Hanwha Power Systems

sCO_2 Power Systems

Status of Technology Maturation

February 22, 2022

Global Leader in New Product Development for Turbomachinery

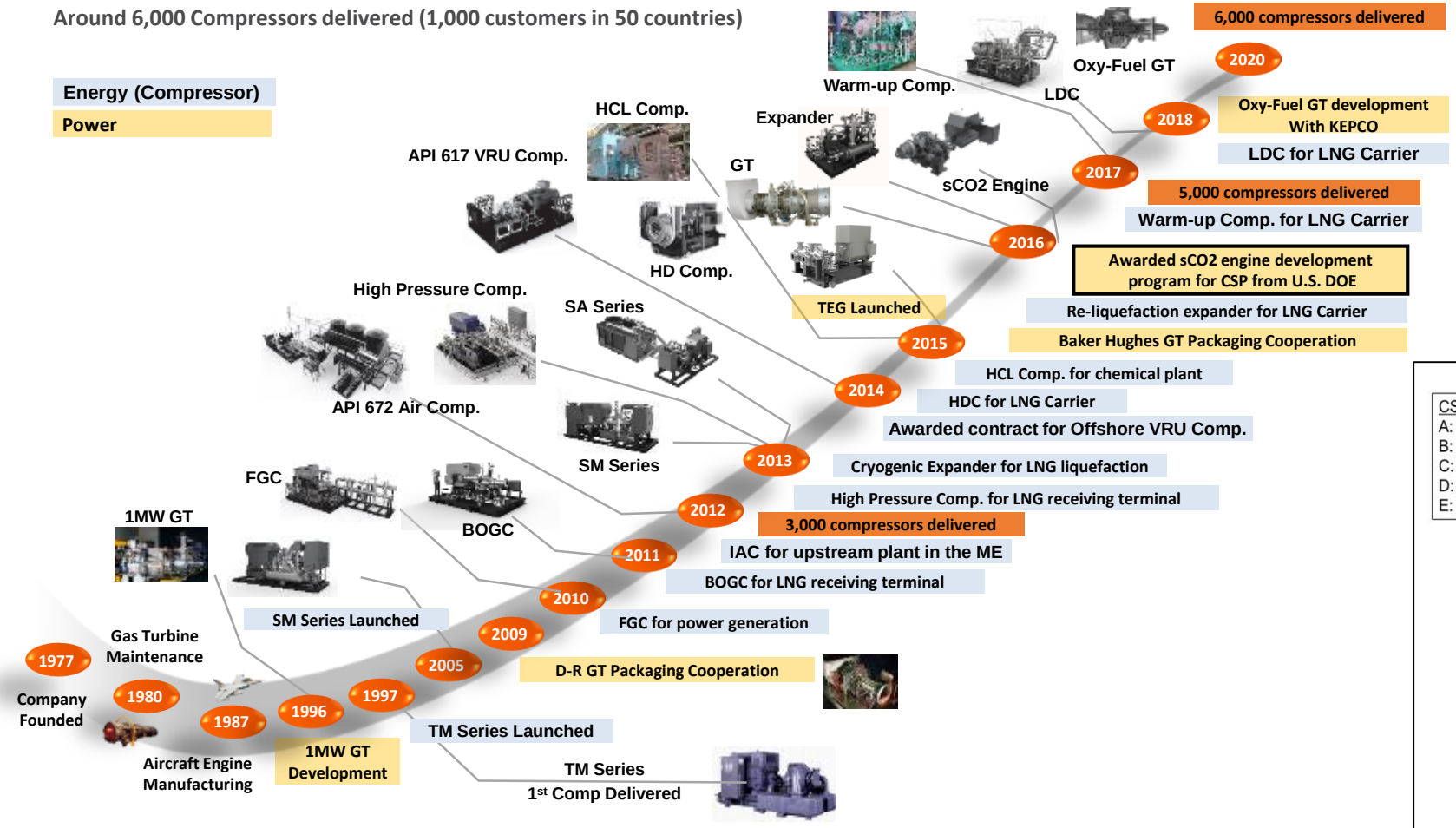
Hanwha Power Systems

One of the fastest growing companies in power generation and oil & gas industry

Around 6,000 Compressors delivered (1,000 customers in 50 countries)

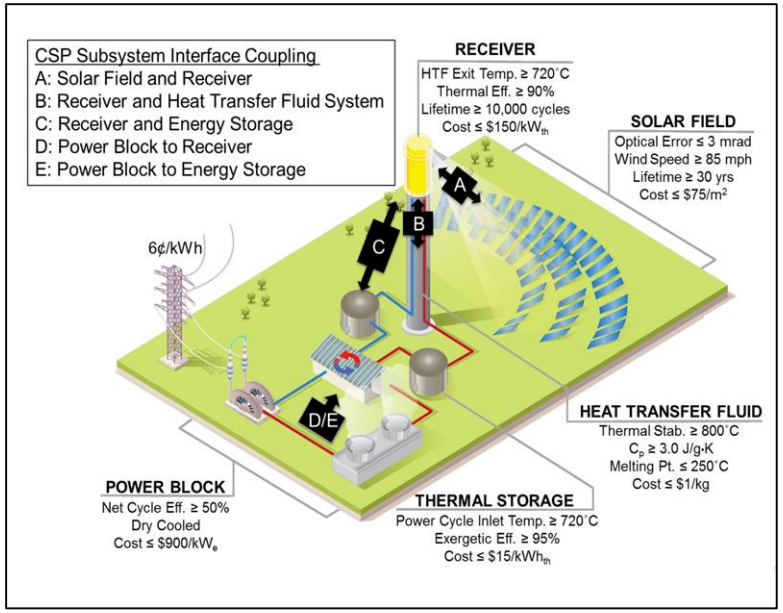
Energy (Compressor)

Power



* GT : Gas Turbine * HDC : High Duty Compressor * LDC: Low Duty Compressor * BOGC : Boiled Off Gas Compressor * FGC : Fuel Gas Compressor * API : American Petroleum Institute * VRU : Vapor Recovery Unit
* KEPCO : Korea Electricity Power Corporation * CSP : Concentrated Solar Power

DOE Apollo



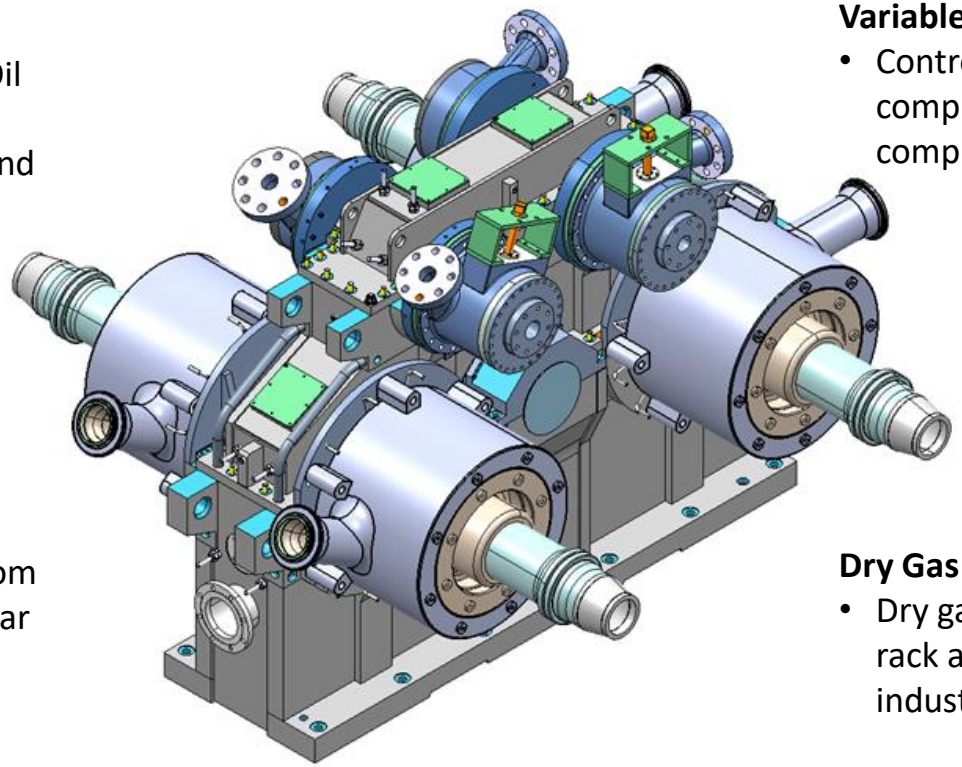
Product Approach: Leverage Commercial Grade Components for Maximum Reliability

Our fundamental approach to the Integrally Geared sCO_2 Power Systems is unique in that it 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



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.

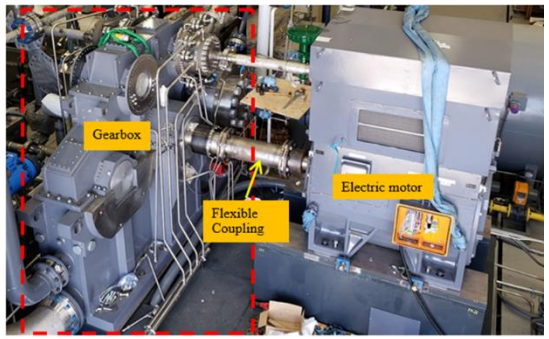
- Project successfully completed three funding phases.
- 10MW electrical (size basis)
- System built and tested:
  - Full size main compressor,
  - Full size expander 1st stage,
  - Full mechanical system
  - Sealing system,
  - Lubrication system,
  - 1+ MW testing loop infrastructure

Validate Integration of Turbomachinery Components: Apollo

Hanwha Power Systems

- Six key reliability risks of the sCO2 power system have been identified according to the difference in operating medium and operating conditions from conventional IG turbomachines.
- Reliability risks were mitigated by design and verified by analysis, component tests and full scale production testing

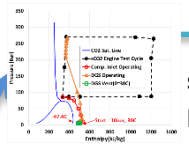
sCO_2 Power System



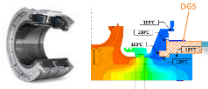
	Experience	sCO_2 Testing
Gas	Air, N2, CH4,	sCO_2
Operating Conditions	T: ~288℃ P: ~75bar	T: 705℃ P: 277bar

1) DGS : Dry Gas Seal

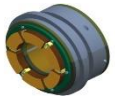
Reliability Factor



sCO_2 gas properties

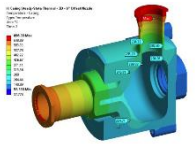


DGS[1]

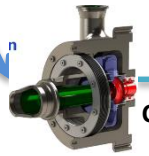


Bearings

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

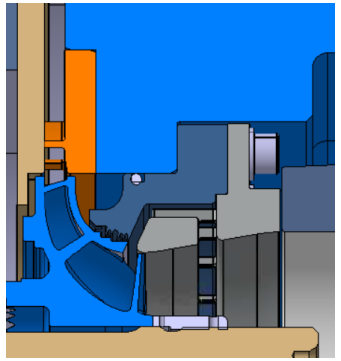
Integrated Verification

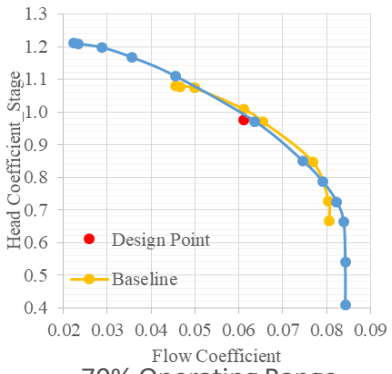
DOE Testing Program Validates Critical CO2 Characteristics

Validate Approach: Extensive Component Testing of Critical Areas

The highest risk areas were the subject of component tests. All component tests were completed were successfully completed without incident which helps establish design integrity.

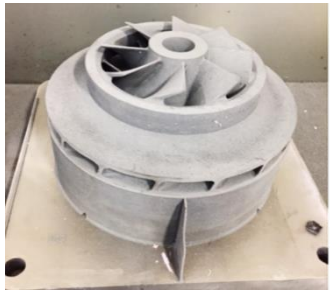
Compressor Air Test





70% Operating Range

Additive Manufacturing



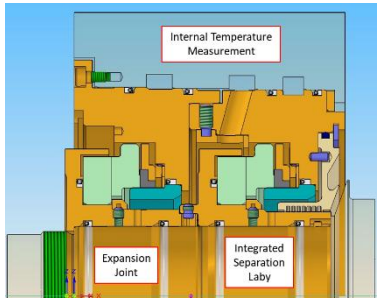
Highest Tip (**625 m/sec**) Speed Closed Impeller Ever Tested by ~40% (limited only by spin pit)

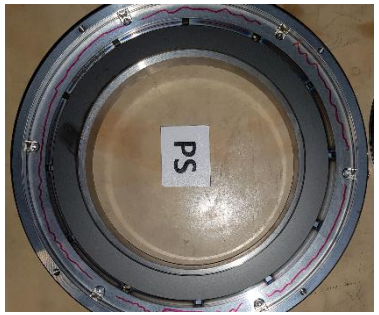
High-Pressure Casings

Stage 2 Casings Passed Hydro-test at **477 bar**

Stage 1 Casing Passed Hydro-test at **347 bar**

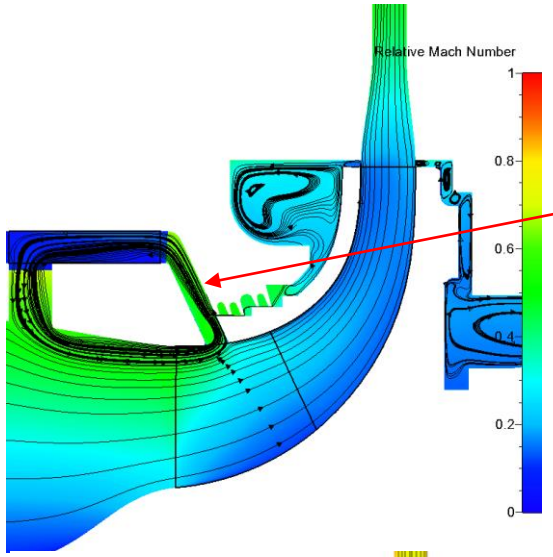
Dry Gas Seals

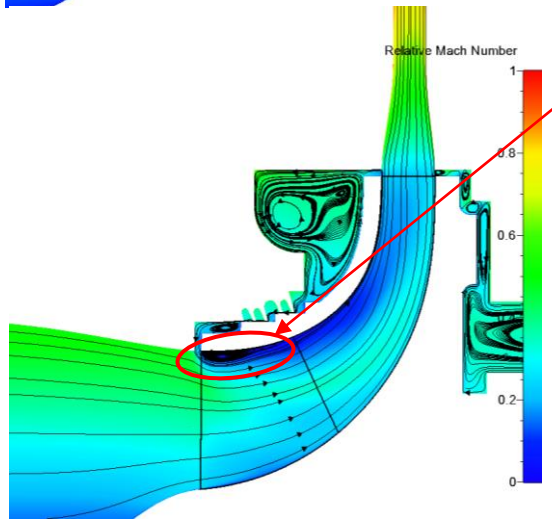


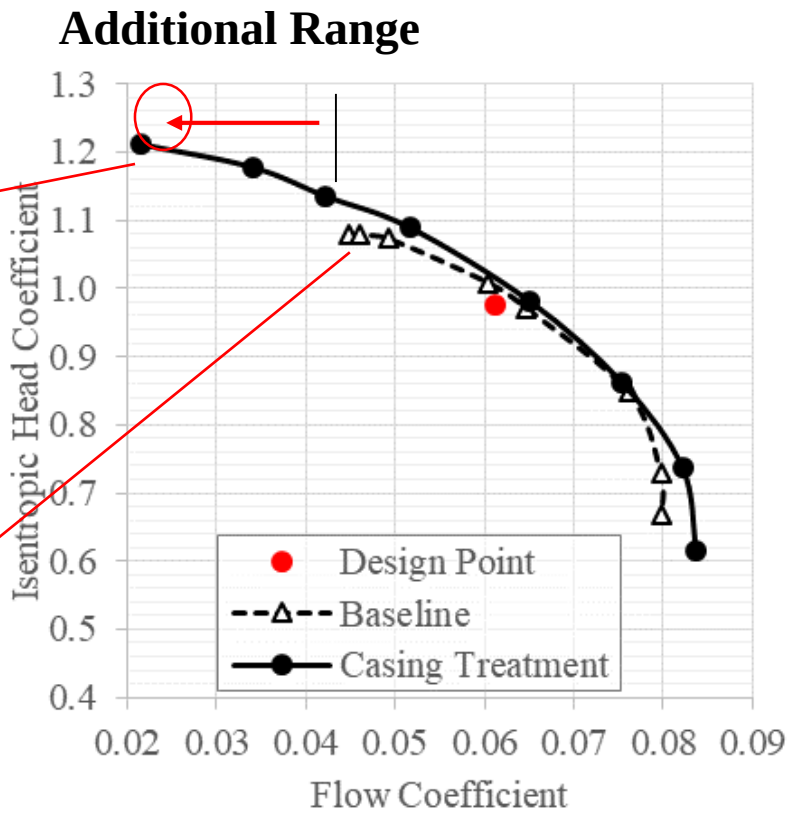


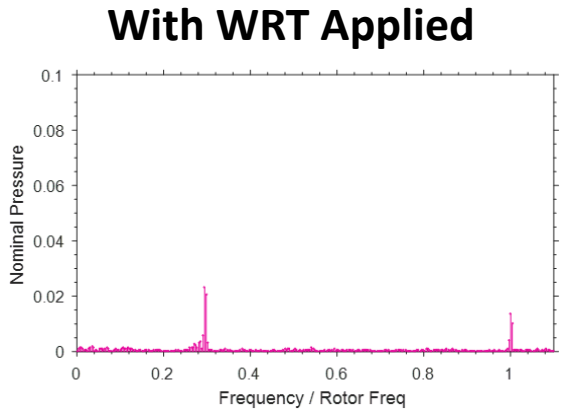
Seals Shop Test to Full Pressure and Rotational Speed in N_2

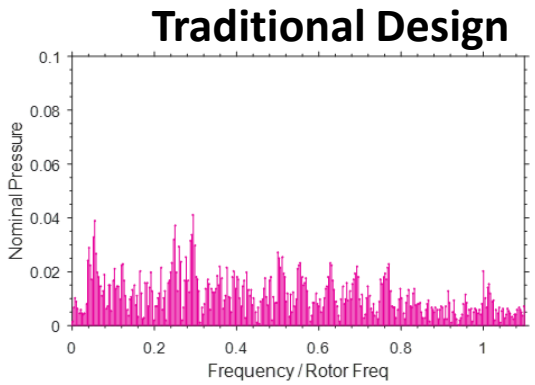
Wide Range Technology Improves Reliability and Operational Range





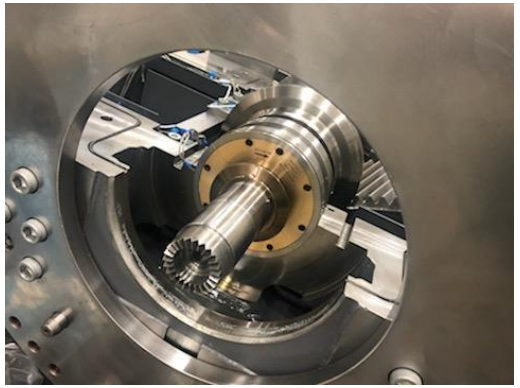


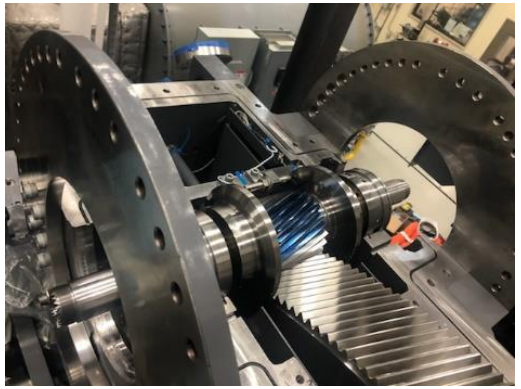


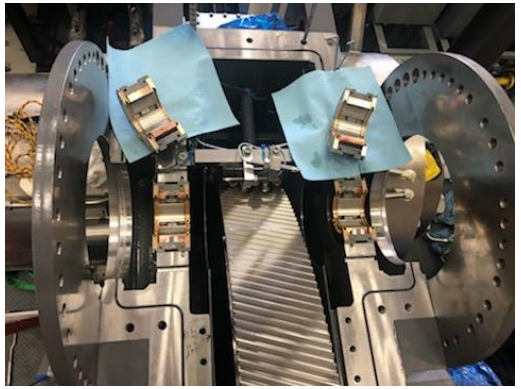


- Casing treatment designed based on extensive computational fluid dynamics (CFD) analysis
- Analysis based on real gas properties since the compressor operates near the critical point
- Incorporating a casing treatment was found to extend the operating range significantly (**from 43% to 74%)**
- Very minor efficiency penalty is predicted due to the casing treatment
- 92% reduction in pre-surge energy

Demonstrated Sustained Operation at 720 C EIT and 260 bar EIP



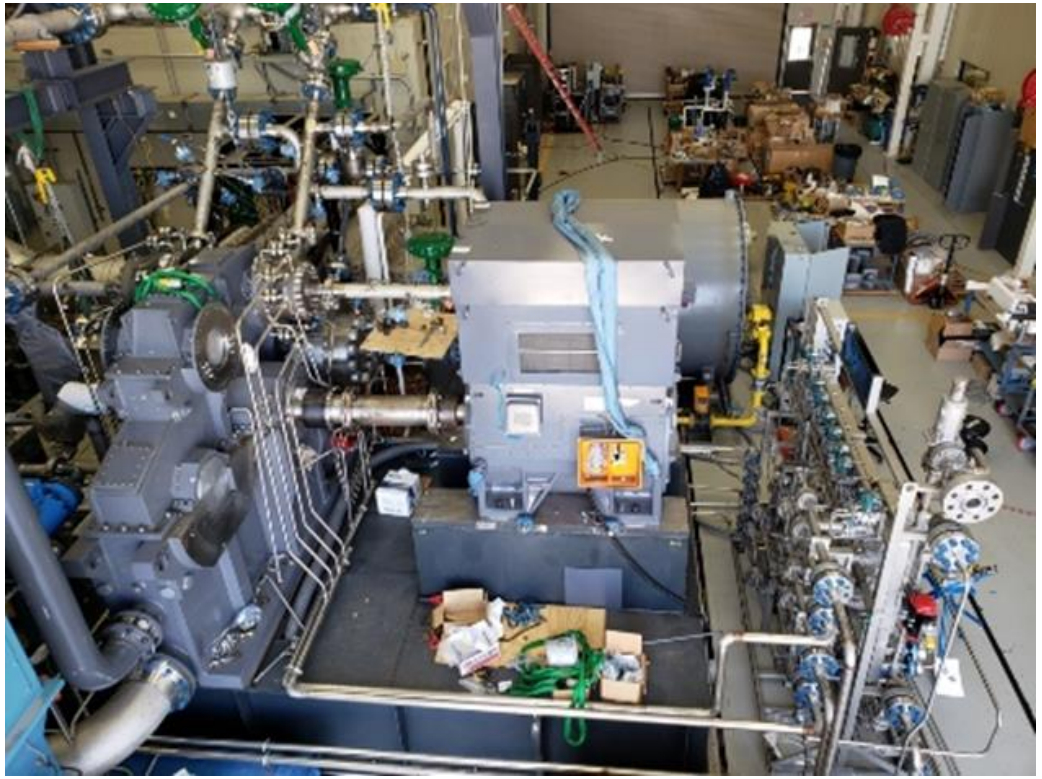




Design/Manufacture: Hanwha Power Systems
Tested: Southwest Research Institute

Some Accomplishments:

- Highest inlet expander temperature for CO2,
- Lowest leakage IG CO2 compressor,
- Widest range compressor,
- Highest efficiency compressor stages



Compressor Operation and Performance Near Critical Point

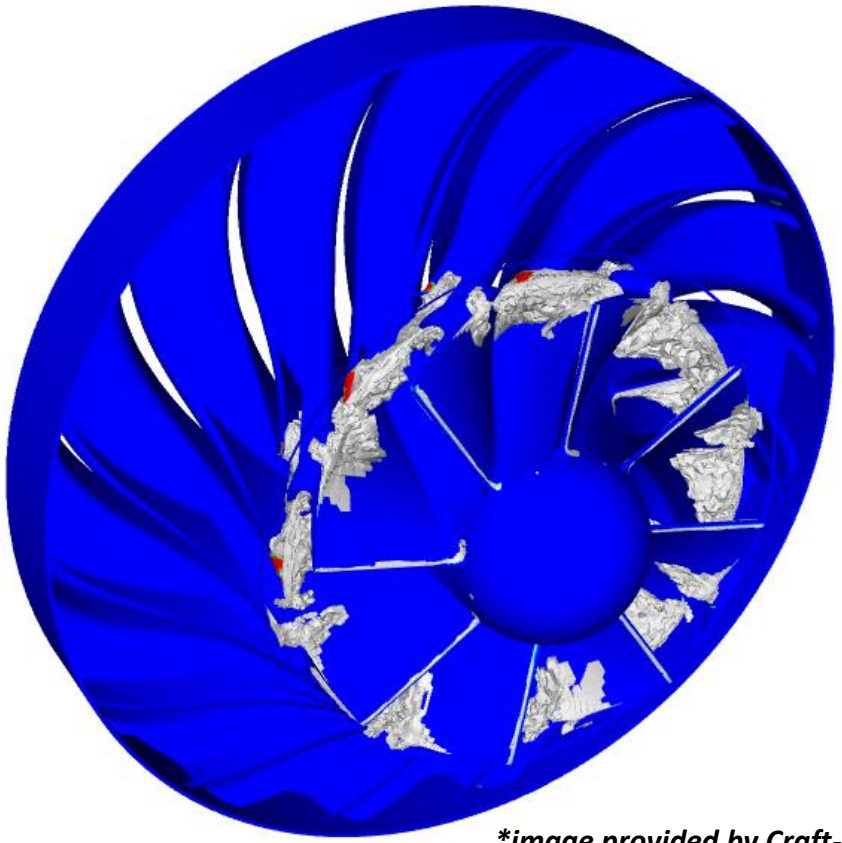
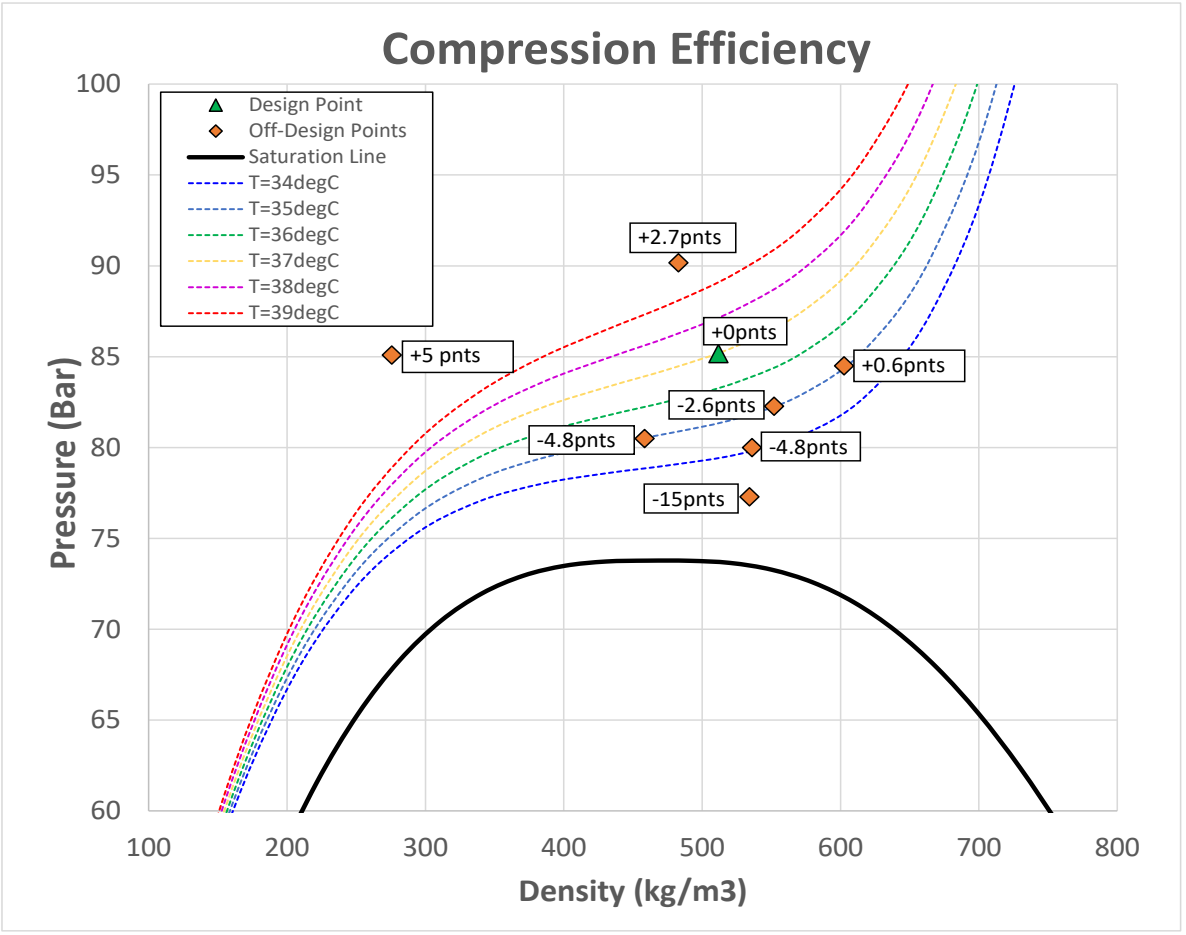


**image provided by Craft-Tech*



- Test data shows variation in compressor efficiency near the critical points.
- Performance variation may be due to the development of liquid regions where local static temperature and pressure are suppressed due to high passage velocity.
- Off-design cycle modeling can be updated to give an improved estimate of power production

Post Apollo Test: Passed 12 hr sCO_2 Mechanical Endurance Test

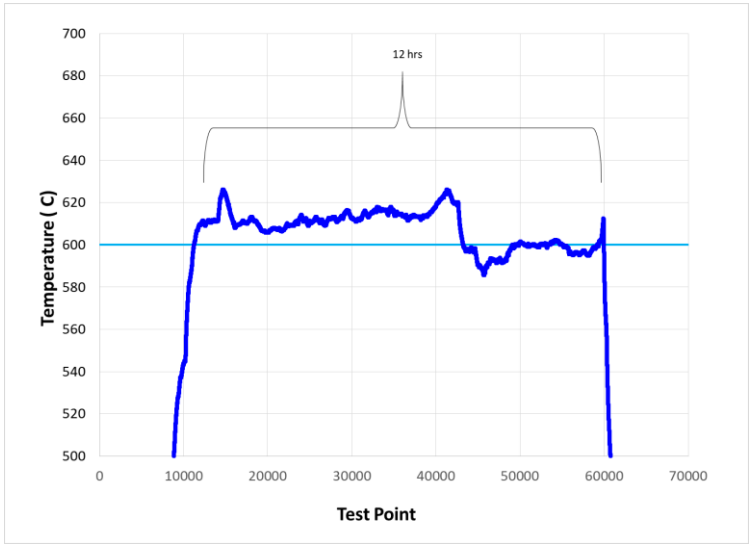
From a commercial standpoint demonstrating machinery endurance is critical:

- ✓ Customer confidence
- ✓ Allows ability for OEM to more readily offer warranties, guaranties, etc.

HPS sCO_2 Power System passed *Endurance Test*:

- ✓ Full scale,
- ✓ Full-speed,
- ✓ Full pressure,
- ✓ Full temperature, and
- ✓ Full success on endurance test.
  - ✓ 12 hr continuous operation test passed
  - ✓ Total operational time > 100 hrs.
  - ✓ Peak operating Temperature > 705 C

Test Data: 11.94 hrs at average P= 247.27 bar



Average T= 606.8 C

Expander Thermal Management Verification

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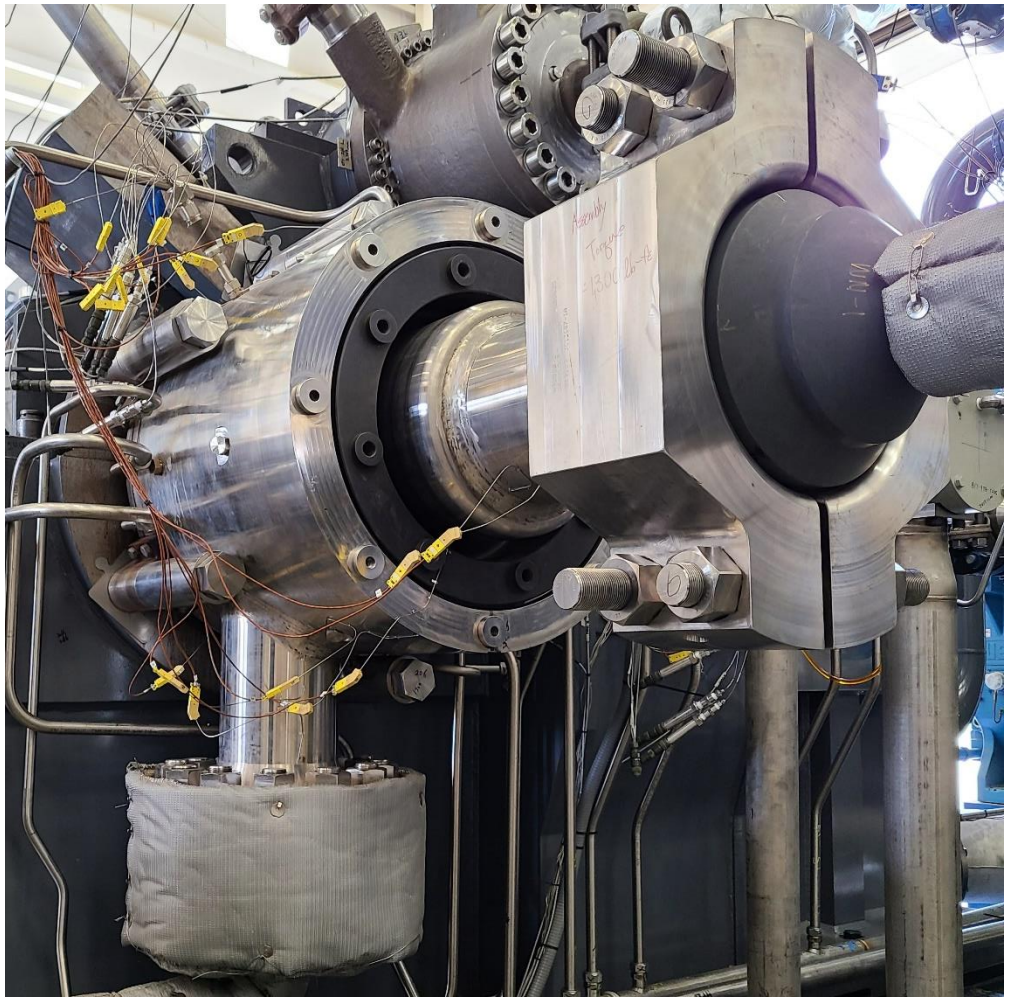
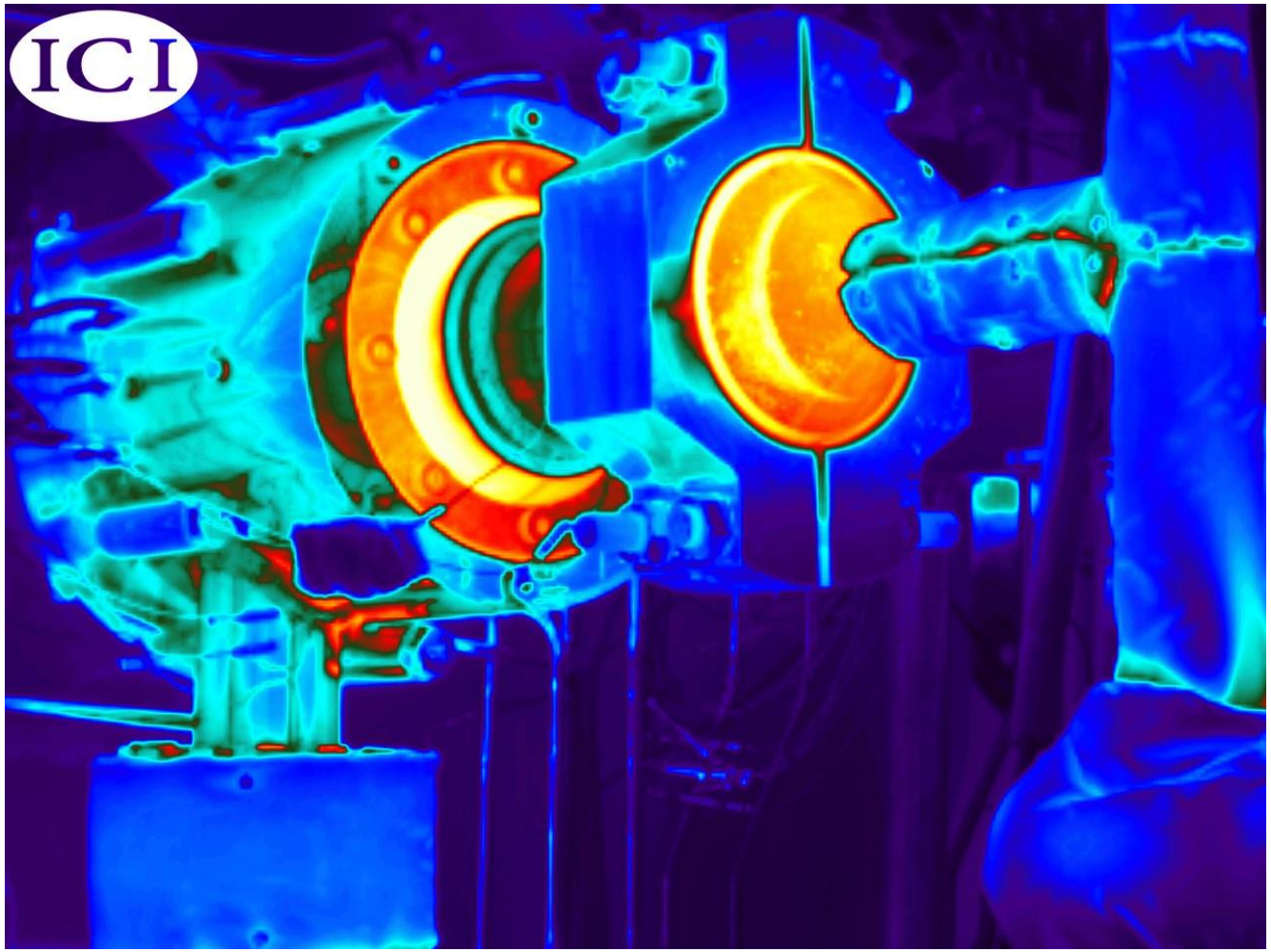
- Thermal gradients in the expander measured with embedded thermocouples and visualized with a thermal imaging camera
- Results confirmed performance expected based on analytic simulations



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Hanwha Will Be the Sustainable Energy for Your Future