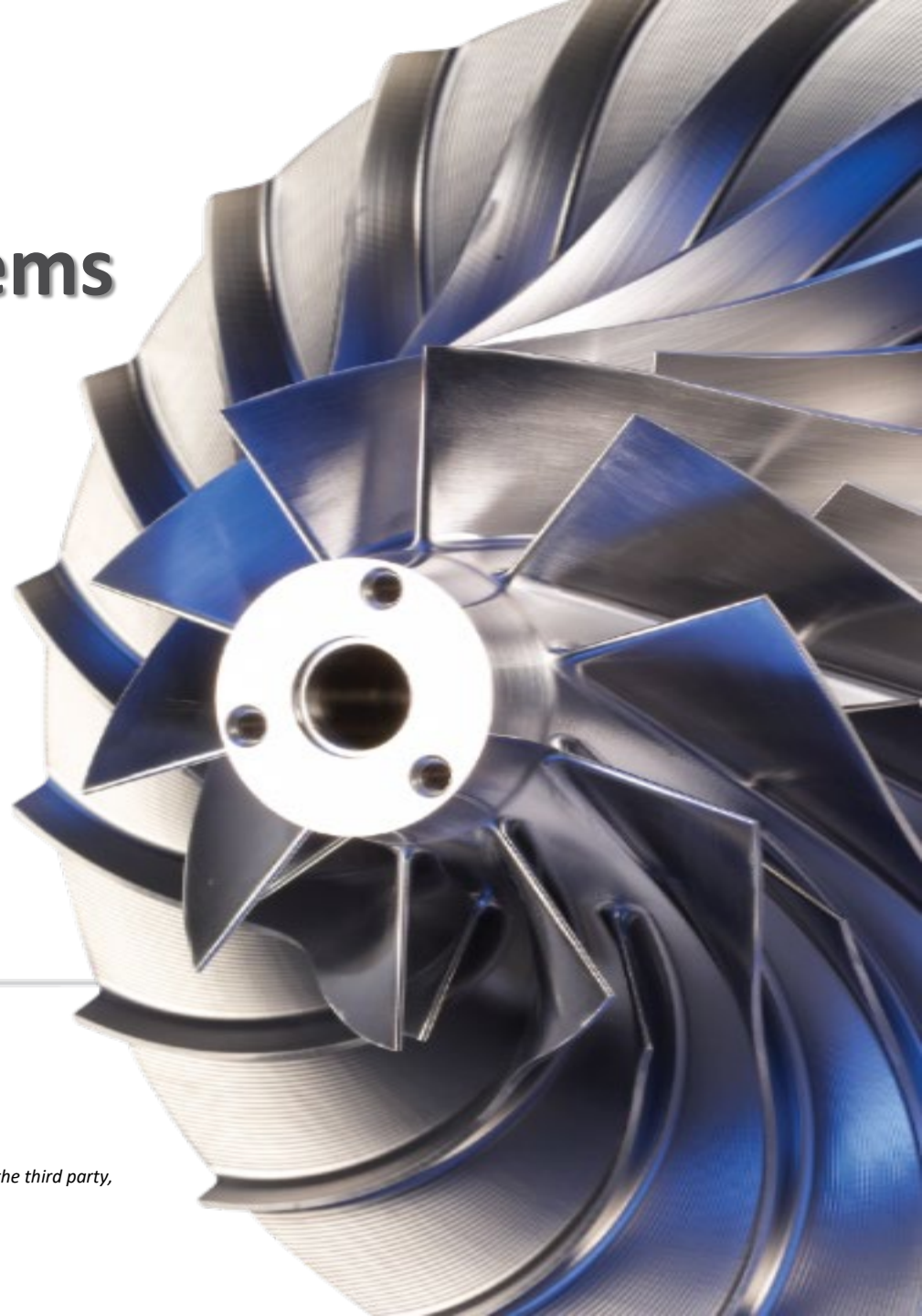
Hanwha Power Systems

Integrally-Geared sCO_2 Power Systems

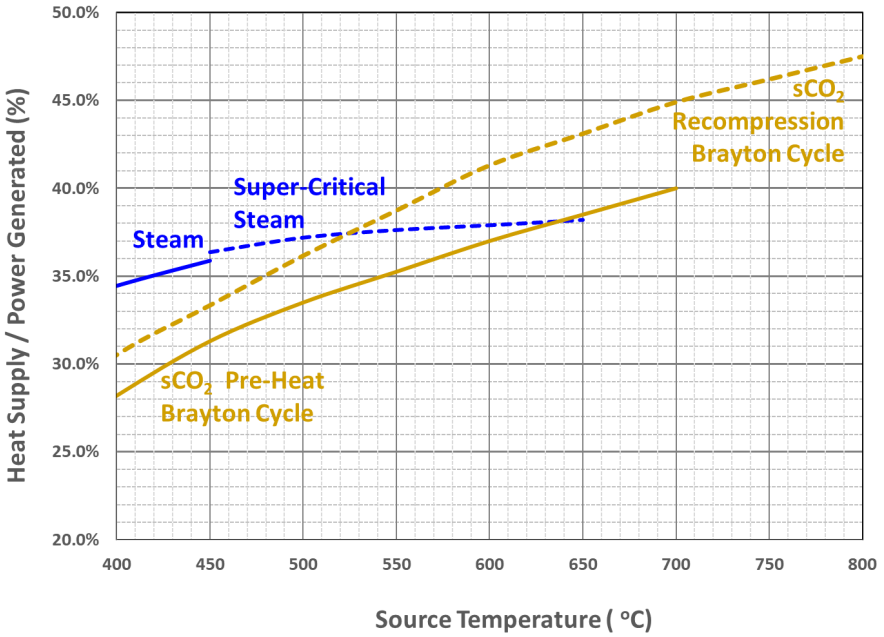


Industrial Processes Emissions Reduction Technology Workshop

April 6, 2022

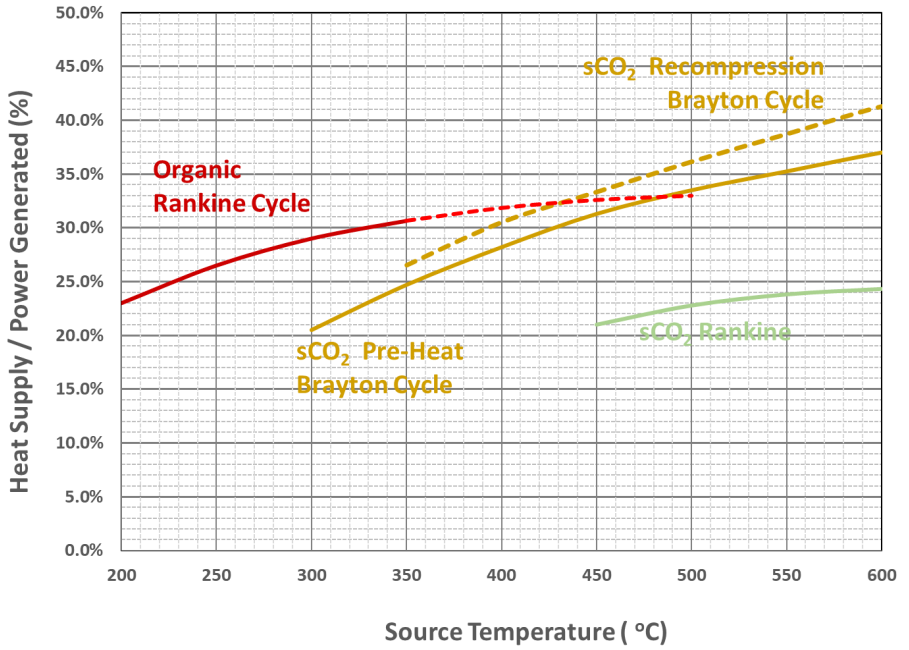
Technologies Waste Heat Recovery (5 – 10 MWe Size Range)

Power Generation



- Steam Rankine cycles have been the benchmark for power generation for over a century
- As the industry has looked for further performance gains, sCO2 Brayton cycles have been identified as an option
- sCO2 Brayton cycles offer:
  - ***Compact machinery***
  - ***High performance***
  - ***Do not require water.***

Waste Heat Recovery



- Many industrial processes result in significant amounts of waste heat
- It is a challenge to identify a waste heat recovery option that is technically and financially viable
- Steam Rankine is often used for large, high grade waste heat sources.
- ORC may be applicable for smaller, low temp heat sources
- **An sCO2 Brayton cycle is also an option as source temps get over 400C or where water is not available.**

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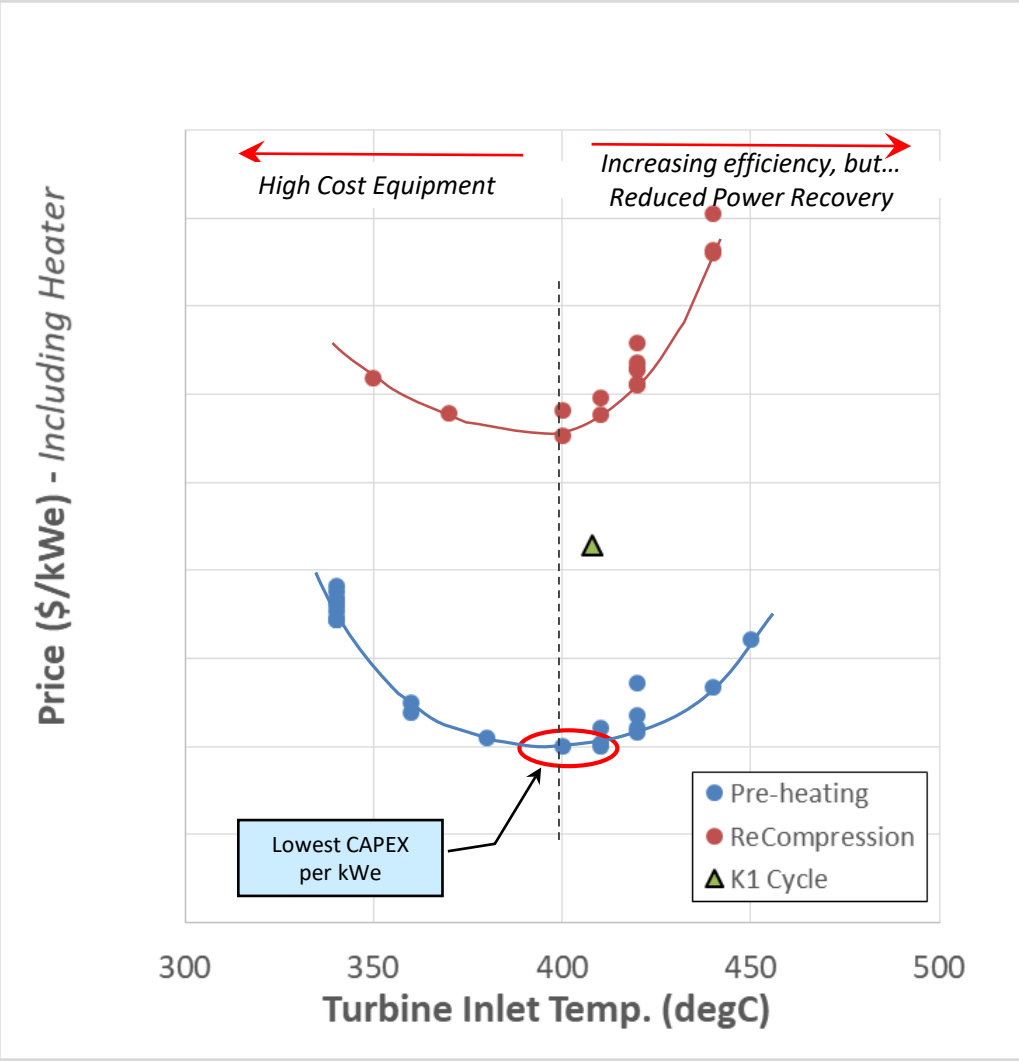
Optimizing System CAPEX and ROI



- A waste heat recovery system and cycle is optimized for each application to minimize the cost per kWe
- More complexity can be added to the cycle to enhance power recovery, but the added cost isn't necessarily justified.
  - Reheat
  - Intercooling
  - Recompression, etc.
- The max power recovery is typically achieved by operating the cycle with some margin between the peak temperature of the working fluid and the source temperature
- For the case of a small GT engine with an exhaust temperature ~500degC, the lowest cost per kWe cycle is achieved with a turbine inlet temperature ~400degC
- Additional gains in performance are possible by incorporating larger heat exchangers
- At some point the size of the heat exchangers begins to increase exponentially for small gains in performance and cannot be justified.

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Pre-Apollo: Leverage Commercial Grade Components for Maximum Reliability

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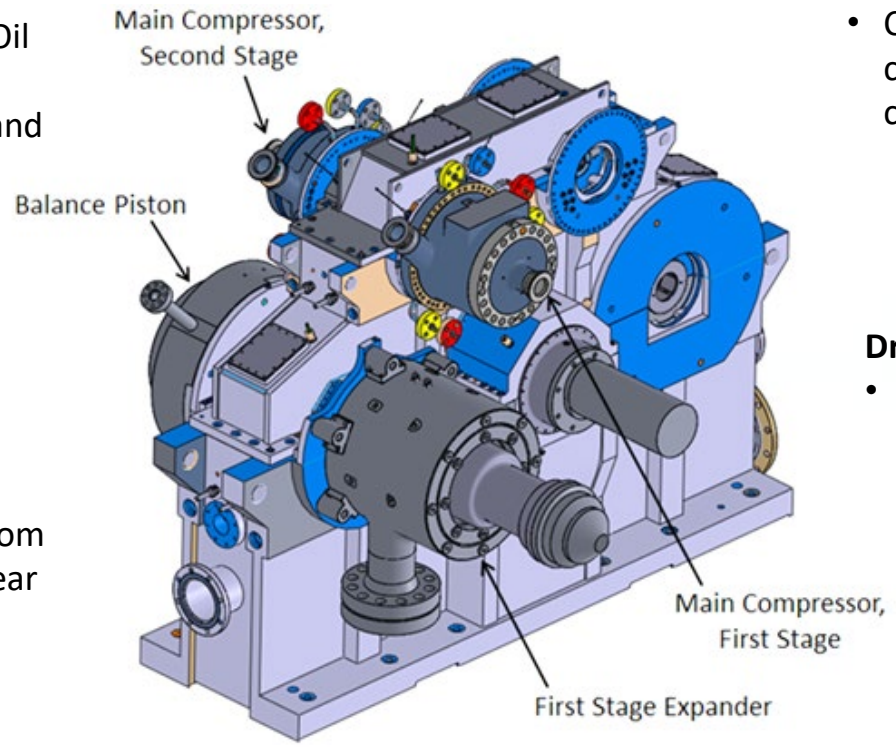
Our design approach to the *Integrally Geared sCO_2 Power System* is built largely on existing industrial grade equipment.

Tilting Pad Journal Bearings
- Conventional – 5 Pad TPJB Oil lubricated configuration.
- Excellent bearing stiffness and damping.

Thrust Management System
- Bull Gear – Fixed geometry thrust collar
- Thrust collars pass thrust from high-speed pinion to Bull gear

Lubrication System
- Oil lubrication system allows direct start-stop without need



Inlet Guide Vane
- Flow control

Variable Inlet Guide Vane
- Controls the flow to the main compressor and the re-compressor.

Dry Gas Seal Rack
- Dry gas seals and dry gas seal rack are common in O&G industry.

Generator
- Low-Speed generator is industry standard and highest reliability.

Southwest Research Institute and Hanwha Power Systems partnered to develop an sCO2 Power System based on an integrally geared turbomachinery concept.

- Project successfully completed three funding phases.
- 10MW electrical (size basis)
- System built and tested:
  - Full size main compressor,
  - Full size expander 1st stage,
  - Full mechanical system
  - Sealing system,
  - Lubrication system,
  - 1+ MW testing loop infrastructure

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Apollo - Validate of Integrated Turbomachinery Components Achieved

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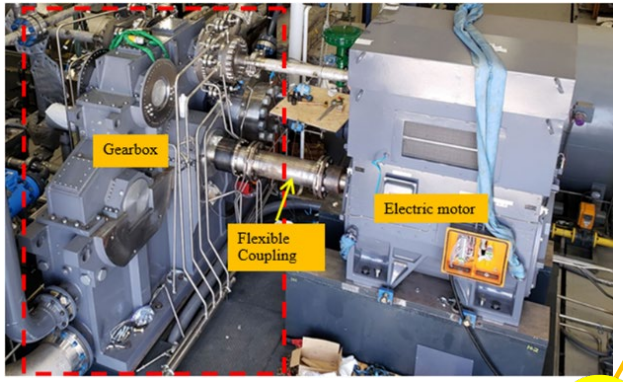
- Reliability elements of the sCO2 power system have been identified related to conventional IG turbomachines.
- Reliability factors were verified by design/interpretation/component tests and MRT, and Apollo integrated test.

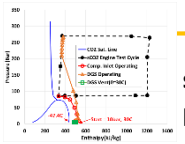
sCO_2 Power System



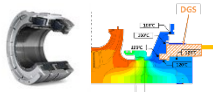
	Prior Experience	sCO_2 Testing
Gas	Air, N2, CH4,	sCO_2
Operating Conditions	T: ~288℃ P: ~75bar	T: 705℃ P: 277bar

1) DGS : Dry Gas Seal

Reliability Factor



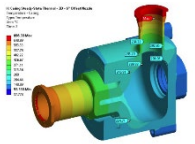
sCO_2 gas properties



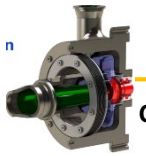
DGS[1]

Bearings

3D Printing



Casing Thermals



Casing Pressures

Solution

Real gas properties integrated and verified through test

Commercial supplied with HPS peripheral cooling

Loads and Speeds with experience limits

Extensive validation and over-speed testing

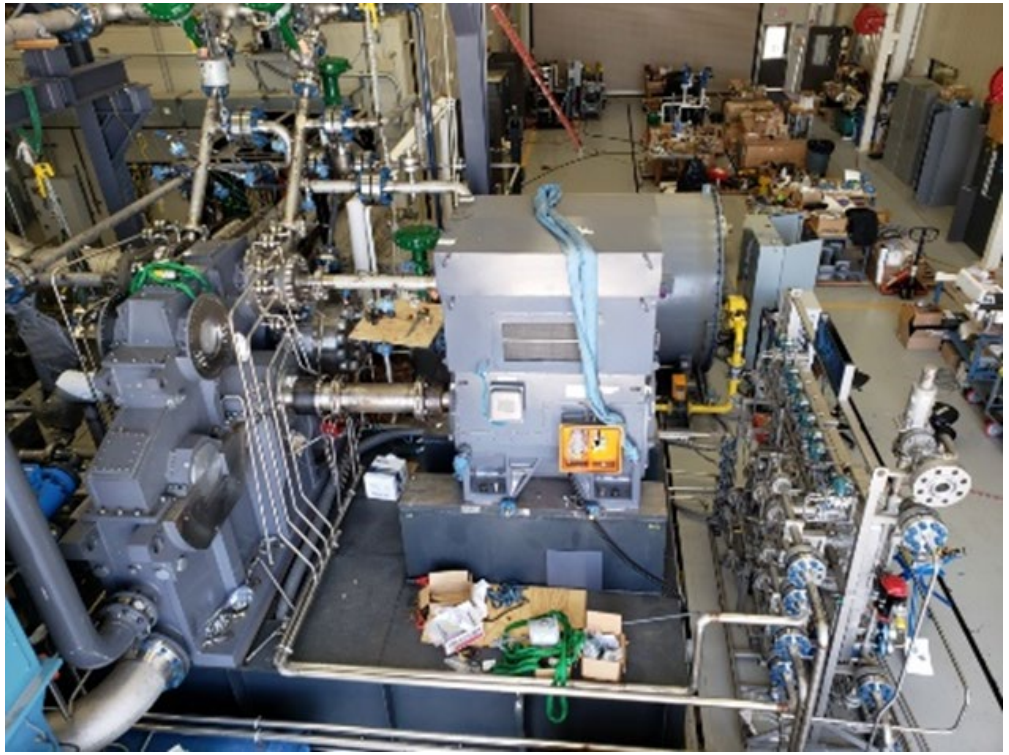
Thermal management of casing demonstrated

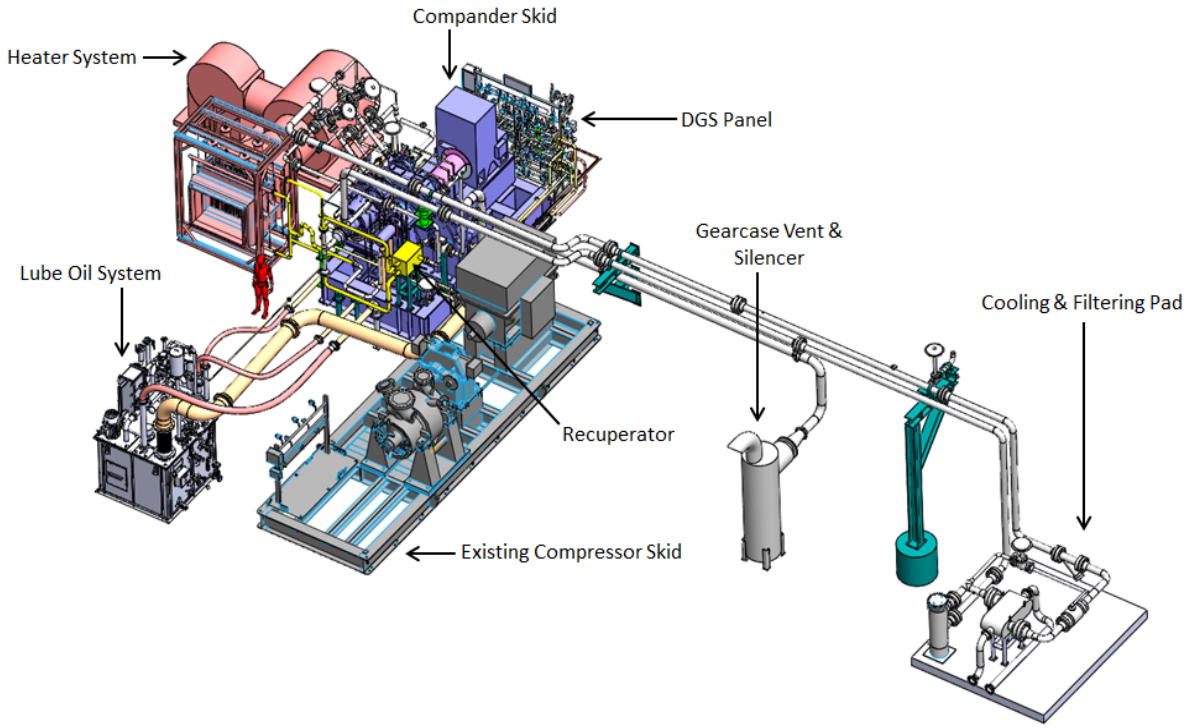
Casing pressure containment within ASME BPVC

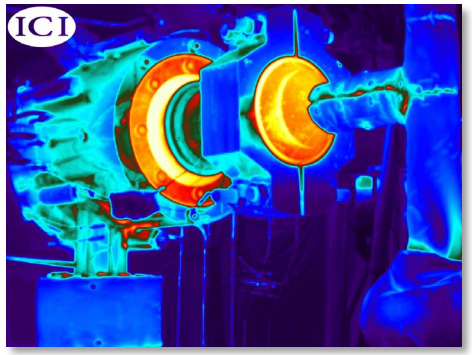
Integrated Verification

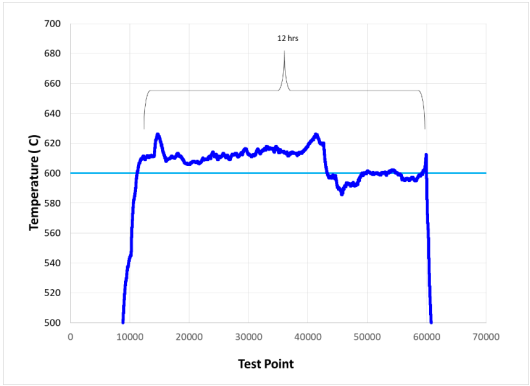
DOE Testing Program Validates Critical CO2 Characteristics

Apollo - Operation at Expander Inlet Conditions (720 °C and 260 bar)









OEM: Hanwha Power Systems
Tested: Southwest Research Institute

Program Achievements:

- Highest inlet expander temperature for CO_2
- Lowest leakage IG CO_2 compressor
- Widest range sCO_2 compressor
- Highest efficiency sCO_2 compressor stages

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