



Bechtel Marine Propulsion Corporation
Knolls Atomic Power Laboratory
Schenectady, NY
Bettis Atomic Power Laboratory
West Mifflin, PA

Supercritical Carbon Dioxide Power Cycle Development Overview

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Bechtel Marine Propulsion Corporation

September 10, 2014

BMPC Development Program Overview:

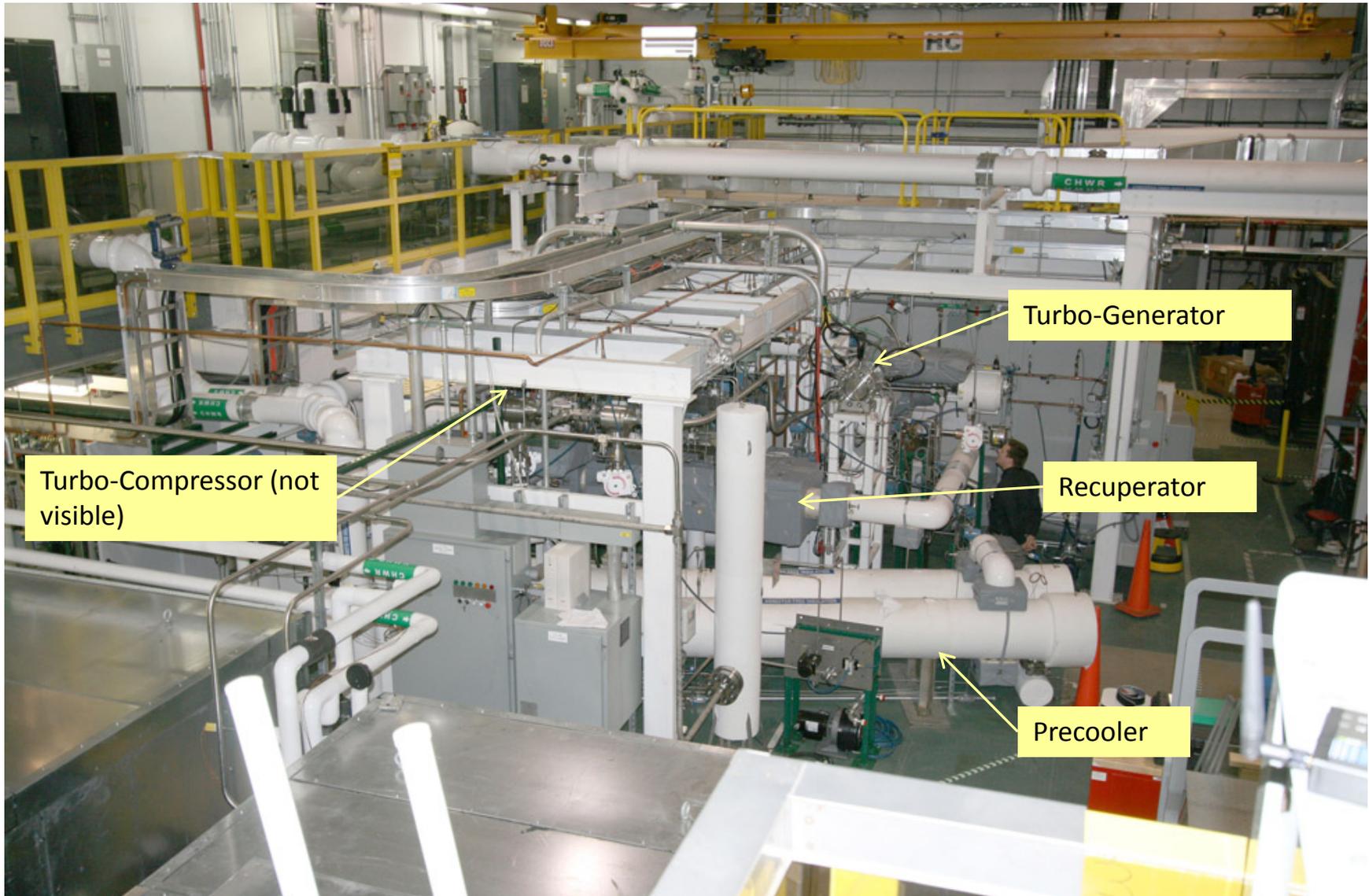
- S-CO₂ Brayton Cycle Integrated Systems Test (IST)
 - Turbo-machinery (turbine, compressor, bearings, seals)
 - Control system (startup, power control)
 - Heat exchangers (shell and tube)
 - Practical considerations (mass control, instrumentation, system leakage)
- Compact Heat Exchanger Development
 - High pressure, compact, fatigue resistant, affordable
- MW scale development vision
 - Based on kW development
 - Scale-up issues
 - Transition from experimental to demonstration stage



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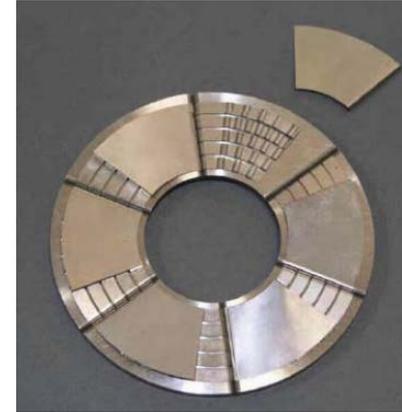
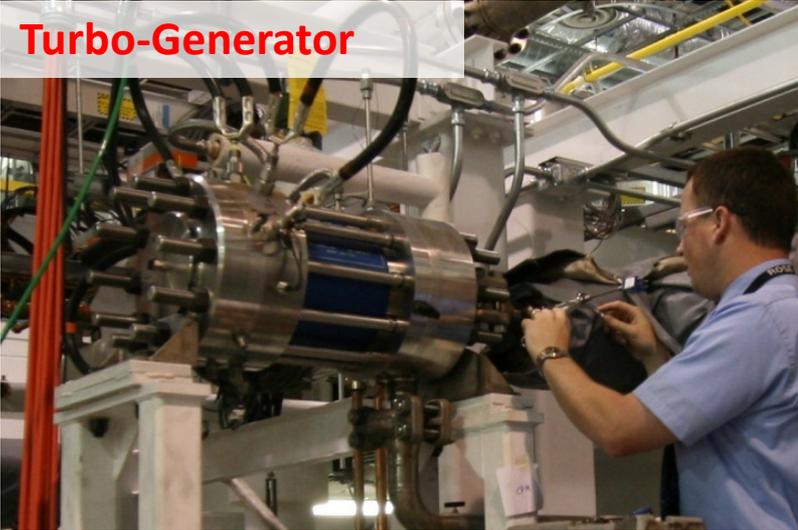
S-CO₂ Integrated System Testing

IST Physical Layout



IST Turbomachinery

Turbo-Generator

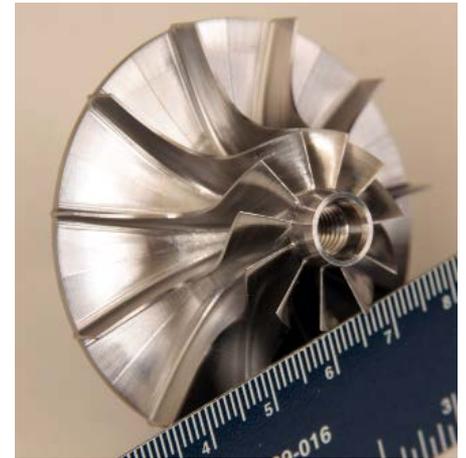


Thrust Bearing

Turbo-Compressor



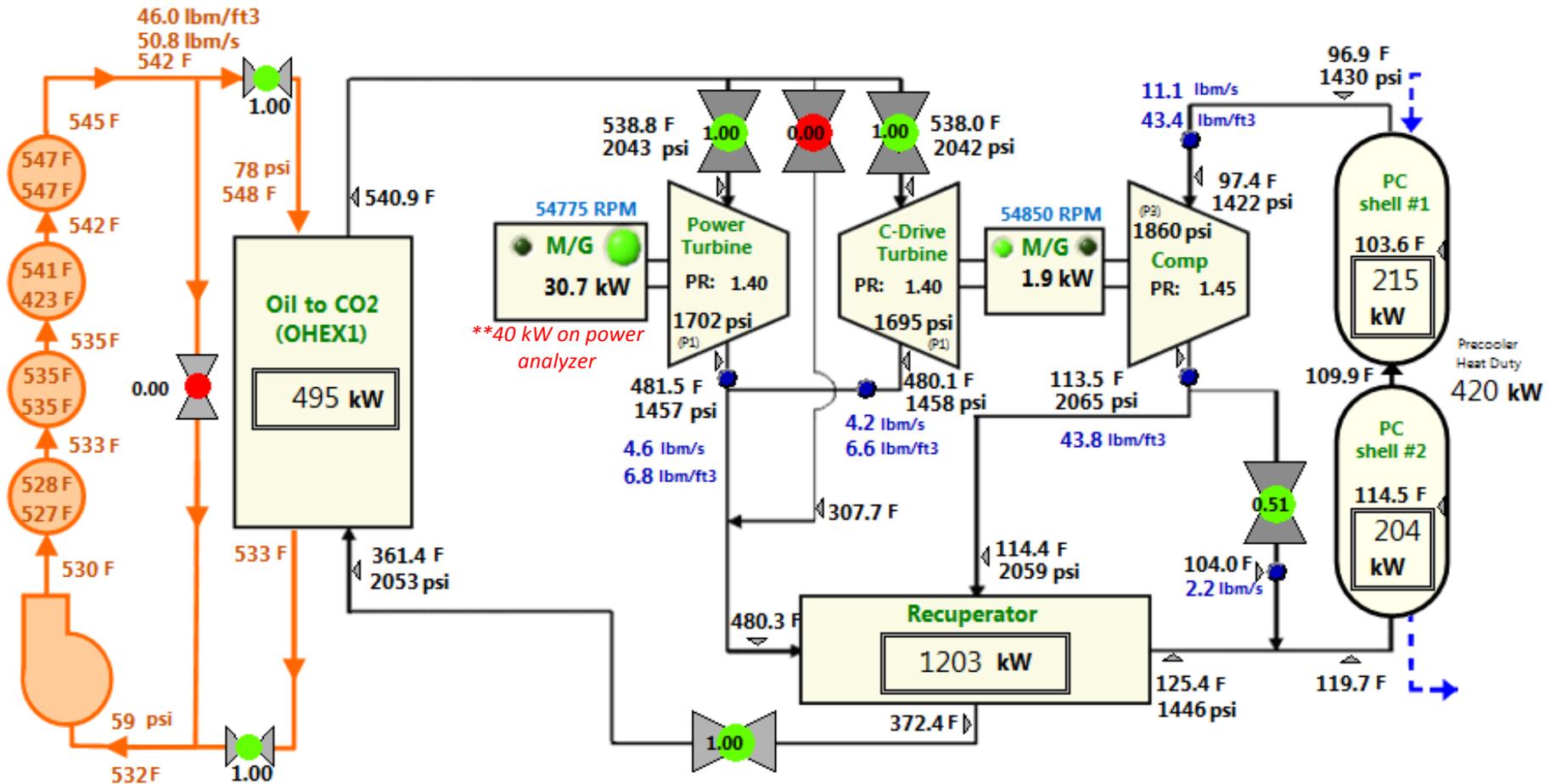
Compressor/Diffuser



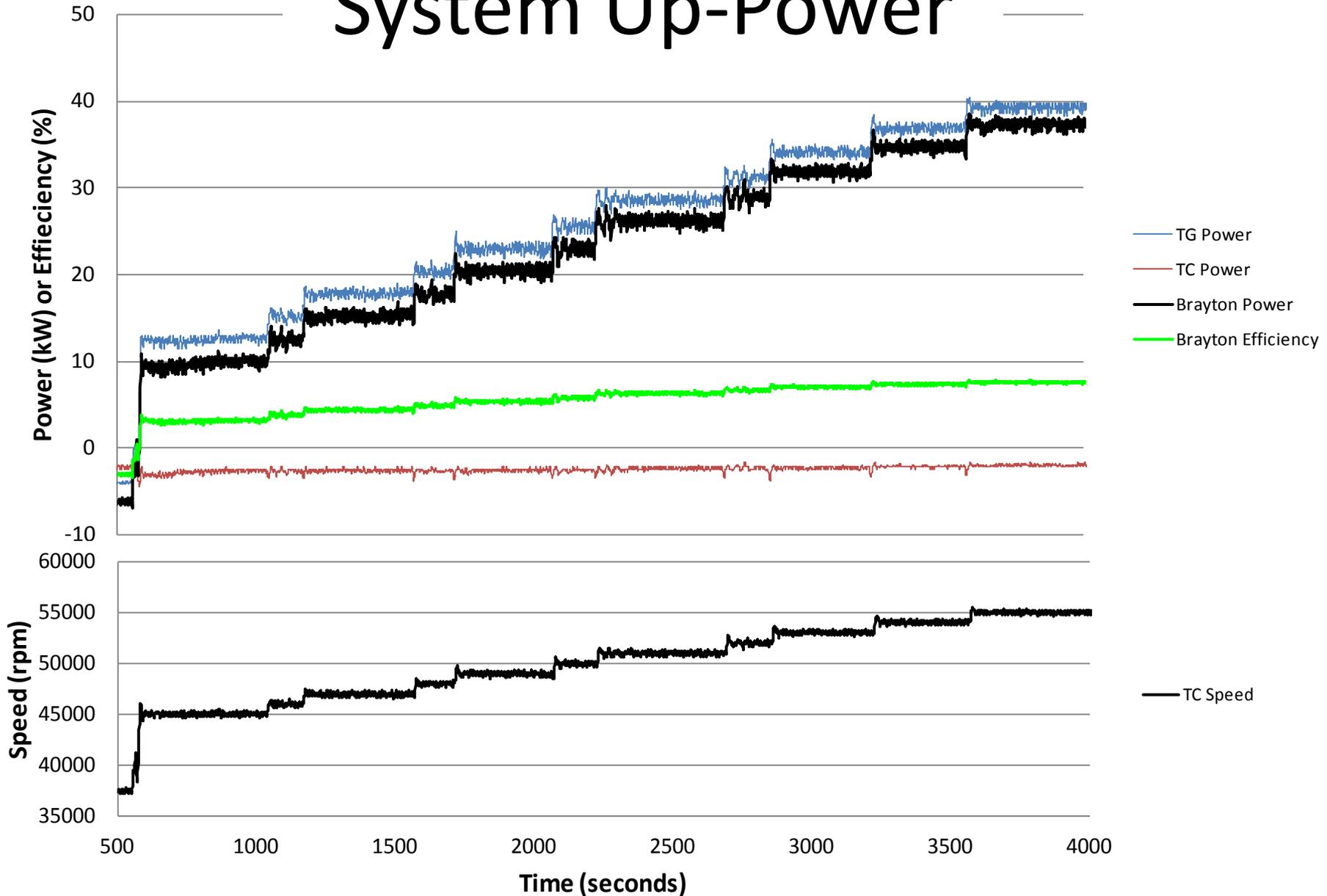
Turbine

Maximum Power Operation

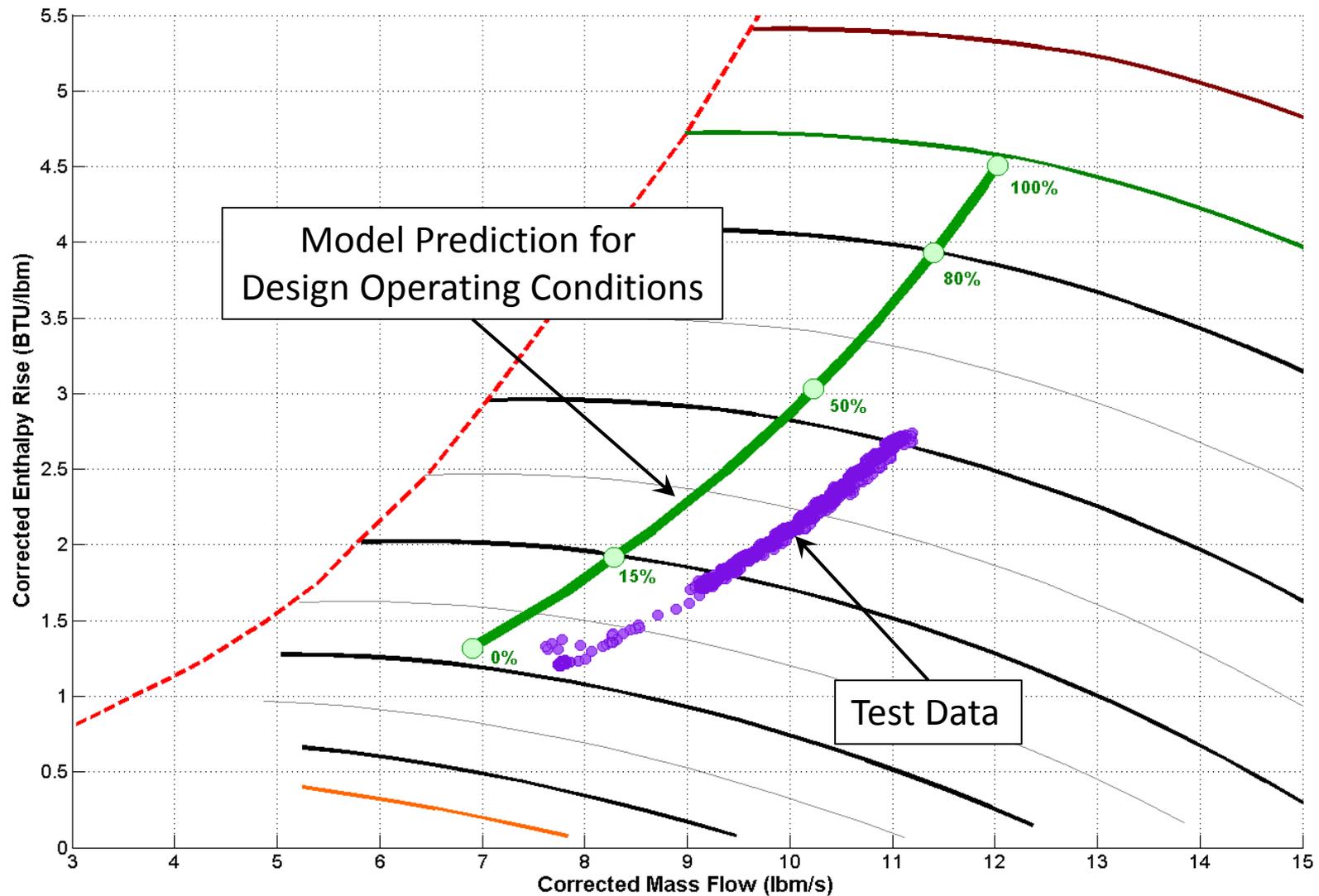
November 2013 – 40kWe



System Up-Power



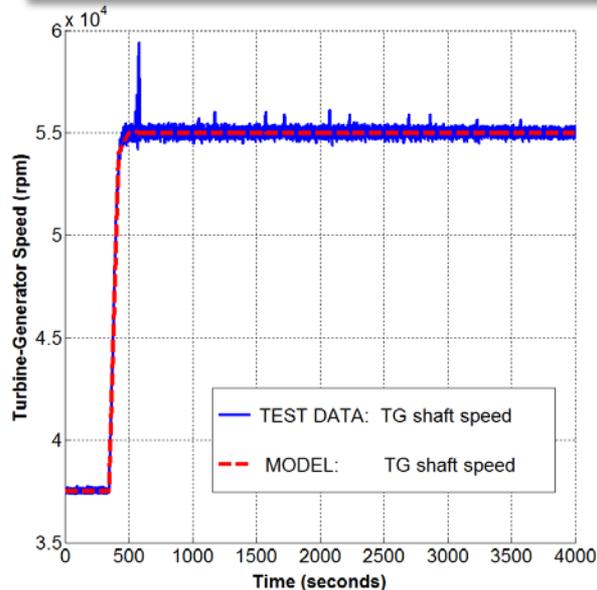
Compressor Map



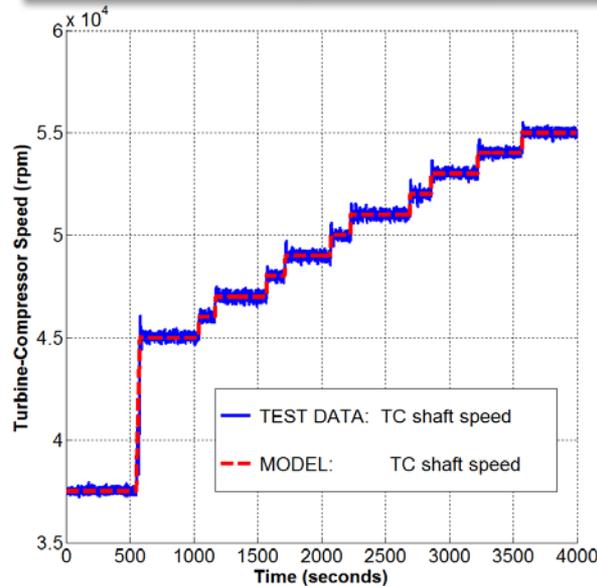
Power Increase Transient

- Initial Conditions: Hot Idle (540°F/37,500 rpm)
- TG speed increased
- TC speed increased in steps
- Compressor recirculation valve decreased in steps
- Water flow automatically controlled to maintain compressor inlet T

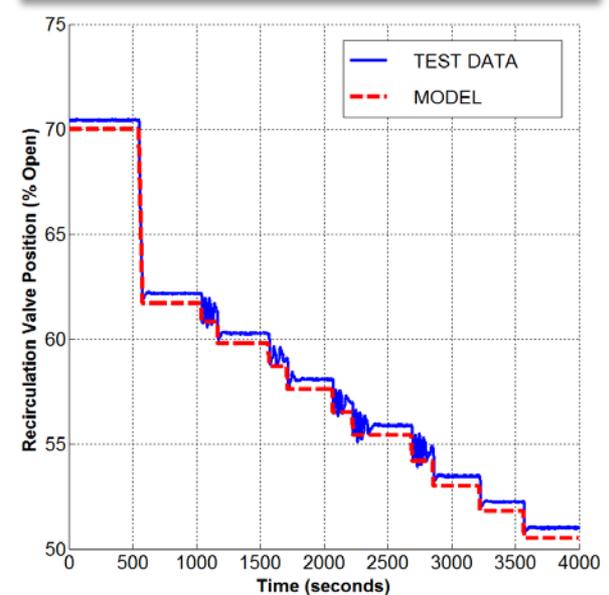
Turbine-Generator Speed



Turbine-Compressor Speed

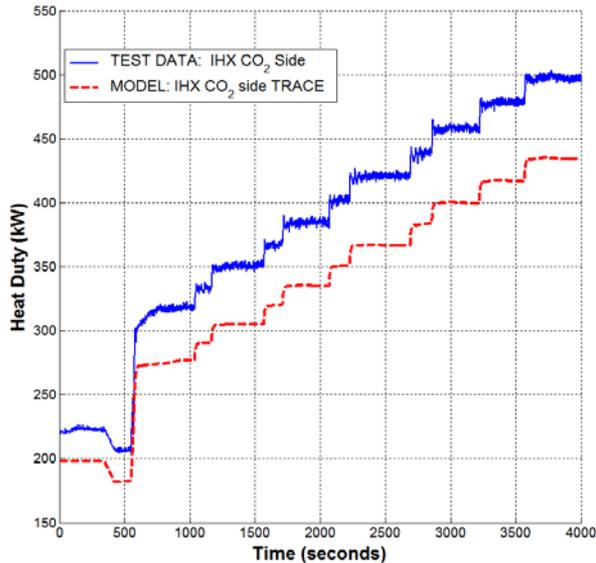
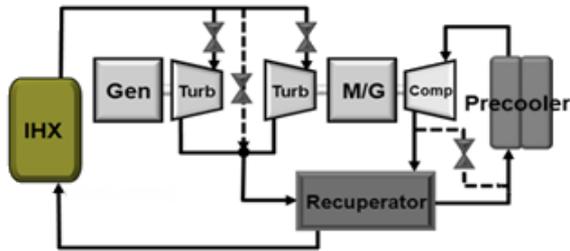


Recirculation Valve Position

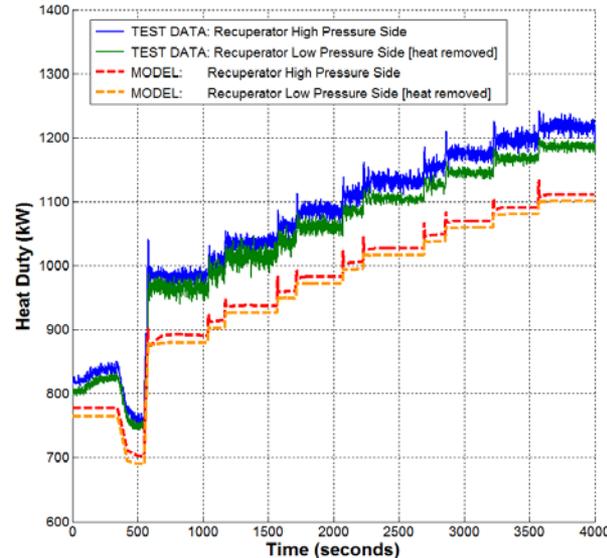
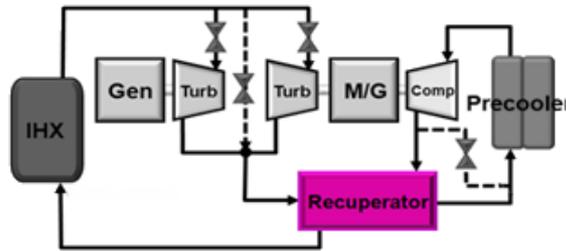


Power Increase Transient: Heat Exchanger Heat Duties

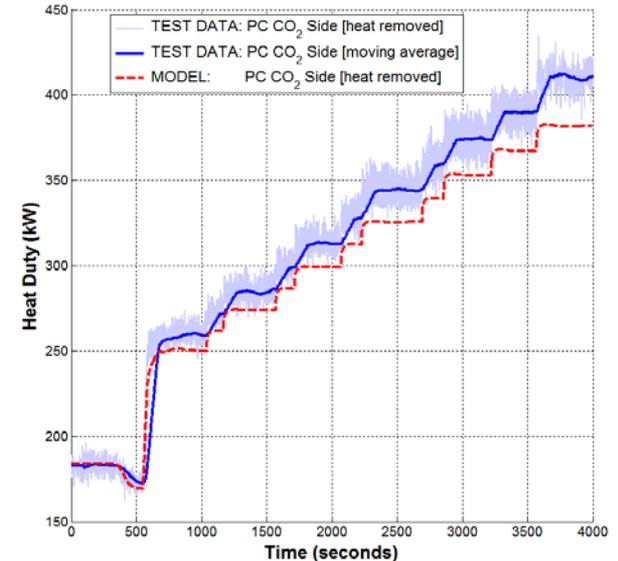
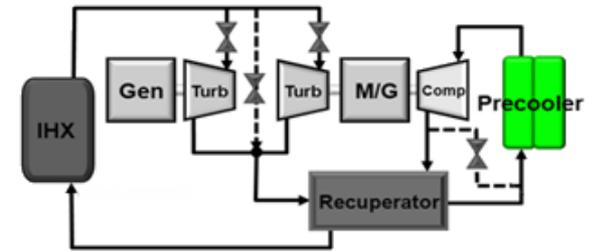
Intermediate Hx



Recuperator

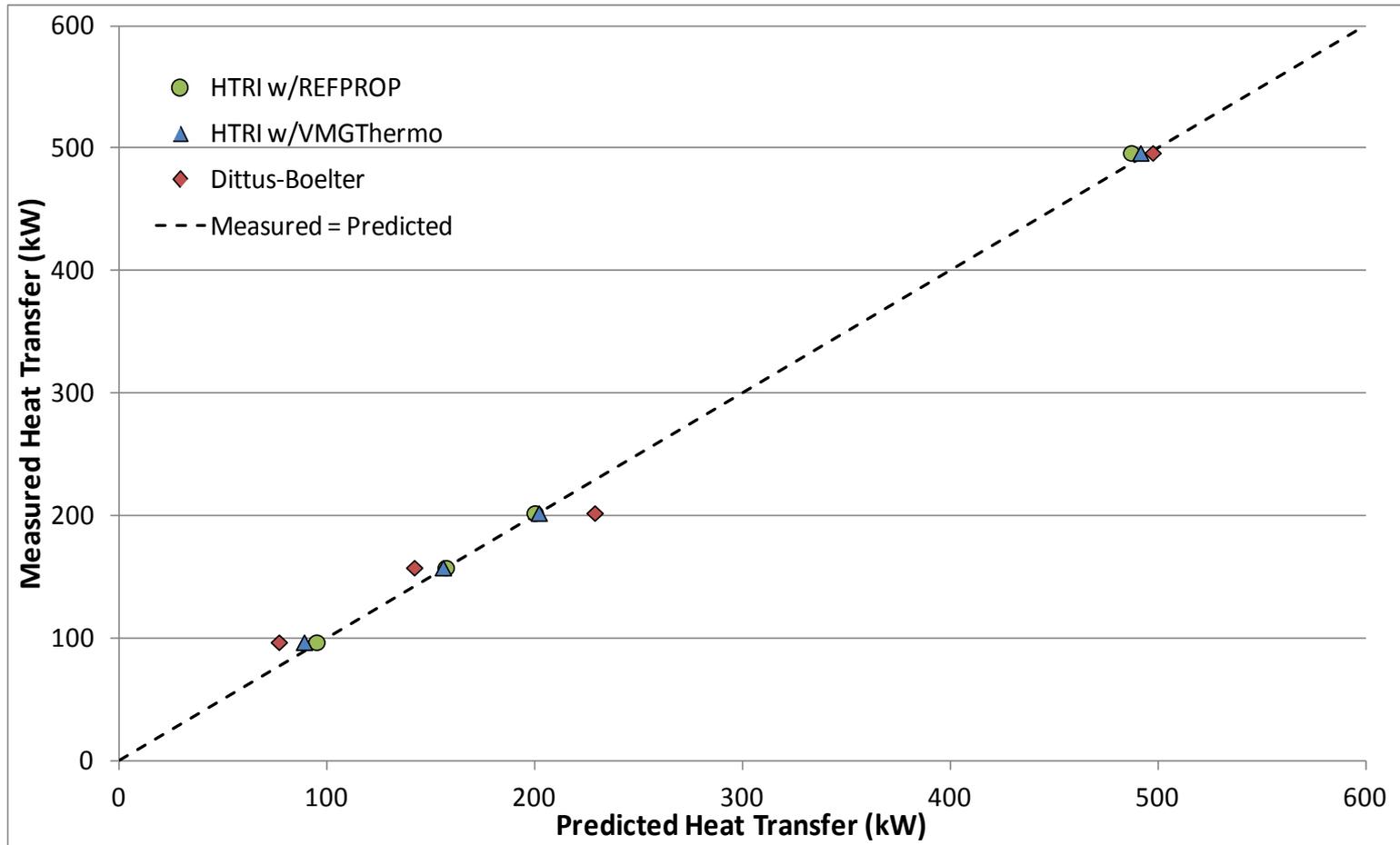


Precooler



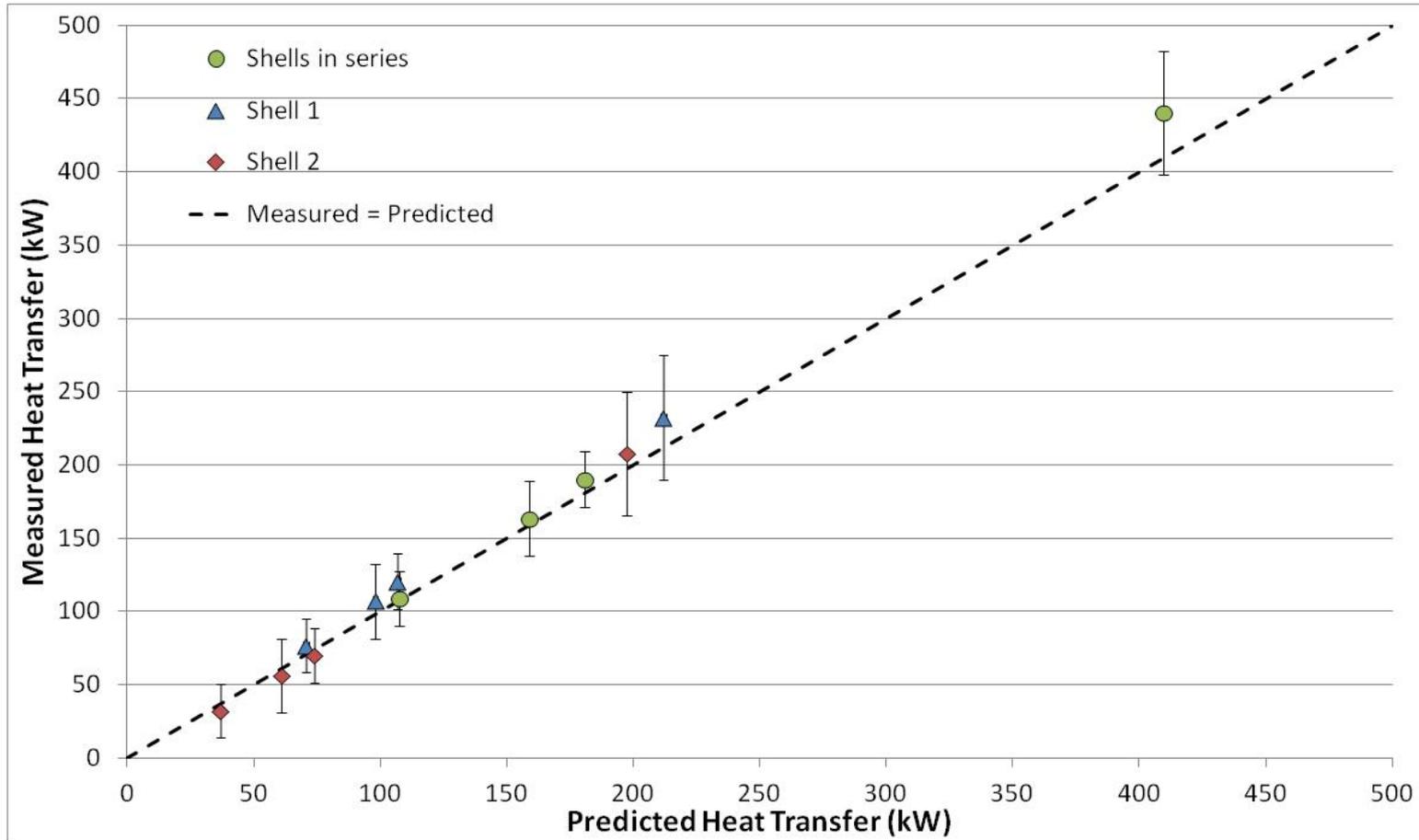


IHX Heat Transfer





Precooler Heat Transfer





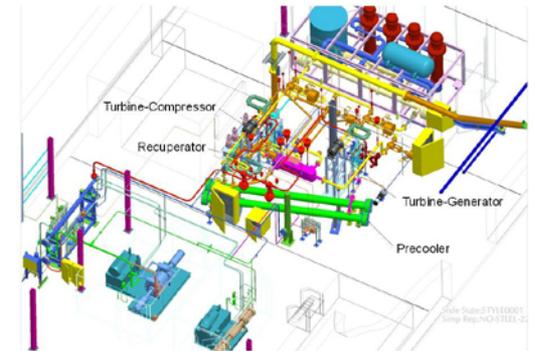
Practical Aspects of Supercritical Carbon Dioxide Brayton System Testing

E. M. Clementoni & T. L. Cox, Bechtel Marine Propulsion Corporation



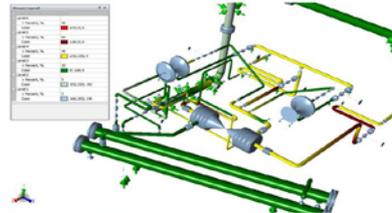
Operational Experience

- 100 kWe Integrated System Test
- Shakedown started Fall 2011
- Over 165 hours of Brayton system operation
- Achieved 40% of design power



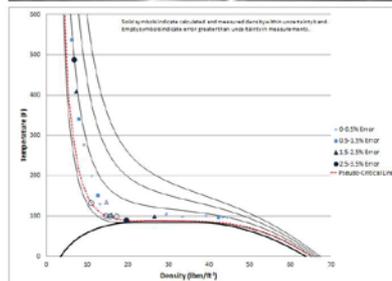
Design Considerations

- Off-design/transient model valuable for startup & low power operation
- Good experience with Grayloc & Swagelok fittings and ANSI flanges
- Thermal stresses need considered early for compact arrangement



Loop Cleanliness

- S-CO₂ is a great solvent
- Material quality and cleanliness controls are important
- EPDM acceptable, Viton and Teflon tape problematic
- Turbine nozzle erosion believed to be caused by debris in system



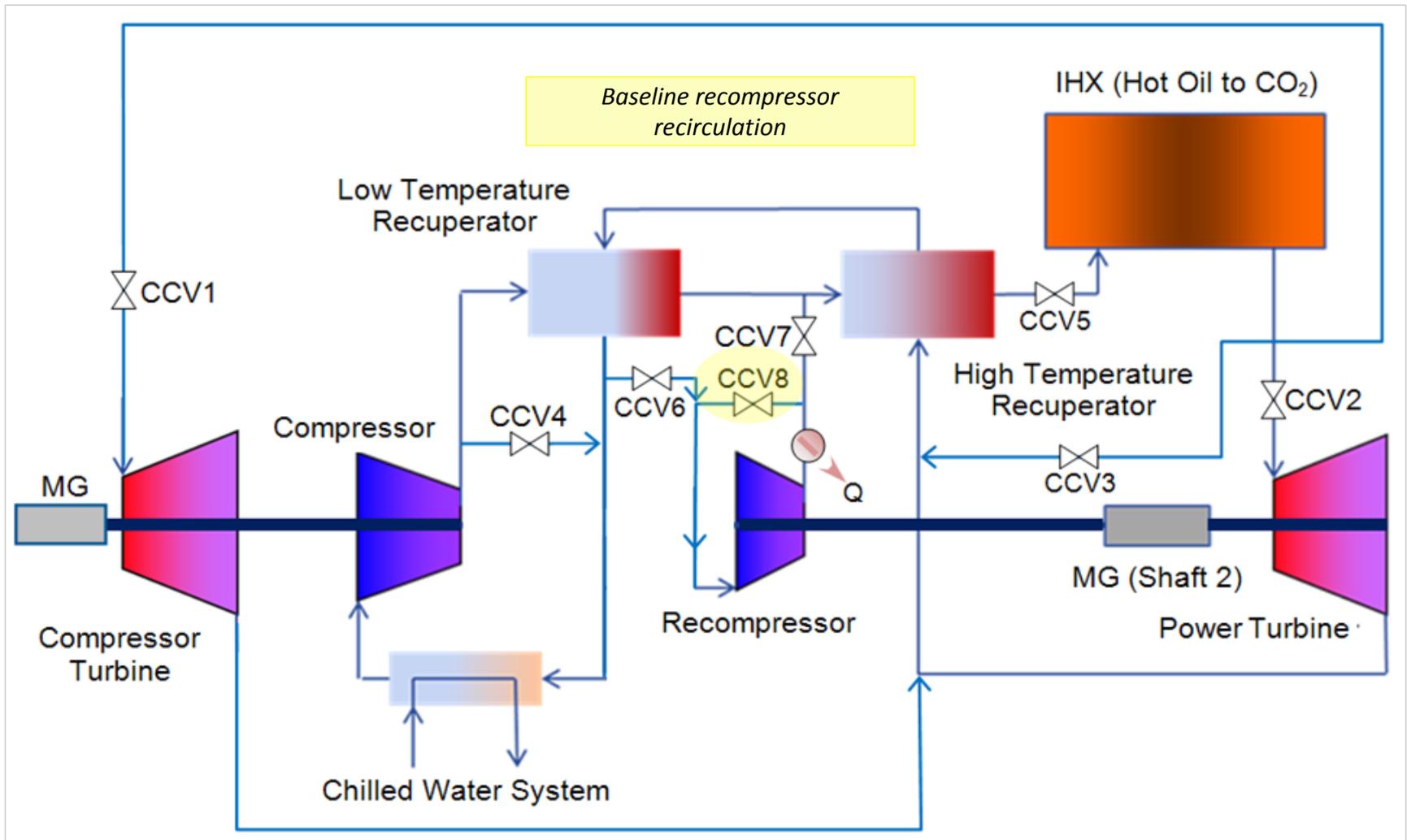
System Fill and Leakage

- IST uses Coleman Instrument grade (99.99%) CO₂ for fill
- Three cycles of pulling vacuum and filling to atmospheric pressure before full fill
- Low leakage levels from valve stem packing and large shaft seals

Instrumentation

- Marlin Type T SLE thermocouples
- Rosemount pressure transducers
- MicroMotion Elite Coriolis meters
- REFPROP calculated density (T&P) agrees well with measured density

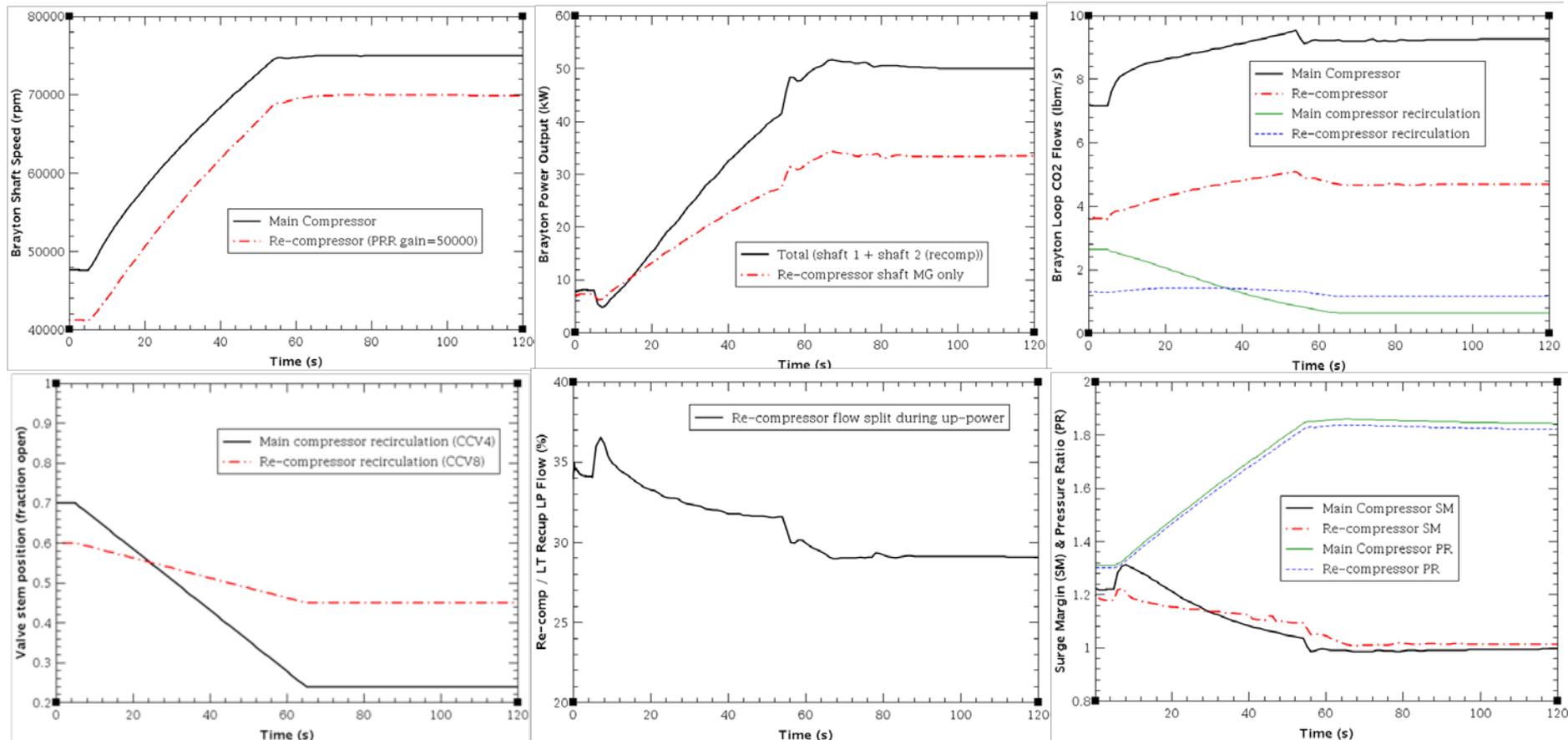
IST with Recompression Cycle Control Features



This loop design shows how recompression control features could be placed in the IST, allowing loop hydraulic control for startup, heatup and low power operation.

IST Up-Power Maneuver in Recompression Configuration

Using end states that have been optimized for adequate surge margin this up-power transient shows good performance, with minimal under/over shoot.



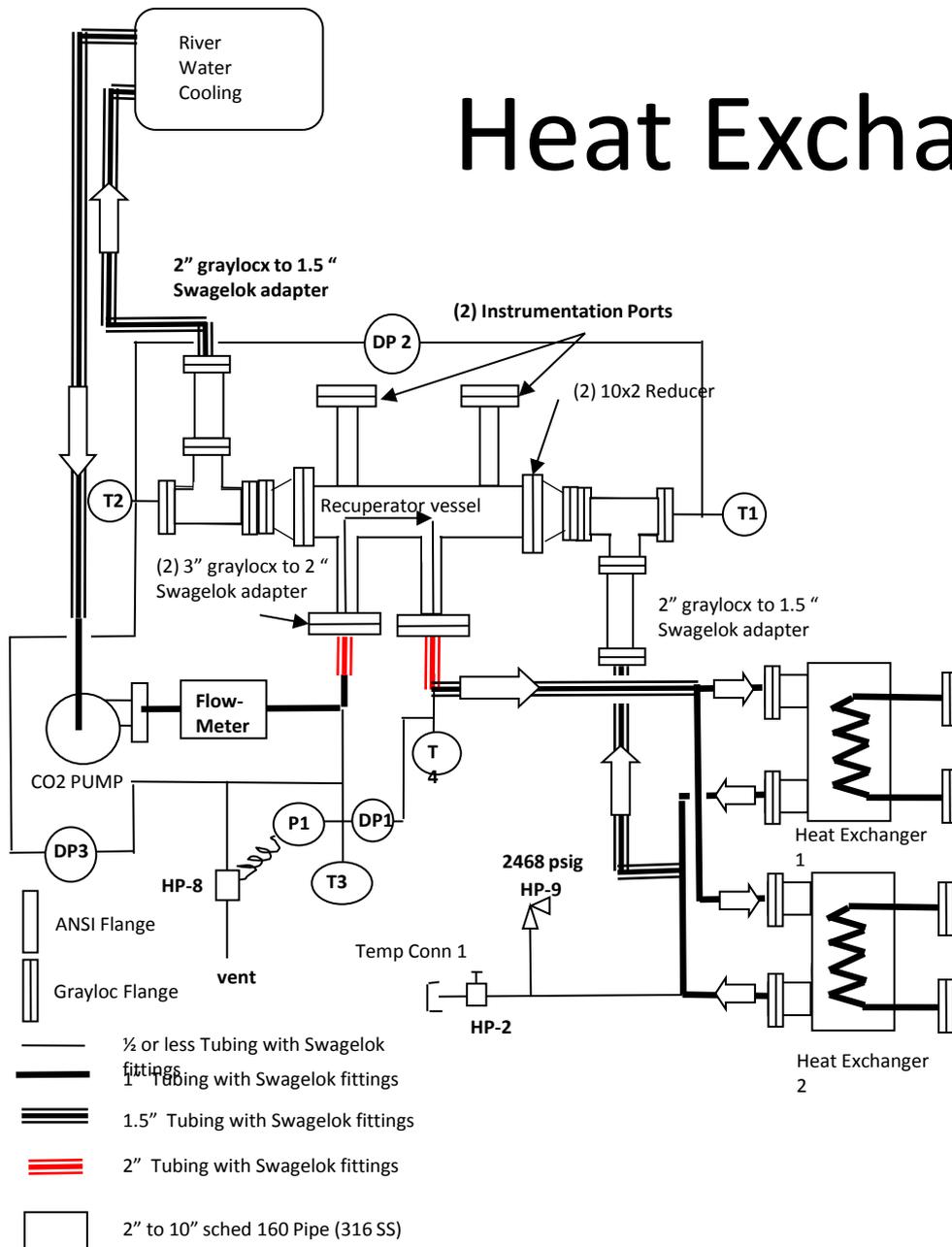
Up-power rates $>1\%/s$ would be possible for a well designed recompression loop.



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S-CO₂ Heat Exchanger Development

Heat Exchanger Testing



Testing Conditions:

Heat Input/Rejection 20-90 kW_t

Pressure: ≈1,200-1,500 psi

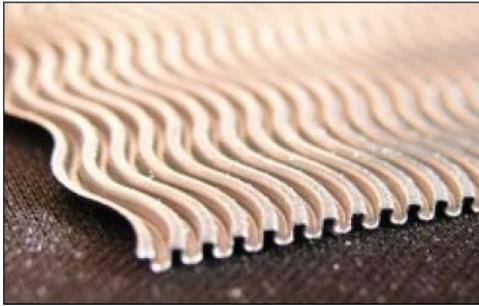
Temperature: ≈300-500°F

Flow rate: ≈2-3 lbm/second

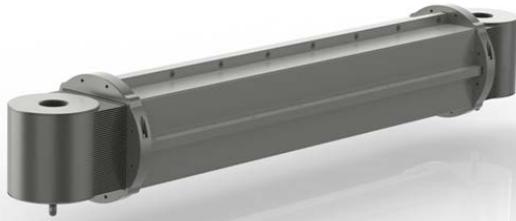


Recuperator Designs Tested

WavyFin



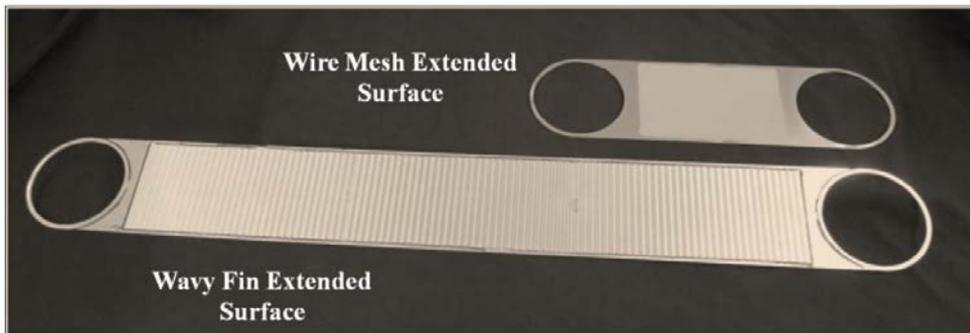
$\beta=3,300-4,500 \text{ m}^2/\text{m}^3$



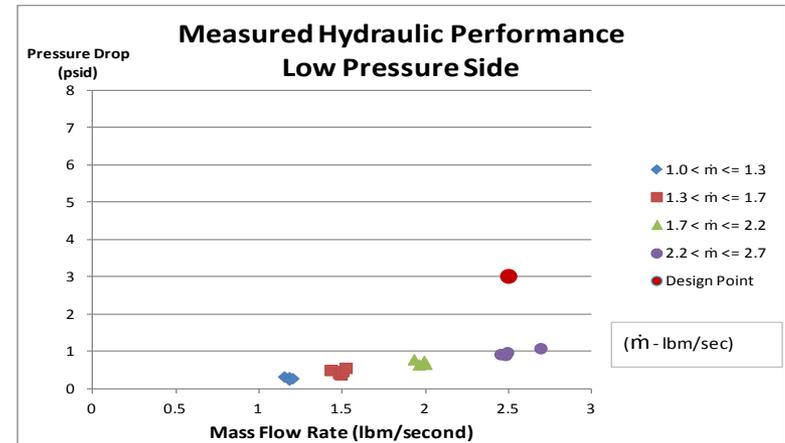
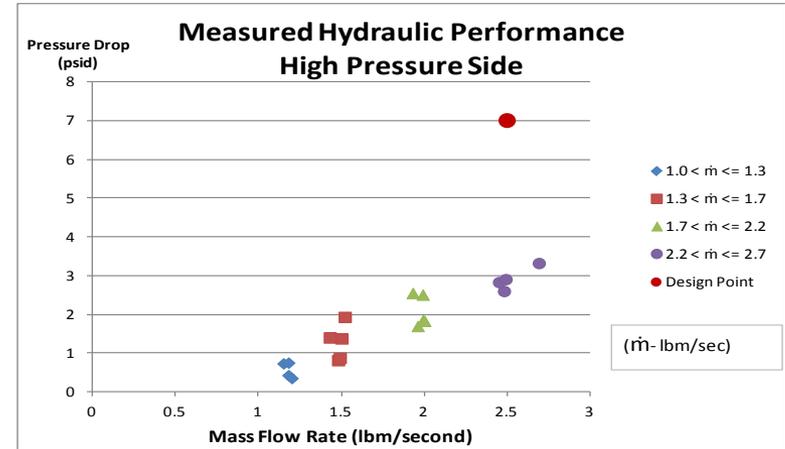
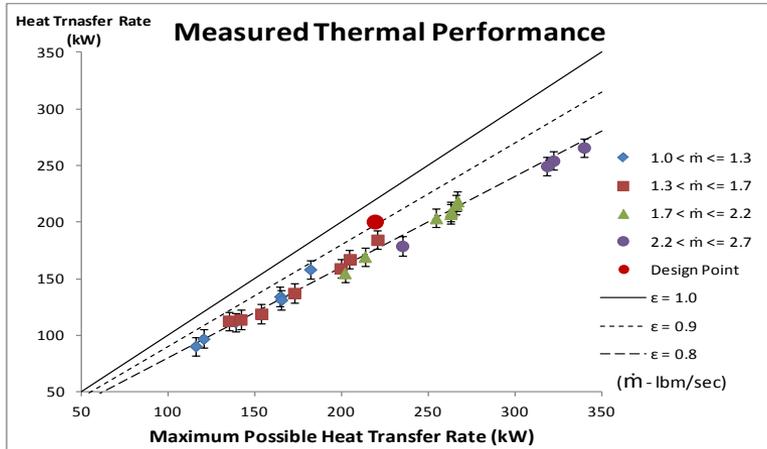
Wire Mesh



$\beta=7,000-8,000 \text{ m}^2/\text{m}^3$



Folded Wavy-Fin Results



Prototype demonstrated thermal-hydraulic performance.



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Summary of Progress to Date

S-CO₂ Integrated System Testing

- IST demonstrating controllability of a two shaft simple S-CO₂ Brayton cycle
- Normal power operation over range of power levels up to ~50 kWe has commenced
- TRACE transient modeling:
 - Validation has commenced
 - Approaching real time execution
 - Demonstrates controllability of re-compression cycle

S-CO₂ Heat Exchanger Development

- IST heat exchangers meeting expectations and validating performance models
- More compact/fatigue resistant heat exchangers being designed, fabricated and tested in dedicated 300kW test facility



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MW Scale Development

S-CO₂ Power Cycle Development Approach

Fundamental Testing

Concept Development

Small Scale System and Component Tests

Large Component Development

Large Scale System Test

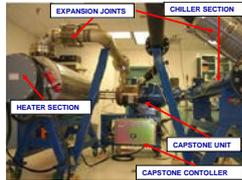
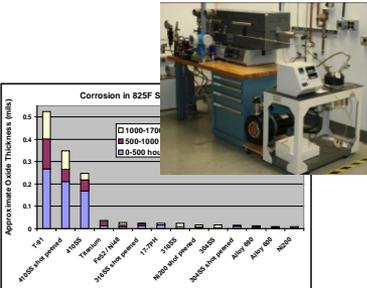
Fluid Behavior



Safety Implications



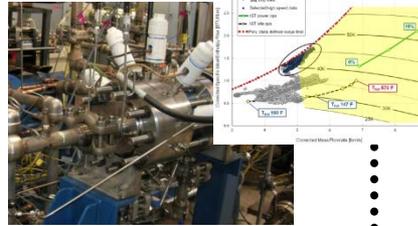
Material Behavior



Sandia Closed Brayton Loops



Small System Test



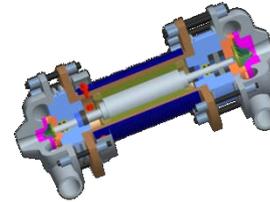
Operational Test

Integrated System Test



HX Development & Test

Turbomachinery Performance

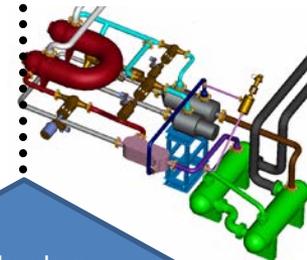


Validated Design Tools

Heat Exchanger Performance



Plant Concept Development



Component and System Modeling Development

Path to S-CO₂ Power Cycle Commercial Implementation

