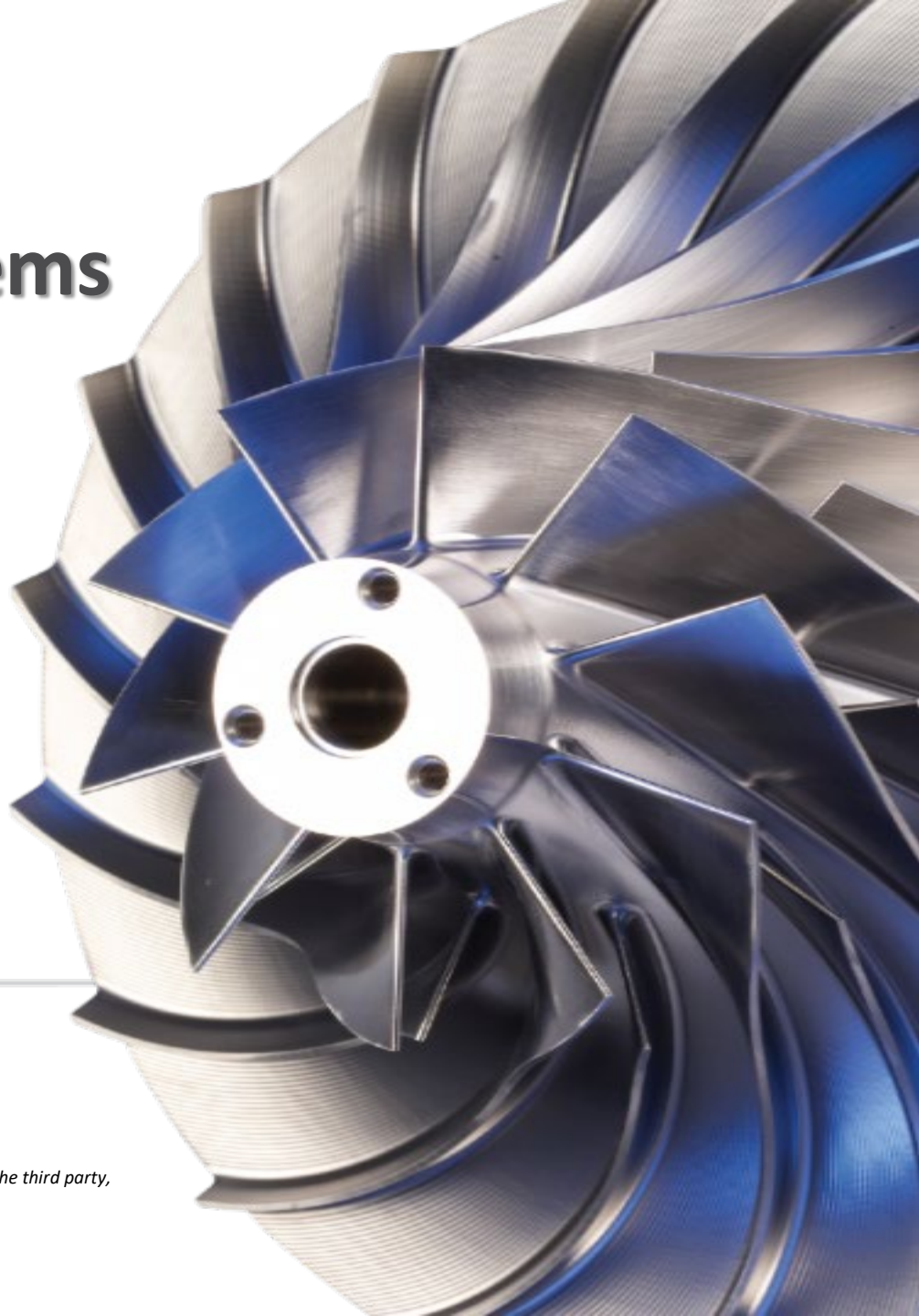
Hanwha Power Systems

Integrally-Geared sCO_2 Power Systems

Design, Test, and Commercialization of an Integrally-Geared sCO_2 Power System



February 22, 2022

About Hanwha Power Systems

Hanwha Group leverages ‘ Hanwha spirit’ blended with trust and loyalty and core values of challenge, dedication and integrity to expand its business boundary in manufacturing, construction, finance, services and leisure industries.

Hanwha

Major Affiliates

Manufacturing & Construction

Hanwha Corporation	Hanwha Power Systems
Hanwha Aerospace	Hanwha General Chemical
Hanwha Systems	Hanwha Total Petrochemical
Hanwha Defense	Yeochun NCC
Hanwha Techwin	Hanwha Energy
Hanwha Precision Machinery	Hanwha Engineering & Construction
Hanwha Solutions	Hanwha City Development

Finance

- Hanwha Life Insurance
- Hanwha General Insurance
- Hanwha Investment & Securities
- Hanwha Asset Management
- Hanwha Saving Bank

Services & leisure

- Hanwha Hotels & Resorts
- Hanwha Galleria
- Hanwha Galleria Timeworld
- Hanwha Estate
- Hanwha Station Development
- Hanwha Eagles

Apollo Development / Test Phase

Technology Progression Lead to Closed Loop sCO_2 Power System

Hanwha Power Systems

2016

CLOSED MASTER IMPELLER
- Entry into O&G applications
- Entry into higher-pressure applications

THRUST COLLAR DESIGN TOOL
- Texas A&M
- Improved reliability
- SOA analytics

2018

RANGE EXTENSION
- Passive technology
- Competitive advantage
- Reduced risk of surge damage.

2019

HIGH TEMPERATURE EXPANDER
- Solution minimizes Inconel,
- Reduced cost,
- Creep life testing,
- Ensure wide product range

2019

ADDITIVE MANUFACTURING
- Improved Reliability
- Improved design flexibility
- General trend of other manufacturers

2020

HIGH-PRESSURE CASINGS
- Extended product range for O&G
- Increased reliability

2021

HIGH-TEMPERATURE CASINGS
- Unique Expander abilities
- High Reliability

2021 Present

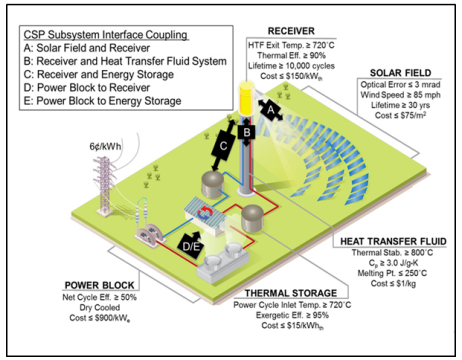
5MW sCO_2 Power Systems
- Limited market competition,
- Small foot print,
- Rapid skid deployment – foot print and skid confirmation to occur 2021

2022-2024

RECOMPRESSION PILOT SITE
- Allows long term validation,
- Provides site specific references,
- Establish cost savings opportunity

RECUPERATED PILOT SITE
- WHR
- Power Generation
- Min CAPEX

U.S. DOE Apollo



Product Approach: Leverage Commercial Grade Components for Maximum Reliability

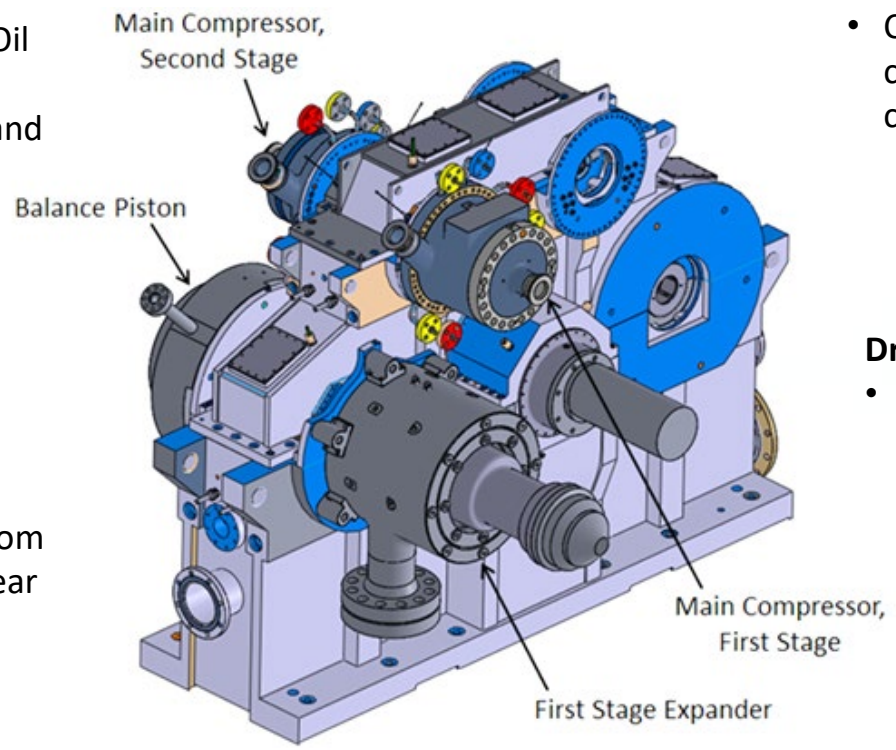
Hanwha Power Systems

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



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

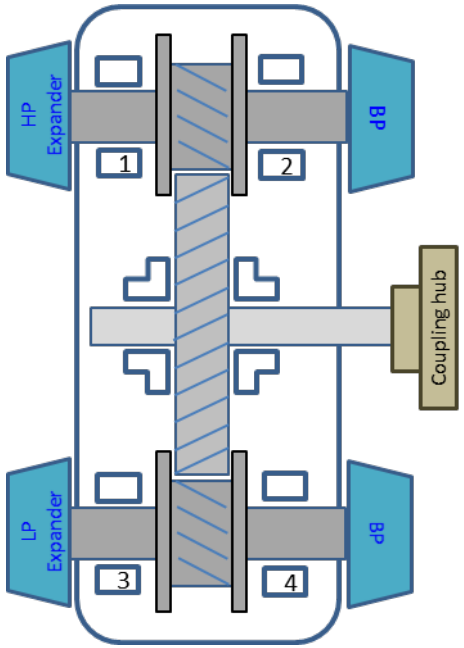
Dry Gas Seal Rack
- Dry gas seals and dry gas seal rack are common in O&G industry.

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

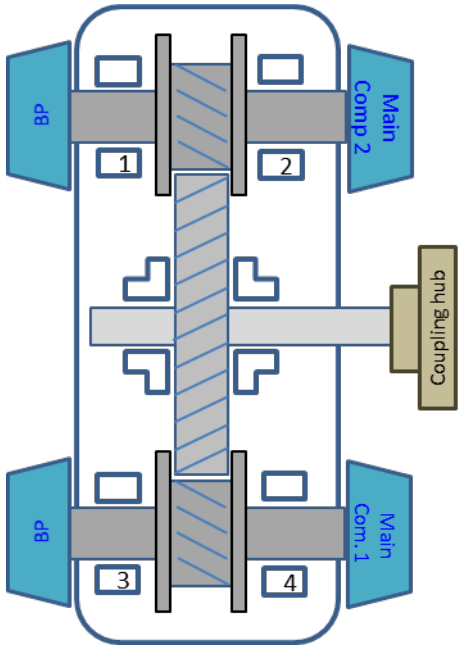
Southwest Research Institute and Hanwha Power Systems partnered to develop an sCO2 Power System based on an integrally geared turbomachinery concept.

- 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

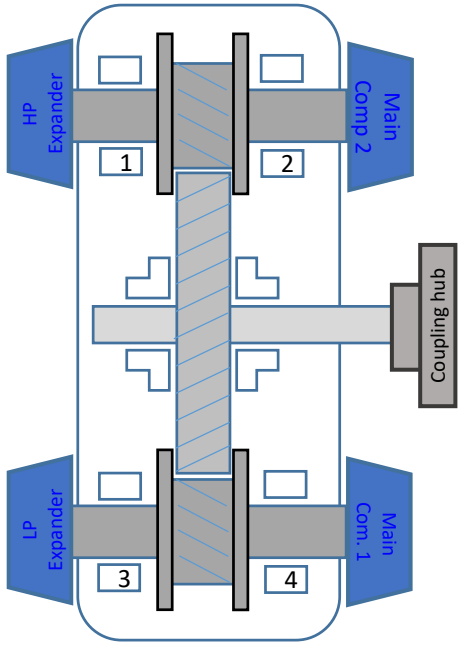
IG Arrangement Offer Tremendous Cycle and Product Flexibility



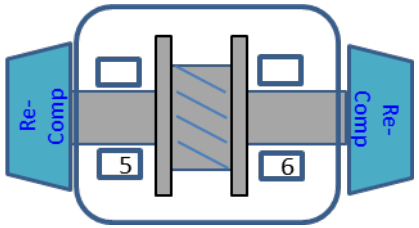
Turbomachinery
(Expansion Only)



Turbomachinery
(Compression Only)



Turbomachinery
(Expansion and Compression)



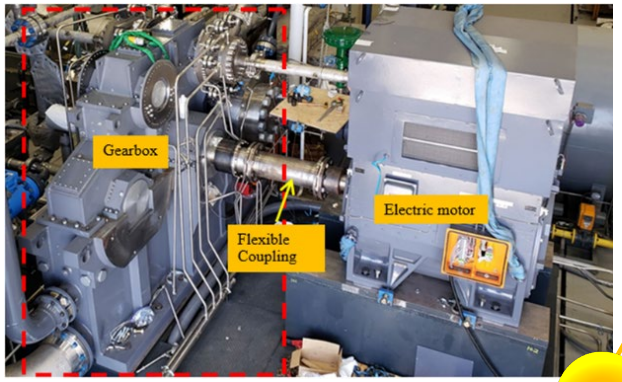
Recompression Cycle

Ability to offer variability allows commercial advantages: adjusting cycle and configuration to meet customer needs

Validate of Integrated Turbomachinery Components Achieved

- 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.

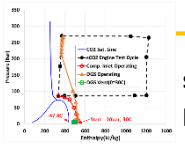
sCO_2 Power System



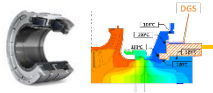
	Prior Experience	sCO_2 Testing
Gas	Air, N2, CH4,	sCO_2
Operating Conditions	T: ~288℃ P: ~75bar	T: 705℃ P: 277bar

1) DGS : Dry Gas Seal

Reliability Factor



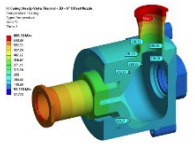
sCO_2 gas properties



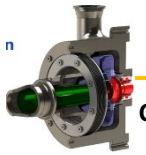
DGS[1]

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

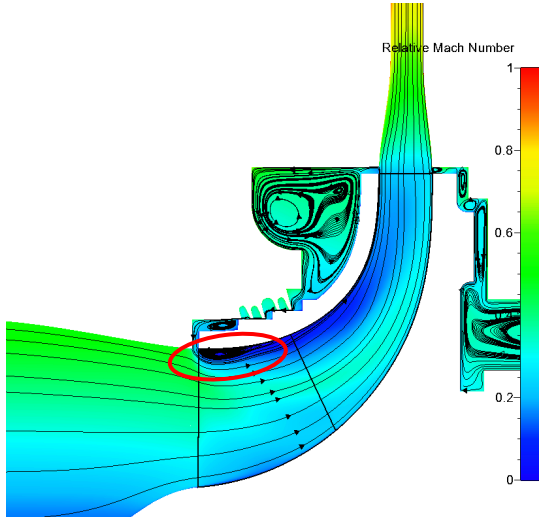
DOE Testing Program Validates Critical CO2 Characteristics

Wide Range Technology Improves Reliability and Operational Range

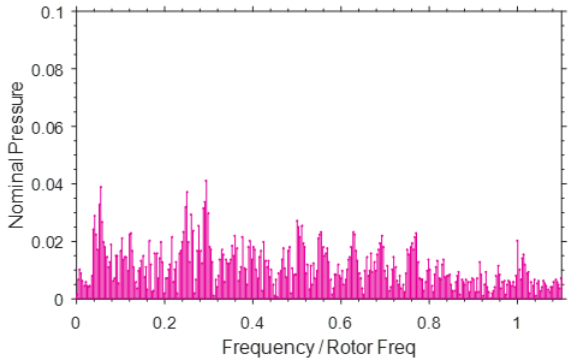
Hanwha Power Systems

- 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%**)

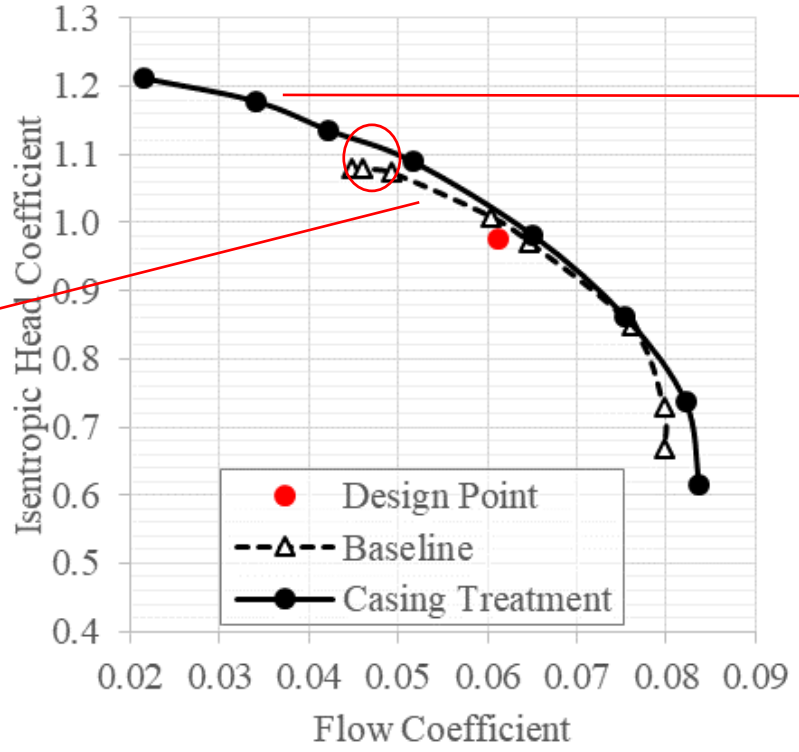
- **Improved Reliability (Passive)**
- Reduced Dynamic Stress
- Increased Operating Range

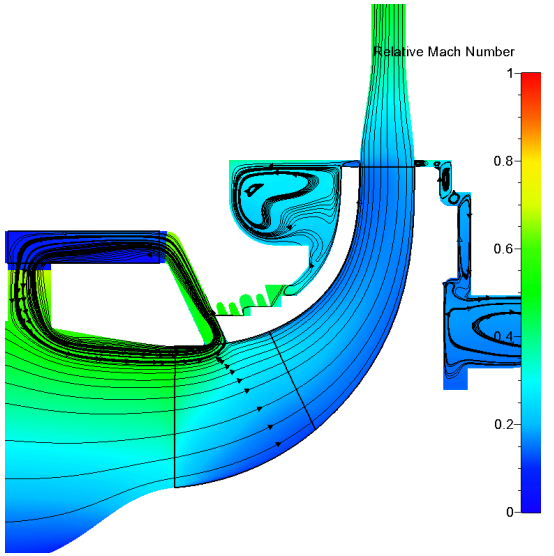


Traditional Design

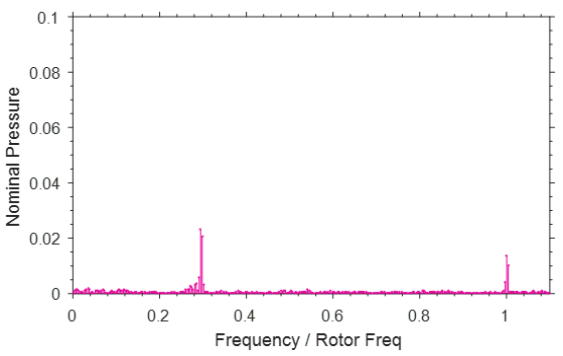


Scaled Test Results



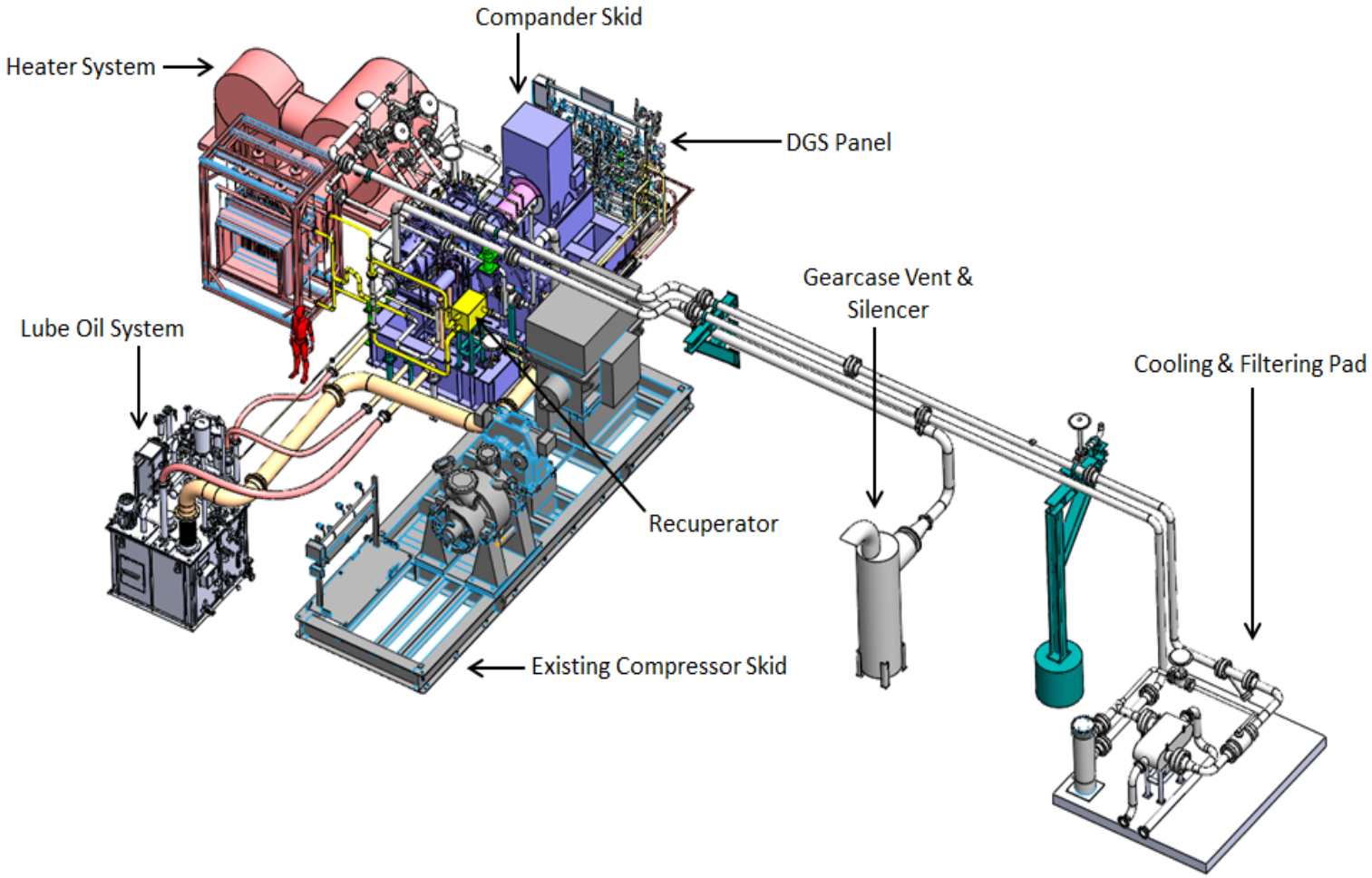


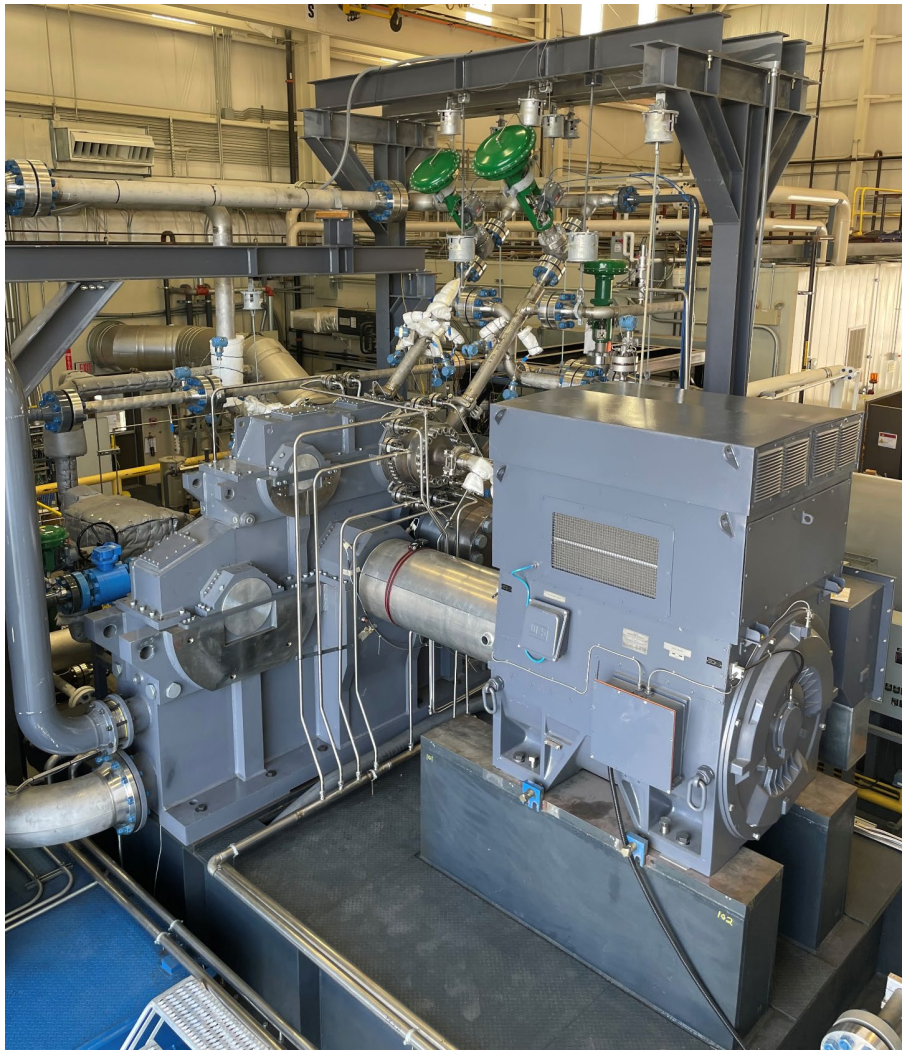
Wide Range Technology



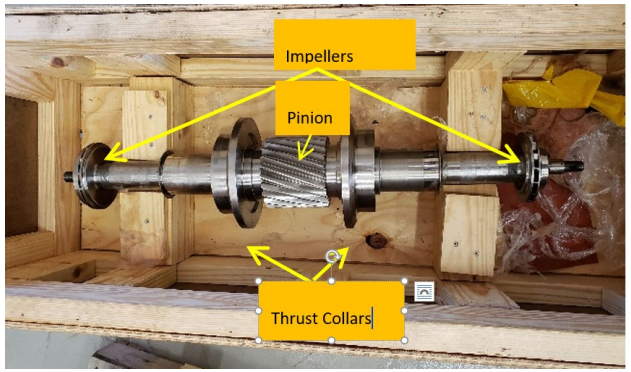
Apollo IG sCO2 Test Facility at Southwest Research Institute

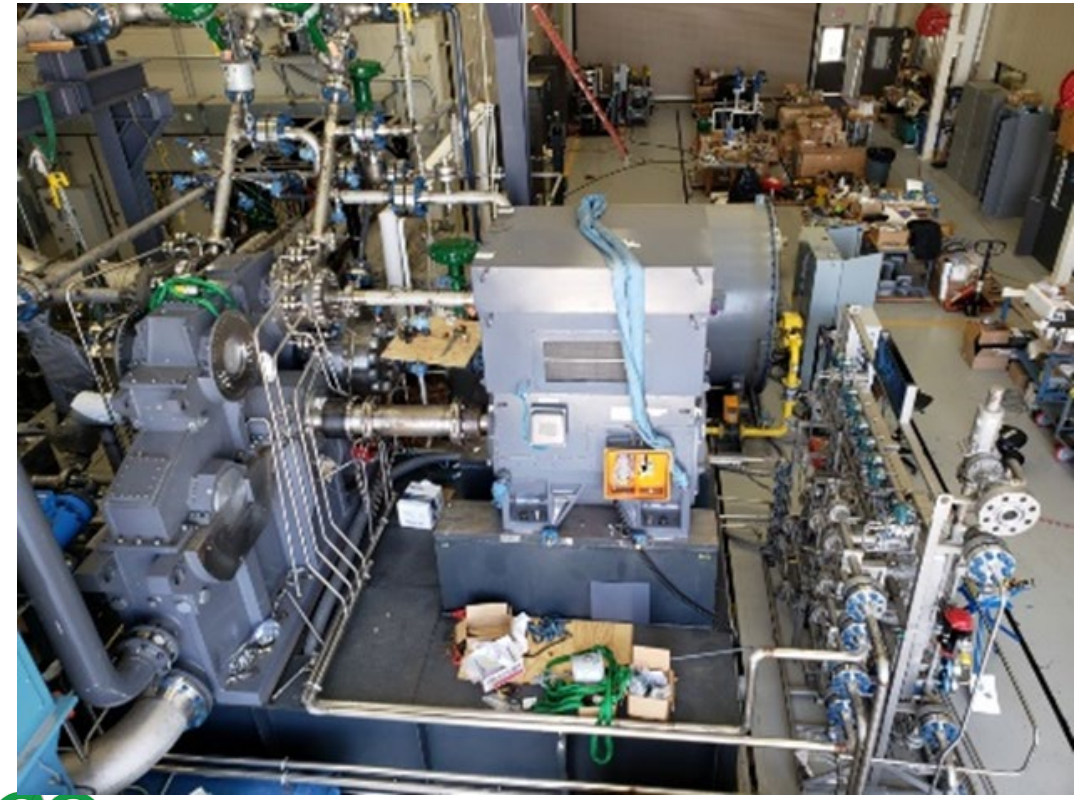
- Highest power test loop currently available for proof of concept testing





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





OEM: Hanwha Power Systems

Tested: Southwest Research Institute

DOE 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

Maximize Reliability in Operation

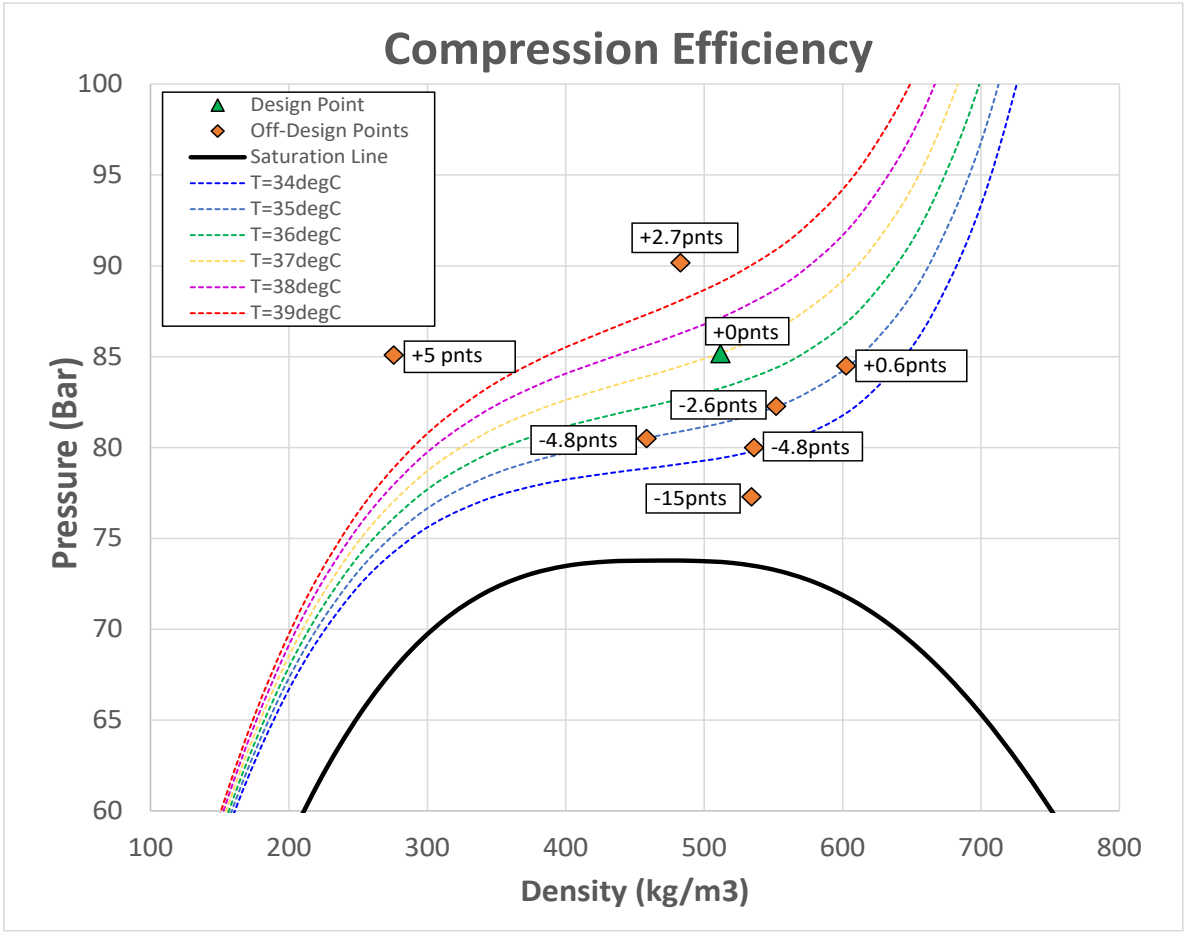
EERE APOLLO program (EE0007114)

- to convert sunlight to power at a 700 °C inlet temperature
- η=50%

- **Design Conditions**
  - CIT: 37 ° C (95-120 °F)
  - TIT: 700 ° C (1300 °F)
  - TIP: 275 bar (4000 psi)
  - Mass Flow: 50-70 kg/s
  - Nominal Power: 10 MW

Post-Apollo Testing

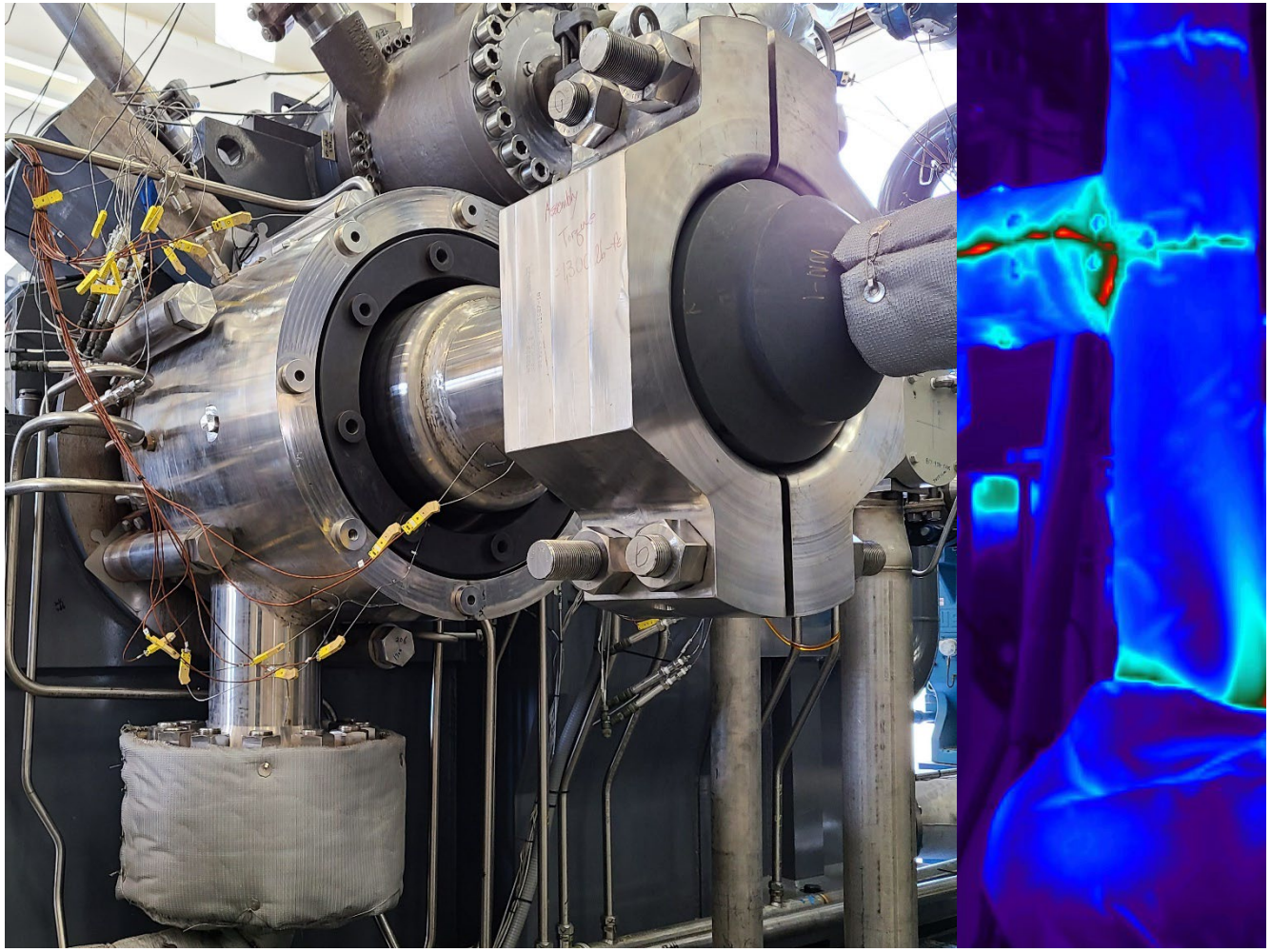
Compressor Operation and Performance Near Critical Point



- 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.

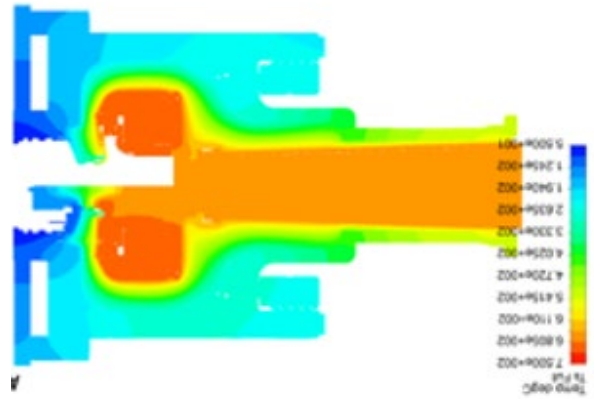
Expander Thermal Management Approach Validated at 720 C

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



Patented Thermal Management System

- Apollo test proved thermal-mechanical integrity
- Leakage controlled dry gas seals
- Low-Loss thrust collar management system
- Titling pad journal bearings (Robust rotor-bearing system)



Expander Casing Thermal Analysis

Post Apollo Test: Passed 12 hr sCO_2 Mechanical Endurance Test

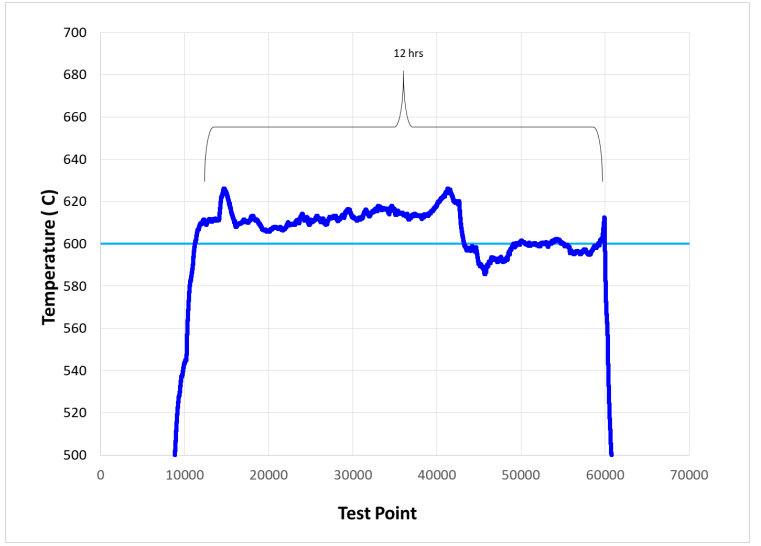
Demonstrated machinery endurance is critical:

- ✓ 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

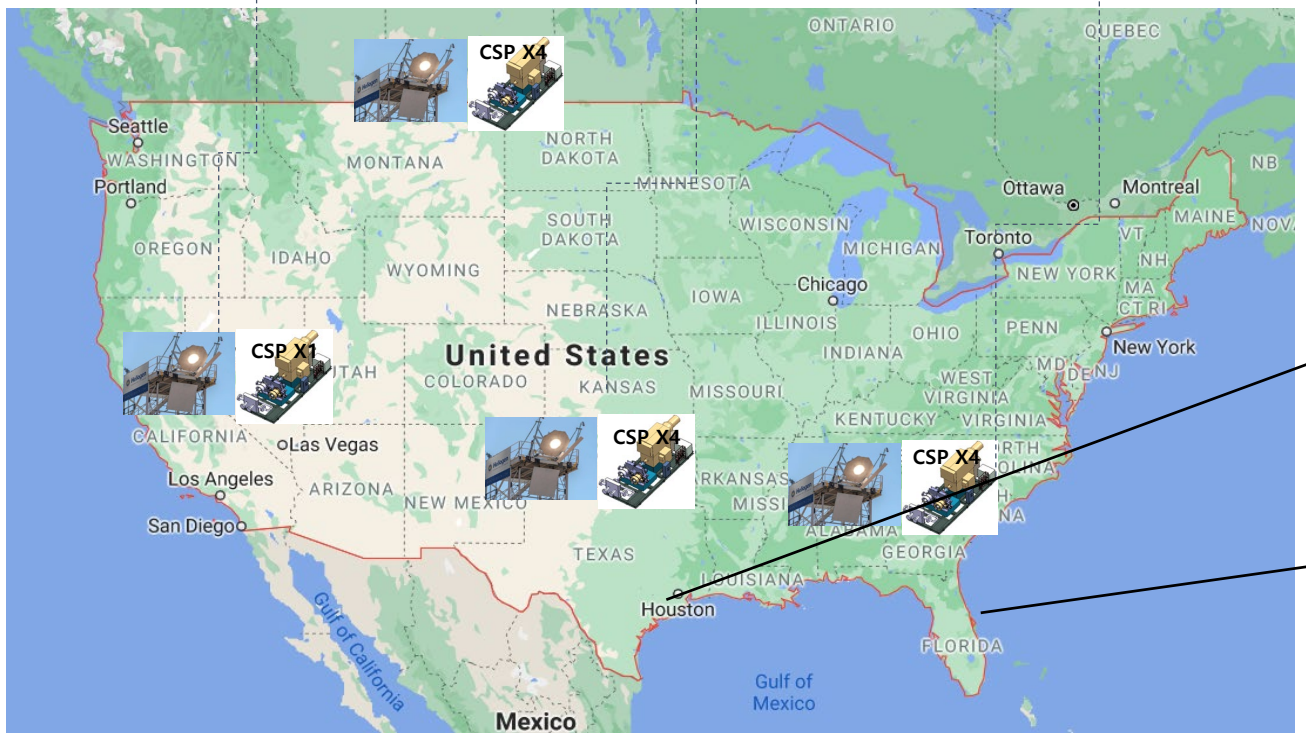


Test Data: 11.94 hrs at average P= 247.27 bar
Average T= 606.8 C

Commercial Phase

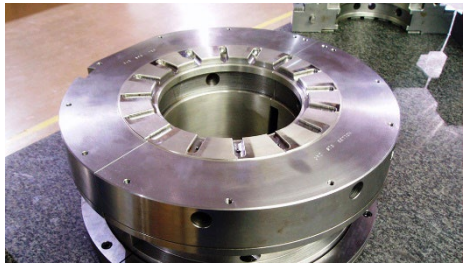
Business Growth for Condition Based Health Monitoring with Partnerships

- Leverage Existing Inventory stocking and service capabilities in U.S.
- Real-time monitoring of the operation status of multiple sites through the web environment at our central monitoring center
- Real-time storage and management of operating data of the sCO_2 power system on a remote server

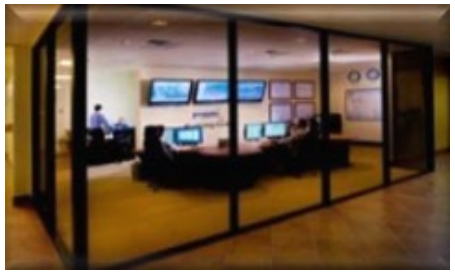


Internet

Cloud Server



Repair Center (BGA)
Houston, TX



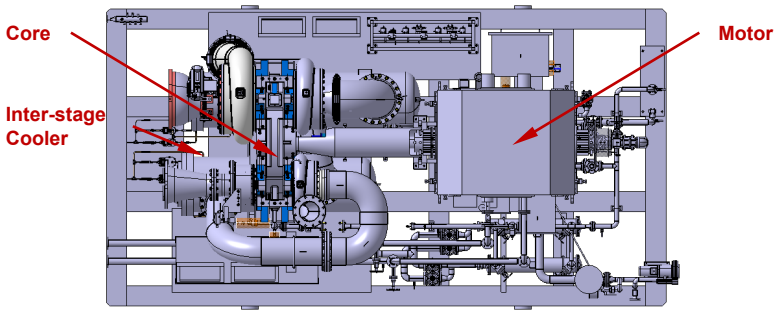
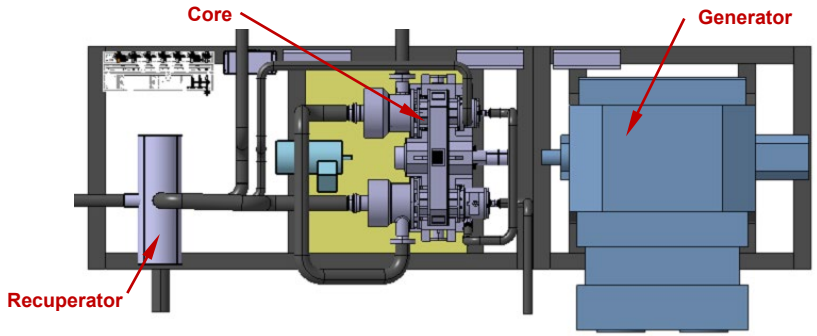
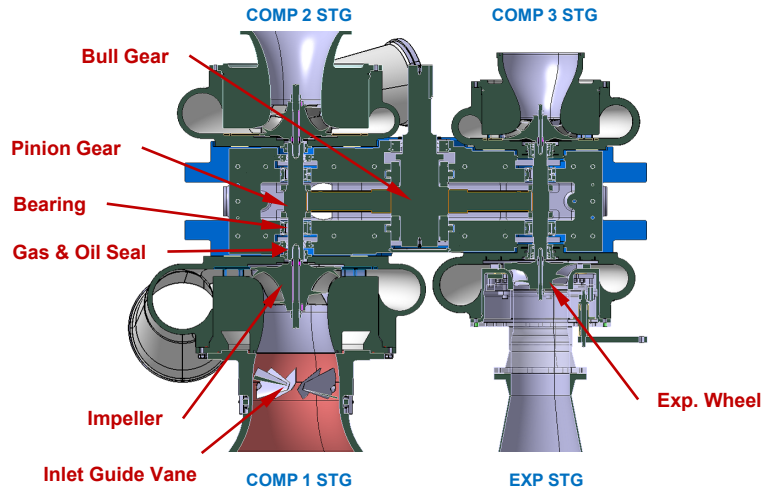
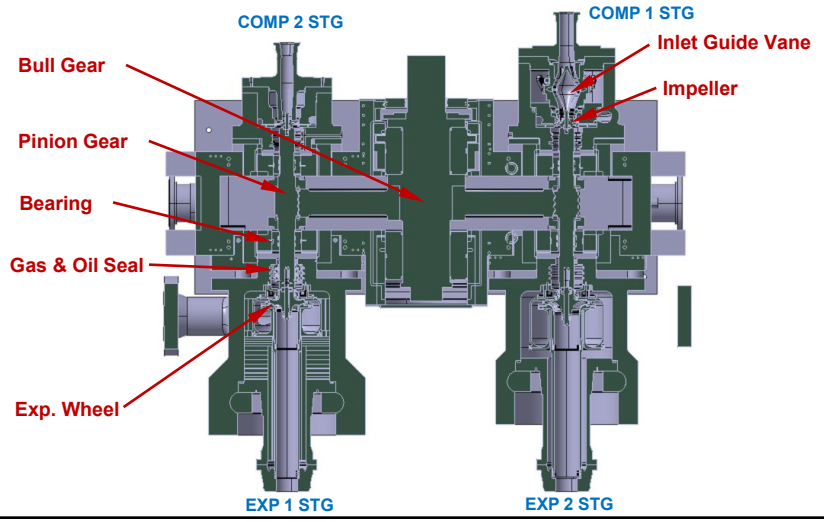
Monitoring Center (PSM)
West Palm Beach

24/7 sCO_2 Power Plant Performance & Status

- Operational information
- Consumable parts are replaced
- Regular/predictive preventive maintenance

5MW Size can be Modular and is Highly Similar to Existing Product Portfolio

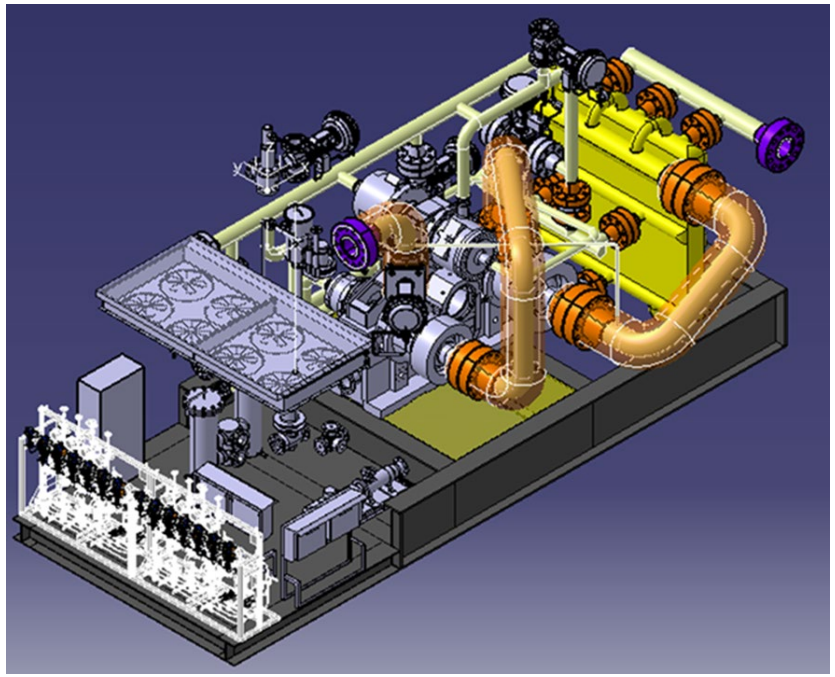
- HPS's sCO2 Power System applies the same structure and operation method as IG-Type turbo equipment
- More than 6,000 HPS references are held for IG-Type turbo equipment (field operation reliability has been proven)

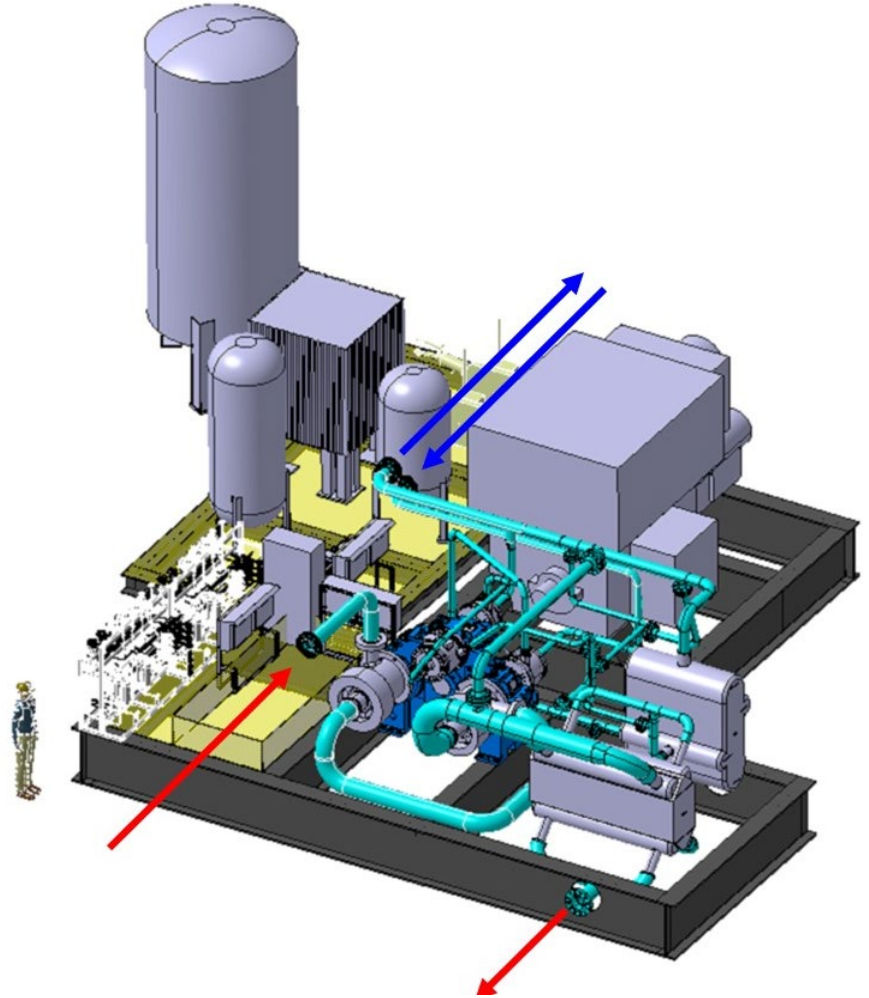
	IG Gas Compressor-Expander	IG sCO_2 Power System
Package		
Machinery		

5MW Recompression Product: sCO_2 Power Systems

- **Recompression Cycle Allows High Efficiency, Modular, Compact Design**
  - 5 MWe, 600 ºC Expander Inlet Temperature,
  - Recompression Brayton Cycle – chosen for optimal efficiency
  - Modular: (1) Turbomachinery Skid, (2) Inventory Control, (3) Generator
  - Integrated: lubrication system, dry gas sealing, recuperator, piping, etc.

- **Target Deployment - Early 2024**
  - Field test allows full validation of integrated system
  - sCO_2 Power System allows compact cluster of reflector mirrors





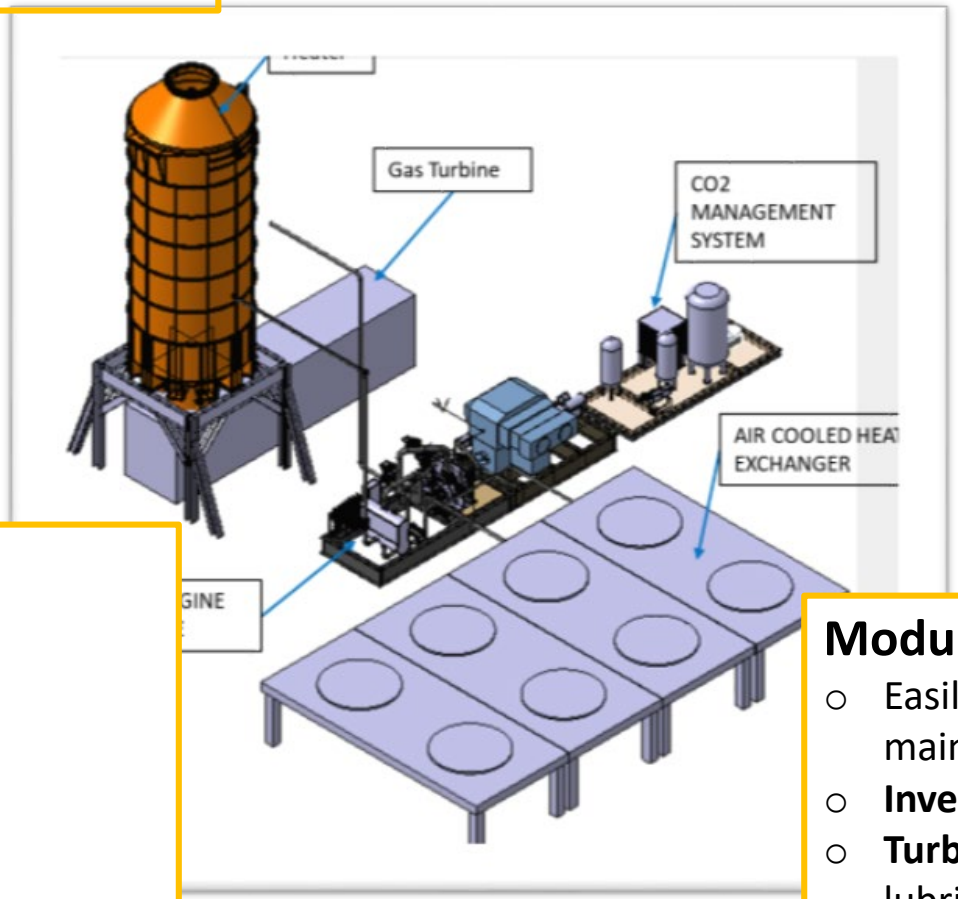
5.5MW Recuperated sCO_2 Power System for Gas Turbine Heat Recovery

Split Recuperated Brayton Cycle

- Air-Cooled (no water needs)
- 5.5 MW electric
- Optimized for CAPEX/OPEX/Heat Recovery

Service and Maintenance

- 24/7 Remote monitoring for control and health management



Build-Own-Operate Model

- **Design Point:**
- **Technical Features:**
  - Wide Range Technology™
  - Dry gas seals
  - Titling pad journal bearings
  - Thrust collars
-

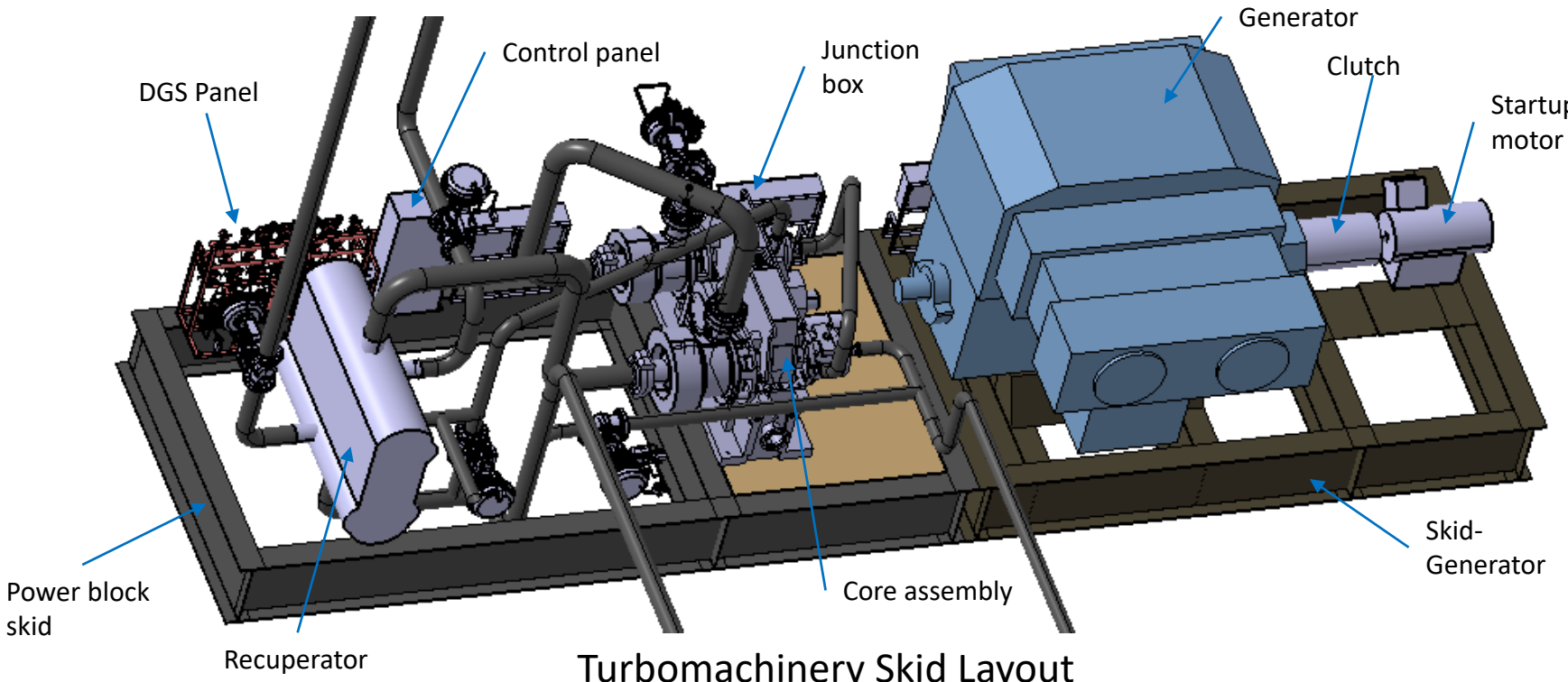
Modular Solution

- Easily deployable for installation and maintenance
- **Inventory Control Skid**
- **Turbomachinery Skid** – integrated sealing and lubrication
- **Generator Skid**

Turbomachinery Skid is Compact and Based on Experience

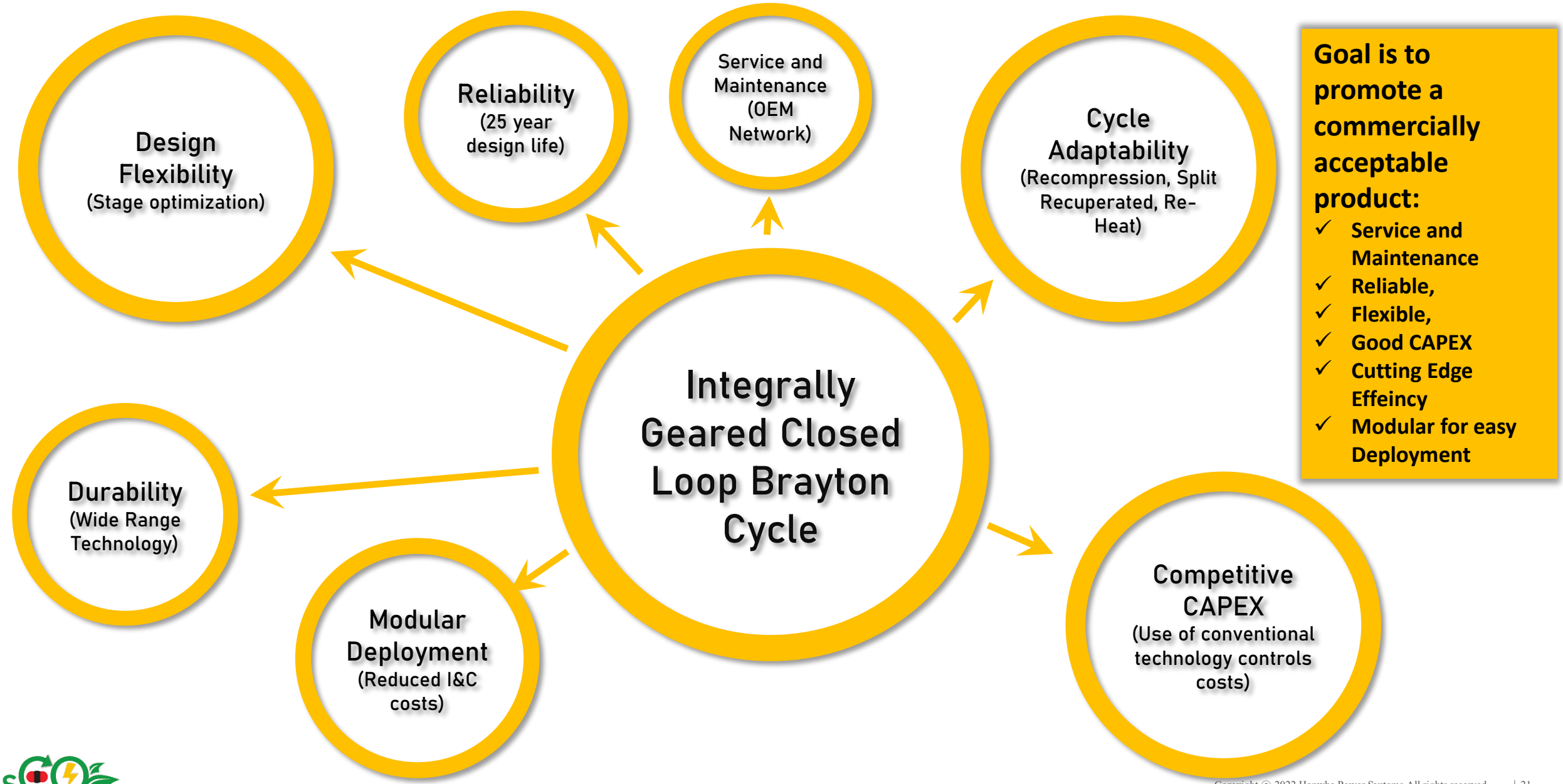
- The turbomachinery skid layout consists of the following major components: core assembly, oil reservoir, skid, oil cooler, generator, seal rack, control panel, recuperator, recovery compressor etc.
- Core (G/B) assembly includes two compressors and two expanders mounted on the gearbox
- Size of the main skid will be approximately 9m(29.53')Lx4.2m(13.78')W. Second skid 6.9m(22.64')Lx4.2m(13.78')W will be used inline with the main skid for the generator, clutch & startup motor for the package.
- Height of the package will be around 11.8ft (3.6m.) To avoid the extra height of the package for the shipment some pipe & generator cooling sections can be shipped loose.

	Weight
Core assembly	47,620 lb (21.6 metric Ton)
Power block skid & LOS	44,093 lb (20 metric Ton)
Skid generator	19,842 lb (9 metric Ton)
Generator	55,116 lb (25 metric Ton)
Startup motor	3,307 lb (1.5 metric ton)
Recuperator	33,069 lb (15 metric ton)
Aux equipment & others	TBD
Total	**218,258 lb (99 metric ton)**



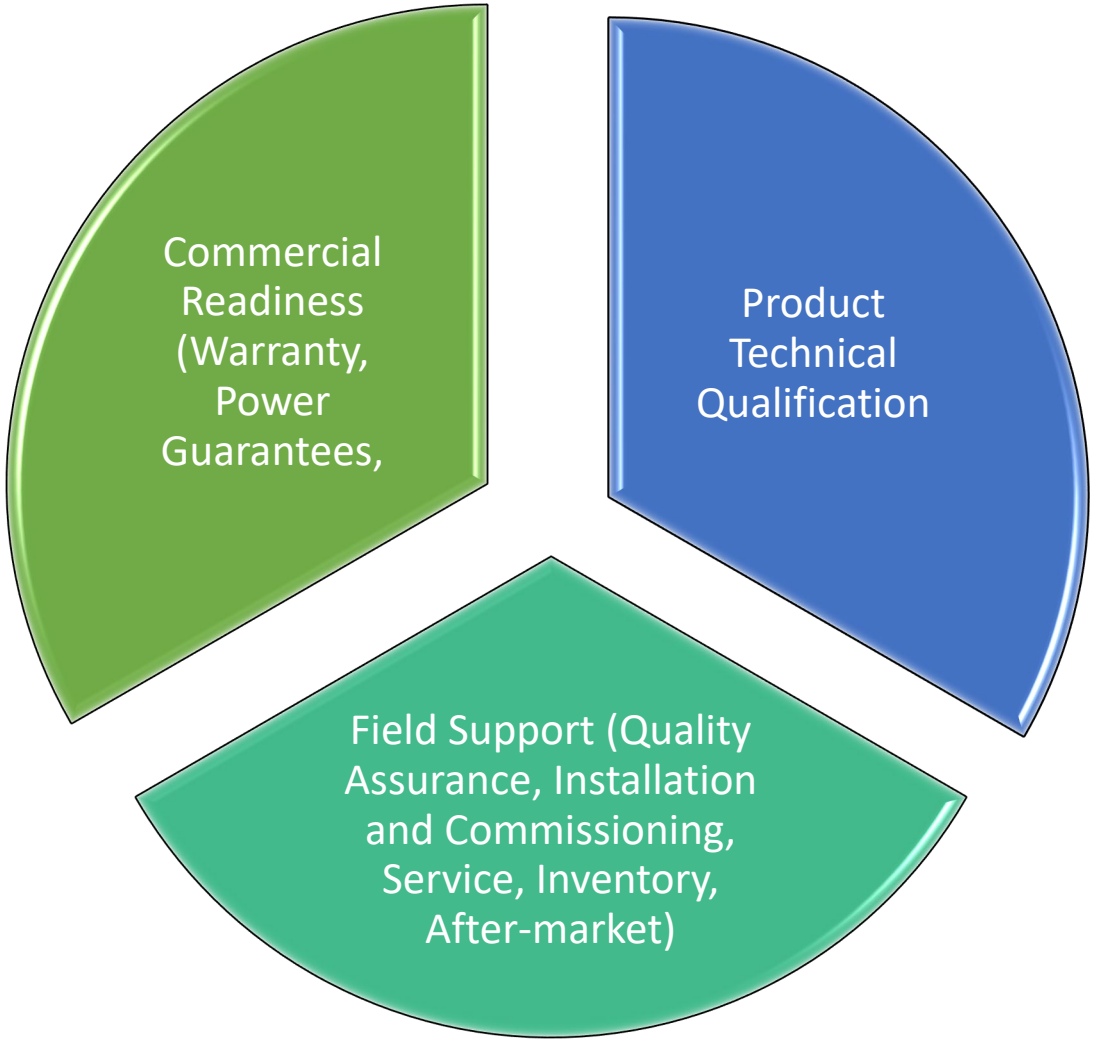
Turbomachinery Skid Layout

Super-Critical CO_2 Power System – Application Focused Approach



Customer Acceptance of Market Readiness

1) **Technical ability and risk reductions**
   - TRL is useful guide,
   - Customers want to see evidence of reliability "endurance" testing
2) **Commercial Capability**
   - Warranty – Pricing - Guarantees
     - ability to identify launch customers and take financial loss on first unit(s) if required.
     - CAPEX competitive to entrenched technologies
   - Installation & Commissioning – expertise to manage site logistics
3) **Service and maintenance support**
   - Coming from an organization that is newer to Americas and familiar to new products, the most common question is always "how will you support this product." This is a major weakness of new/smaller organizations.
   - Large organizations have the ability to leverage existing installations capabilities



Thank You