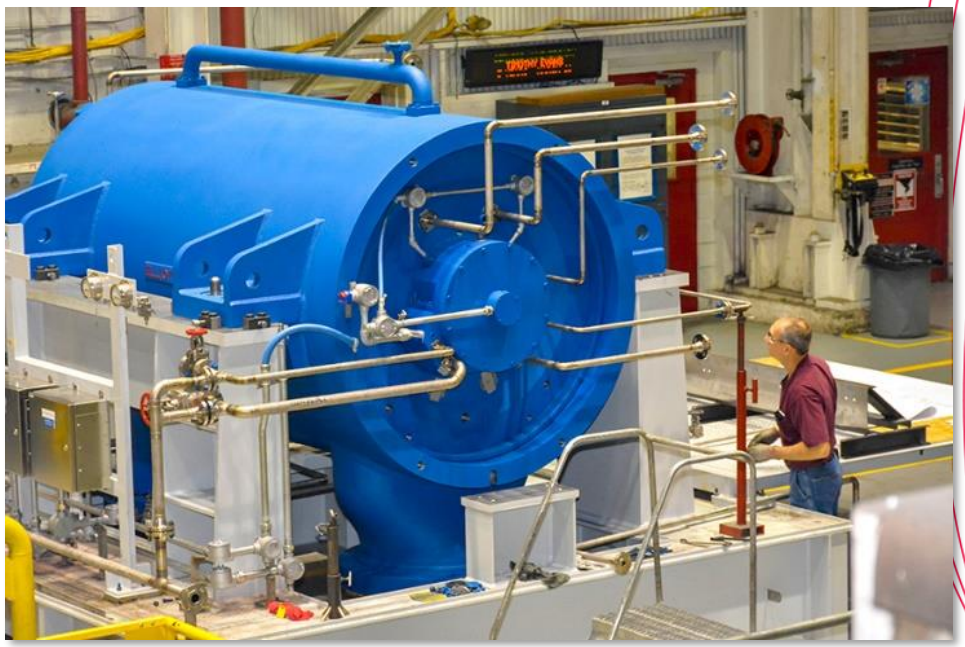




CAPEX and OPEX Targets Impact the Design of the CO_2 Compressor

- 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.

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Summary

- Conventional Geothermal Systems do not have a large need for compression.
- But the expectation is that need will grow over time.
- sCO_2 Power Systems have applications in future Geothermal systems.
    - Challenges do existing in the compressor designs.