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The Role of sCO2 in the Global Energy Transition

the perspective of turbomachinery OEMs

Lorenzo Toni, PhD

Senior Team Leader

Compressor & Expander Technology Development

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Something About Me

I am currently Compressors Development Leader within centrifugal compressors and turbo-expanders New Product Development department at Baker Hughes.

I'm leading the technology development team for centrifugal compressors, reciprocating compressors, radial expanders and bearings design, both for conventional portfolio and energy transition applications.

Prior the current role I have been Technical Leader for Compressors, Team Leader for Aerodynamic and Aeromechanic design, Senior Engineer for Aerodynamics and Test and Data Analysis Engineer in GE Oil & Gas and Baker Hughes.

I hold a PhD in Energy Engineering and a MSc in Mechanical Engineering

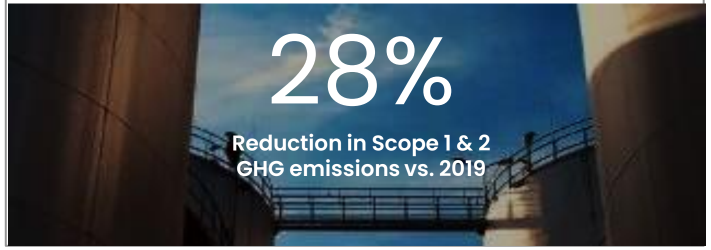
We are Baker Hughes, an energy technology company. Together, we're making energy safer, cleaner, and more efficient for people and the planet.

Energy for today and tomorrow

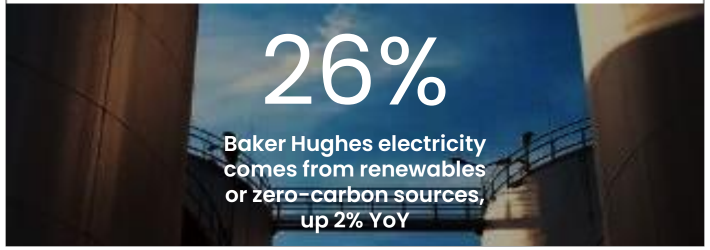
The energy sector is changing, faster than ever before. The energy trilemma—solving for energy security, sustainability, and affordability—is rebalancing our priorities and creating a new path forward for the industry. We believe we can meet those objectives together.

We take energy forward - making it safer, cleaner, and more efficient for people and the planet

Baker Hughes is committed to reducing our emissions by 50% by 2030 and net-zero by 2050



We are bringing our core technology capabilities to lead in the energy transition and enable a decarbonization path for energy and industry



We are taking energy forward by delivering the highest efficiency productivity outcomes for broader energy and industry

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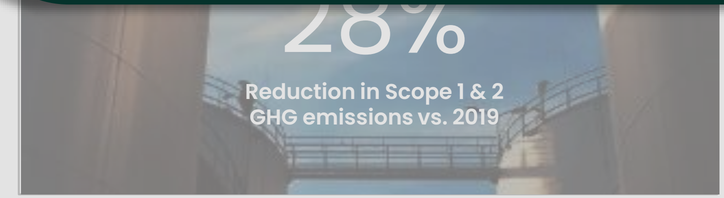
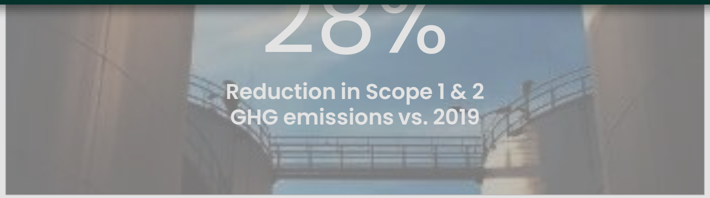
We take energy forward - making it safer, cleaner, and more efficient for people and the planet

- ✓ sCO_2 is part of BH energy transition strategy
- ✓ BH is involved in several projects dealing with sCO_2





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BH - sCO2 Programs Summary
Externally Heated Power Cycles

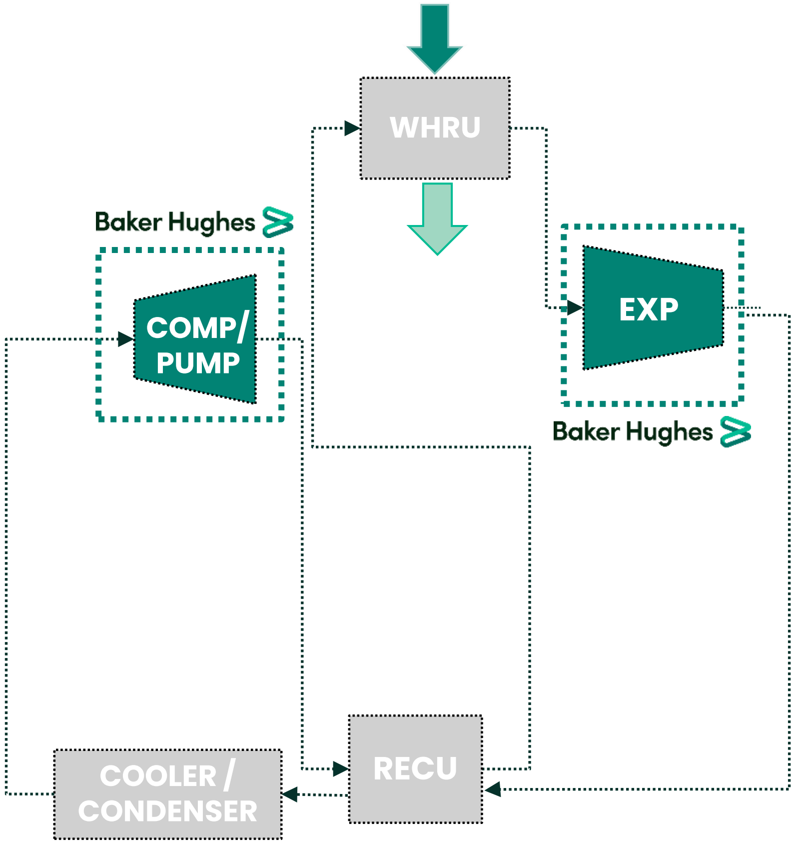
Project	Region	Objective	Application	BH scope	Status	Plant output (MWe)	Plant max T (°C)
CO2OLHEAT	EU	WHR from Industrial exhaust gases	Waste Heat to Power	Compressor & HP Turbine Design Compander mfg & Test	In Progress	2-25	360 - 720
APOLLO	US	WHR from gas turbine exhaust	Waste Heat to Power	Impeller	In Progress		
STEP DEMO	US	sCO2 tech. for utility scale conventional PP (gas-fired)	PowerGen	Compressor Design, Mfg, Type 2 Test	Test on site in progress		
sCO2flex	EU	sCO2 tech. for utility scale conventional PP (gas-fired)	PowerGen	Compressor Design, Mfg, Test in actual condition Expander Deign	Completed		
SOLAR sCO2OL	EU	Pilot thermal Energy Storage for CSP	CSP	Compressor, Mfg & Test	In Progress		
DeSOLination	EU	sCO2 tech for CSP to improve efficiency of desalination plant	CSP	Pump	In Progress		
SCARABEUS	EU	sCO2 blends definition to improve CSP cycle eff. @ambient T>40°C	CSP	Design pump & turbine	Completed	Design only	
sCO2-4-NPP	EU	Consultancy for turbomachinery design under Nuclear regulation	Nuclear	Design compressor & turbine	Completed		

Ongoing R&D Programs BH Engagement Overview

	Compressor		Turbine
	BCL	SRL	RAD/AX
2023	TRL6	TRL5	TRL3
2025-26	TRL7	TRL7	TRL7

EU/DOE Programs

- sCO_2flex
- STEP DEMO
- SOLAR sCO_2OL
- $CO_2OLHEAT$
- DeSOLination



EU/DOE Programs

- sCO_2flex
- SCARABEUS
- $CO_2OLHEAT$
- DeSOLination

Developed know-how to provide **complete plants solutions**

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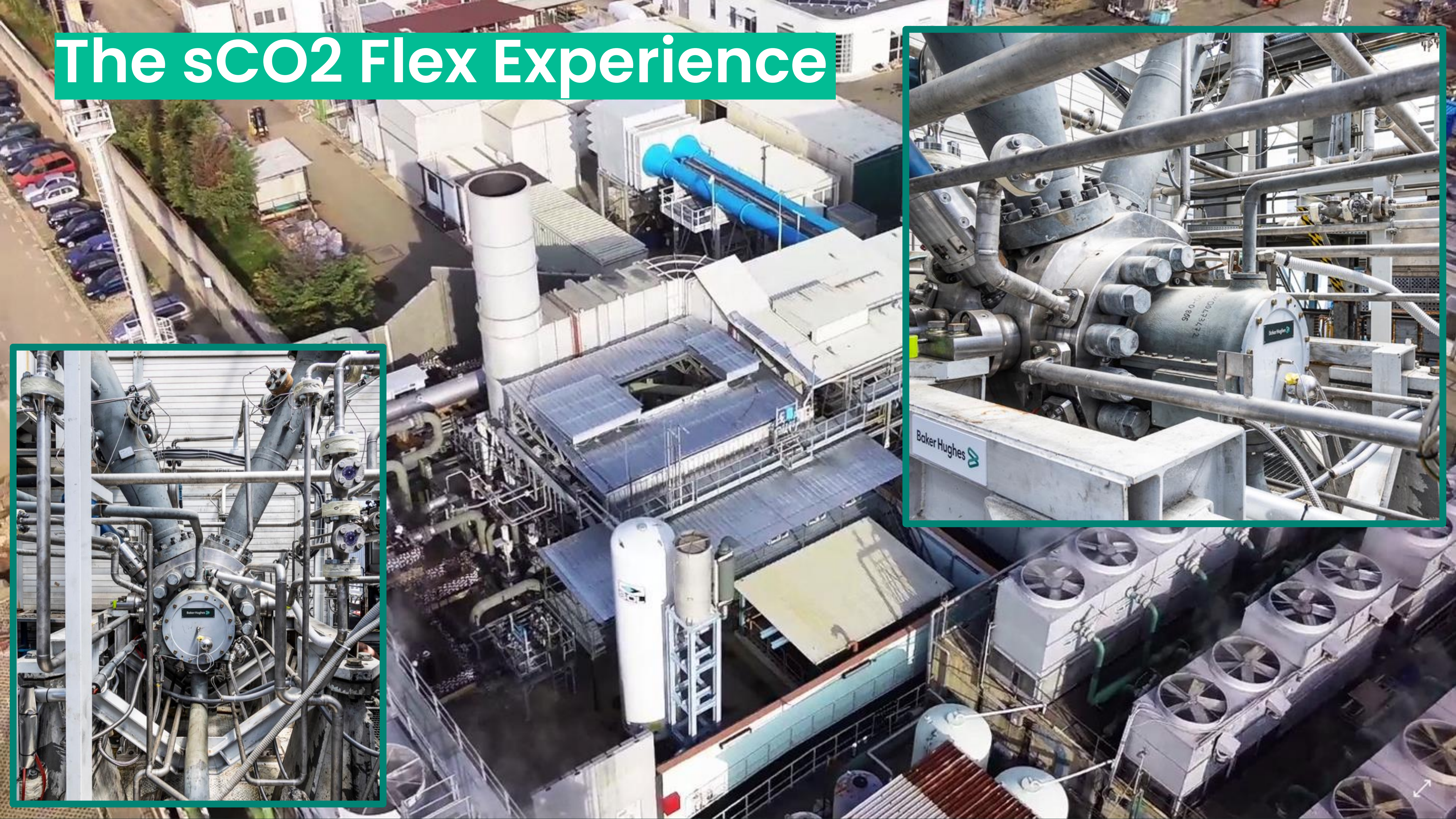
The sCO_2 Flex Experience



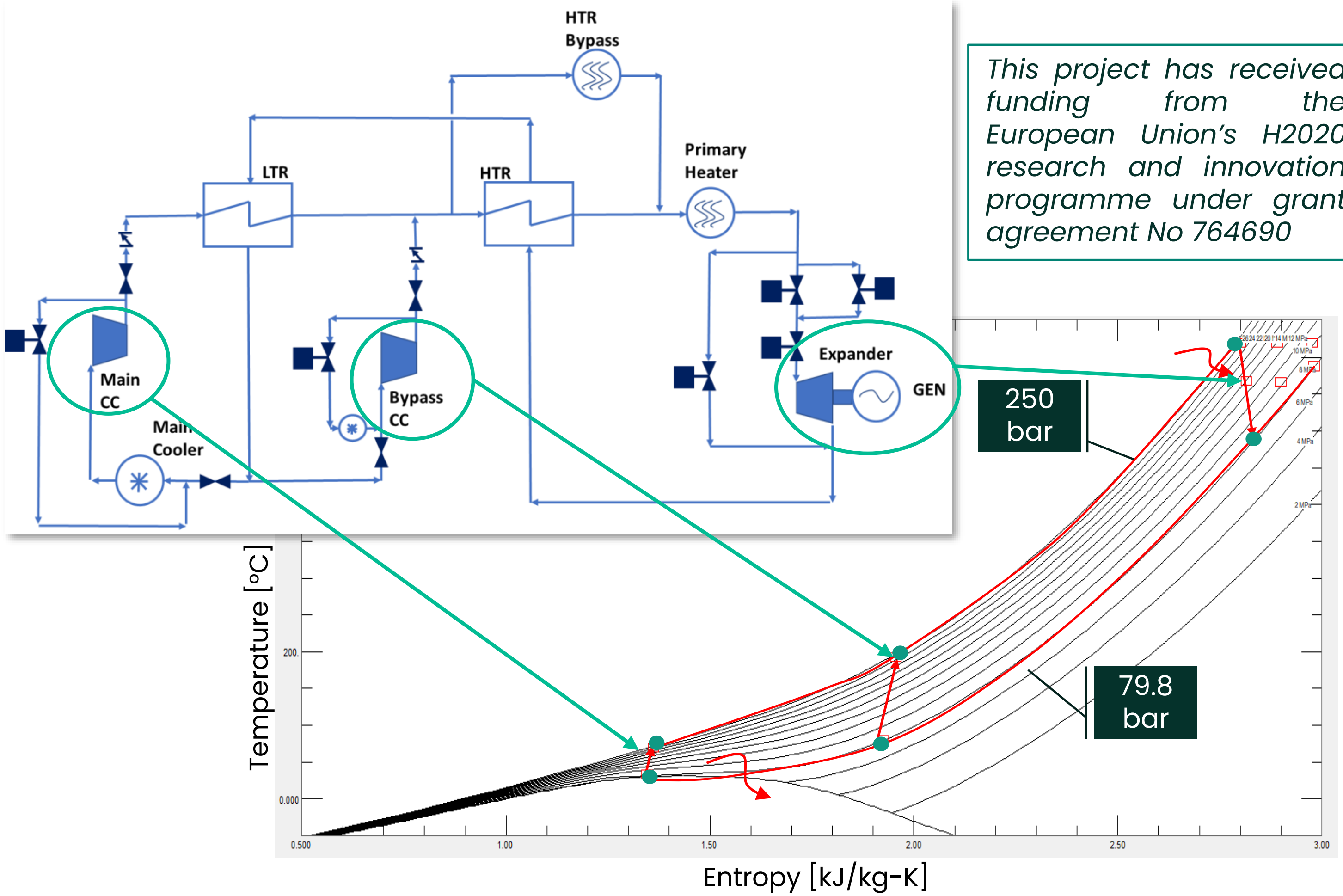
Cycle Overview

Project Objective

- Make fossil fuel-based **electricity production flexible** to foster **integration of renewable** energy sources **minimizing water consumption**, **reducing GHG** emissions with highly **flexible** (20-100%) and **efficient** power plants

How

- Brayton cycle in closed-loop, supercritical CO2 as working fluid and recompression layout



This project has received funding from the European Union's H2020 research and innovation programme under grant agreement No 764690

Design and Testing of a 5MW Supercritical CO2 Centrifugal Compressor

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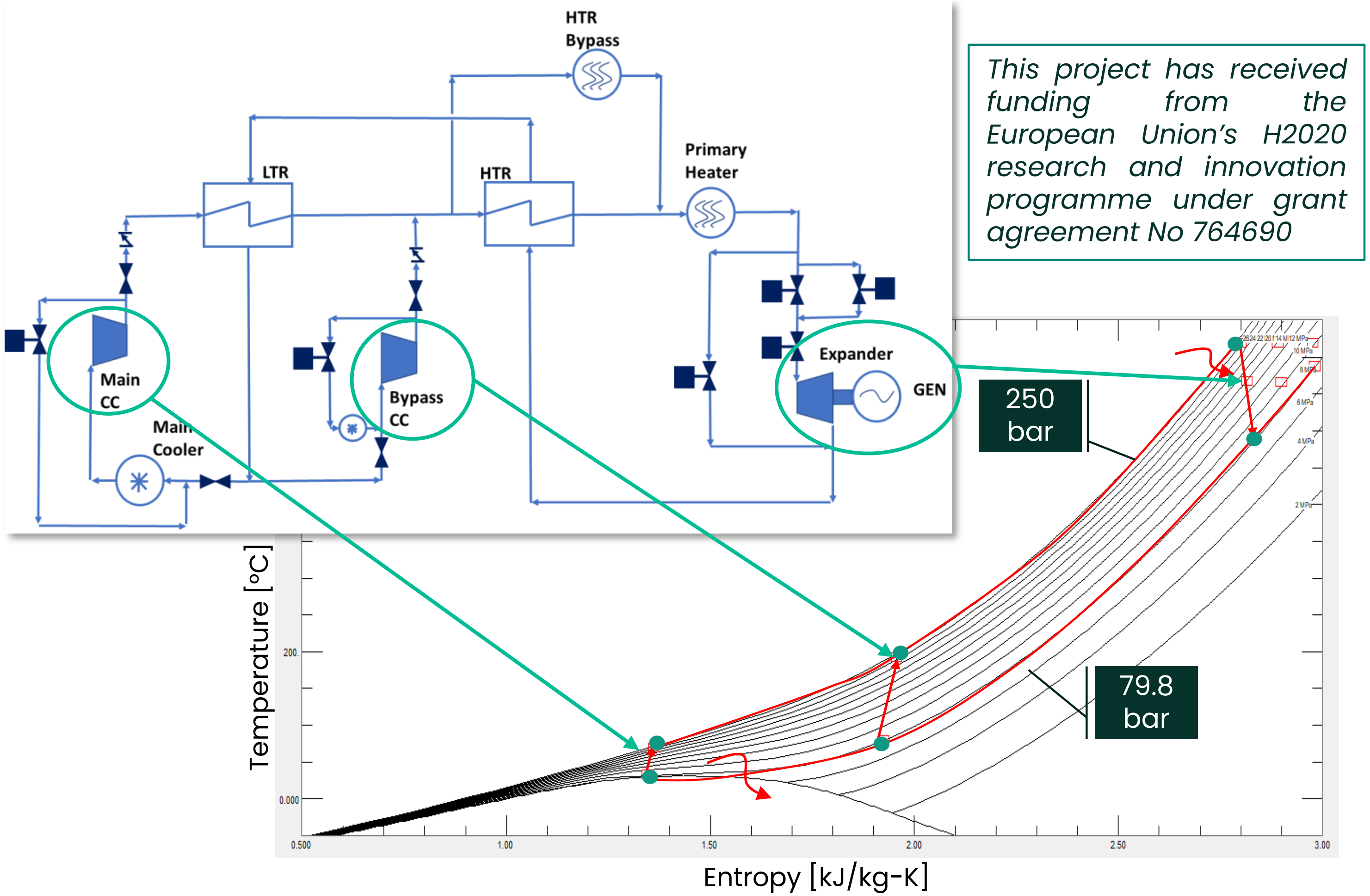
Cycle Overview

Baker Hughes main deliverables

- ✓**Design** of compressors and one turbine expander
- ✓**Test** of prototype compressor working close to CP
- ✓Plant **simulation** in design and off-design condition
- ✓Cost-effectiveness of the project



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Design and Testing of a 5MW Supercritical CO2 Centrifugal Compressor

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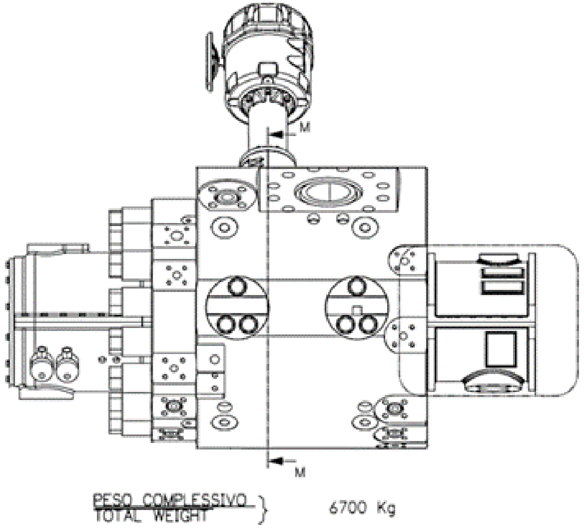
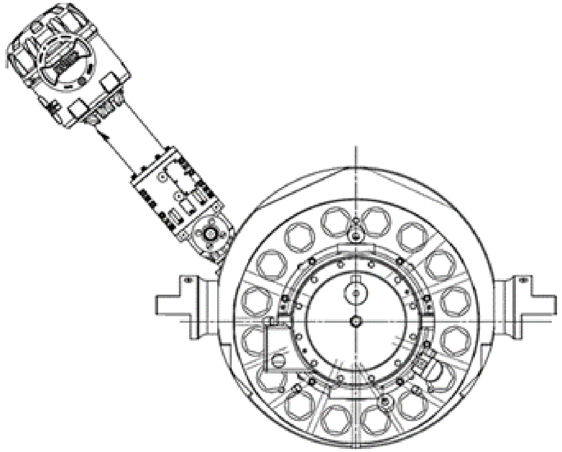
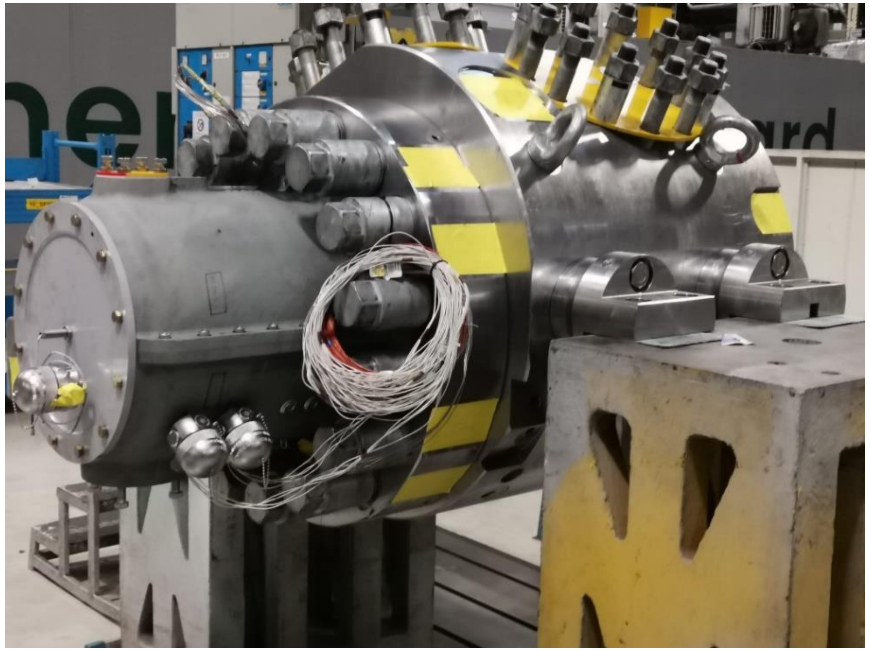
Compressor: Architecture

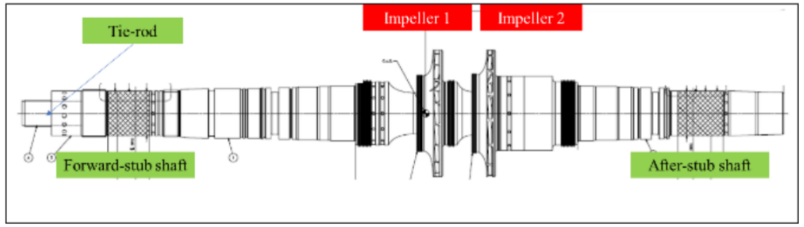




Main CC - Prototype



CC DATA	
Compressor Model	BCL/B
Bearing span [mm]	1127
Rotating speed [rpm]	11400
JB diameter [mm]	90
Rotor weight [kg]	150
Compressor weight [kg]	6700



Design Features

- **Barrel type compressor** with and studded process flange
- First stage impeller **new design** to handle with sCO2
- **Variable flapped IGV** at compressor suction
- **Stacked rotor** with friction coupling and **integral diaphgram**
- **PDS** used on balance drum

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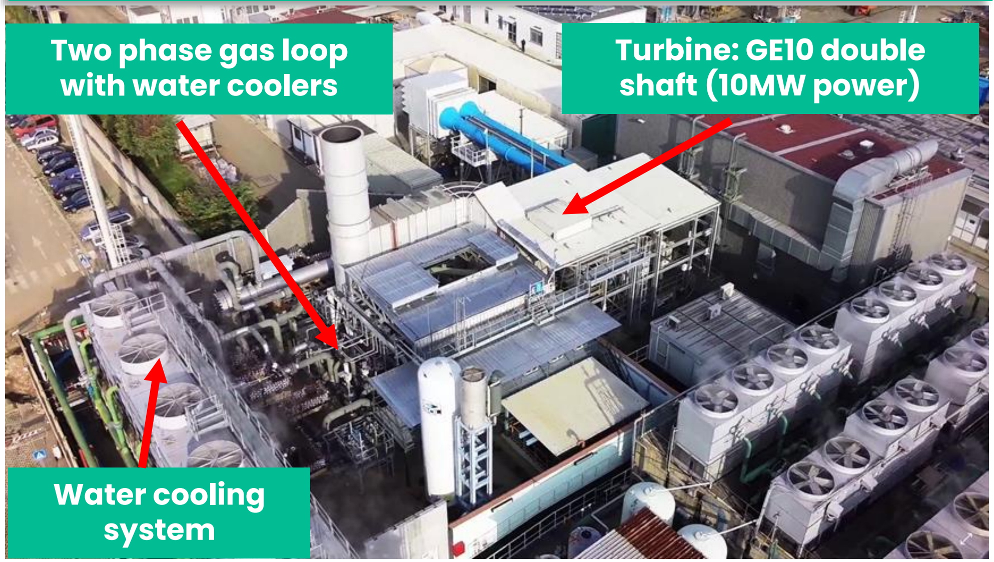
sCO2 Testing

- Test performed at Turbomachinery Testing Laboratory (TTL), at Baker Hughes, Florence
- 5.4 MW centrifugal compressor prototype
- Closed-loop test rig, with gas turbine as driver and a bypass loop for temperature control

Compressor test rig at the Baker Hughes facility in Florence, Italy



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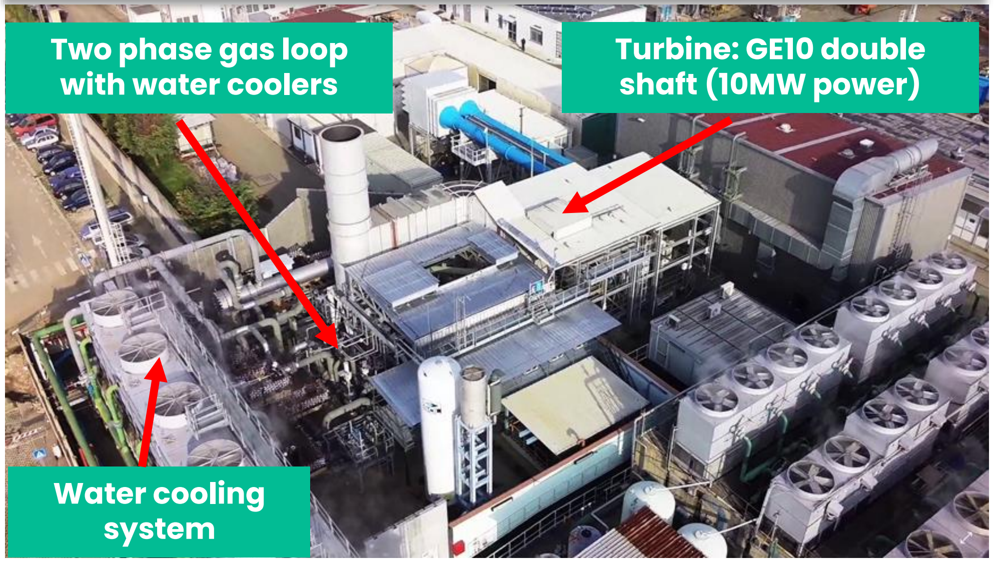

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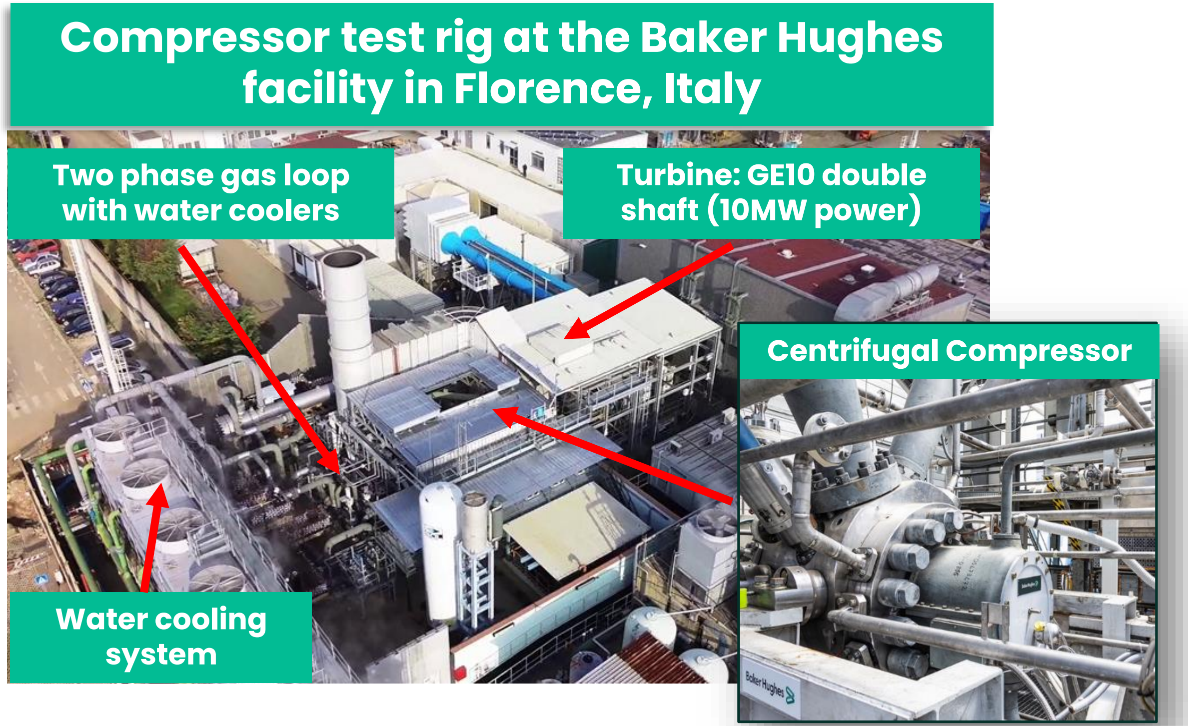
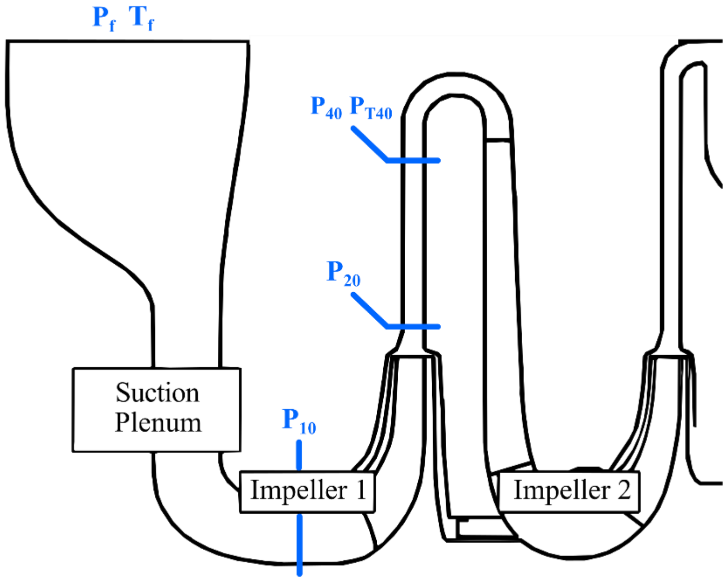


Instrumentation

Section	Instrumentation
Inlet Flange	P_{tot}, T_{tot}
Impeller Inlet – Sec 10	P_{stat}
Diffuser Inlet – Sec 20	P_{stat}
Diffuser Outlet – Sec 40	P_{tot}, T_{tot}
Outlet Flange	P_{tot}, T_{tot}



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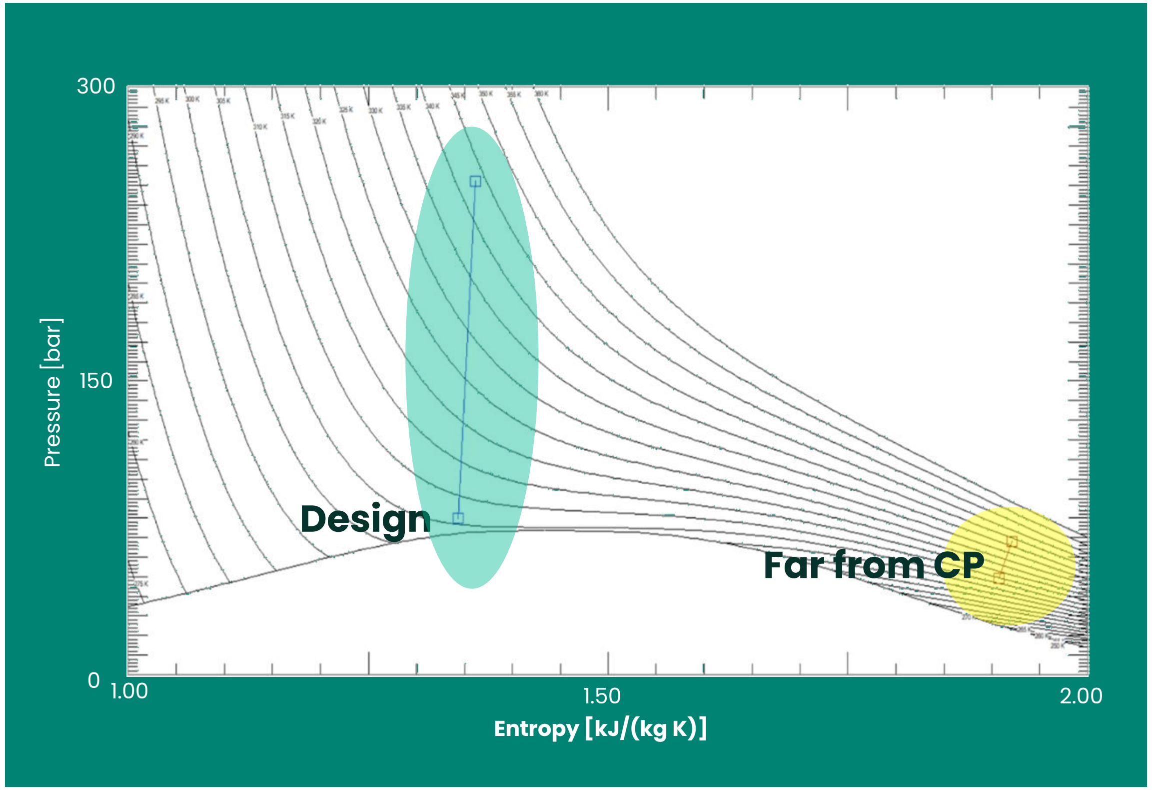
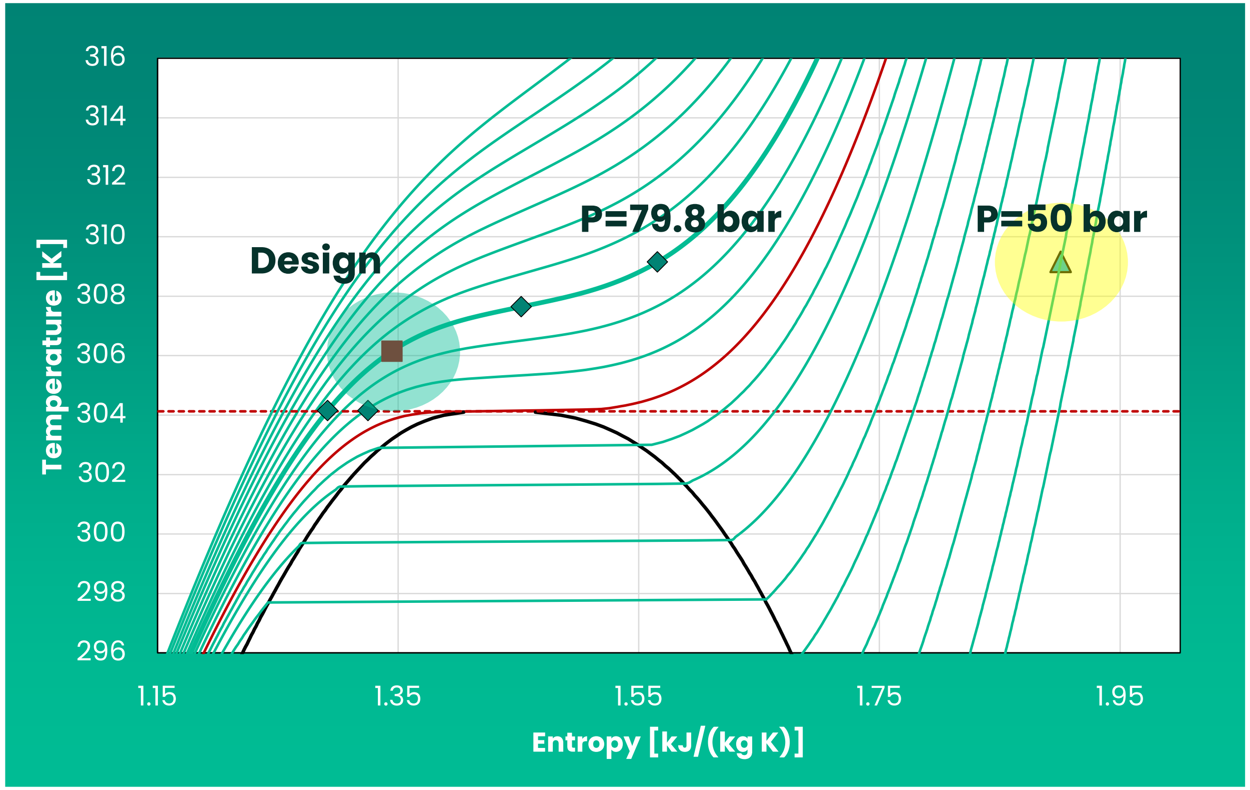
sCO2 Test Matrix

- Design validation with inlet conditions far from critical point, 36 °C & 50 bar
- Compressor Map at Design conditions, 33 °C & 79.8 bar
- Compressor Map at Different inlet temperature/pressure in the close to CP region
- Compressor Maps with different IGV positions
- Machine has been run for totally 125 hours, along different testing days.





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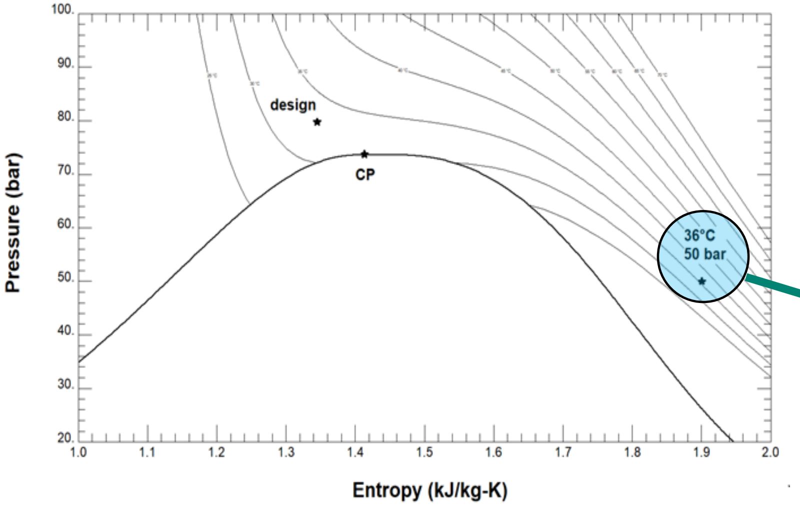
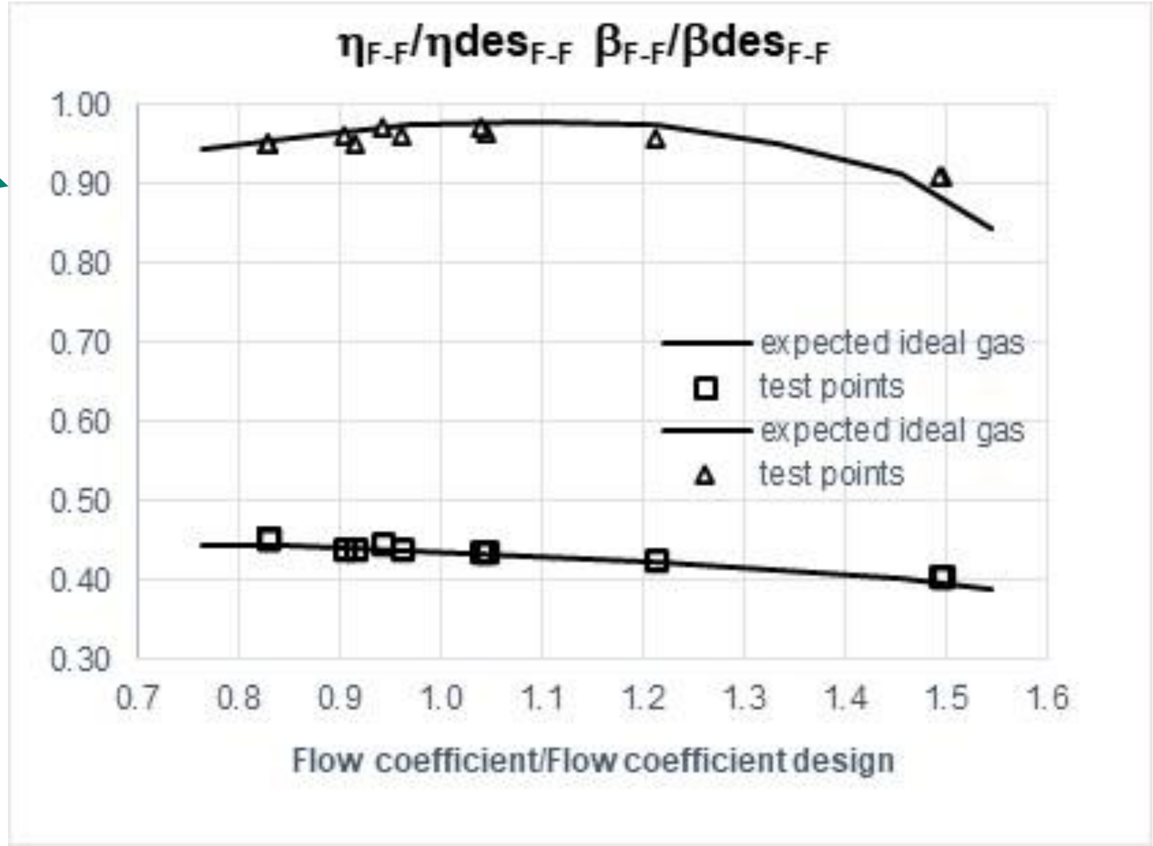
Test Results: Performance @ 50 bar

Far from Critical Point



Experimental results are in good agreement predicted performance



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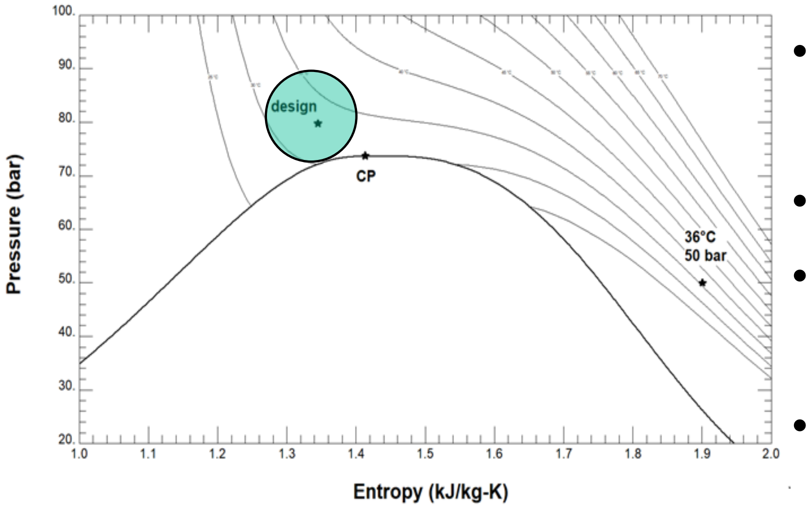
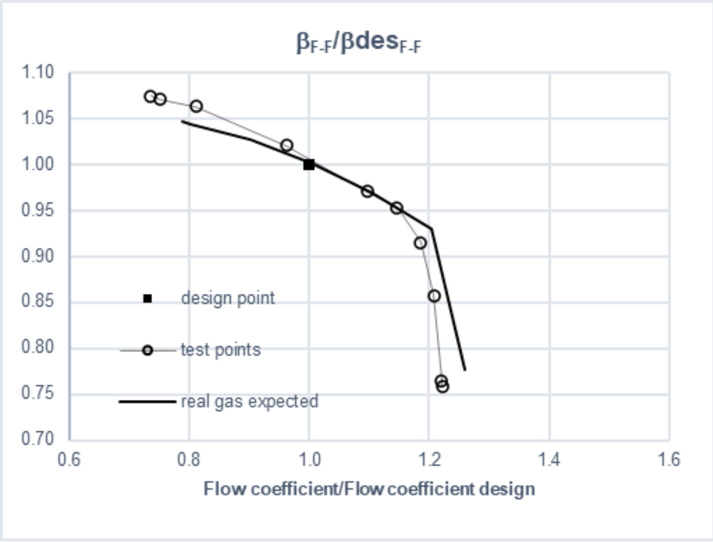
Test Results: Performance @ 79.8 bar (design point)

Close to Critical Point



- At design condition compressor performance in line with expected: the barotropic HEM formulation matches the prediction of right limit
- Shape of efficiency and pressure ratio curves are closely reproduced
- The real-gas exhibits a sharp drop in performance connected to choked operation that is coherent with experimental data
- Overall pressure ratio: 3.1



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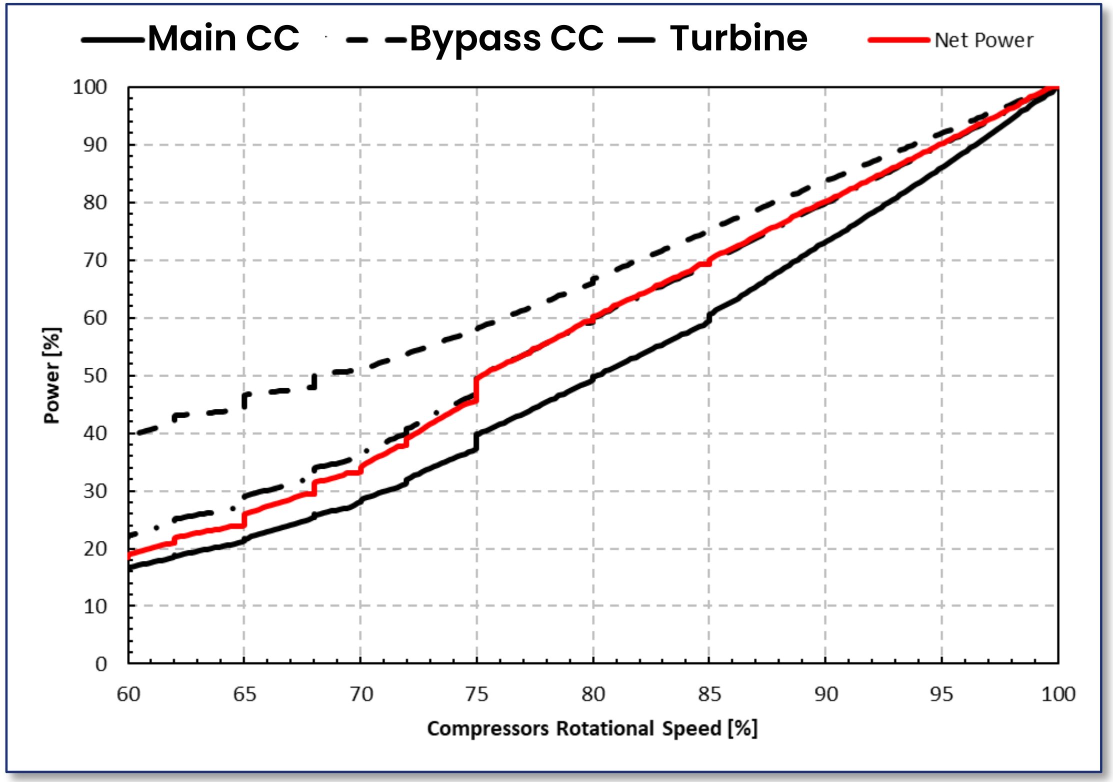
Further Highlights 1 of 3

Partial Load Operation

- Guarantee large power flexibility to the system: 20% and 100% of nominal power
- 100% - 50% reduction achievable acting on speed of the compressors and IGV position
- 50% - 20% reduction obtained by also extracting CO_2 from the loop



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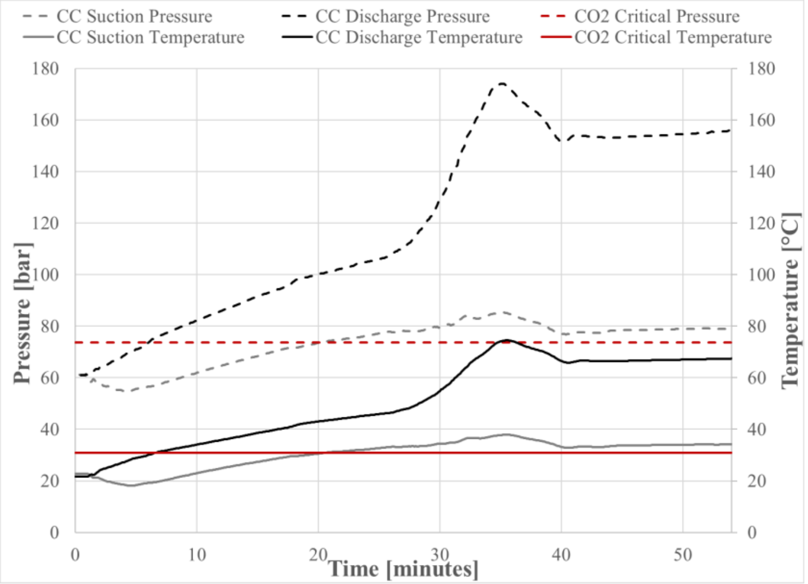
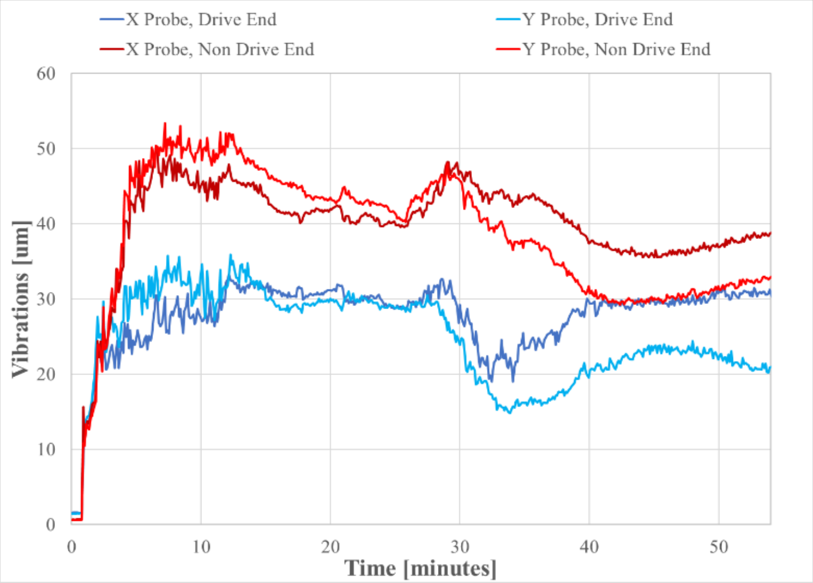
Further Highlights 2 of 3

Two Phase Restart

- In some cases of pressurized stops, a transition to two-phase region may happen
- No significant variations were measured in absorbed power during phase transitions
- Slight vibrations in the initial phase; started diminishing when suction conditions were still within the dome





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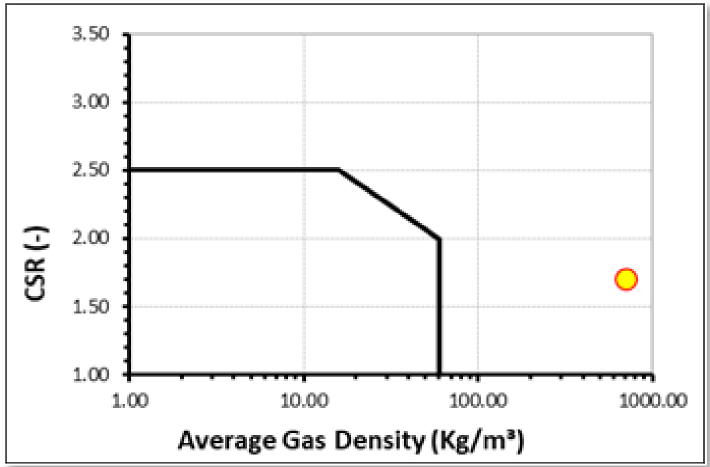
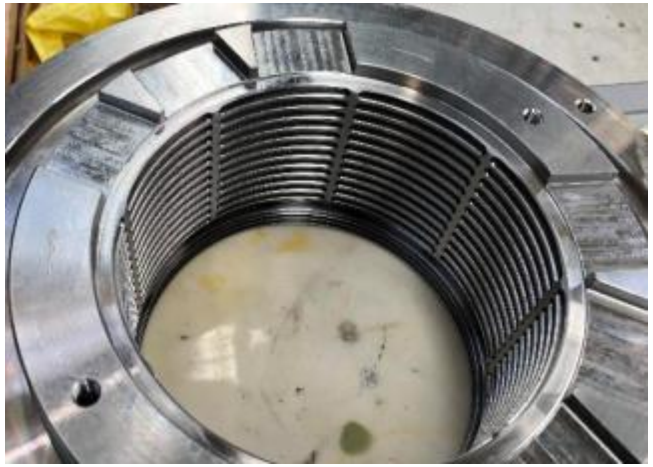
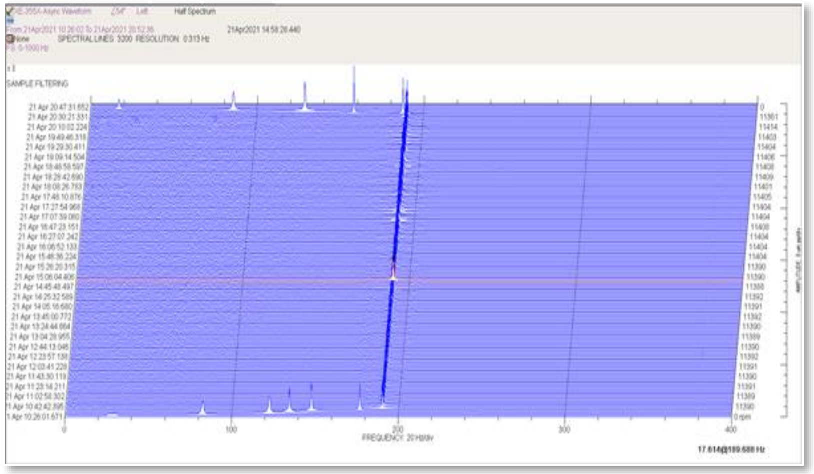
Further Highlights 3 of 3

Rotordynamics

- Tilting pad JB, with Integral Squeeze Film Damper (ISFD) to improve the damping capability
- Pocket damper seal at balance piston has been installed, in particular to increase the stability in case of phase change in such region
- First three modes are critically damped with low amplification factors
- Spectrum is very clean; no other frequencies except the 1X rev







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Concluding Remarks

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Lesson Learned from sCO_2 programs

	Compressor	Expander
2023	TRL6	TRL3
2026	TRL7	TRL7

Highlights & Benefits

- ✓ Developed fluid simulation/characterization capability
  - ✓ Performance prediction around critical point **validated** via sCO_2 Flex compressor test
- ✓ Operation
  - ✓ Proven operation of centrifugal compressor in dense phase fluid with density close to 700 kg/m^3
  - ✓ **Two-Phase restart**
- ✓ Critical T near ambient temperature
  - ✓ Advantages for loop **components**
- ✓ High vapor density
  - ✓ **Reduced machinery footprints**
- ✓ Inert fluid with stability at high temperature
  - ✓ **Safe** deployability with different heat sources (Nuclear, Fossil, CSP, Waste Heat)
- ✓ Only alternative to Steam Rankine Cycle for high T applications
  - ✓ Theoretically higher efficiency, no water needed

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Lesson Learned from sCO2 programs

Design Guidelines

- ✓ Impeller design
  - ✓ Post-pone, **delay two-phase flow region**
  - ✓ Upper limit to **impeller loading**; according to thermodynamic and service conditions, split pressure ratio in more stages
- ✓ Statoric components
  - ✓ Flow control to avoid condensation
- ✓ Internal leakages
  - ✓ Particular care due to small size of the compressors

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Lesson Learned from sCO2 programs

Challanges

- ✓ **High Inlet/Outlet P & T**
  - ✓ up to 250 bar and 700°C at inlet and ≈ 70-120 bar at exhaust >> high plant rating >> high CAPEX/weight
- ✓ **Efficiency highly affected by heat source T**
  - ✓ sCO2 limited for applications T>400-450°C
- ✓ **DGS and cooling system**
  - ✓ DGS + reinjection system necessary to minimize leakages from turbomachinery >> dedicated cooling system (design T 200°C) + site storage/inventory >> additional complexity/CAPEX
- ✓ **Heat transfer coefficient:**
  - ✓ very high thermal stress on hot components
- ✓ **Material selection of process components**
  - ✓ corrosion due to high T (CO2 and mixtures) and high density >> nickel-based alloy or martensitic steel characterization >> limited supply chain/high CAPEX/long lead times
- ✓ **Compressor Control/Operability**
  - ✓ Operation close to CP leads to relevant change in thermodynamic properties for slight variations in temperature

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