Compression Challenges for Carbon Dioxide

July 31, 2024

Robert Pelton

Introduction

Primary Applications for Super-Critical CO_2 Compression

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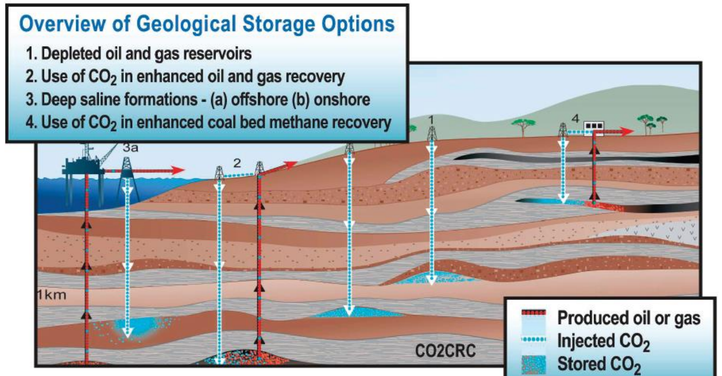
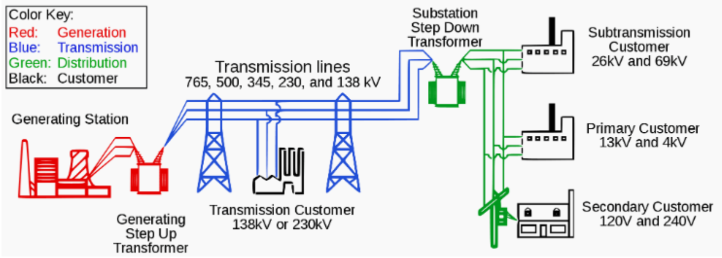
Carbon Sequestration

- **High Efficiency:** Its high density and low viscosity allow for better mass transfer, resulting in higher capture rates.
- **Lower Energy Consumption:** sCO_2 can lead to lower energy requirements for the carbon capture process
- **Reduced Footprint:** The compact nature of sCO_2 systems allows for smaller equipment sizes and reduced infrastructure compared to other capture technologies.
- **Versatility:** sCO_2 can be used in a variety of carbon capture applications, including pre-combustion, post-combustion, and oxy-fuel processes.



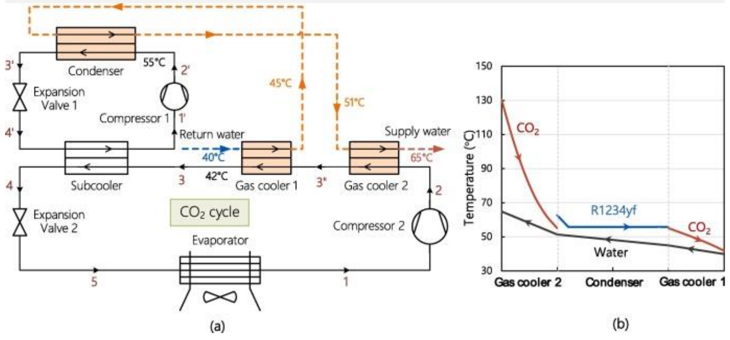
Power Generation

- **Higher Efficiency:** sCO2 power cycles operate at higher temperatures and pressures compared to steam turbines, resulting in higher thermodynamic efficiency.
- **Compact Size:** more compact than steam turbines, allowing for smaller footprint power plants. This is especially advantageous in situations where space is limited or where decentralized power generation is desired.
- **Flexibility and Load Following**: Ability to ramp up and down more quickly, making them well-suited for supporting variable renewable energy sources like wind and solar.



Heat Pumps

- **Efficiency:** Ability to operate at high pressures and temperatures, which allows for efficient heat transfer, resulting in lower energy consumption.
- **High Temperature Capability:** One of the advantages of sCO2 is its ability to reach high temperatures, making it suitable for industrial applications where high-temperature heat is required, such as in industrial processes or power generation.
- **Compact Design:** compact making them suitable for installations where space is limited. a natural refrigerant with low global warming potential (GWP) and zero ozone depletion potential (ODP).



Introduction
Compression Equipment Configurations

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Beam Style

- **Low Maintenance Requirements:** The design of integrally geared compressors typically results in lower maintenance requirements.
- **High Reliability:** Robust configuration with minimal seals, minimal bearings, and low dynamic pressures makes for a robust design at high pressures.
- **High Efficiency at High Flow Rates**: Centrifugal barrel compressors are highly efficient at handling high flow rates. They can effectively compress large volumes of gas to moderate pressures with relatively low energy consumption.

Integrally Geared

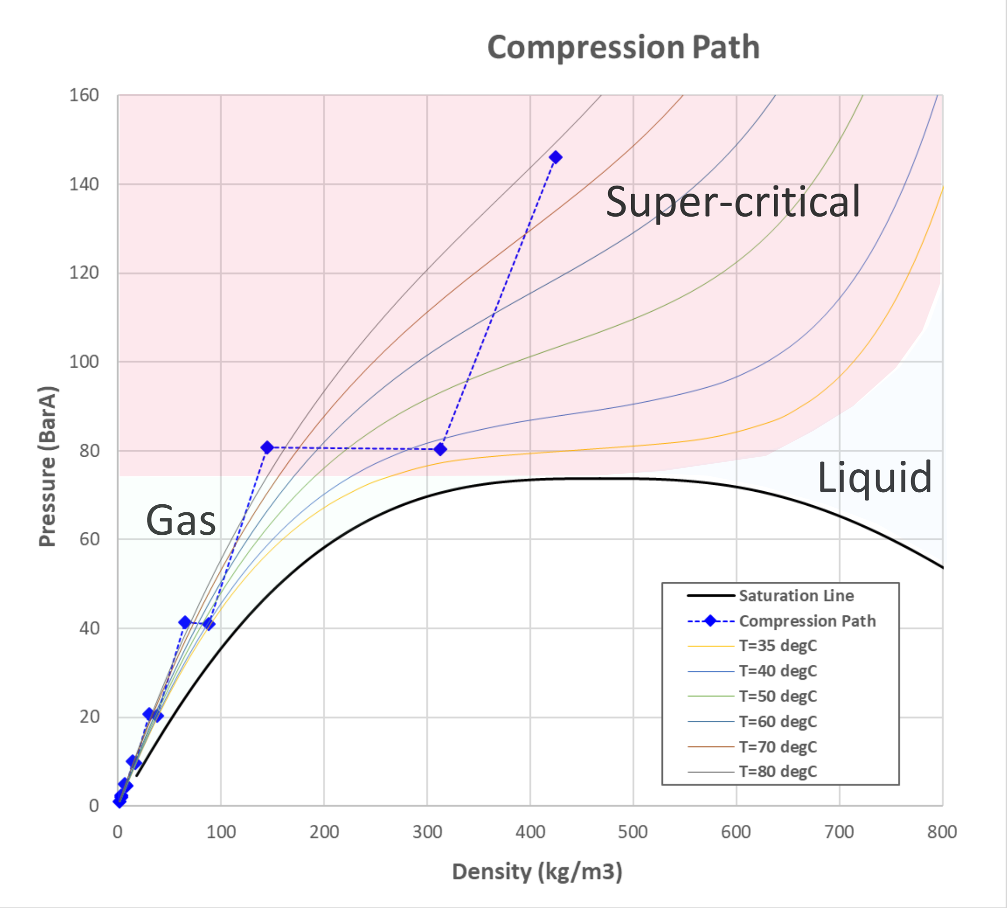
- **Modular Design:** These compressors feature a modular design with multiple compressor stages driven by individual gears. This modular construction allows for flexibility in configuration and scalability.
- **Inter-cooling:** Ability to inter-cool each stage allows the ability to reduce power consumption by approaching.
- **Compact Footprint:** Despite their high capacity and performance, integrally geared compressors have a relatively compact footprint compared to other types of compressors with similar capabilities.

Reciprocating

- **High Compression Ratios:** Reciprocating compressors are capable of achieving high compression ratios, making them suitable for applications requiring high-pressure delivery.
- **Cost-effectiveness for Small to Medium Applications**: Generally more cost-effective for small/medium applications. They have lower initial capital costs and are simpler in design.
- **Efficiency at Low Flow Rates**: Reciprocating compressors excel at handling low flow rates efficiently. Suitable for applications where variable demand is common or where the compressor needs to operate at different flow rates.

CO2 Sequestration

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

Compression and Dense Phase Pump Solution for CO_2 Sequestration

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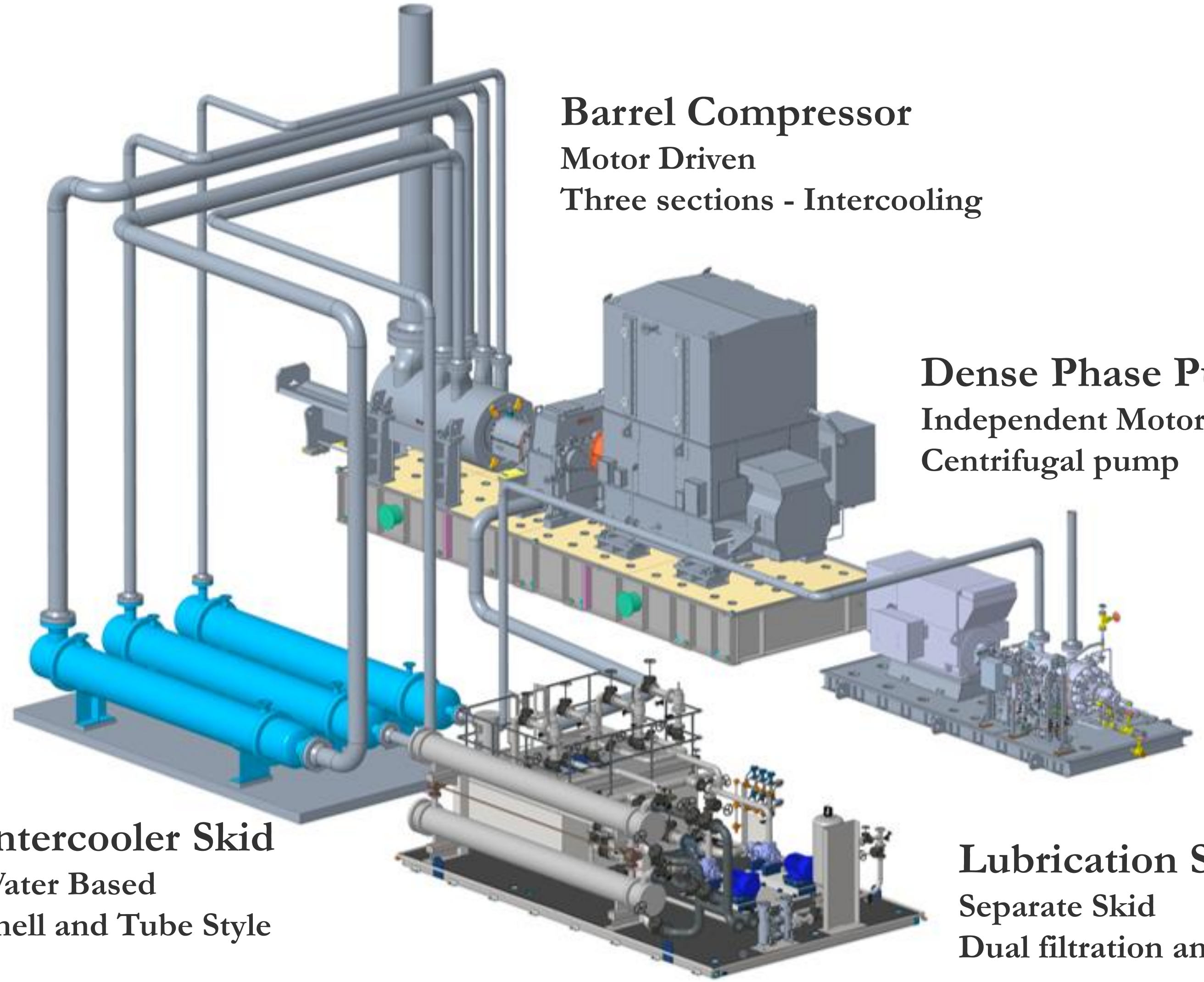
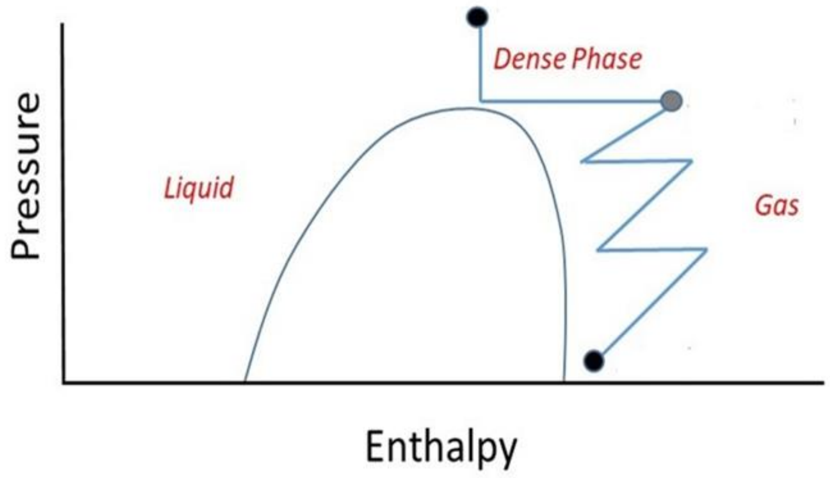


Barrel Compressor
Motor Driven
Three sections - Intercooling

Dense Phase Pump
Independent Motor Drive
Centrifugal pump

Intercooler Skid
Water Based
Shell and Tube Style

Lubrication System
Separate Skid
Dual filtration and heat exchangers



CO_2 Sequestration
Highly reliable process to raise CO2 to dense phase.

Integrally Geared Compressor for CO_2 Sequestration

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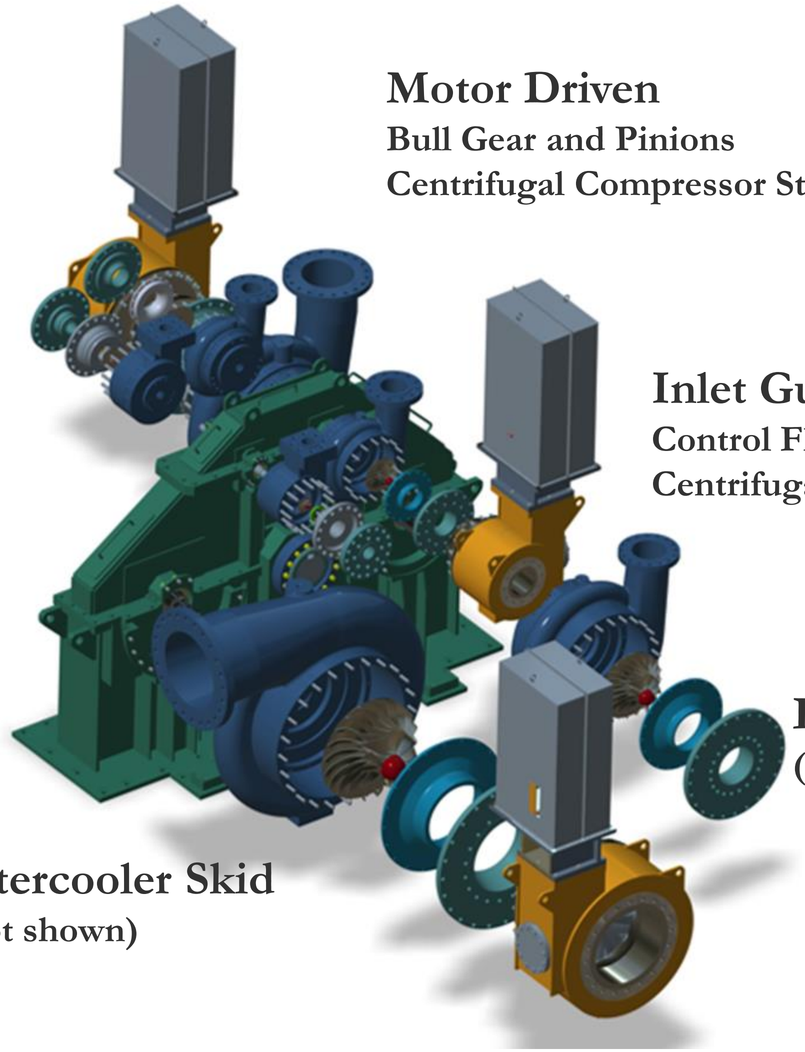


Motor Driven
Bull Gear and Pinions
Centrifugal Compressor Stages are Overhung

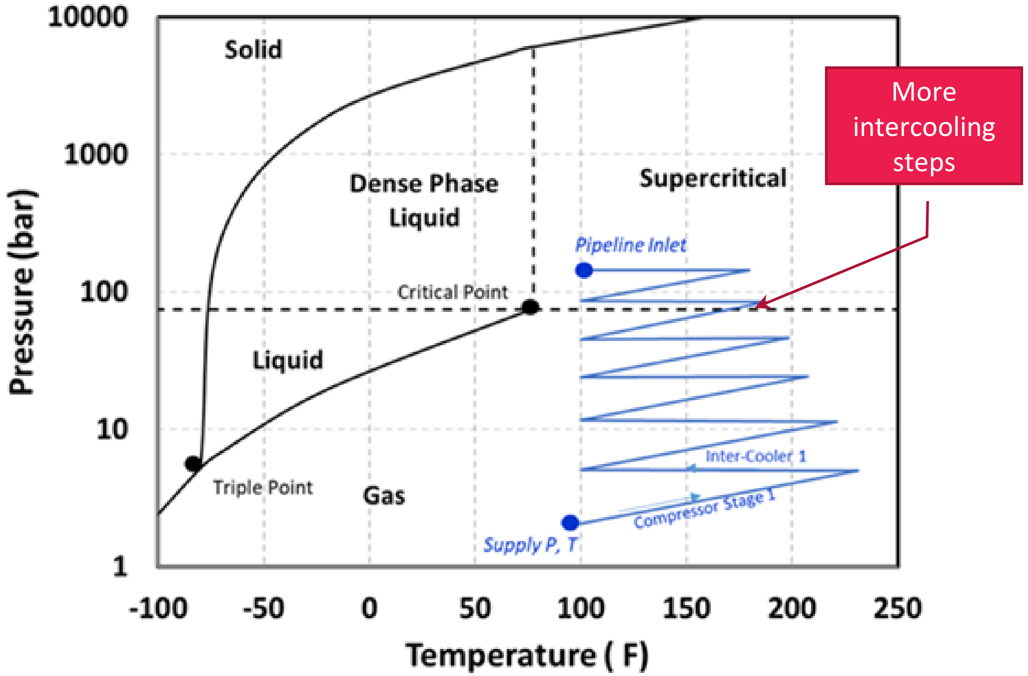
Inlet Guide Vanes
Control Flow Rate
Centrifugal pump

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.



Compression Options for MW Scales

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	Integrally Geared Compressor	Beam Style Compressor
Open Loop Systems *(Sequestration)*	**OPEX:** Simple integration of stage intercooling to reduce power consumption	**Reliability:** Reduced number of gas seal points is advantage for barrel configuration.
Closed Loop Systems *(Power Generation & Heat Pumps)*	**Modularity:** over-hung stages allow ability to quickly adjust design in development or test stand. **Wide Operating Range**: ability to apply range extension technologies. **Expander Stage Integration:** Can integrate expander. Good for 2-25 MW (WHR)	**Mature Technology:** for high-pressures. **Hermetic Seal Potential:** Ability to seal against lower pressures. **Mechanical Losses:** fewer number of bearings and reduced losses. Good for 10-200 MW (Nuclear/Power Gen)

Technology/Risk Areas to Address

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	Integrally Geared Compressor	Beam Style Compressor
Open Loop Systems *(Sequestration)*	Mature Technology. Seal Improvements for Leakage.	Commercially accepted technology in O&G markets CAPEX and OPEX tend to be higher than IGC.
Closed Loop Systems *(Power Generation & Heat Pumps)*	Seal Improvements for improve reliability and leakage reduction. Limited data near critical point.	Gas Bearings/ Magnetic Bearing for seal-less systems. Limited data near critical point.

Conclusions

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- Challenge in **Sequestration systems** is managing the change is gas density.
- Challenge in **Closed Loop Systems** is managing leakage flow:
  - Hermetically sealed systems (gas or magnetic bearings)
  - Non-hermetically sealed systems (seal leakage and recovery)
- A general challenge is **managing performance and operability** of the cycle with stages operating near the dome.

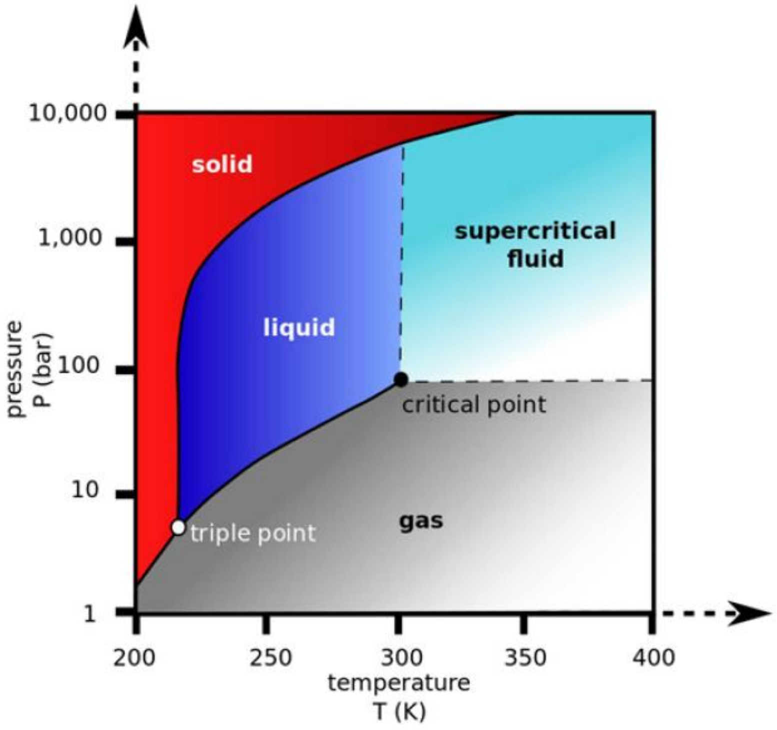
Material Considerations for Carbon Dioxide Compression and Storage

Derrick Bauer

July 31, 2024

Carbon Dioxide Storage

- Stored as a compressed gas or liquid
  - Material must be suitable for process temperature
- Corrosion
  - Dry CO_2 is not corrosive to steel
    - Carbon steel has been successfully utilized
  - Wet CO_2
    - Forms carbonic acid, highly corrosive to carbon and low alloy steels
    - 300 series stainless steels must be utilized
    - 13%Cr-4%Ni stainless steel (CA6NM) has been successfully utilized for wet CO_2 applications



CO2 Corrosion Rate on Carbon Steel

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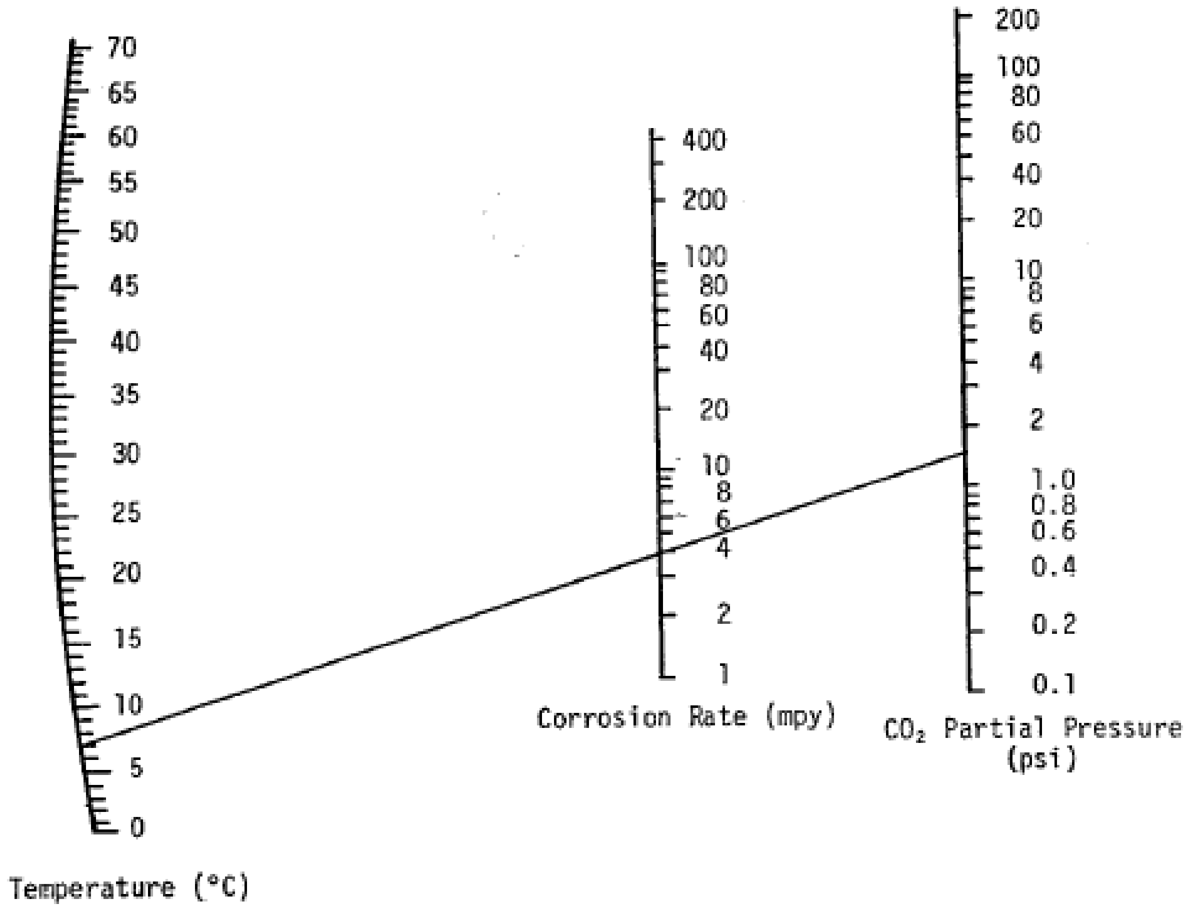

Source:

Corrosion Due to Use of Carbon Dioxide For Enhanced Oil Recovery, DeBerry, D. W., Clark, W. S. 1979

CO2 Corrosion in Oil and Gas Production – Selected Papers, Abstracts and References

NACE Task Group T-1-3

How much water makes CO_2 "wet"

Table 4-1 Indicative limits on maximum water content

Reference	*Maximum water content*				*Source of CO_2*
	[lb/MMScf]	[ppmW]	[ppmV]	[ppm/Mol%]	
Mohitpour, Golshan and Murray, 2006	18 - 30	157 – 261			-
Kinder Morgan, 2020	30	261			CO_2 reservoir
Equinor operated Snøhvit			50		CH_4+ stream
Dynamis CO_2 quality recommendations, De Visser et al., 2008				500	CCS

Source: DNV DNV-RP-F104

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Carbon Dioxide Storage and Compression

- DNV DNV-RP-J202
  - Provides recommended materials.
  - Temperature is only considered for temperatures below 400°C (750°F)

Table 5-1 Candidate material types compatible with dense and vapour CO_2

	No free water		*With free water*	
Material types	Pure CO_2	$CO_2 + H_2S$	Pure CO_2	$CO_2 + H_2S$
C-and low alloy steel	•	•		
304	•	•	•	•
316	•	•	•	•
13Cr	•	(•)	•	(•)
22Cr (duplex)	•	(•)	•	(•)
25Cr (duplex)	•	(•)	•	(•)
Nickel based alloys	•	•	•	•

Corrosion Testing in CO_2 Atmospheres

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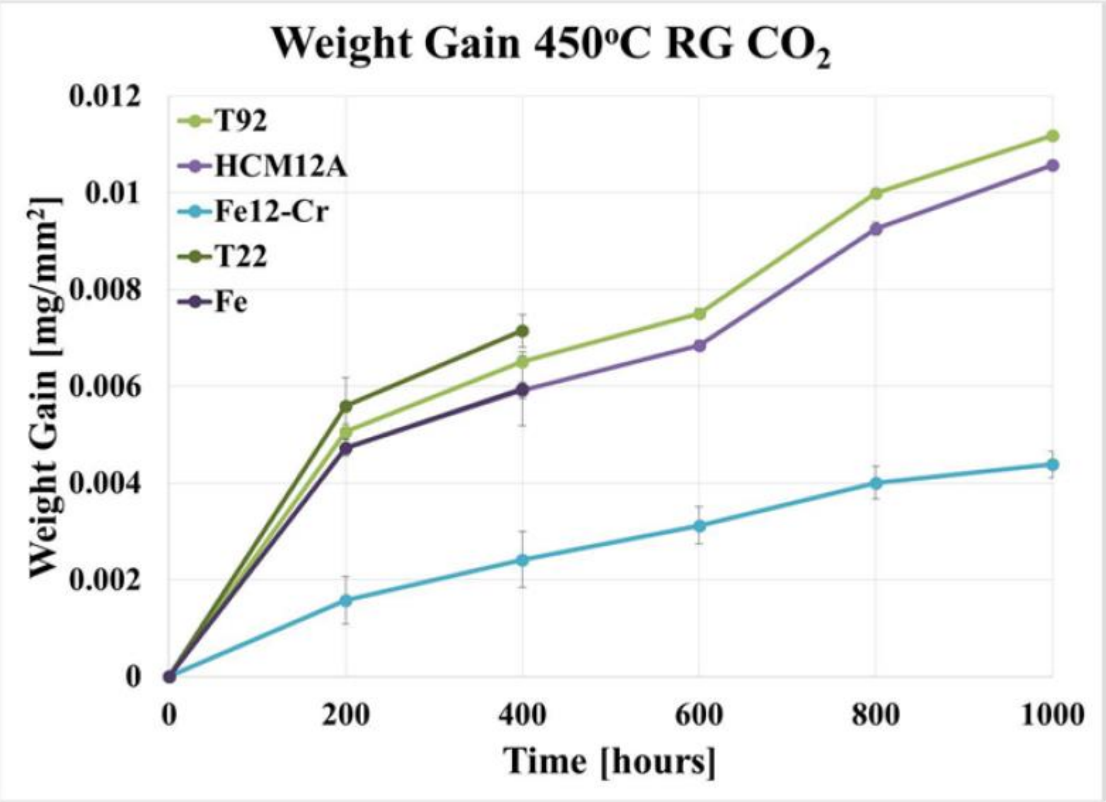
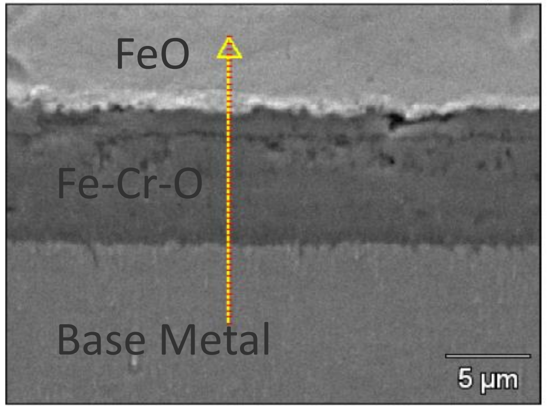
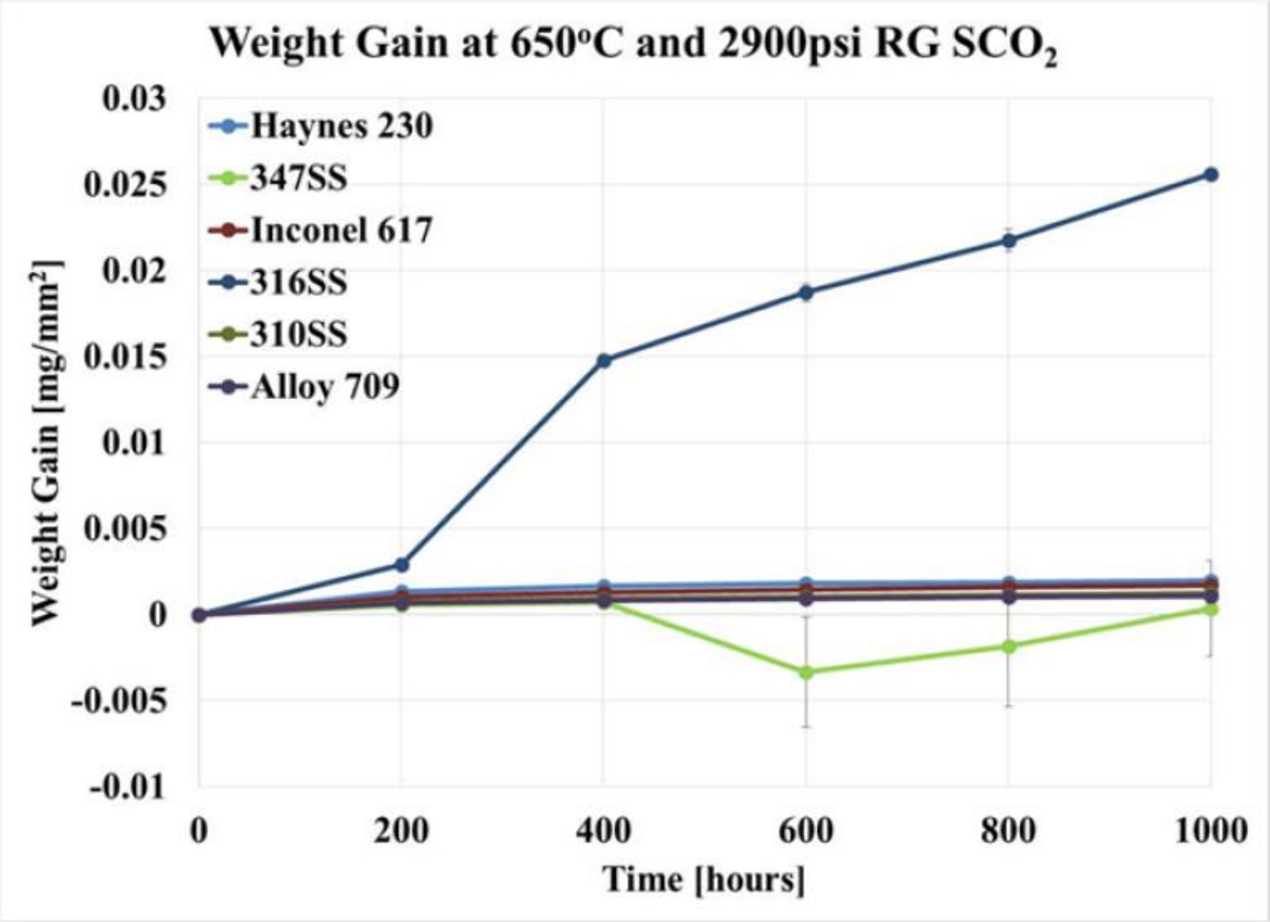
- Conditions
  - 2900 psi (20 MPa)
  - 3 ppm H_20
- 12%Cr stainless steel performed best compared to lower alloy materials
- All non-stainless steels experience oxide layer formation





Higher Temperature CO_2 Applications

- Conditions
  - 2900 psi (20 MPa)
  - 3 ppm H_20
  - 650°C (1200°F)
- Nickel based alloys showed best resistance to corrosion
- Impurities can result in significant changes to corrosion rates



Supercritical CO_2 Applications

- Oxidation of 316 stainless steel at 650°C
- Sensitization of austentic stainless steels at temperatures above 425°C (800°F) also must be considered over longer time durations

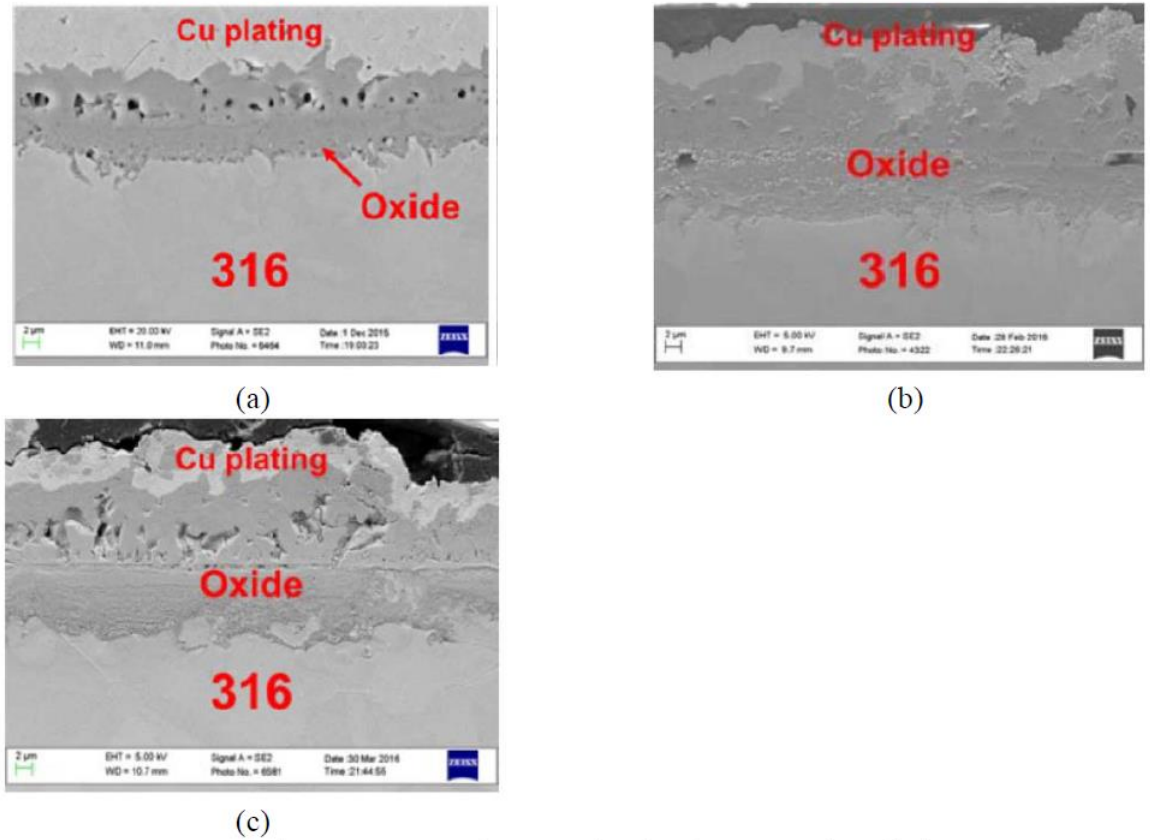


Figure 4.5: Cross-sectional SEM images showing the development of oxide layer on 316 stainless steel as a function of exposure time in RG SC-CO_2 at 650°C, (a) 200 hours, (b) 600 hours, and (c) 1000 hours.

Corrosion Resistant Overlay

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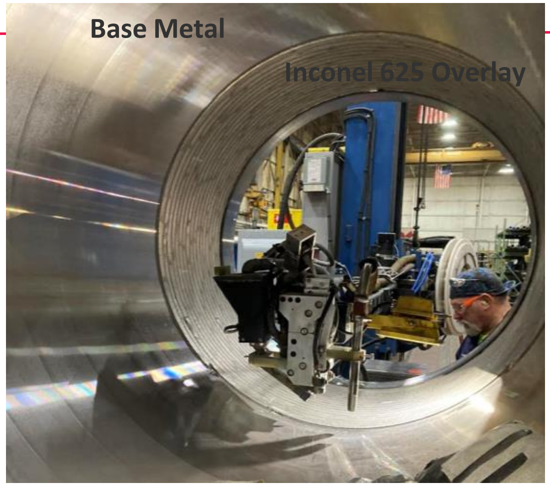
- Option for minimizing costs of compressors casing or storage tanks is to apply a corrosion resistant alloy on carbon steel (cladding)

Inconel 625 Overlay for Compressor Casings

- Utilized for highly corrosive environment
- Outer casing overlaid with Inconel 625
  - 8 mm thick overlay
  - Includes all surfaces contacting process gas
- Impellers are machined through 1-piece construction

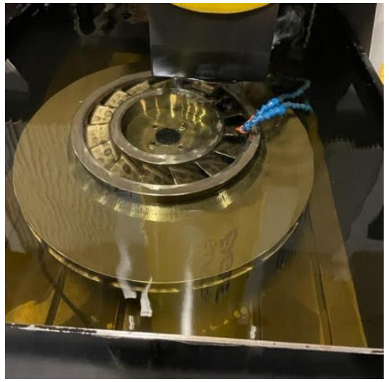


Inconel 625 Overlay Being Applied to Compressor Barrel Forging


Overlay of Compressor Nozzle


Casing with Overlay Ready for Stress Relief


Endwall Overlay


EDM Machining of 1-Piece Impeller

Low Temperature Considerations for Centrifugal Compressor Casings

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- Centrifugal compressor casing material selection is heavily influenced by the Minimum Design Metal Temperature (MDMT)
  - Liquefied CO_2 can be below room temperature
  - API 617 – 8th Edition Annex D provides typical materials
    - Based upon ASME BVPC Section VIII
- Purpose it to ensure that casing materials will remain ductile at the lowest possible temperatures the casings will be exposed to

Multi-Stage Centrifugal Compressor Casing

Slip Planes Provide Ductility

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- Slip planes allow layers of atoms to slide past each other
  - These planes are thermally activated in Body-Centered Cubic Structure
  - Slip planes are always active in Face-Centered Cubic Structure

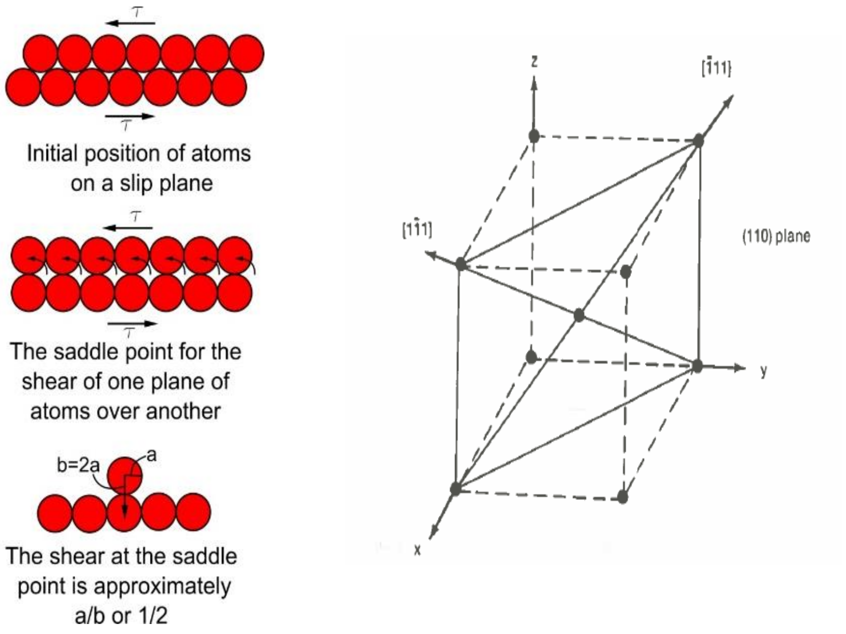
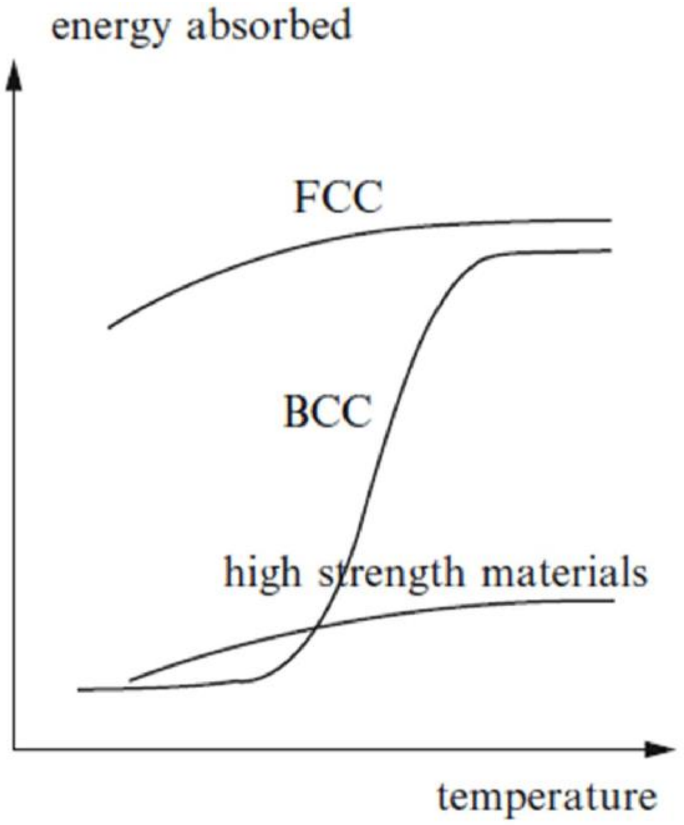


Illustration of Slip Planes within a Metallic Material



Testing the Toughness of Steel and Other Alloys

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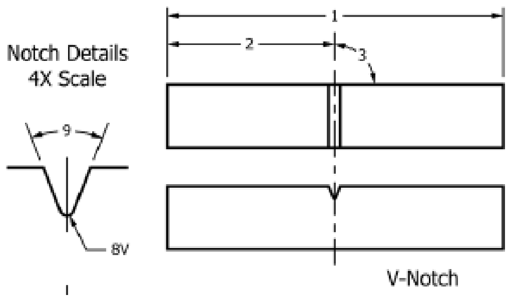
- Charpy V-Notch Impact Testing



Standard Charpy V-Notch Impact Specimen

Charpy V-Notch Impact Specimen submerged in cooling bath at required testing temperature

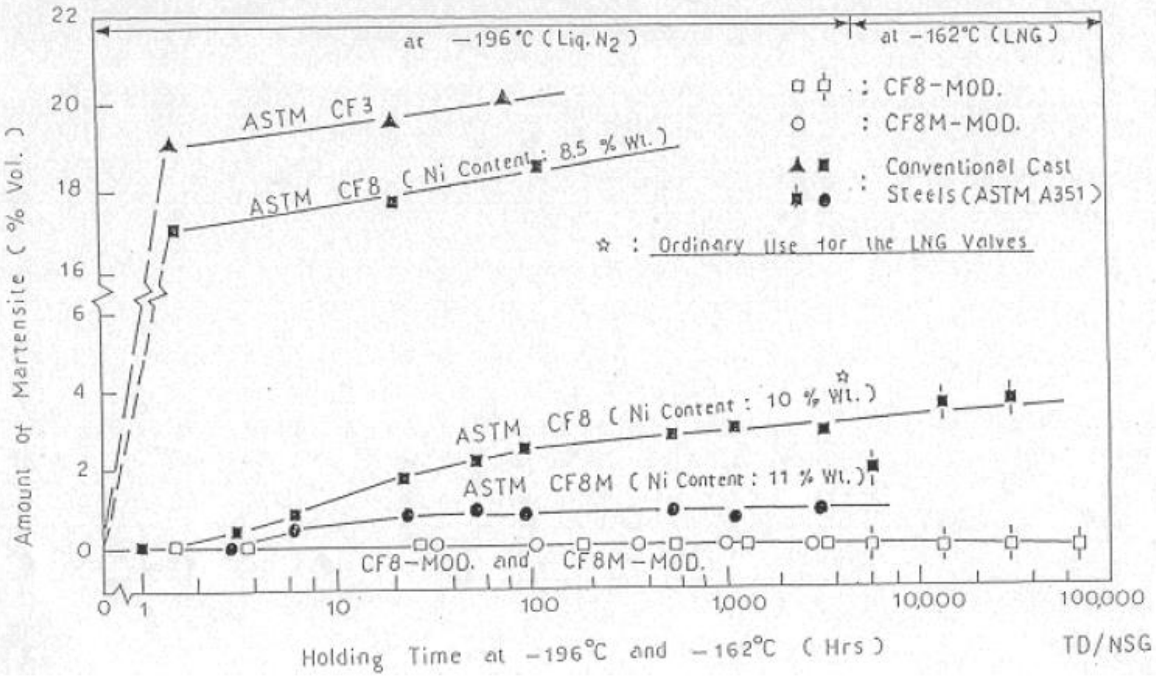
Charpy Impact Tester

Low Temperature Austenitic Stainless Steel Castings

- Austenitic stainless steel castings require additional consideration for low temperature applications

FIG. 2

ISOTHERMAL MARTENSITIC TRANSFORMATION OBSERVED IN CF8-MOD./CF8M-MOD. AND THE CONVENTIONAL AUSTENITIC STAINLESS CAST STEELS



Thank You !