U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

SwRI®

Pumped Thermal Energy Storage Systems: Component Design and Development

Panel 2: Turbomachinery
Experiences with turbomachinery development and testing

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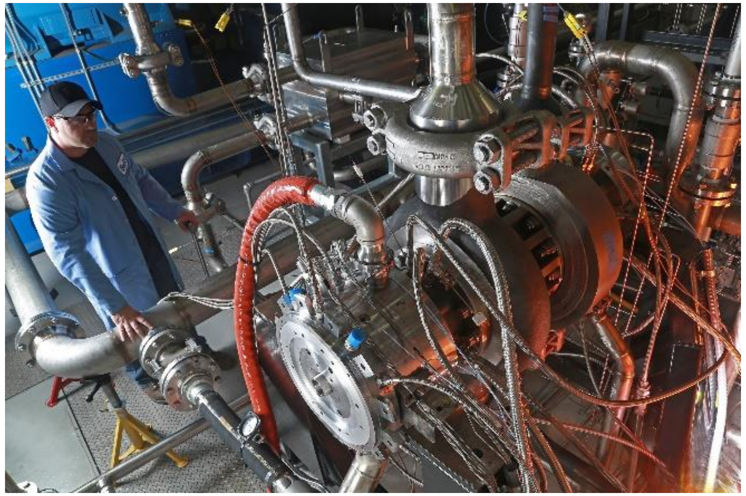
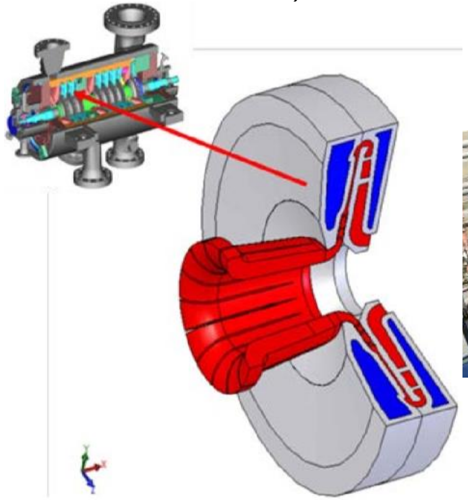
Development Needs for Energy Storage: Machinery & HX

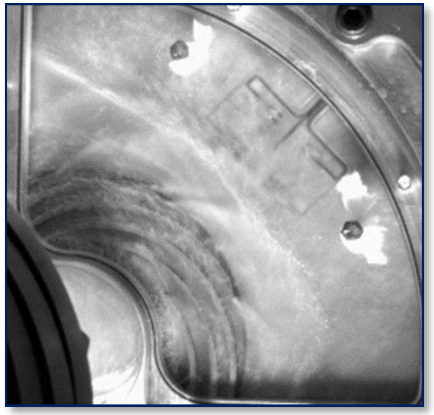
- Most new thermodynamic systems are closed or semi-closed cycles requiring:
  - Very high machinery efficiency over a variety of temperatures, pressures, and scales (radial axial)
  - Low leakage/makeup requirements; consider hermetic machinery
  - High pressures, densities, and temperatures
  - PHES: High-temp compressor; single machinery train for charge/discharge mode
- Integration of compression, expansion, and heat exchange functionality into machinery to improve cost and performance
- Fast ramping and wide operating range
- Low-cost compact HX for gas-liquid and with fast transient capability



High-Efficiency High-Temperature 10 MWe 715 °C Supercritical CO_2 Turbine with Low-Leakage Dry Gas Seals (Moore 2019)



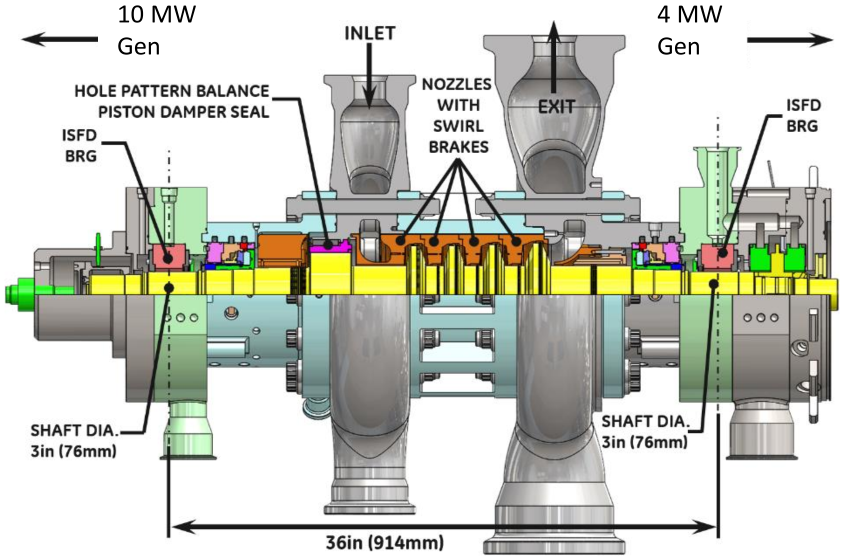
CO2 Compressor for CCS with Internally-Cooled Diaphragms (Moore 2014)

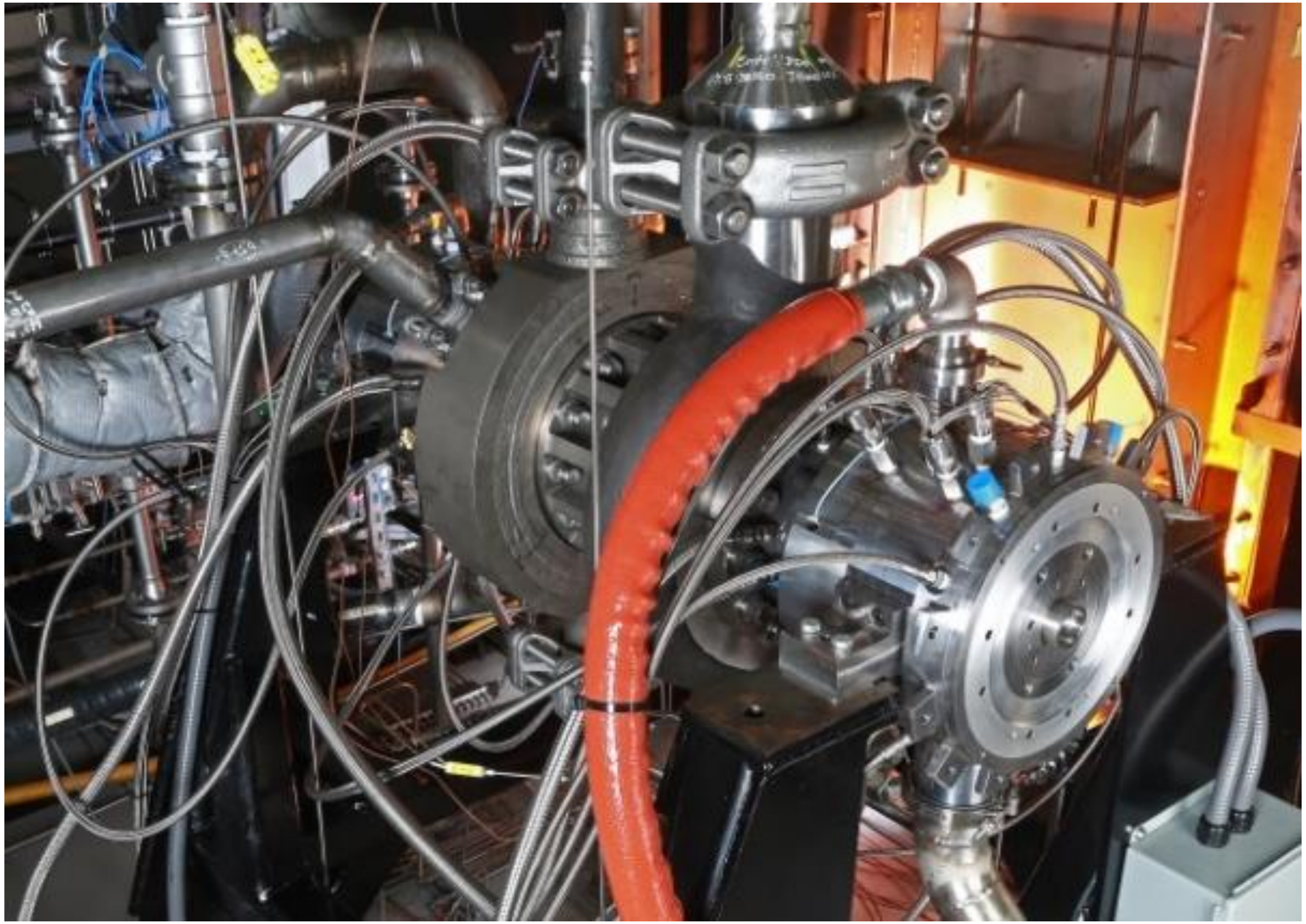


Wet Gas Compression Test (Musgrove 2016)

Sunshot: Development of a 10 MWe Supercritical CO_2 Turbine

- Teamed with GE GRC funded by EERE
- Unlike any steam or gas turbine
- 5 year development effort
- Turbine Inlet Conditions: 715°C, 250 bar SCO2
- 27,000 rpm
- Successfully Tested in 1-MW Flow Loop
- Highest temperature SCO2 turbine in the literature
- Required thermal management system to protect dry gas seals

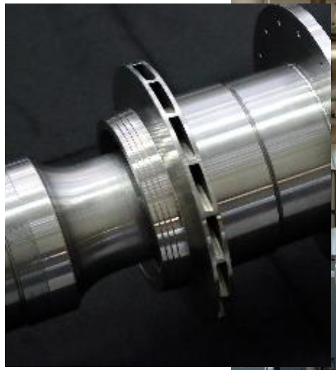


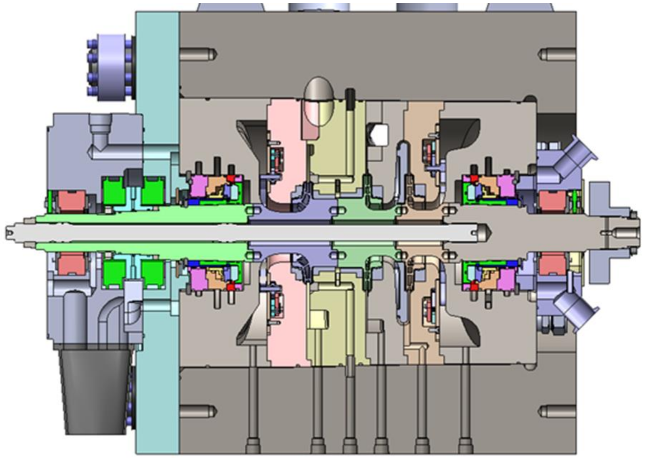


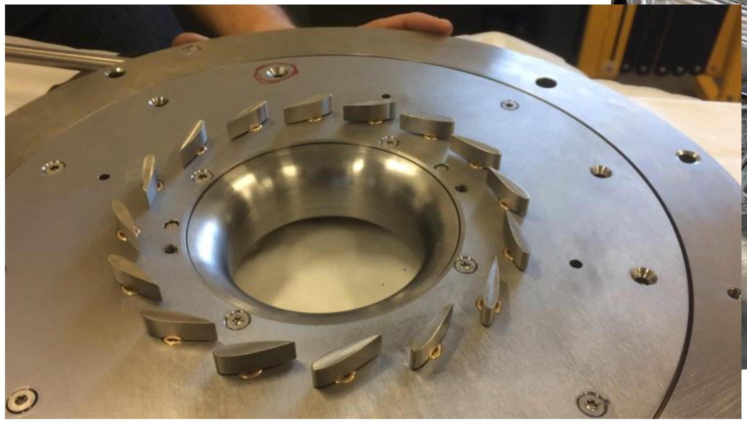
Apollo High-Efficiency sCO_2 Centrifugal Compressor Development

PROJECT OBJECTIVES

- Teamed with GE GRC funded by EERE
- Develop high-efficiency sCO2 compression system for 10 MWe Plant
- High efficiency centrifugal impeller
- Variable IGV
- Successfully tested to full pressure and speed
- Low vibrations
- Highest density compressor in the world (720 kg/m^3)

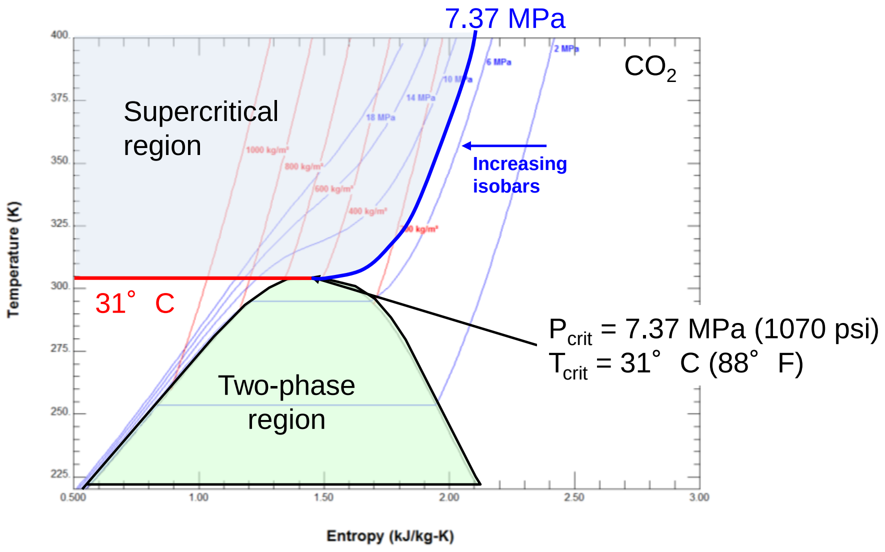


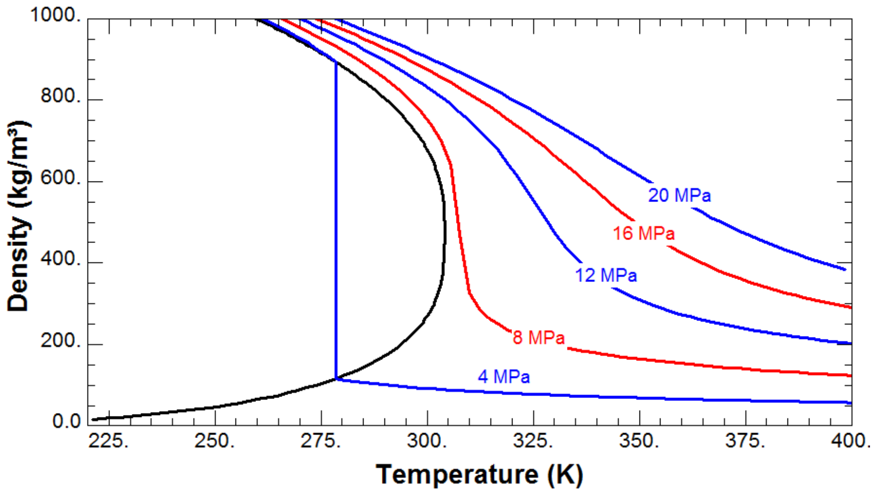




Challenges Compressing CO_2 near Critical Point

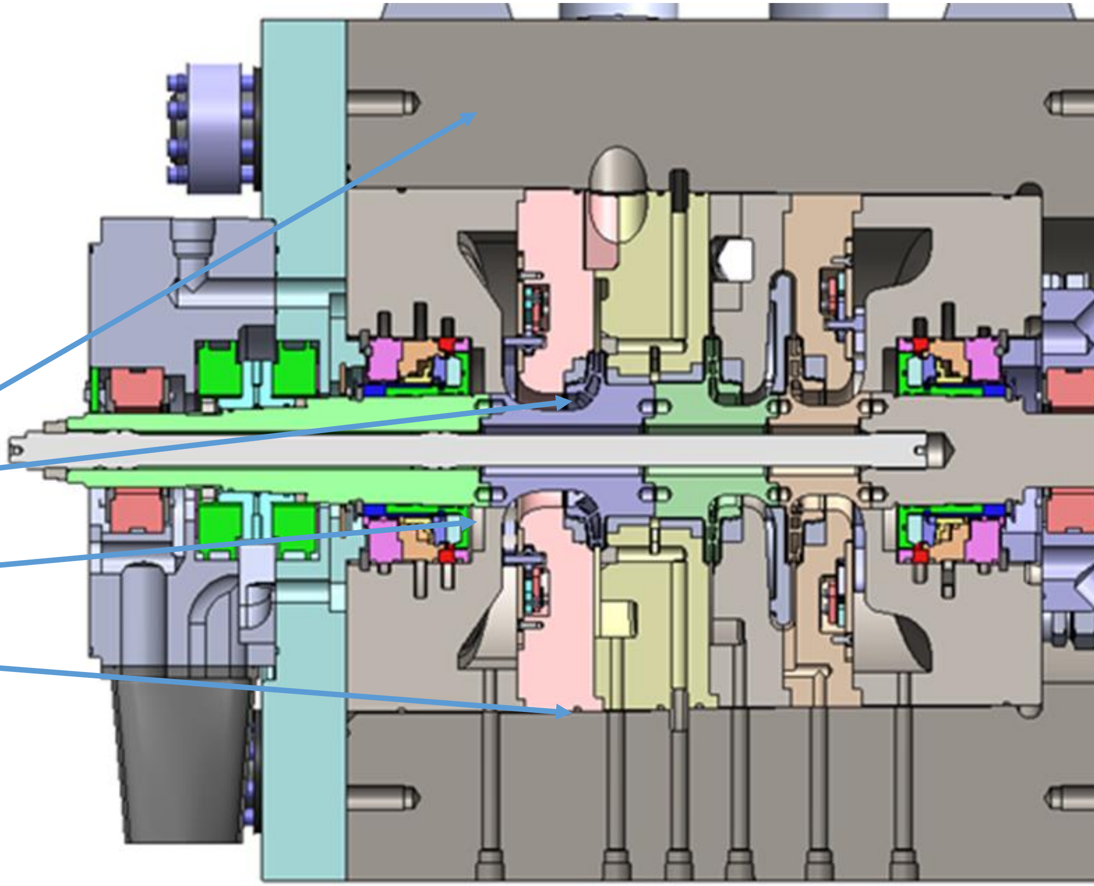
- Large changes in gas properties near the critical point for discharge operation
- 6°C change in temperature changes density by factor of 2 (36 to 30 °C at 80 bar)
- Speed sound drops by 40% with same temperature change causing early choking of the compressor
- Dry ice formation in dry gas seals
- Small diameter impeller challenging to package





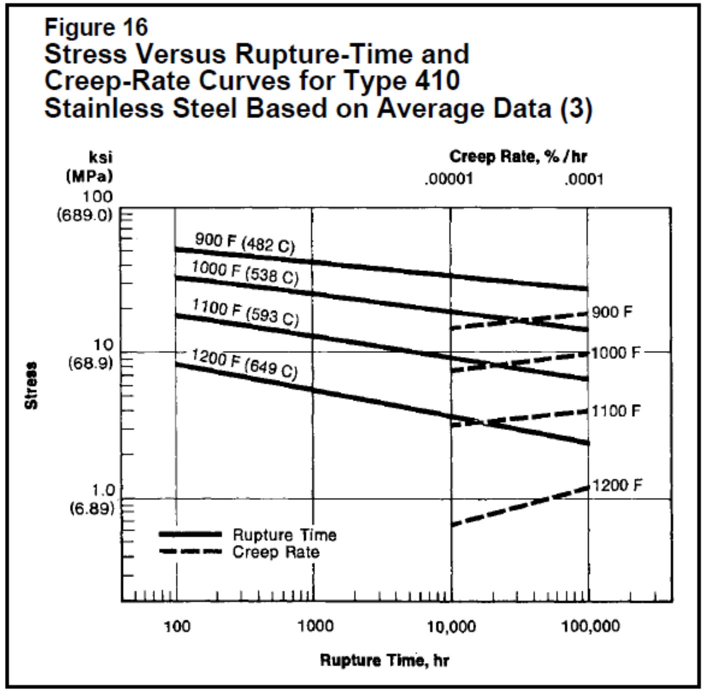
Challenges of Charge Mode Compressor

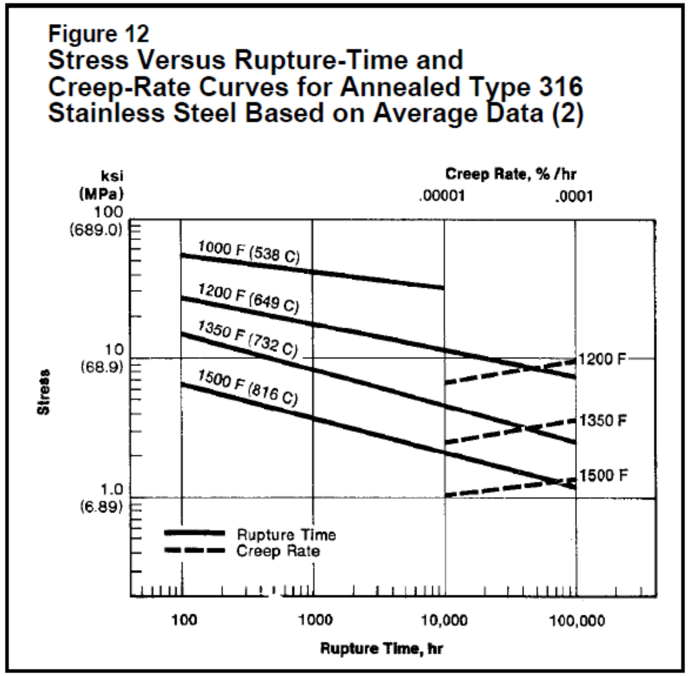
- High temperature at suction (up to 400C) and discharge (up to 570C)
- High temperature increases volume flow and head requirements for a given mass flow and pressure ratio
- Power requirements increase due to higher head
- Frame size will be significantly larger and rotation speed lower than discharge mode compressor
- Case materials: stainless steels or nickel alloy required for case and heads
- Inconel materials likely required for impellers
- Thermal management to protect dry gas seals
- Internal bundle seals must be metallic (rather than elastomer or polymer)
- Thermal stress and LCF must be evaluated in case and shaft



High Temperature Material Properties

- ASME code does not allow 410 SS over 1000F (538C) due embrittlement
- 316 SS or equivalent will be required.
  - Has significantly more thermal growth than 400 series and must be managed.
- Thick case sections will likely result in poor transient thermal performance
- 17-4 at 1100F has 50% of room temperature yield strength, whereas IN718 has 90% of its strength
- Inconel 625 or equivalent likely needed for case and nickel alloy for impellers





Ref: High-Temperature Characteristics of Stainless Steels, Nickel Development Institute, American Iron and Steel

PHES with LP Air

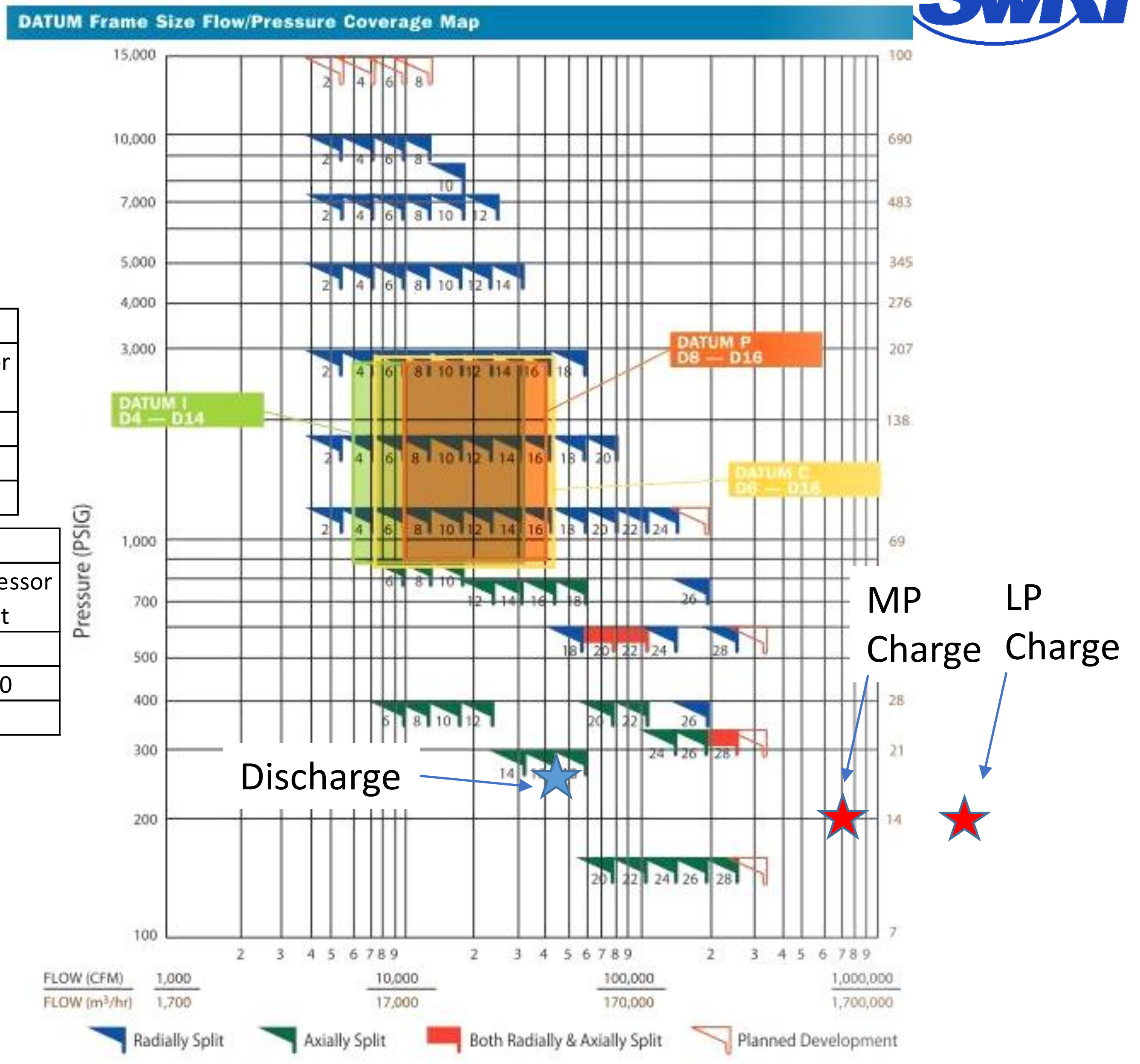
- Sample 100 MWe PHES with 4 bar suction
- Mass Flow = 991/960 kg/s (discharge/charge)
- Compressor Power = 140/265 MW (discharge/charge)
- Pressure ratio = 4

	Discharge		Charge LP		Charge MP	
	Compressor Inlet	Compressor Exit	Compressor Inlet	Compressor Exit	Compressor Inlet	Compressor Exit
ACFM	42,378		1,930,702		768,030	
psi	65	257	26	81	65	202
°F	-13	240	611	1070	613	1073

		Discharge		Charge LP		Charge MP	
		Compressor Inlet	Compressor Exit	Compressor Inlet	Compressor Exit	Compressor Inlet	Compressor Exit
Volume flow	m3/s	20		911		362	
Pressure	MPa	0.45	1.77	0.18	0.56	0.45	1.40
Temperature	°C	-25	116	321	577	323	578

- Discharge mode in middle of frame size
- LP Charge mode requires much greater compressor that currently available (2.75X larger)
- MP Charge mode more reasonable but still above available range for centrifugal (1.7X larger)
- Mass flow of a GE Frame 9F Gas Turbine=600kg/s (498 m3/s) but with atmospheric inlet pressure

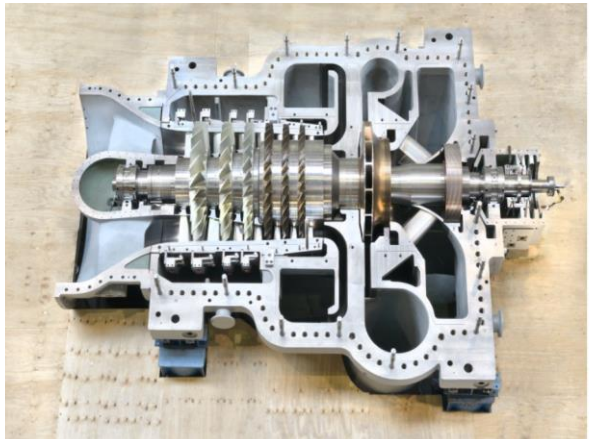
Siemens (Dresser-Rand) DATUM application chart



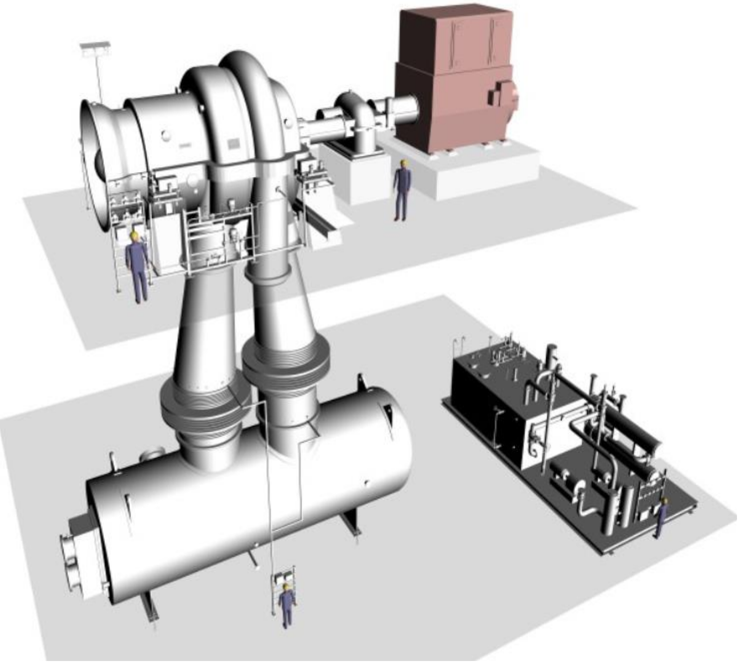
https://www.yumpu.com/en/document/read/12343693/datum-centrifugal-compressors-85188-dresser-rand

World's Largest Compressors

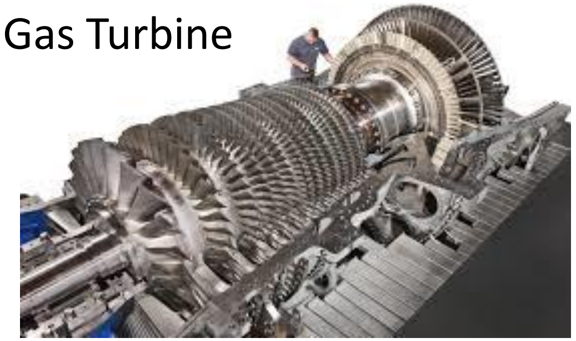
- Largest flow compressor in the world
- Hybrid axial/centrifugal design
- Produced by MAN Diesel & Turbo for air separation
  - Flow rate > 278 m^3/s (588,000 ACFM)
  - Designed for atmospheric inlet pressure
  - 65 MW
- Mass flow of a GE Frame 9F Gas Turbine=600kg/s (498 m3/s) but with atmospheric inlet pressure
- Both too small for LP PHES with air at 100 MWe and not designed for elevated suction pressure or temperature



MAN Axial/Radial



GE Frame 9F Gas Turbine



Ref: ge.com

Ref: https://www.corporate.man.eu/en/press-and-media/presscenter/World_s-largest-air-separation-unit-to-rely-on-a-compressor-solution-from-MAN-195200.html#:~:text=With%20an%20effective%20volume%20flowrate,up%20to%20AR170%20(grey).

PHES with sCO2

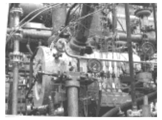
- Sample 100 MWe PHES with sCO2
- Mass Flow = 1680/890 kg/s (discharge/charge)
- Compressor Power = 25.7/256 MW (discharge/charge)

		Discharge		Charge	
		Comp Inlet	Comp Exit	Comp Inlet	Comp Exit
Volume flow	ACFM	2848		50153	
Pressure	psi	1305	3915	1305	4046
Temperature	°F	95	153	752	1070

		Discharge		Charge	
		Comp Inlet	Comp Exit	Comp Inlet	Comp Exit
Volume flow	m3/s	1.344		23.67	
Pressure	MPa	9	27	9	27.9
Temperature	°C	35	67	400	577

- Discharge mode requires smallest frame size while charge requires the largest
- Charge mode is a little above the pressure rating for this frame size

Siemens (Dresser-Rand) DATUM application chart



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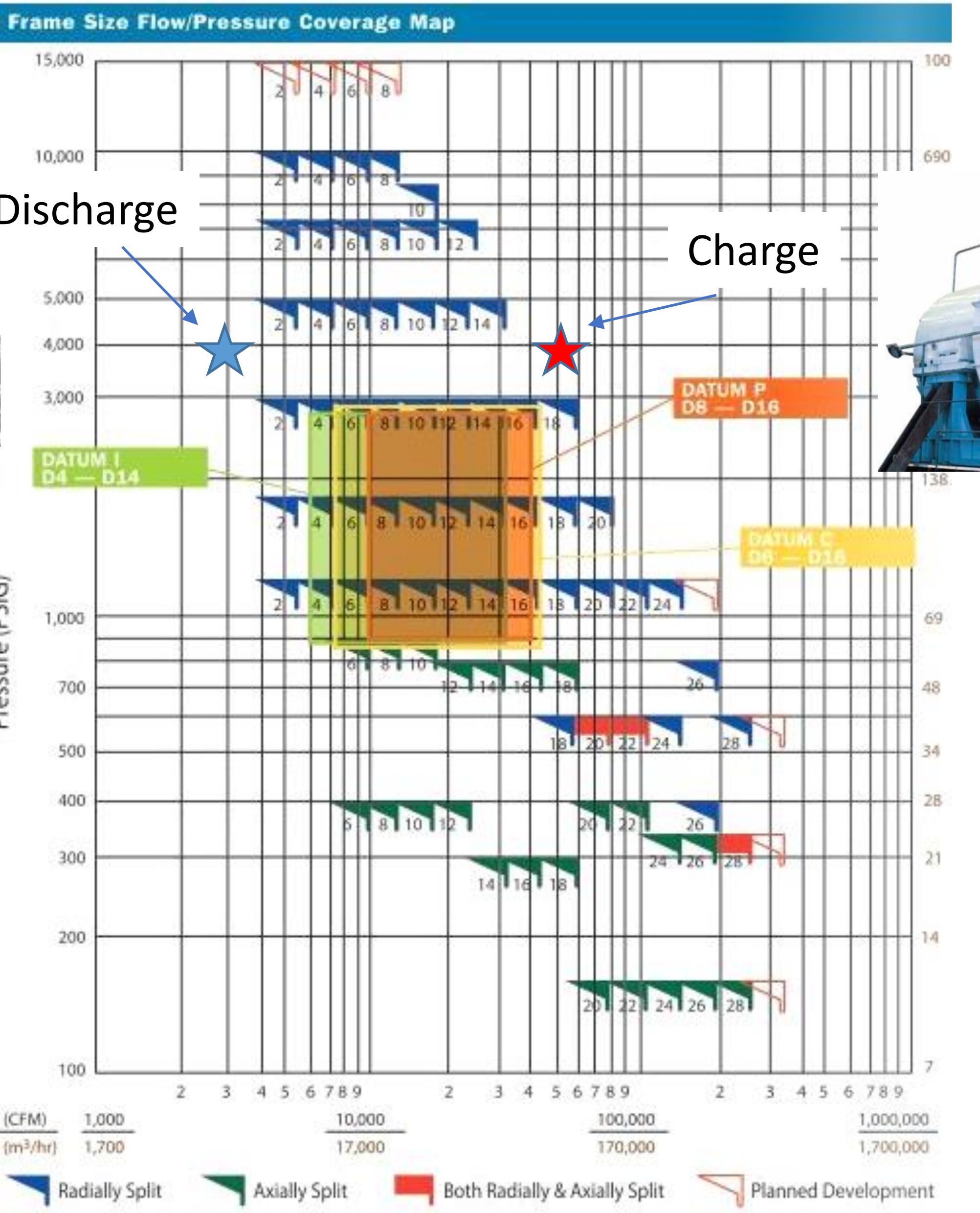

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https://www.yumpu.com/en/document/read/12343693/datum-centrifugal-compressors-85188-dresser-rand

Mechanical Components

- Oil Bearing technology available for very large compressors
- PHES with air can use conventional labyrinth seals
- PHES with SCO2 needs mechanical seals that are pushing the size envelop for charge mode
- Rotordynamics of these very large compressors are unknown
  - Stability
  - Foundation requirements
- Manufacturing and Shipping of these very large frame sizes is a challenge

Summary

- A high temperature charge compressor must incorporate many features of high temperature expanders like metallic seals, thermal management regions, and likely nickel alloys for case and impellers to achieve good thermal transient performance
- PHES with air is larger than currently available compressors, even for the largest axial/radial air separation compressors and much greater power required (265 MW) than current SOTA.
- PHES with sCO2 provides much more reasonable volume flow rates due to higher gas density.
- Leveraging recent SCO2 developments with Apollo program, discharge mode compressor can be produced with current experience although the power (25 MW) is much higher than what has been demonstrated
- The sCO2 charge mode is within the flow range of current compressors, but the discharge pressure and power (256 MW) far exceeds anything ever produced and large power mismatch from charge to discharge.
- Gears are available up to 100 MW, so the charge compressors would have to be direct driven and will require more stages that may not meet rotordynamic requirements
- Motor technology above 100 MW are not available
- Reversible turbomachinery (if developed) would increase charge time (3X) to match volume flow rates and motor/generator rating
- Power cycles need to consider turbomachinery characteristics and limitations.
- New class of high power, high pressure, and high temperature compressors/expanders needed for SCO2.