The 4th International Symposium – Supercritical CO_2 Power Cycles
Technologies for Transformational Energy Conversion
September 9-10, 2014, Pittsburgh, Pennsylvania

Supercritical Carbon Dioxide Power Cycle Development Overview

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Ken Kimball has been actively involved with supercritical CO2 Brayton power cycle development since 2005 working at the Knolls Atomic Power Laboratory in Schenectady, NY, USA. This effort has included working closely with numerous University, National Laboratory and Industry groups. He has a BS degree in mechanical engineering from Worcester Polytechnic Institute and an MS degree in mechanical engineering from Rensselaer Polytechnic Institute. He has previously presented development progress at the Supercritical CO2 Brayton power cycle development symposiums in 2009 and 2011 and the ASME Turbo Conferences in 2012 and 2013.

Abstract

Bechtel Marine Propulsion Corporation (BMPC) is testing a supercritical carbon dioxide (S-CO_2) Brayton system at the Bettis Atomic Power Laboratory. The 100 kWe Integrated System Test (IST) is a two shaft recuperated closed Brayton cycle with a variable speed turbine driven compressor and a constant speed turbine driven generator using S-CO_2 as the working fluid. The IST was designed to demonstrate operational, control and performance characteristics of an S-CO_2 Brayton power cycle over a wide range of conditions. The IST design includes a comprehensive instrumentation and control system to facilitate precise control of loop operations and to allow detailed evaluation of component and system performance. A detailed dynamic performance model is being used to predict IST performance, support test procedure development and to evaluate test results. An overview of IST testing progress and plans is provided. Testing in the IST was initiated in 2012. Test operations to date included successful system startup, initial transition to electrical power generation, increased power operations and transition to load control testing using independent speed control of the turbo-machinery. Results of testing completed to date and future testing plans will be summarized.

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West Mifflin, PA

Supercritical Carbon Dioxide Power Cycle Development Overview

KJ Kimball
Bechtel Marine Propulsion Corporation

September 10, 2014

BMPC Development Program Overview:

- $S\text{-}CO_2$ 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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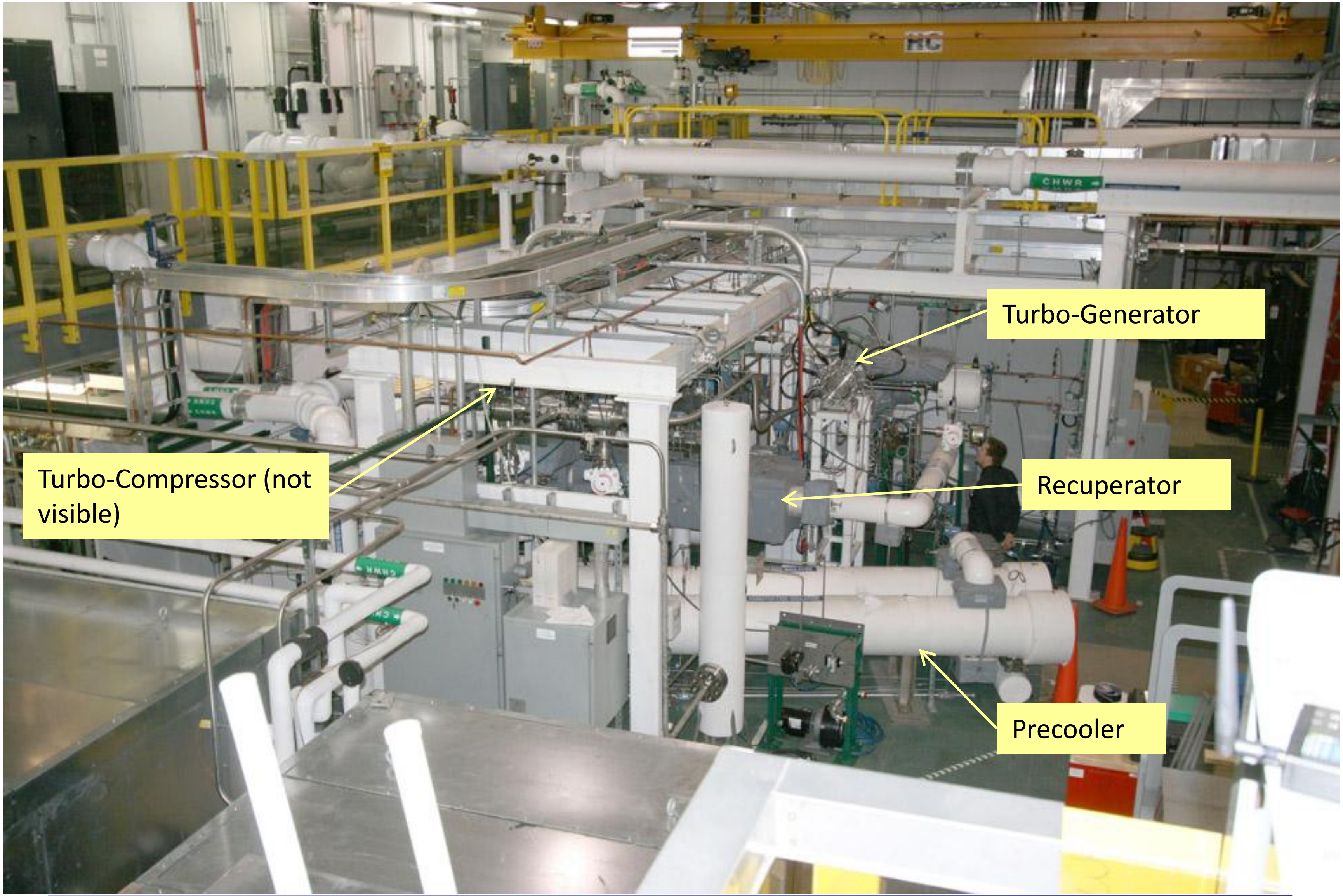
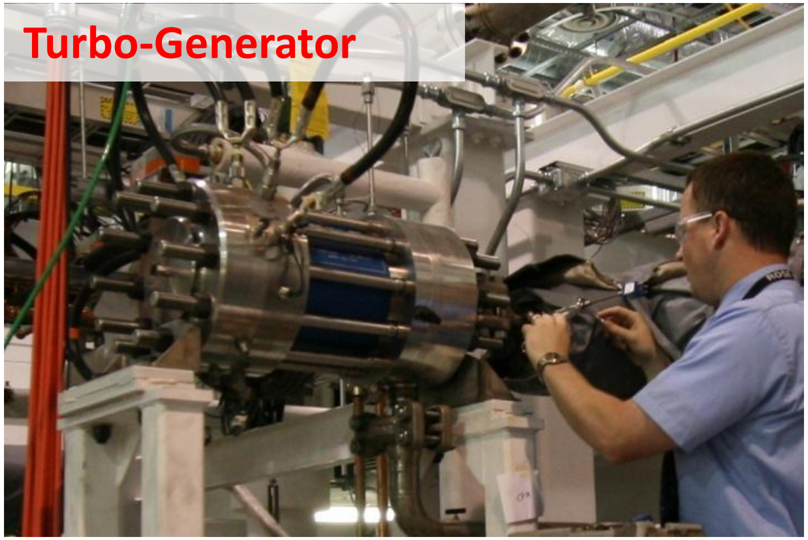
S-CO_2 Integrated System Testing

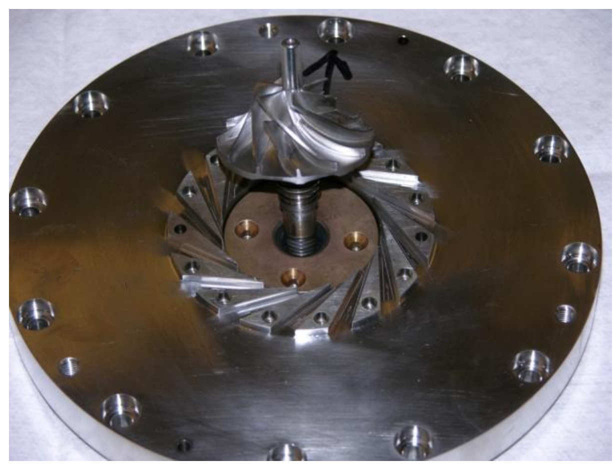
IST Physical Layout



IST Turbomachinery



Thrust Bearing

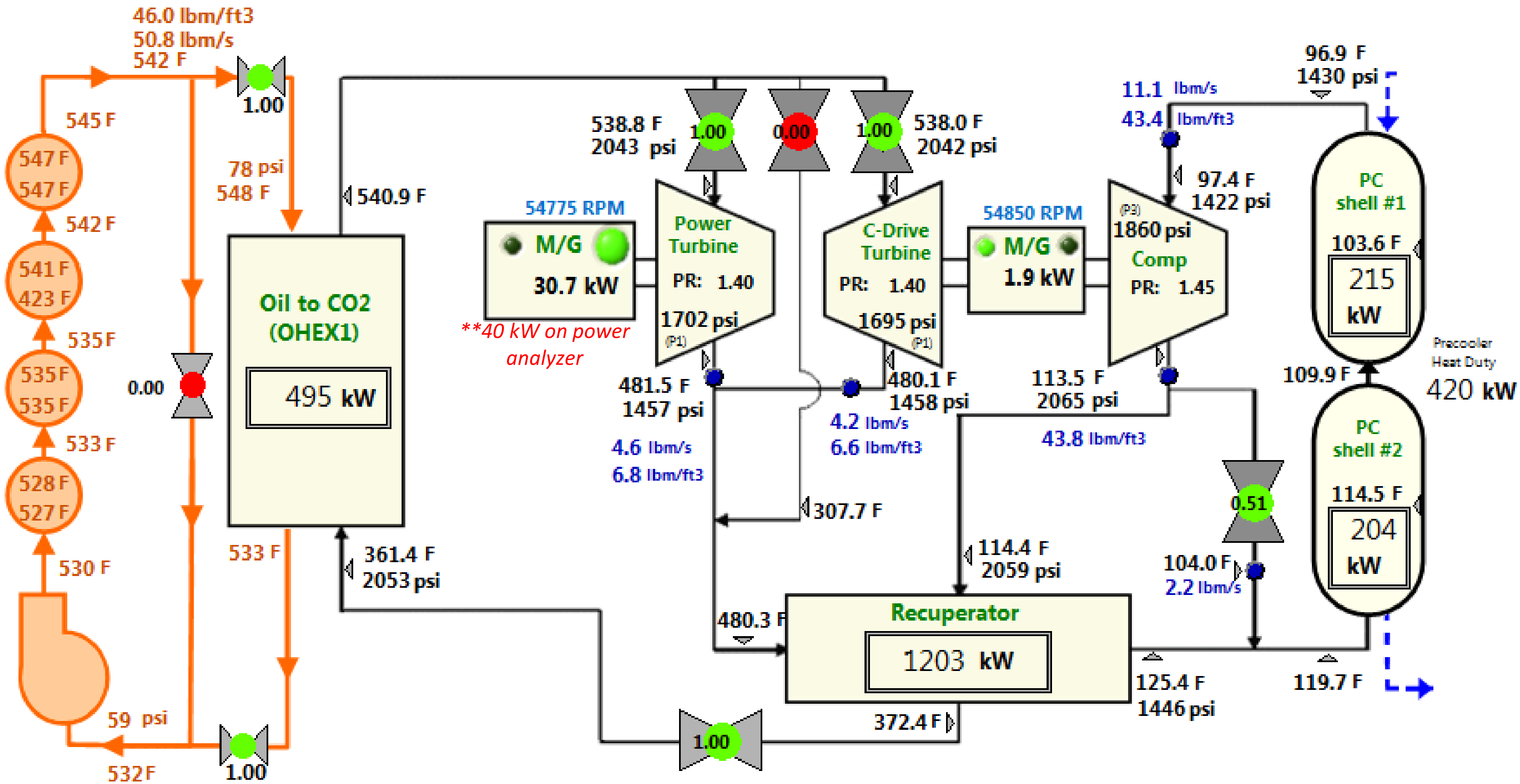


Compressor/Diffuser

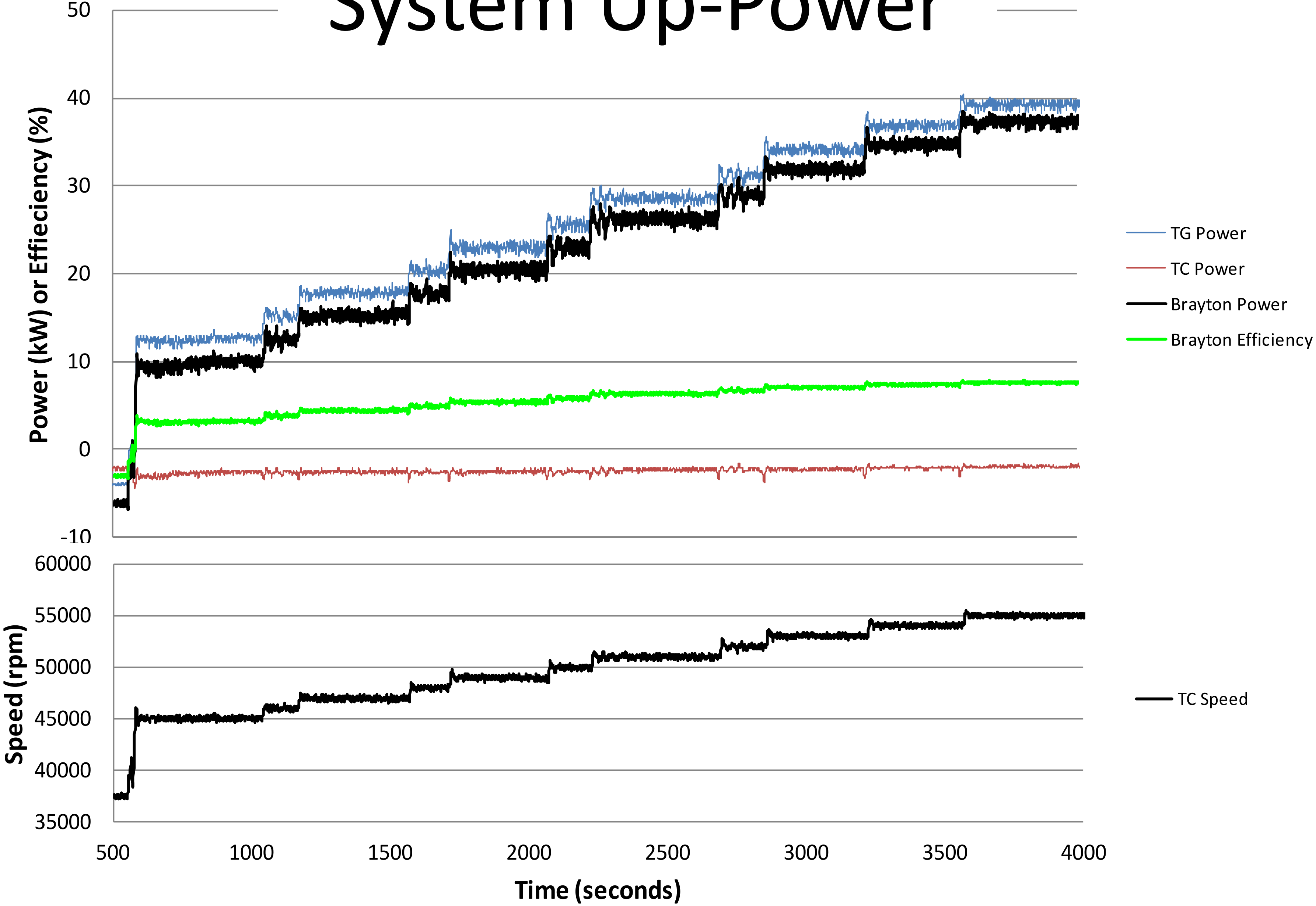
Turbine

Maximum Power Operation

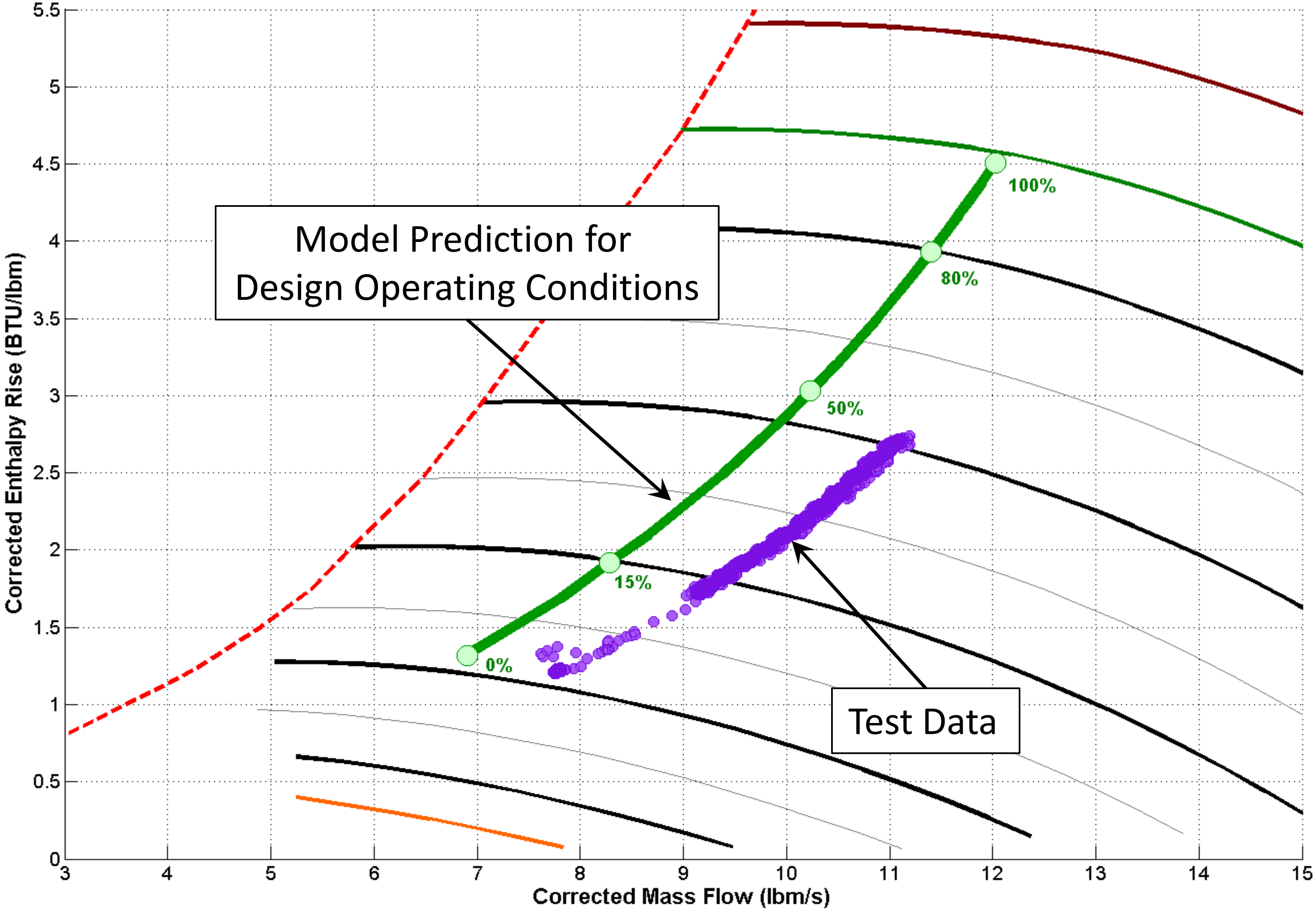
November 2013 – 40kWe



System Up-Power



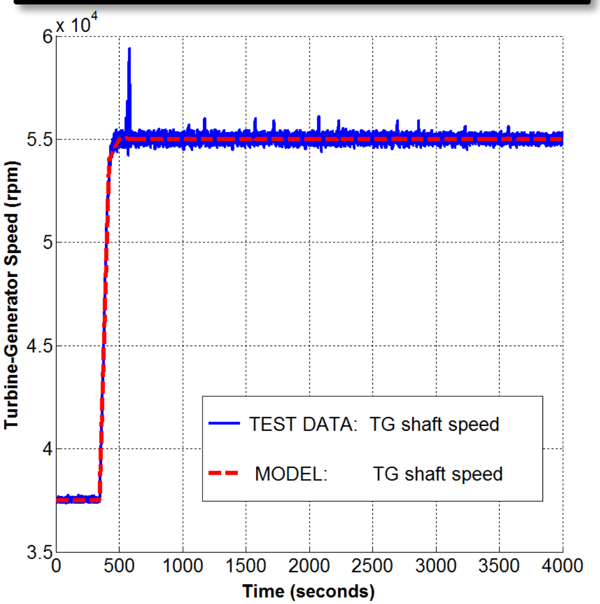
Compressor Map



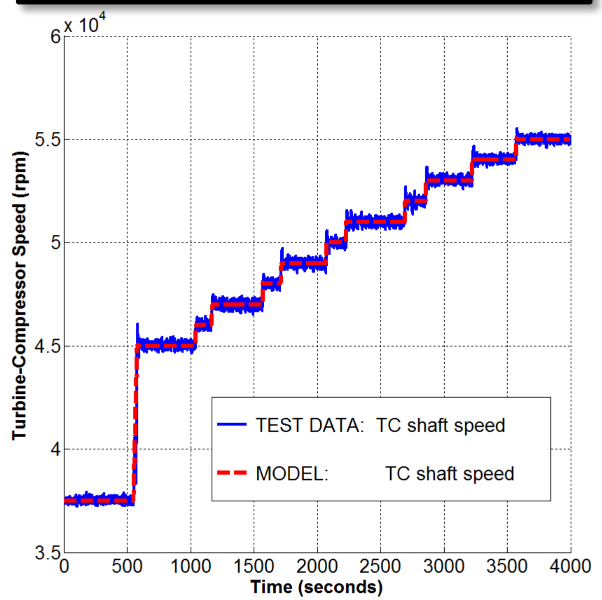
Power Increase Transient

- 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

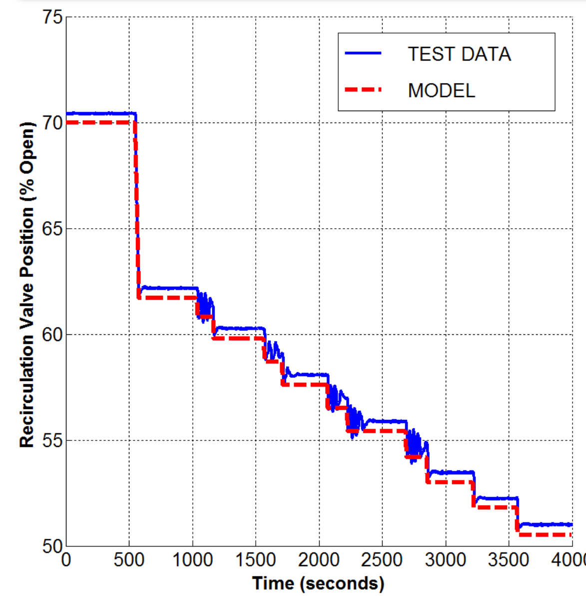
Turbine-Generator Speed



Turbine-Compressor Speed

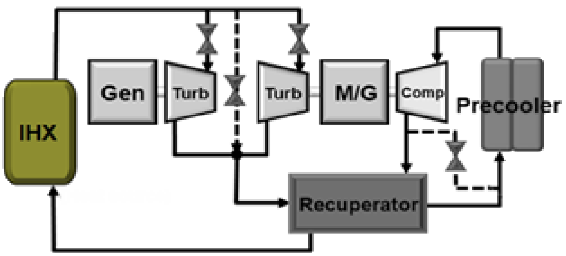


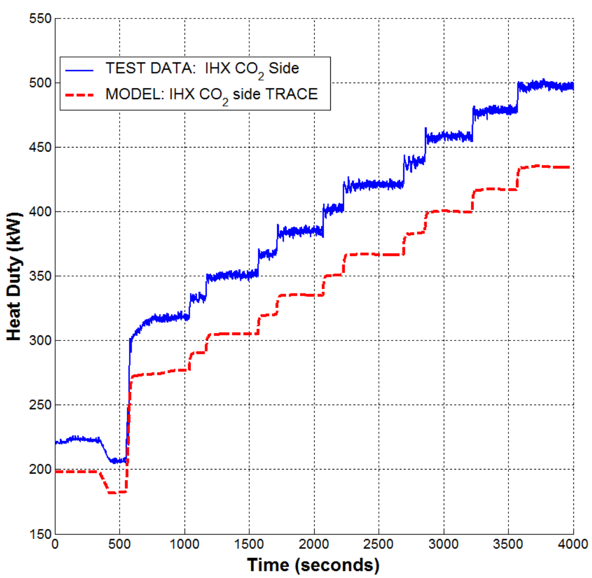
Recirculation Valve Position



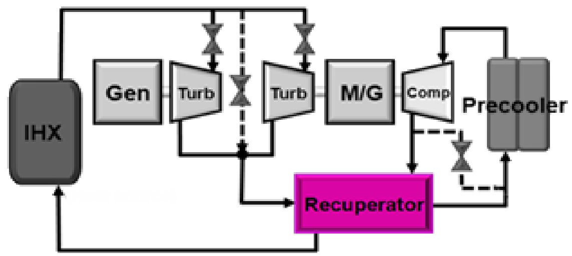
Power Increase Transient: Heat Exchanger Heat Duties

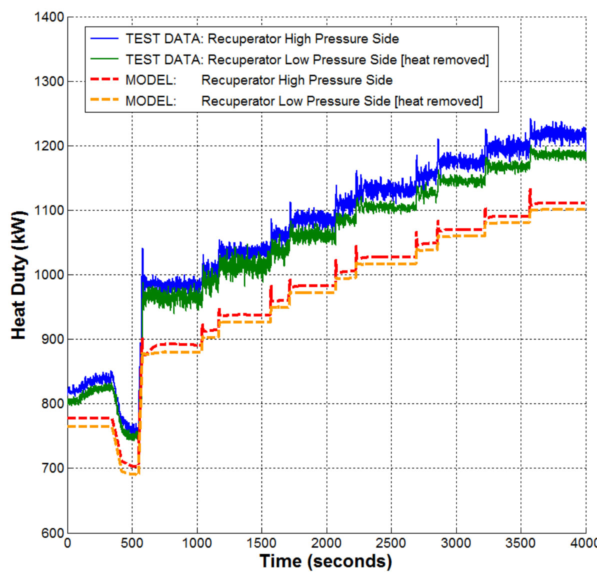
Intermediate Hx



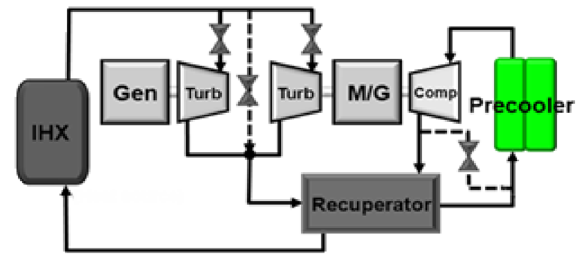


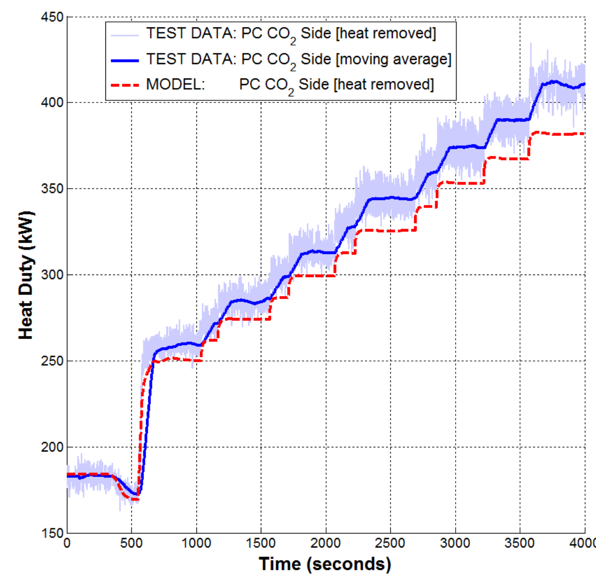
Recuperator



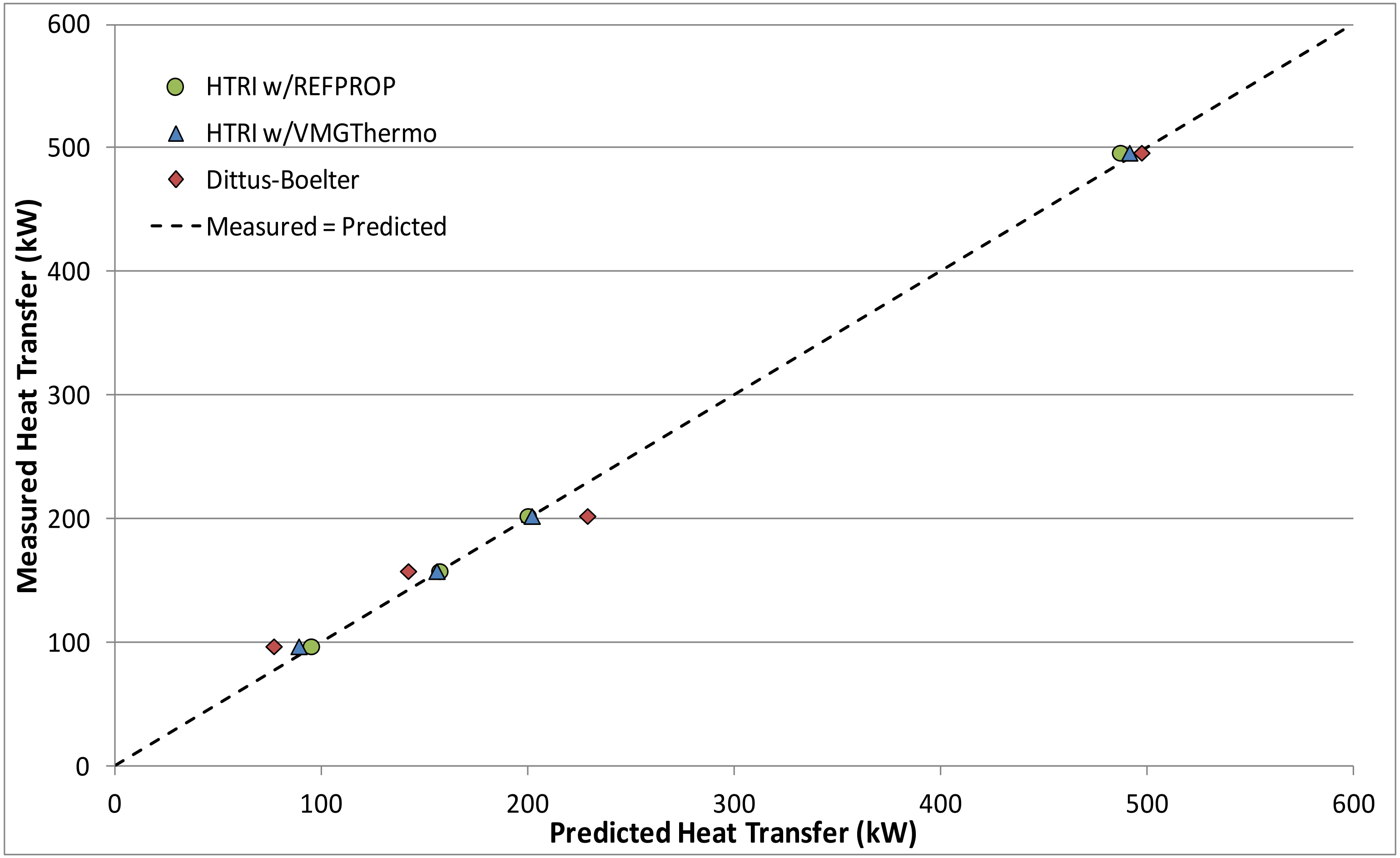


Precooler

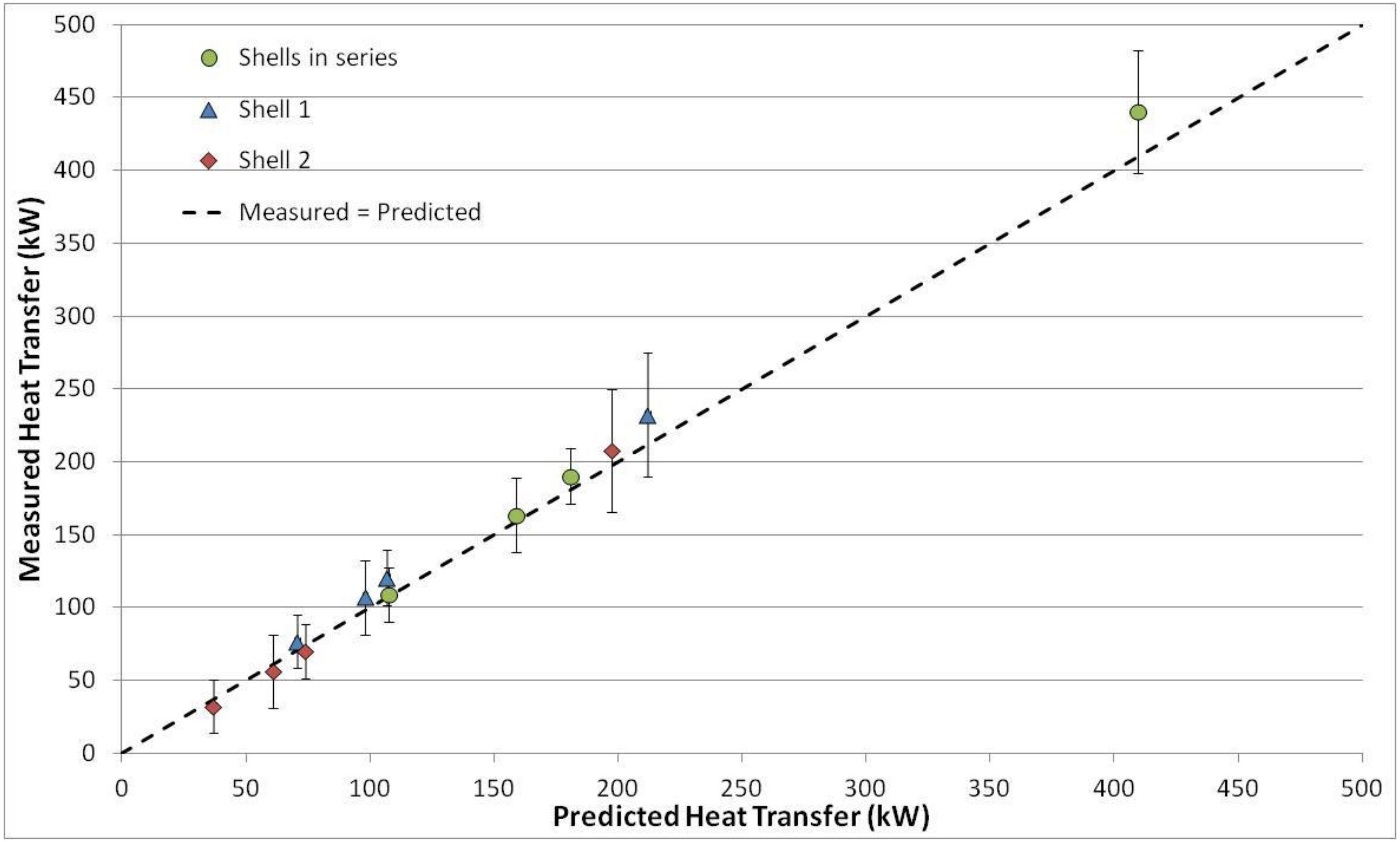




IHX Heat Transfer



Precooler Heat Transfer

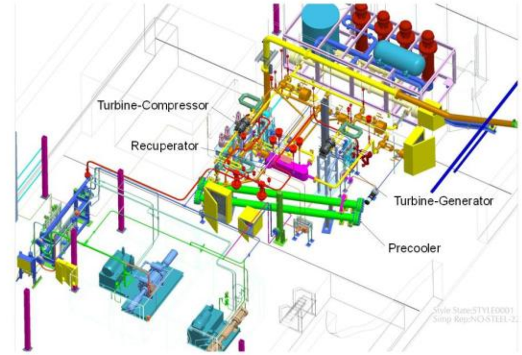


Practical Aspects of Supercritical Carbon Dioxide Brayton System Testing

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

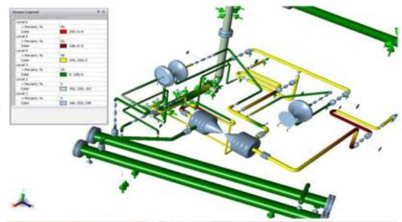


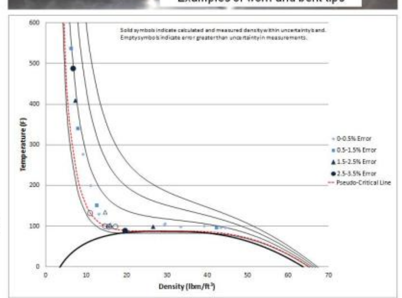
Design Considerations

- 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-CO_2 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





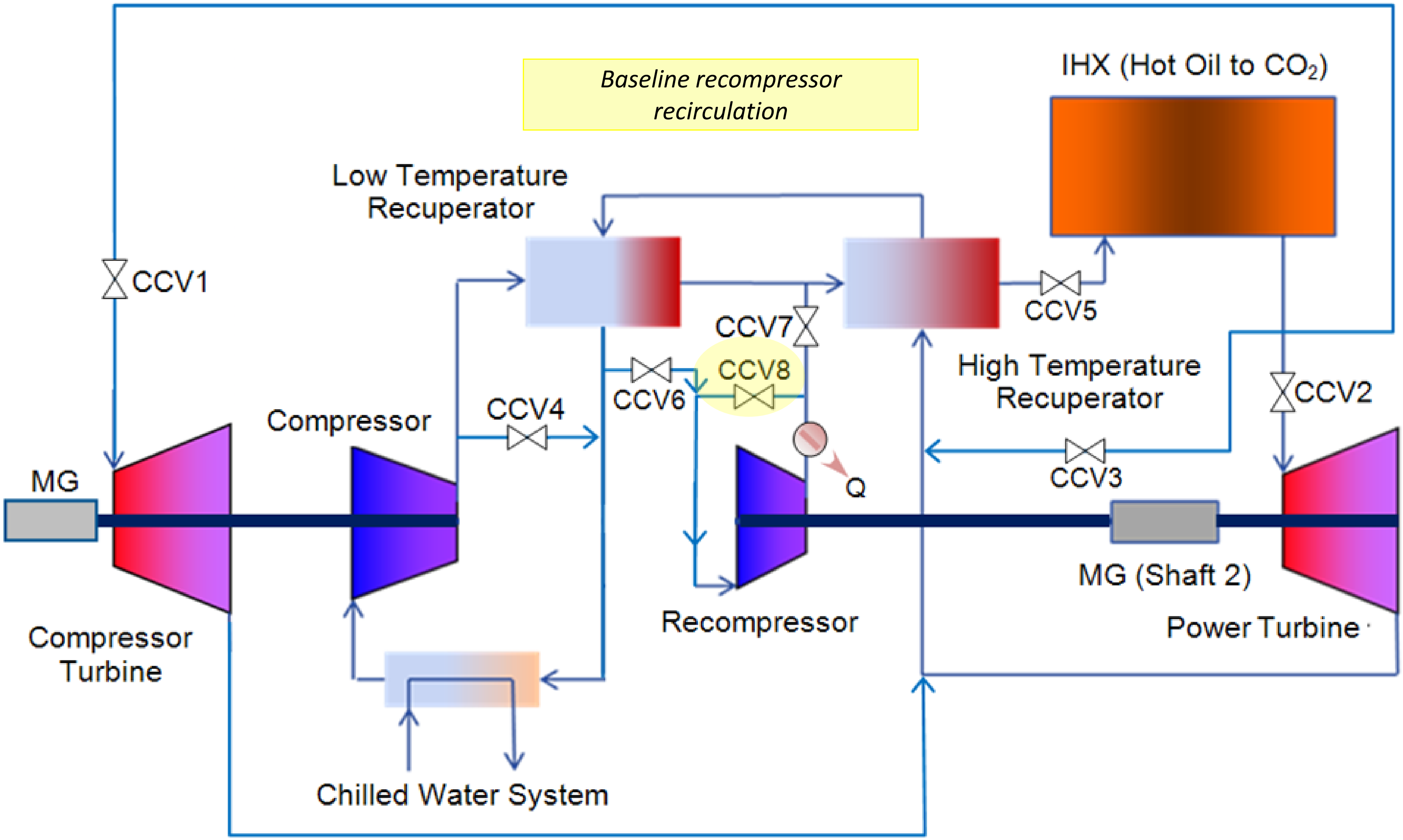
System Fill and Leakage

- IST uses Coleman Instrument grade (99.99%) CO_2 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

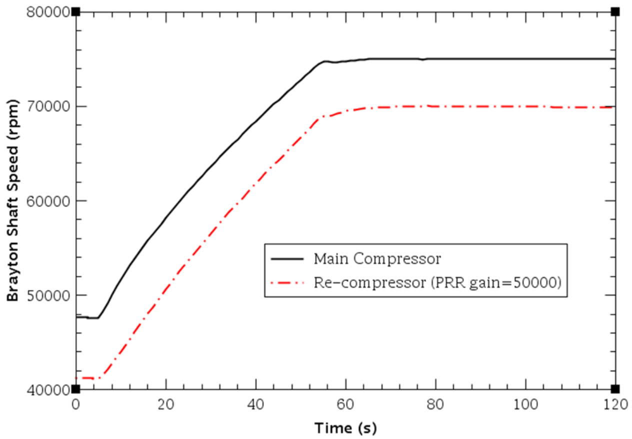
IST with Recompression Cycle Control Features

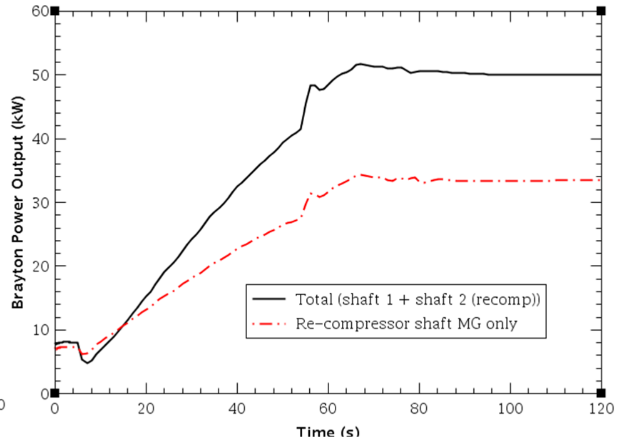


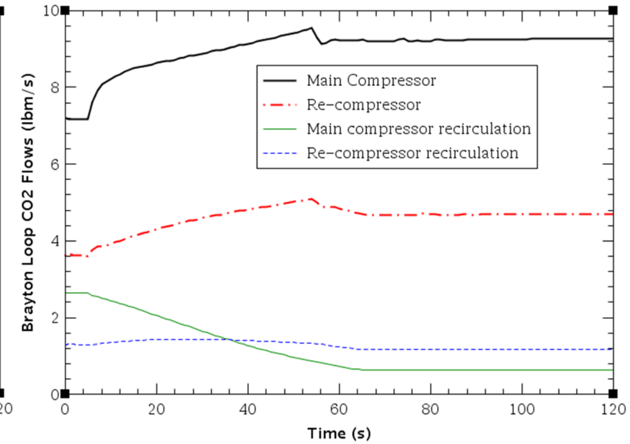
This loop design shows how recompression control features could be placed in the IST, allowing loop hydraulic control for startup, heatup and low power operation.

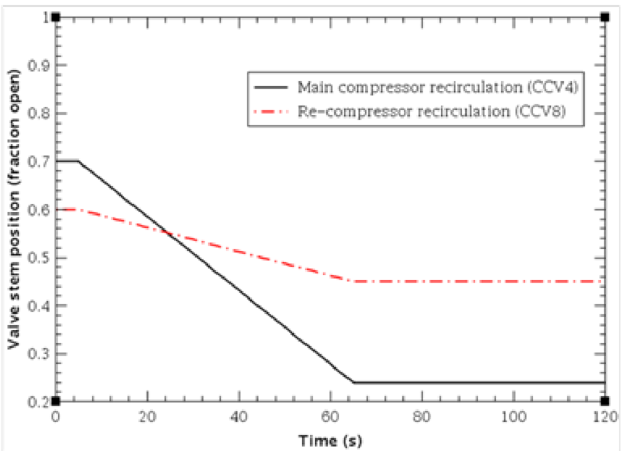
IST Up-Power Maneuver in Recompression Configuration

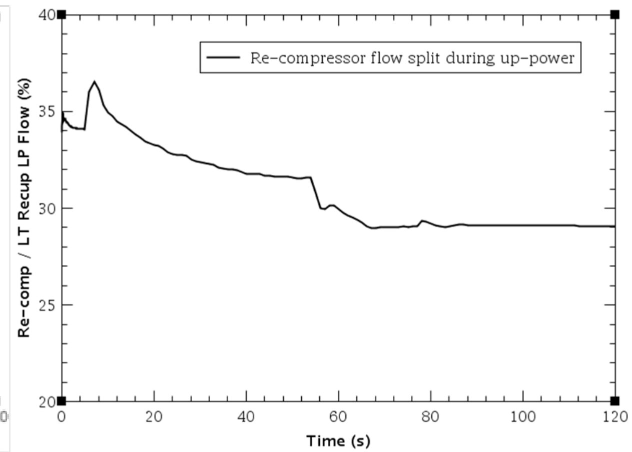
Using end states that have been optimized for adequate surge margin this up-power transient shows good performance, with minimal under/over shoot.

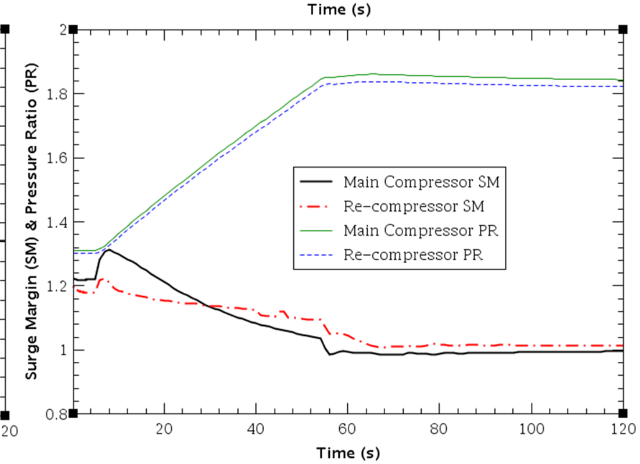












Up-power rates >1%/s would be possible for a well designed recompression loop.

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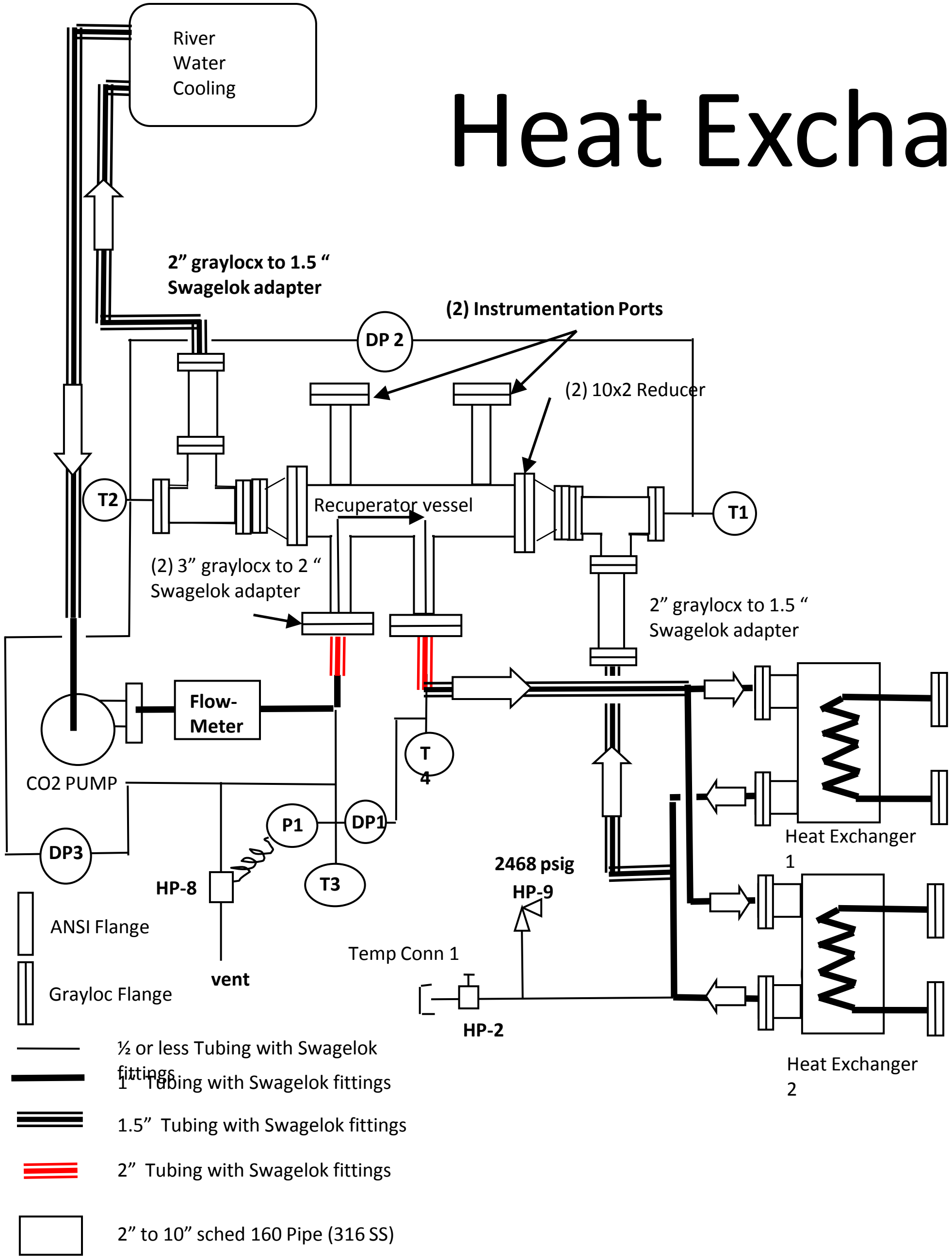
S-CO_2 Heat Exchanger Development

Heat Exchanger Testing



Testing Conditions:

Heat Input/Rejection 20-90 kW_t

Pressure: ≈1,200-1,500 psi

Temperature: ≈300-500°F

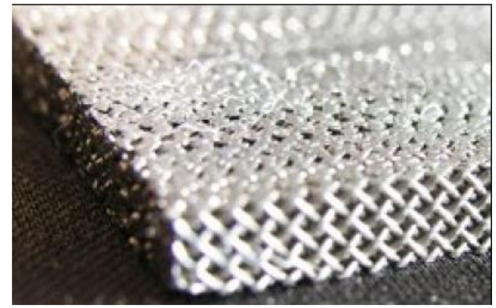
Flow rate: ≈2-3 lbm/second

Recuperator Designs Tested

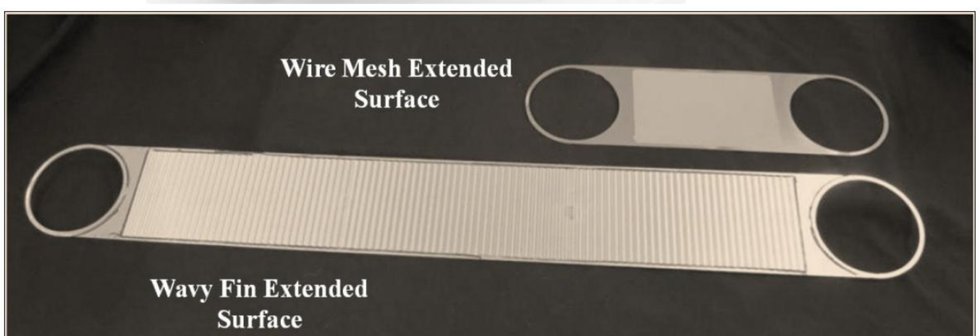
WavyFin

β=3,300-4,500 m^2/m^3

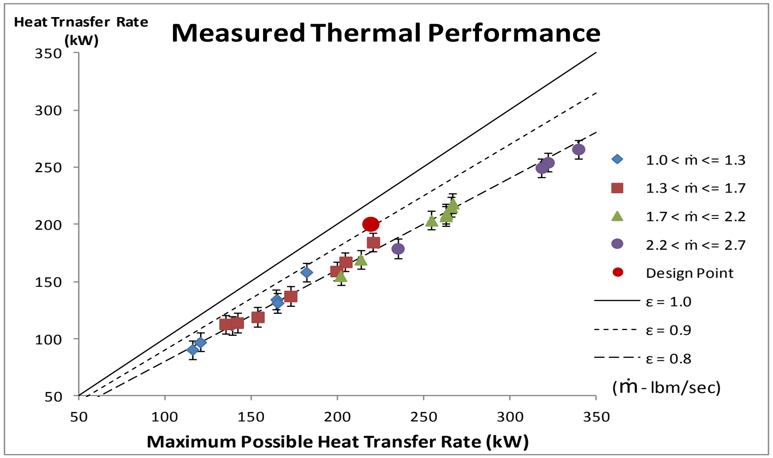
Wire Mesh

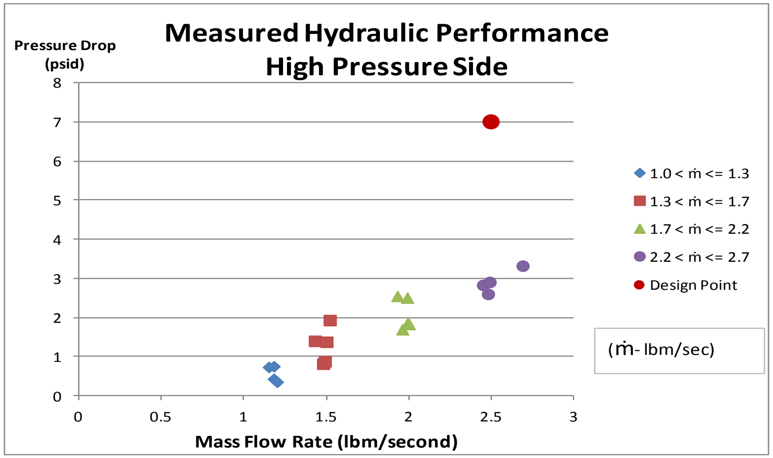


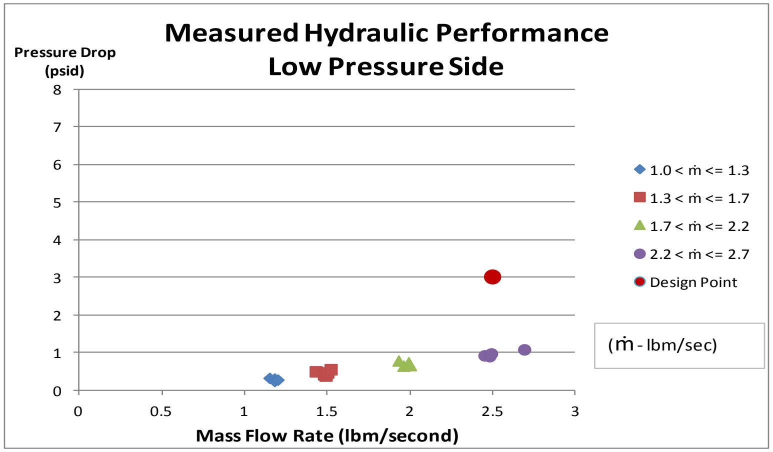
β=7,000-8,000 m^2/m^3



Folded Wavy-Fin Results







Prototype demonstrated thermal-hydraulic performance.

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Summary of Progress to Date

S-CO_2 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-CO_2 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

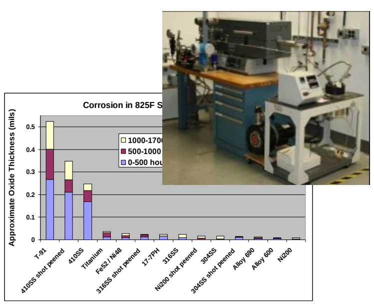
S-CO_2 Power Cycle Development Approach

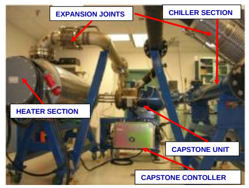
Fundamental Testing | *Concept Development* | *Small Scale System and Component Tests* | *Large Component Development* | *Large Scale System Test*

Fluid Behavior

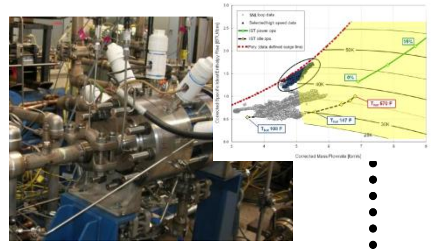
Safety Implications

Material Behavior





Sandia Closed Brayton Loops



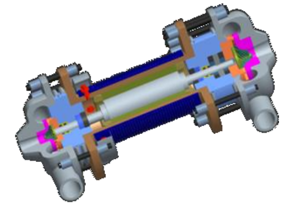
Small System Test

Operational Test

<u>Integrated System Test</u>

HX Development & Test

Turbomachinery Performance



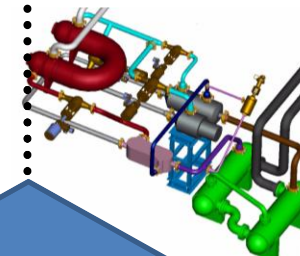
Validated Design Tools

Plant Concept Development

Heat Exchanger Performance

Power Plant Concept Development

Technology Assessment



Component and System Modeling Development

Path to S-CO_2 Power Cycle Commercial Implementation