Commercialization of Supercritical CO_2 (sCO_2) Power Cycles

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ECHOGEN
power systems

Echogen Power Systems

Founded 2007

Mission:

Commercialization of sCO_2 power cycles

Designed, fabricated and tested only MW-scale sCO_2 power cycle

Echogen leads the industry in sCO_2 power cycle development

15KW Lab system

EPS100 – 8 MW

5KW Lab system

250 KW Pilot system

EPS30M – 1.5MW marine

2007 2008 2009 2010 2011 2012 2013 2014 2015

Initial funding (2007)

DRESSER-RAND
SIEMENS (2011)

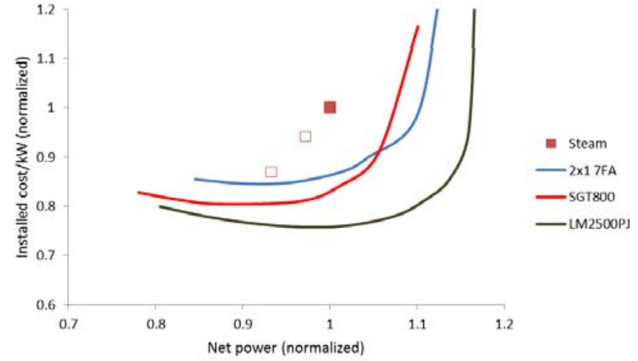
GE Marine (2013)

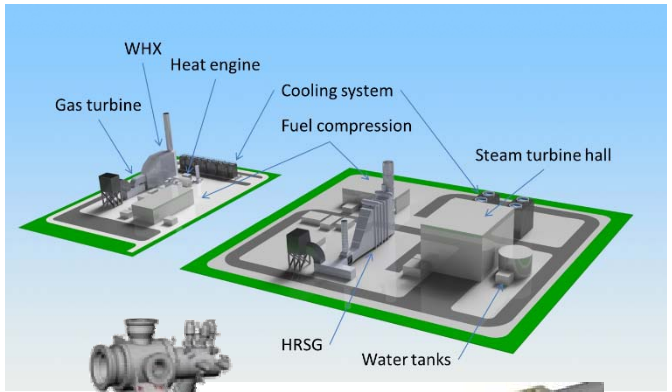
Commercialization of sCO_2 power cycles

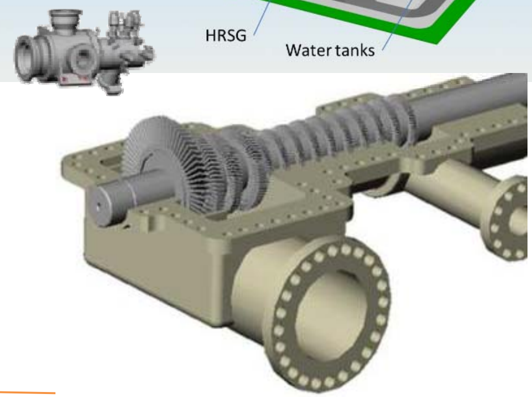
- Challenges and obstacles
  - Reluctance to assume risk of a new technology
  - First-of-a-kind costs vs 100-year-old technology
  - Current low energy costs unfavorable to investment in efficiency
  - Fear of the unknown…

Commercialization of sCO_2 power cycles

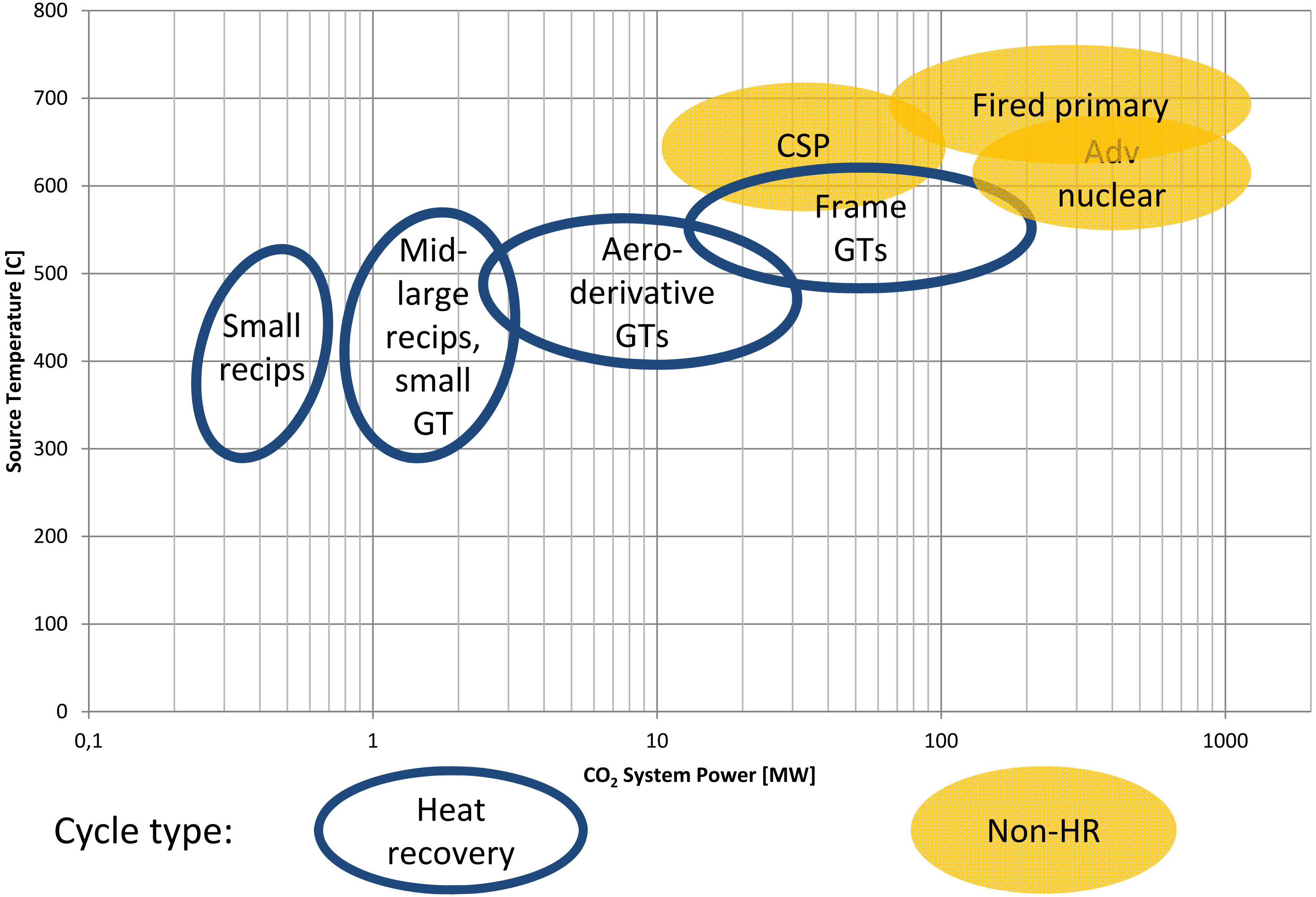
- Opportunities and value proposition
  - Higher efficiency at lower cost (or some combination thereof)
  - Physical size / footprint
  - Startup and turndown capability
  - Air-cooled = zero water power plant
  - O&M cost
  - Reliability & availability







The application space



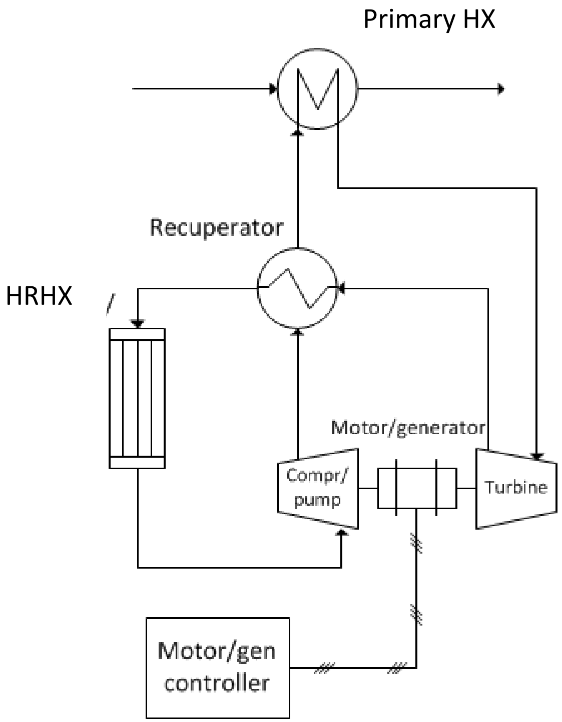
HR vs non-HR cycles

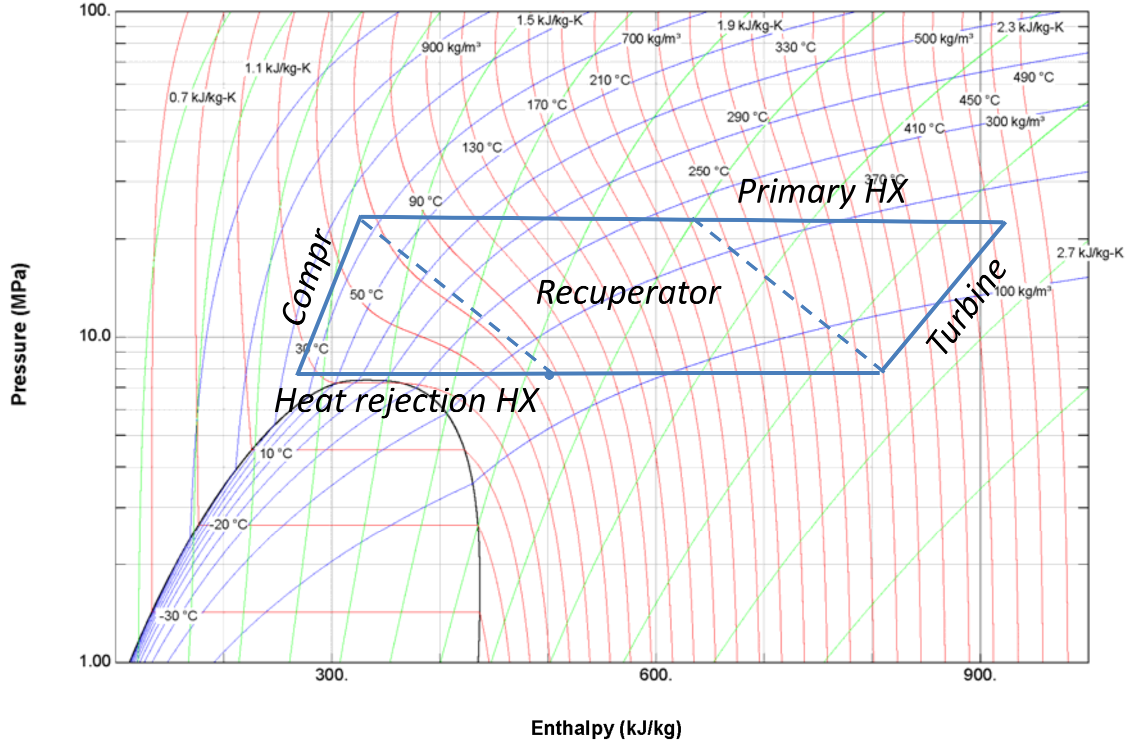
- Heat recovery cycle
  - GT exhaust is a classic example
  - Heat source is non-recycled – any heat not recovered by the power cycle is lost
  - Primary metric is power output for a given application
  - Goal is to maximize both recovered heat and recuperated heat simultaneously

HR vs non-HR cycles

- "non-Heat recovery" cycle (a.k.a. "recompression" cycle)
  - Advanced nuclear power is a classic example
  - Heat source is fully recycled
  - Primary metric is efficiency
  - Goal is to approximate a Carnot cycle – heat addition at very small temperature differential
  - "In-between" applications – e.g. CSP with thermal storage

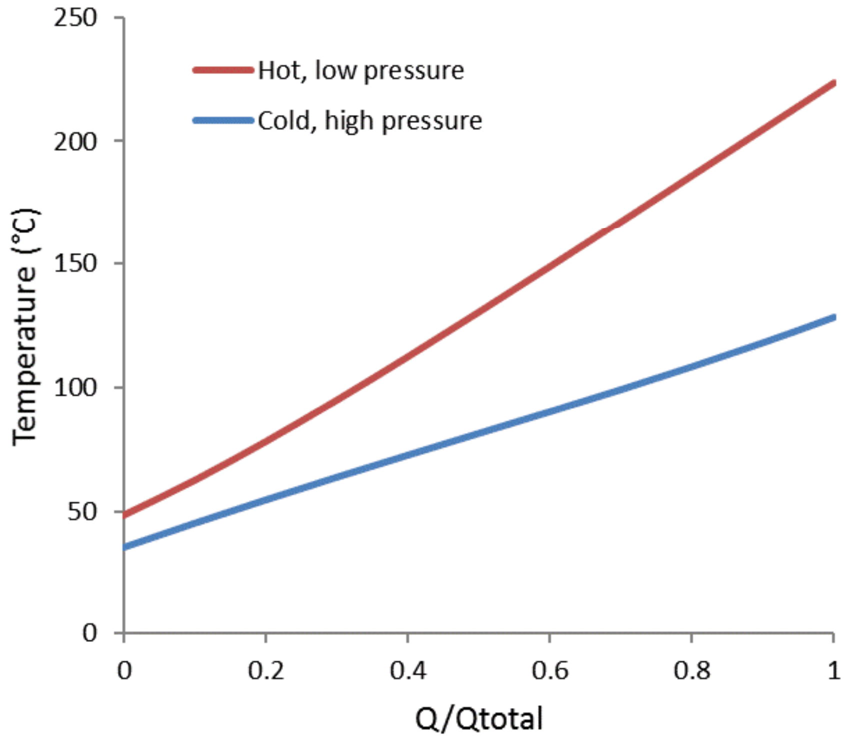
Simple recuperated cycle – somewhere in the middle ground





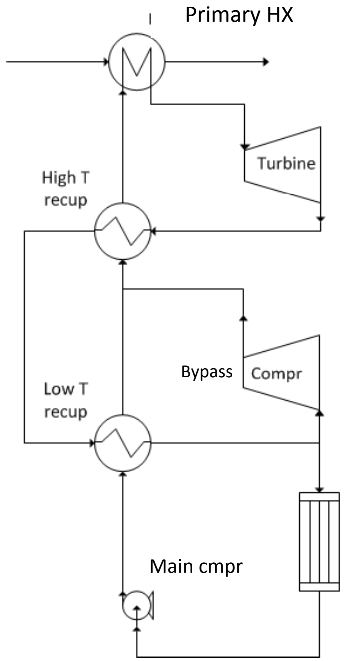
Minimum temperature in primary HX too high for heat recovery, too low for good Carnot efficiency

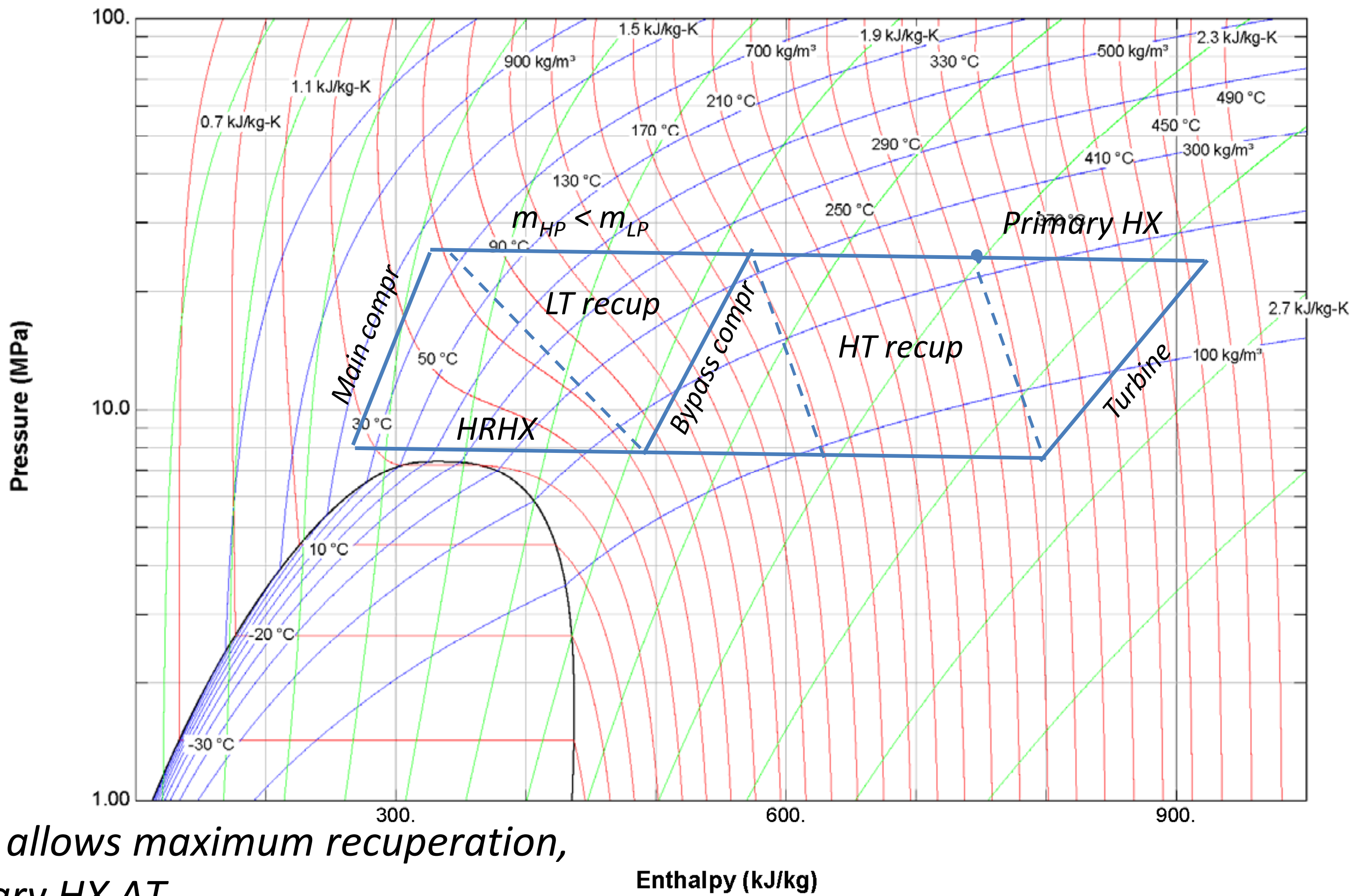
Recuperator characteristics



- Simple recuperated cycle – recuperator “pinches” at low-temperature end
- Consequence of large c_p mismatch between high-pressure and low-pressure CO_2, equal mass flows
- Large exergy destruction with temperature glide mismatch

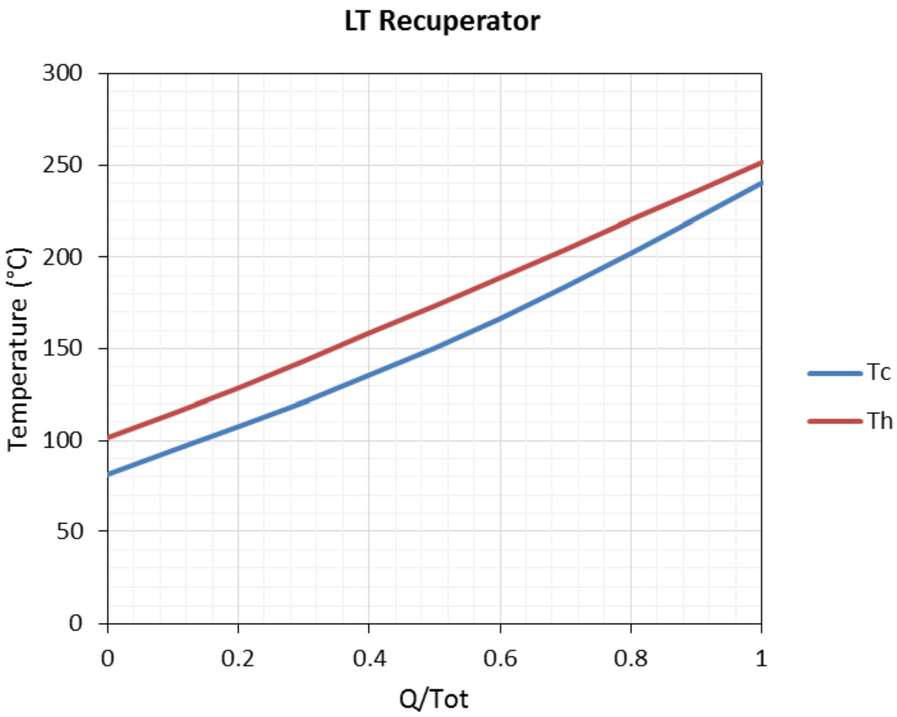
“Recompression” (LT recup bypass) cycle maximizes avg PHX temperature

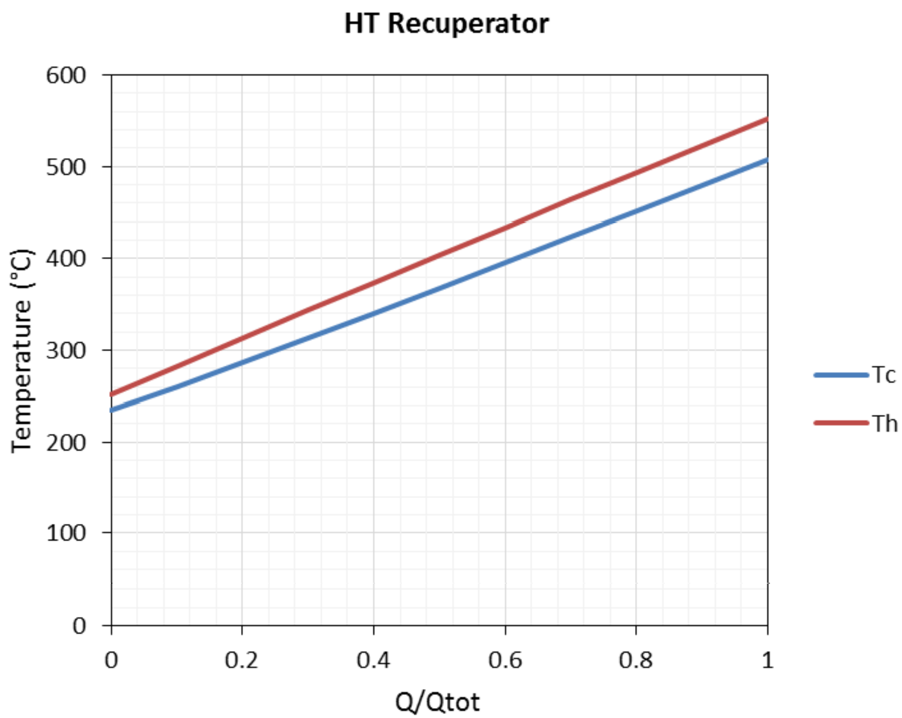




LT recup bypass allows maximum recuperation, minimizes primary HX ΔT

Recuperator characteristics

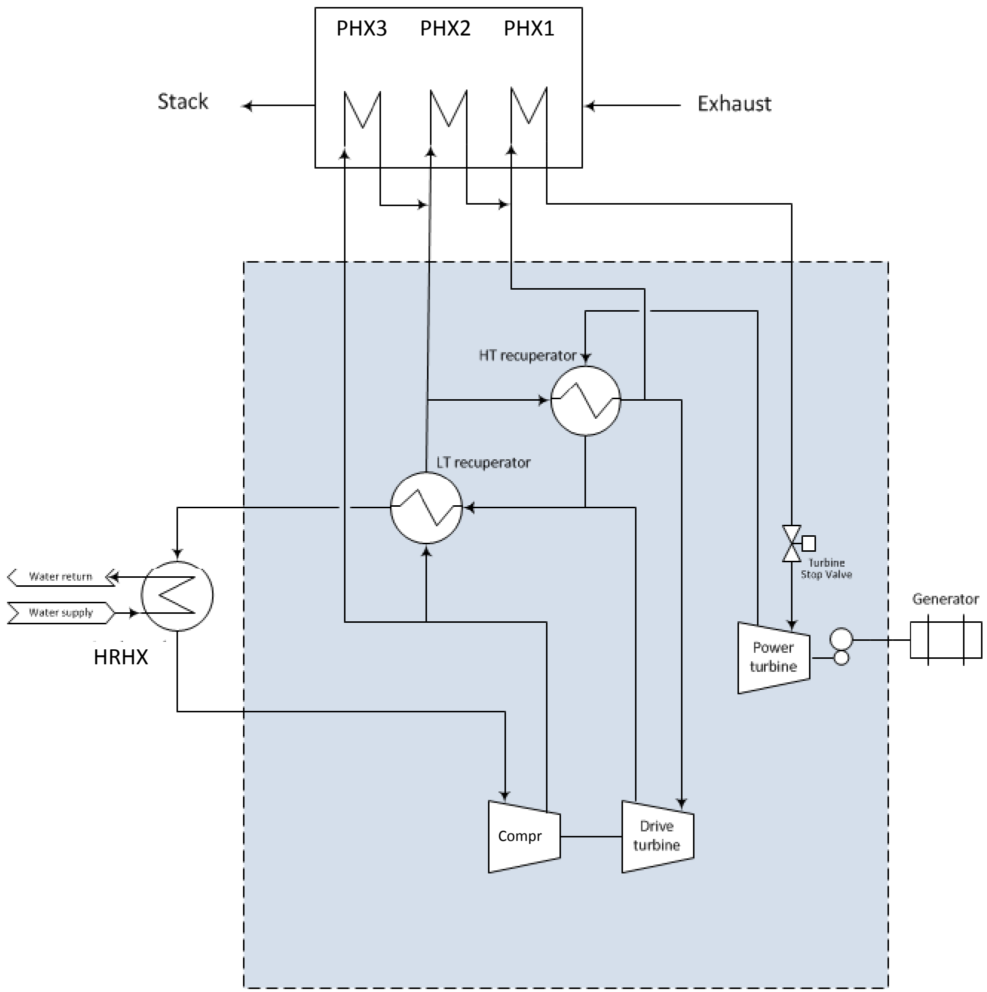




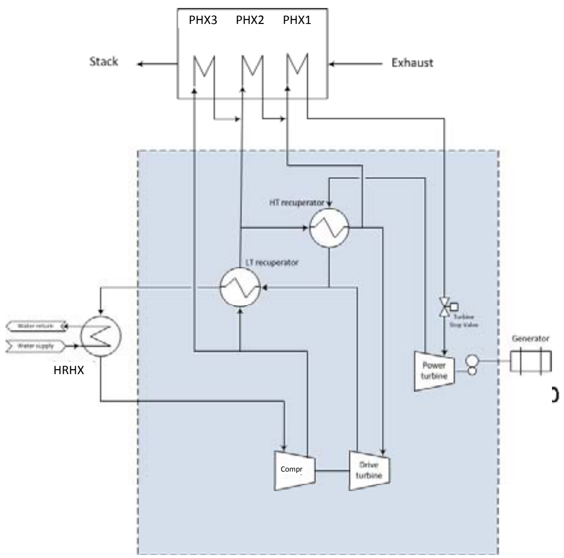
- Cycle optimization drives C_r (C_{min}/C_{max}) toward 1
- Equal slope minimizes exergy destruction
- However, equal slope also implies large UA

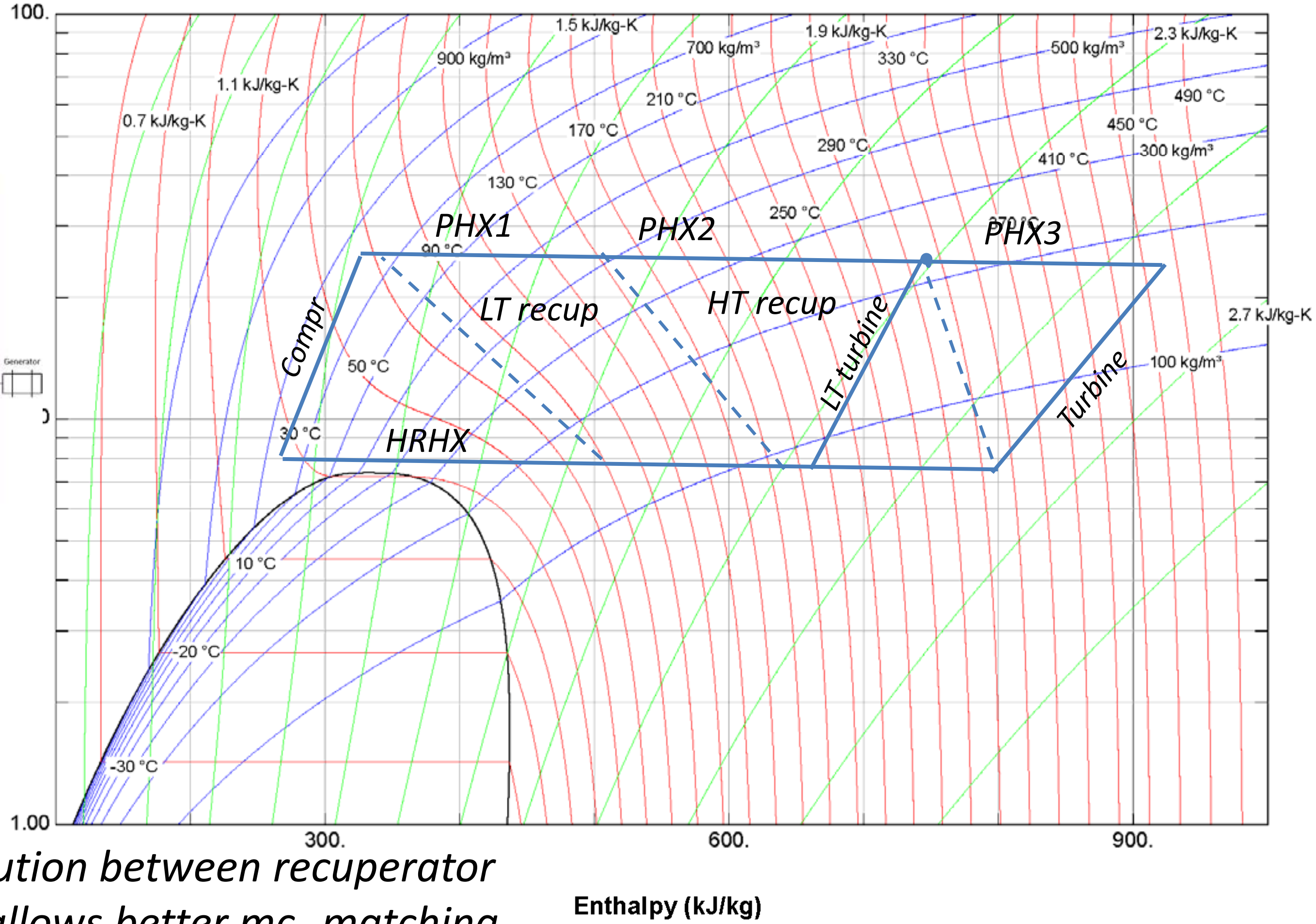
Heat recovery cycle

- "Dual rail" cycle
  - Patent pending
  - Sequence of heat additions via "recuperation rail" and "primary heat exchanger rail"
- Key characteristics:
  - Primary heat transfer over a wide range of temperatures
  - Variable flow splits as progress down primary heat exchanger, matches mc_p of exhaust stream
  - Dual turbines



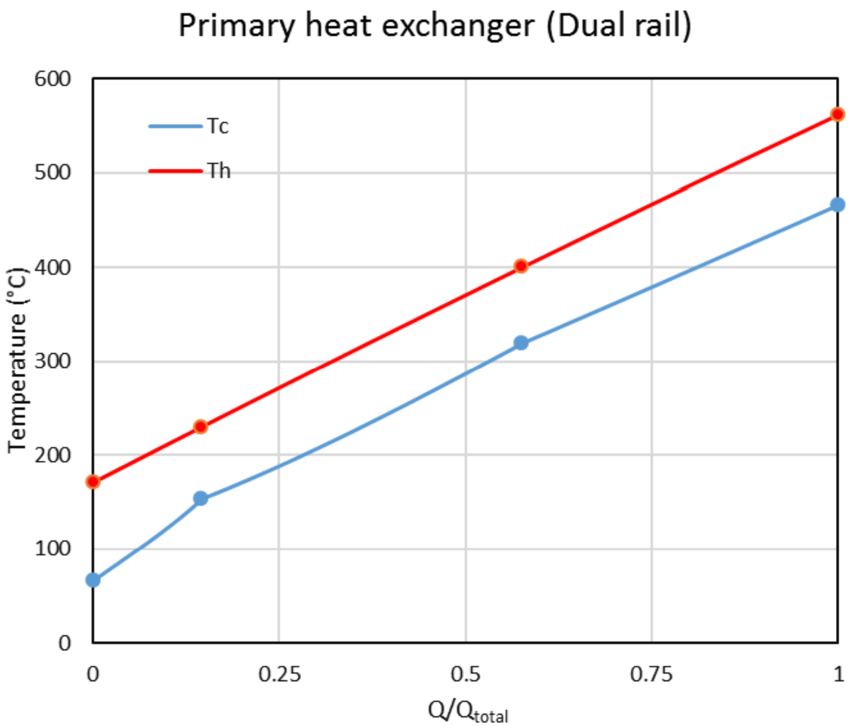
Dual rail cycle maximizes combined utilization of external and internal (recuperated) heat

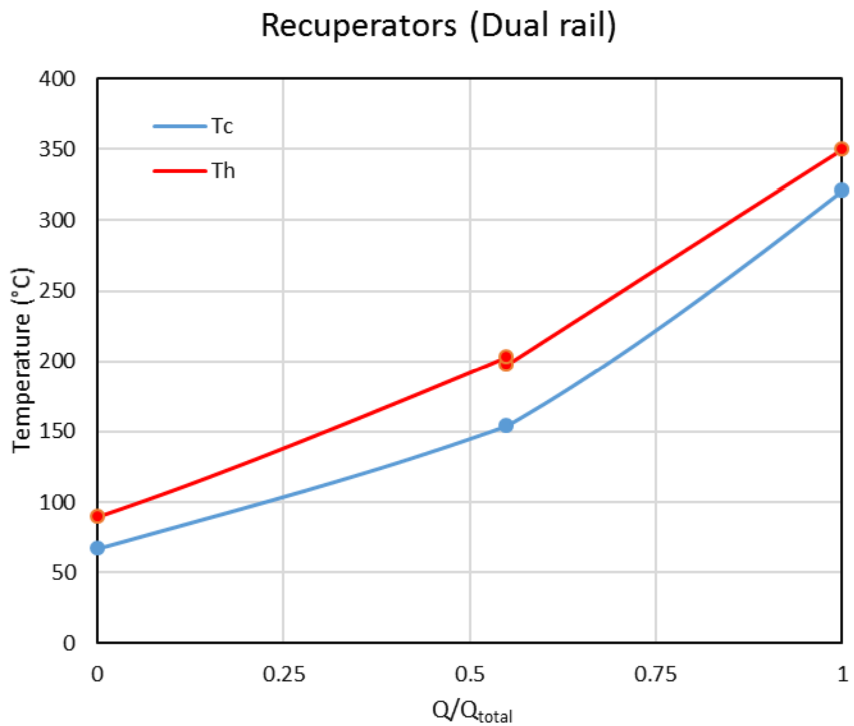




Stepped flow distribution between recuperator path and PHX path allows better mc_p matching

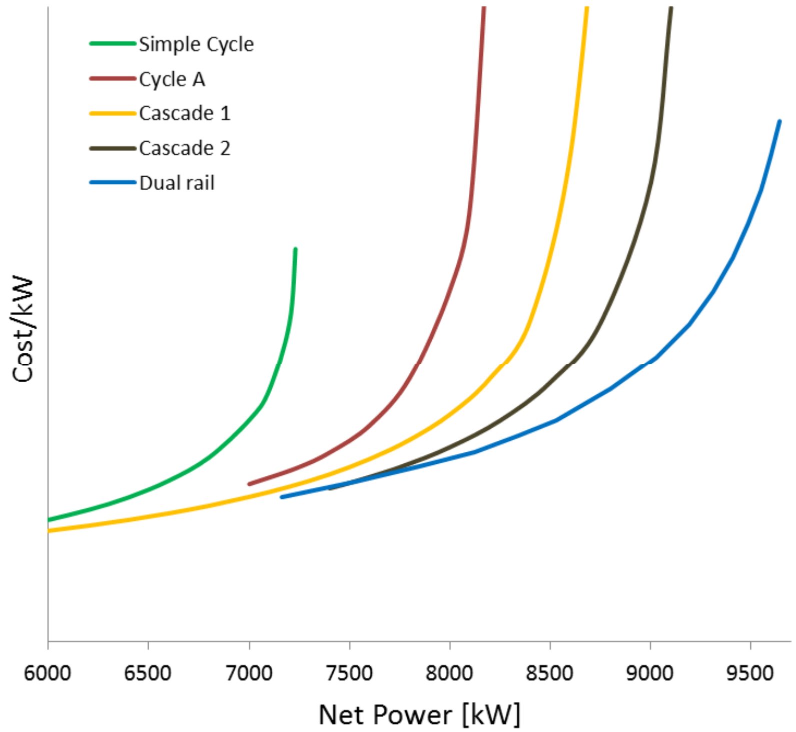
Heat recovery primary heat exchanger





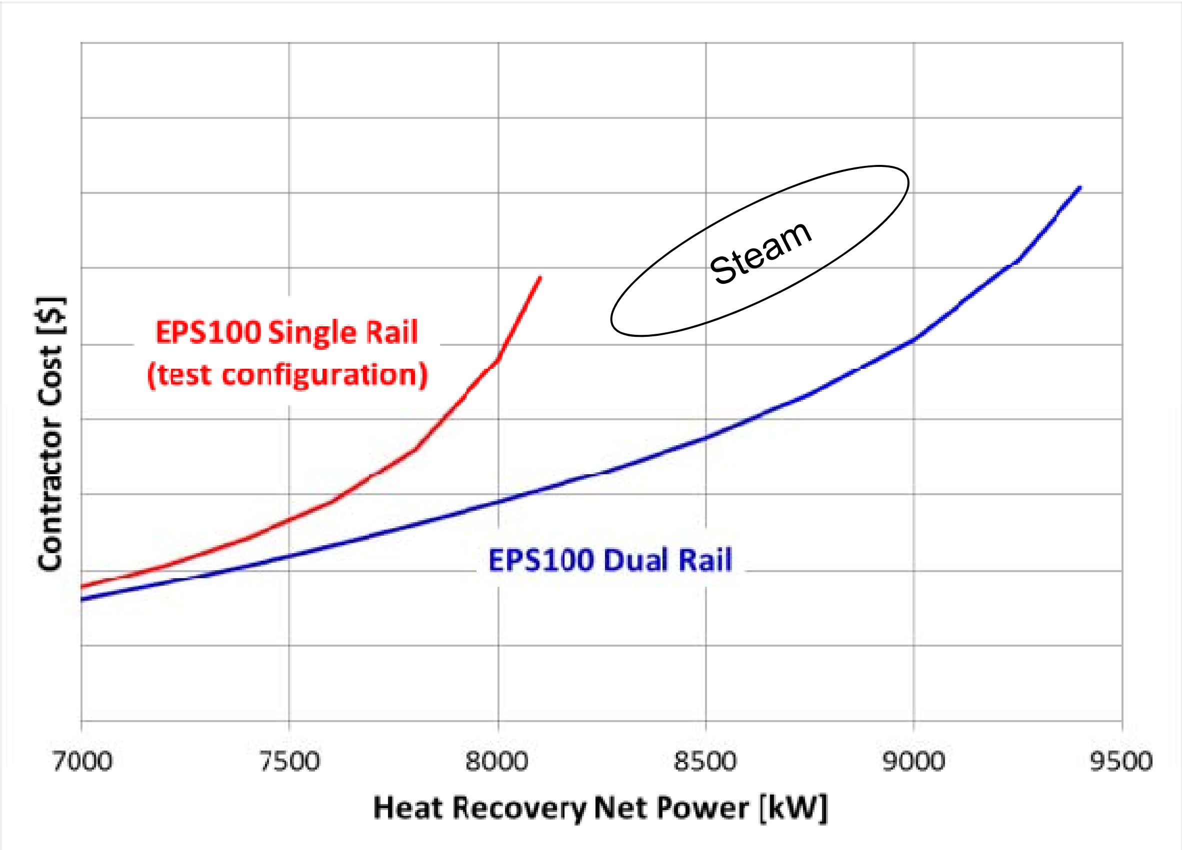
- Optimization drives flow splits and heat exchanger UAs towards equal temperature glide

Cycle / cost modeling



- Optimization process defines cycle with minimum cost for given power output
- Multiple solutions generates curves of cost vs power
- Allows selection of optimal cycle architecture

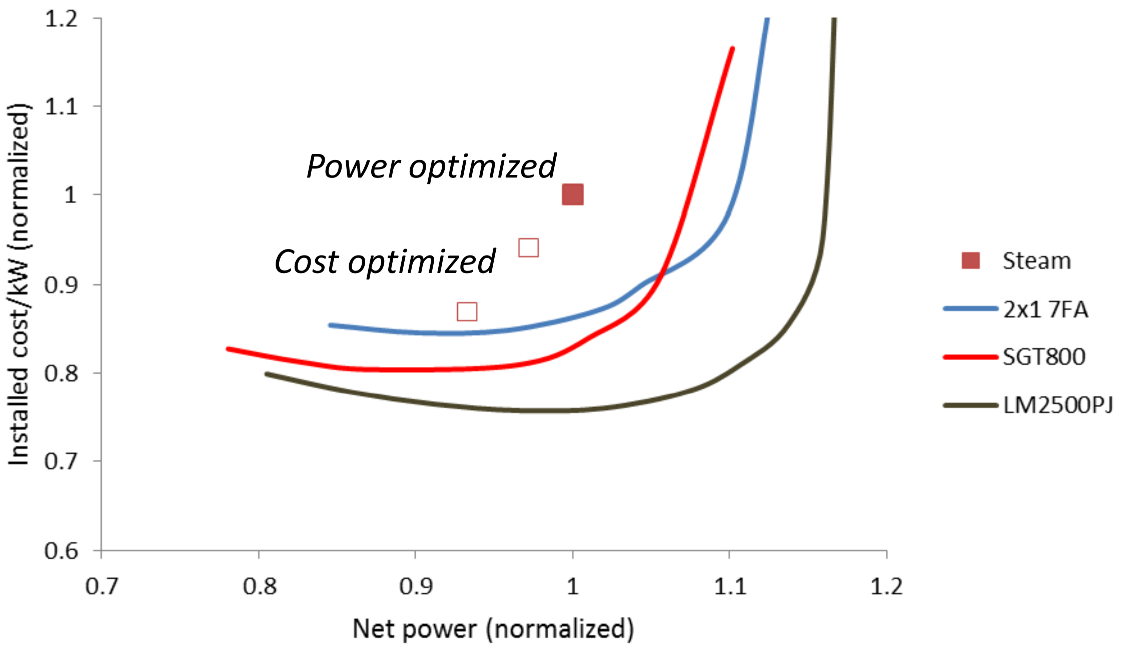
Continued sCO_2 Cycle Improvements



- Comparison of sCO_2 cycles
  - EPS100 (patents pending)
  - Dual Rail (patents pending)
- Current design of EPS100 at 7.3 MW net
- Dual rail cycle offers substantial improvement in performance, outperforms steam at a lower cost

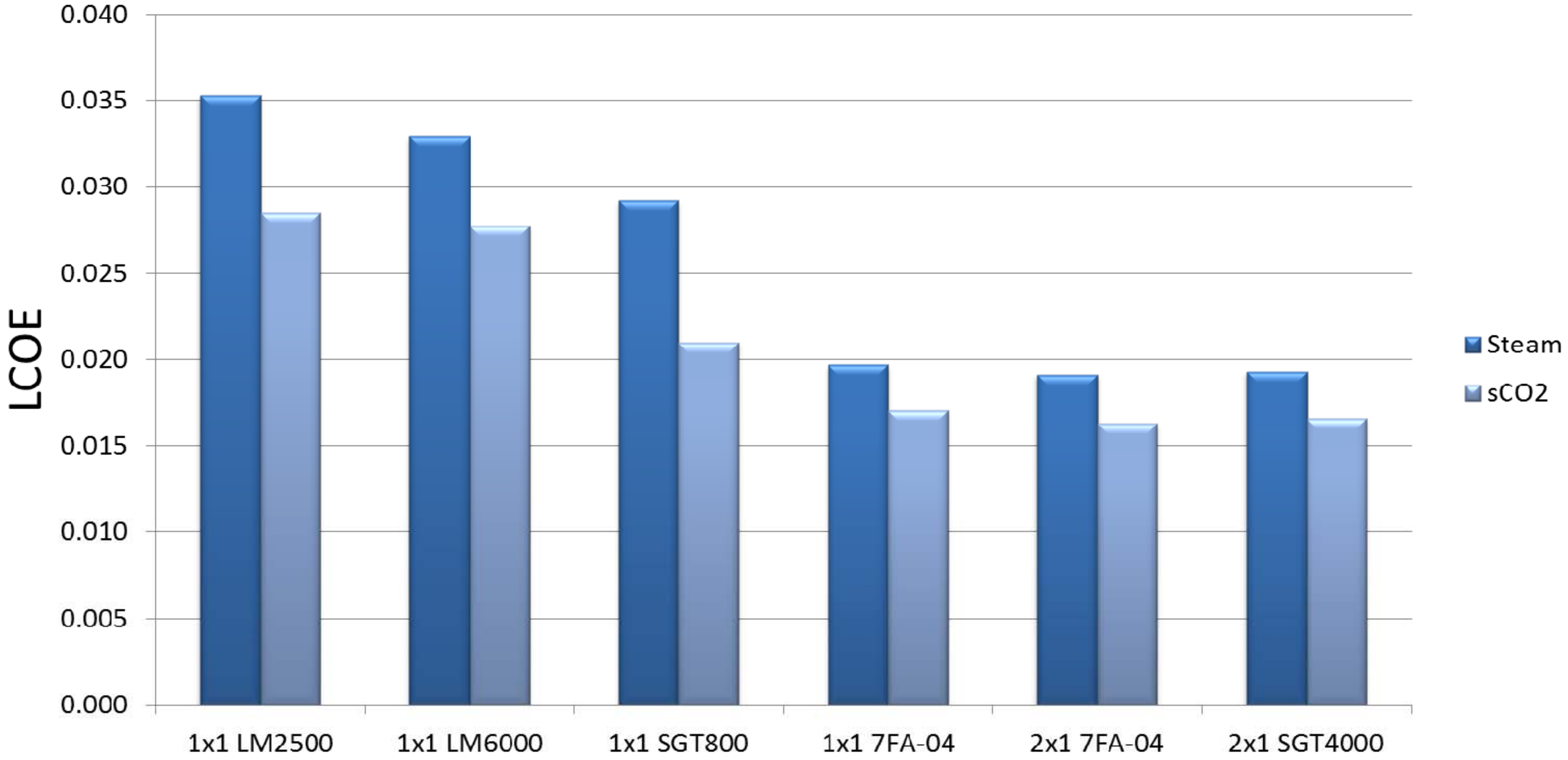
Echogen sCO_2
= lower CAPEX & lower Levelized Cost of Electricity

sCO_2 vs steam – GTCC applications



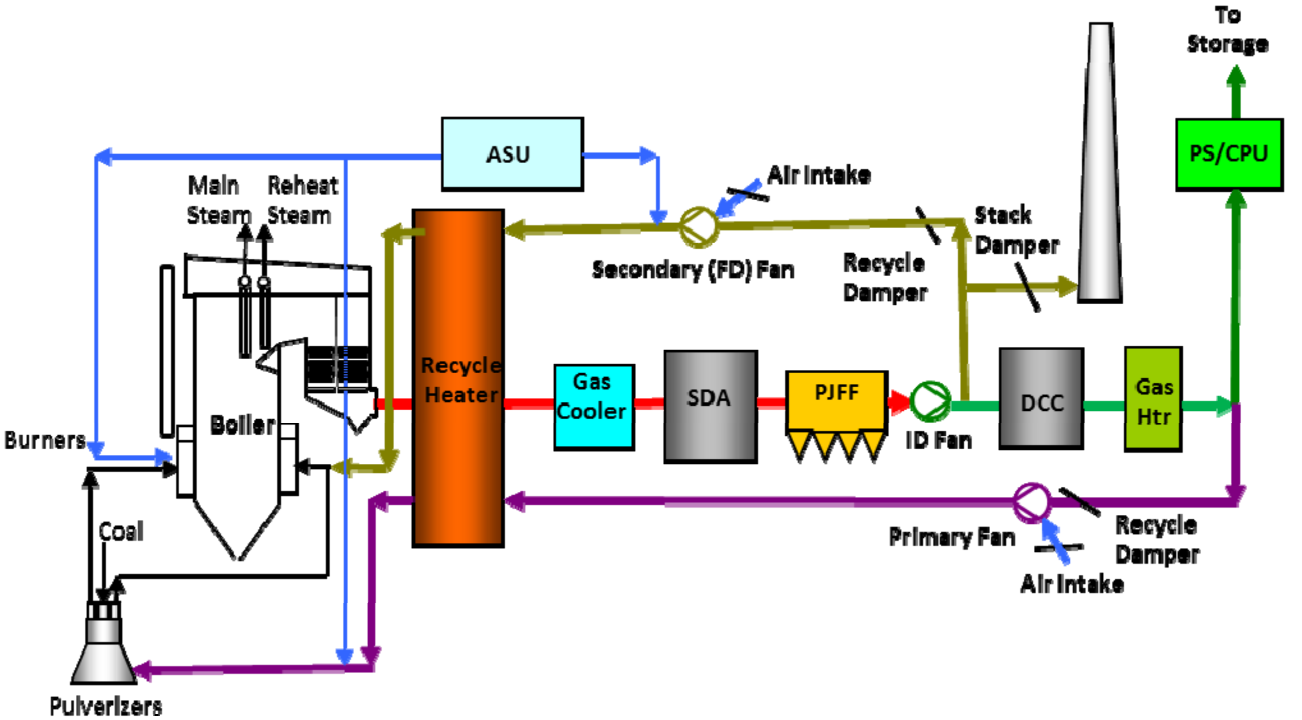
- Normalized to steam power & cost from GT-Pro, "power-optimized" solutions ("cost-optimized" point shown for reference)
- Same exhaust and boundary conditions used for sCO_2
- 10-20% lower cost for same power
- 7-14% higher power for same cost

LCOE – GTCC applications



- Case studies covering 30-800+MW
- Bottoming cycle LCOE consistently lower with sCO_2

Primary power applications



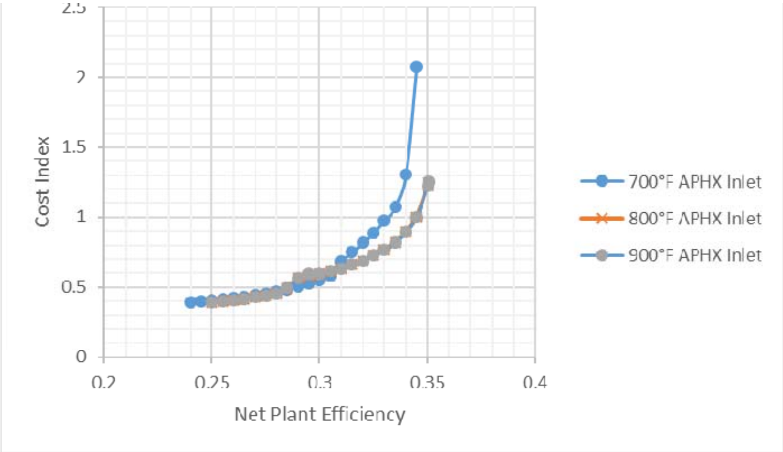
- EPRI-led oxy-coal sCO_2 integration study
- Comparisons to baseline steam cases

sCO2 – Steam Power Cycle Comparison

- Purpose / Goals:
  - Develop power plant process designs that optimally integrate sCO_2 power cycles with oxy-fired coal heaters for comparison to advanced steam cycles
- Method
  - Performance optimization of sCO_2 cycles
  - Varied cycle architectures, cooling sources, power cycle heat exchanger sizes and pressure drops
- Approach
  - System economics within sCO_2 cycle also optimized
    - Heat exchanger cost sensitive to thermal size “UA” and pressure drop.
    - Optimize sCO_2 cycle heat exchanger cost (recuperators and coolers) versus net cycle efficiency
  - Combinations and variants of cascade and recompression cycles—including architectures with multiple compression steps and reheat—were considered

sCO_2 Power Cycle - Effect of Air Preheater Inlet Temperature

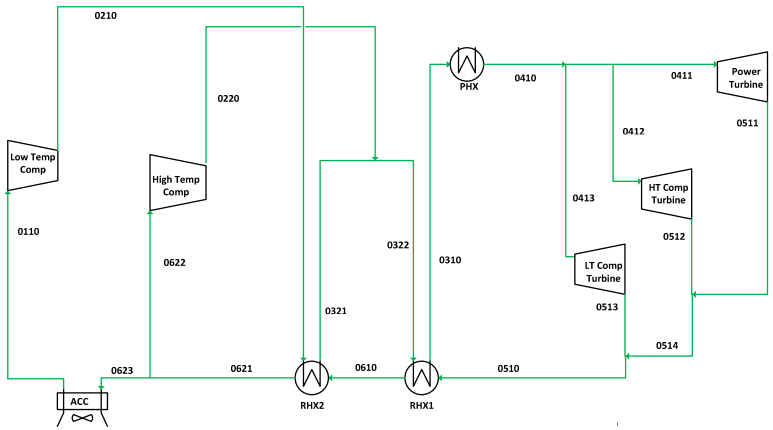
550 MW – Effects of Air Preheat Inlet Temp Case 1:



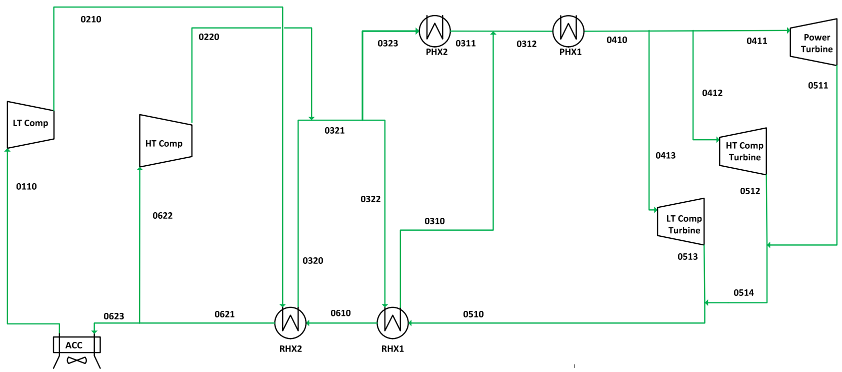
Result:

- Positive effect of air preheater inlet air temperature on cycle efficiency is limited by recuperation of sCO_2 cycle.
- For lower temperature application (T_4 = 593°C)
  - Increasing air preheater inlet temperature above 427°C has little effect on cycle efficiency
- With the addition of low grade heat recovery cycle optimum cycle efficiencies can be achieved with lower air preheat inlet temperature (371°C)

Recompression Cycle:



Recompression Cycle – LG Heat Recovery



Steam – sCO_2 Power Cycle Comparison Summary

Test Case	Power Turbine Inlet Condition	Net Gen (MW_e)	Gross Gen (Mwe)	Cycle Heat Input (MW_{th}) / Heater Efficiency	Net sCO2 Plant Efficiency (HHV)	sCO2 Cycle Efficiency	Baseline Steam Net Plant Efficiency	Baseline Steam Cycle Efficiency
1	593°C / 241 bar	550	736.2	1407 / 88.3%	34.5%	52.3%	31.0%	47.0%
2	730°C / 27.6 bar	550	713.4	1295 / 88.3%	37.5%	57.2%	35.0%	50.6%
3	593°C / 241 bar	550	651.2	1286 / 90%	38.5%	50.6%	35.8%	46.9%
4	730°C / 27.6 bar	550	640.5	1151 / 90%	43.0%	55.6%	41.0%	52.3%
5	593°C / 241 bar	90	101.0	210 / 85.1%	36.5%	48.1%	33.0% (538°C/107 bar no reheat, no CO2 capture)	38.8%
6	730°C / 27.6 bar	90	99.2	186 / 85.1%	41.0%	53.1%		

- Test Case 1 – 2 – Integration with Oxy-fired Pulverized Coal Heater
- Test Case 3 – 4 – Integration with Oxy-fired Chemical Looping Heater
- Test Case 5 – 6 – Integration with Air-fired Pulverized Coal Heater

EPS100

First commercial-scale sCO_2 heat engine

Description and test results

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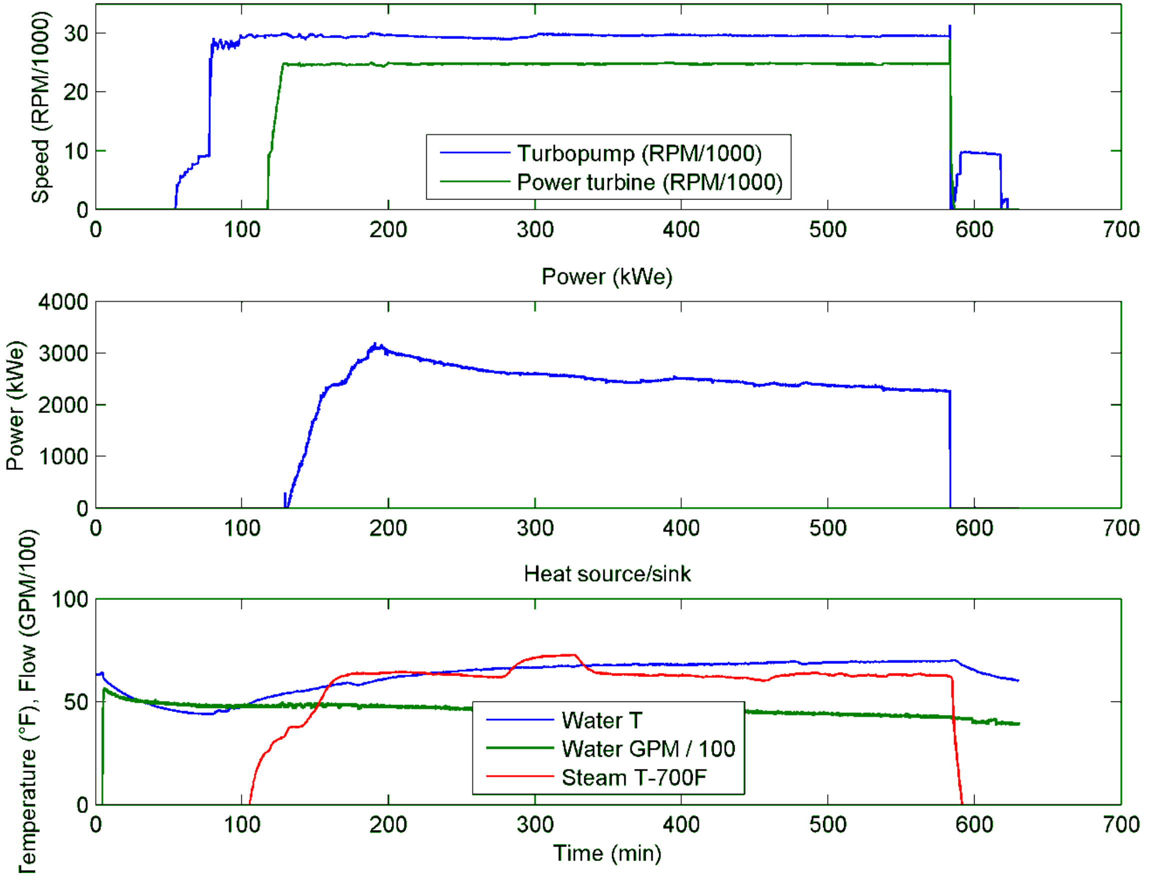
The EPS100

- Designed for 25 MW Aeroderivative GTs
  - GE LM2500PE/PJ
  - R-R RB211 C62
  - Solar Titan 250
  - 8.0 MW gross
  - 7.3 MW net
- Physical Configuration
  - Process skid (right)
  - Power skid (above)
  - Control house
  - CO_2 storage tank and transfer system
  - Cooling system (air or water)

GTs = Gas Turbines

Operational summary – typical test day

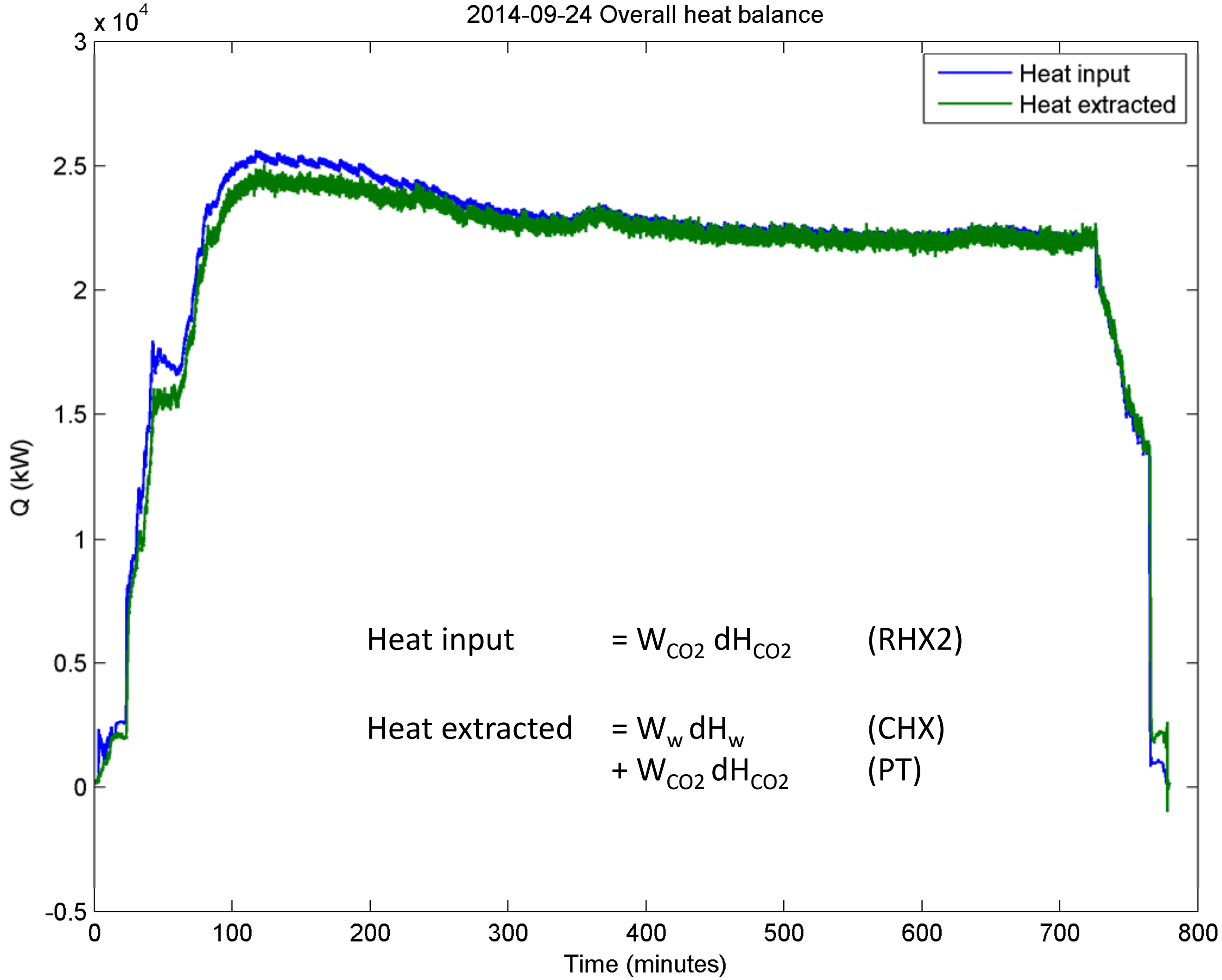


- Maximum power = 3.1 MWe – limited by heat source and water temperatures
- Run terminated by load bank fault. System tripped automatically and safely

A typical test day (compressed to 3 minutes)

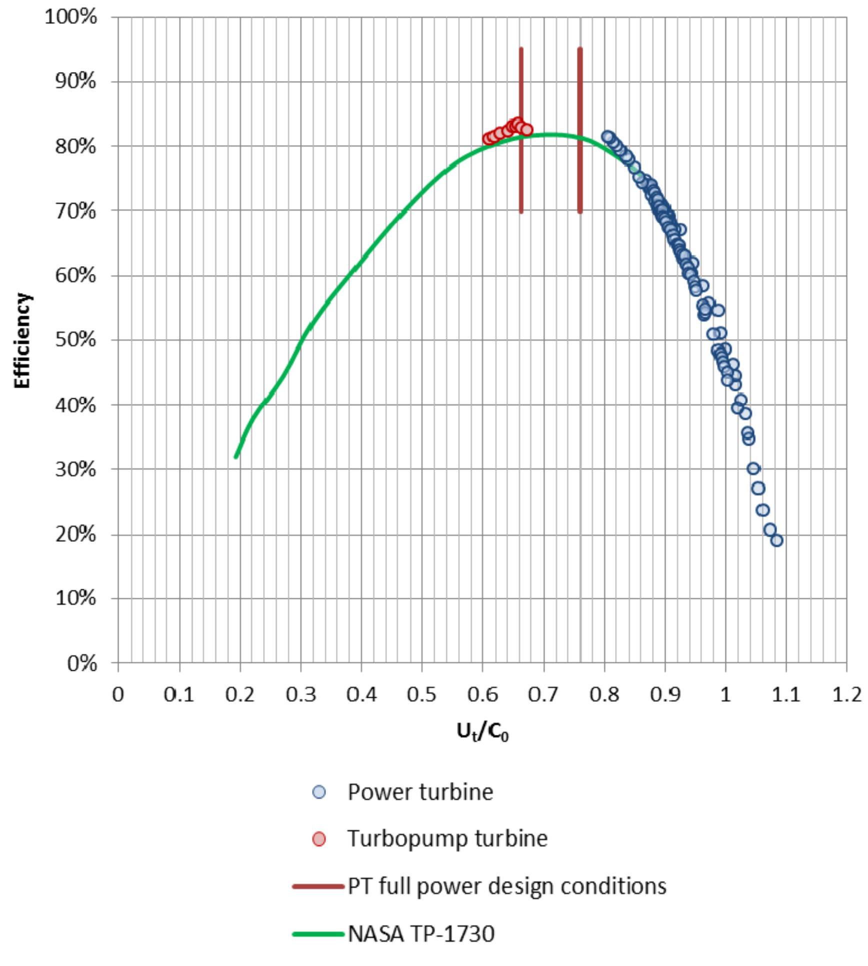
- Play video from file

Overall heat balance



Turbomachinery Validation

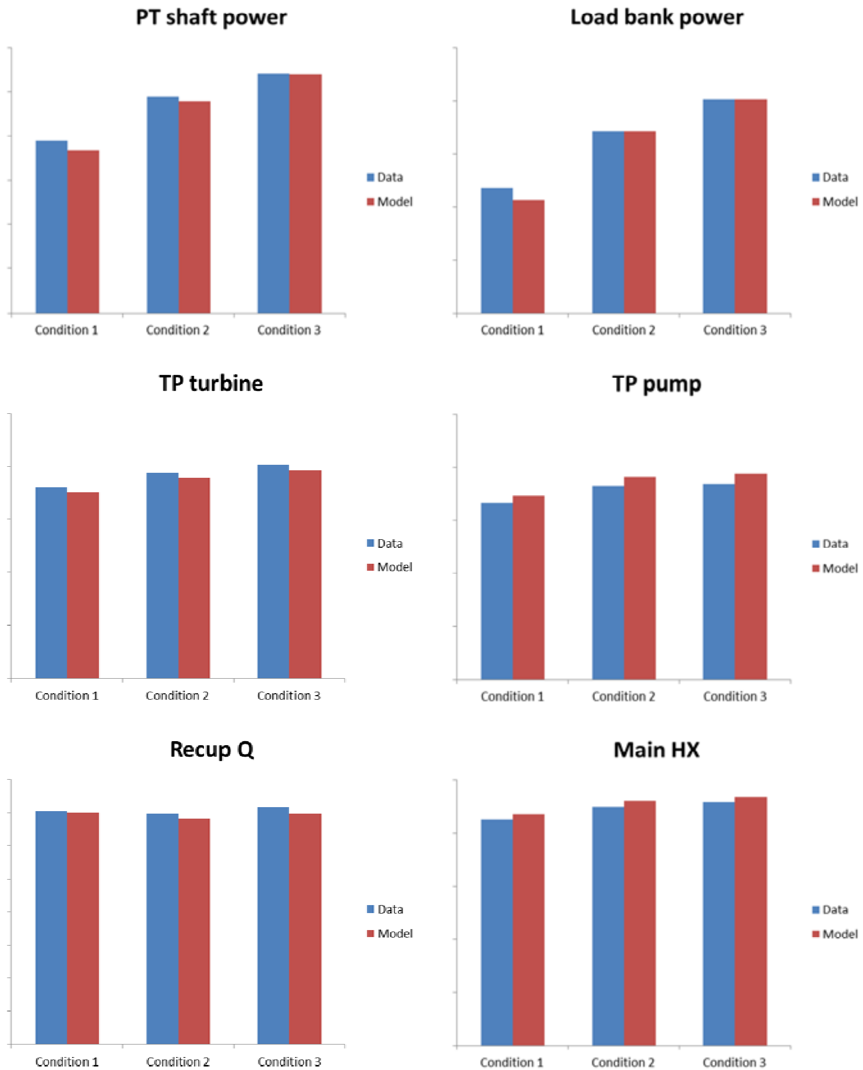
- Power turbine and turbocompressor efficiencies demonstrate excellent agreement with reference curve derived by NASA
- Turbocompressor test data represent operation near full power
- Power turbine data represent significantly off-design conditions of the test cycle configuration. At full power conditions efficiency is expected to be similar to turbocompressor



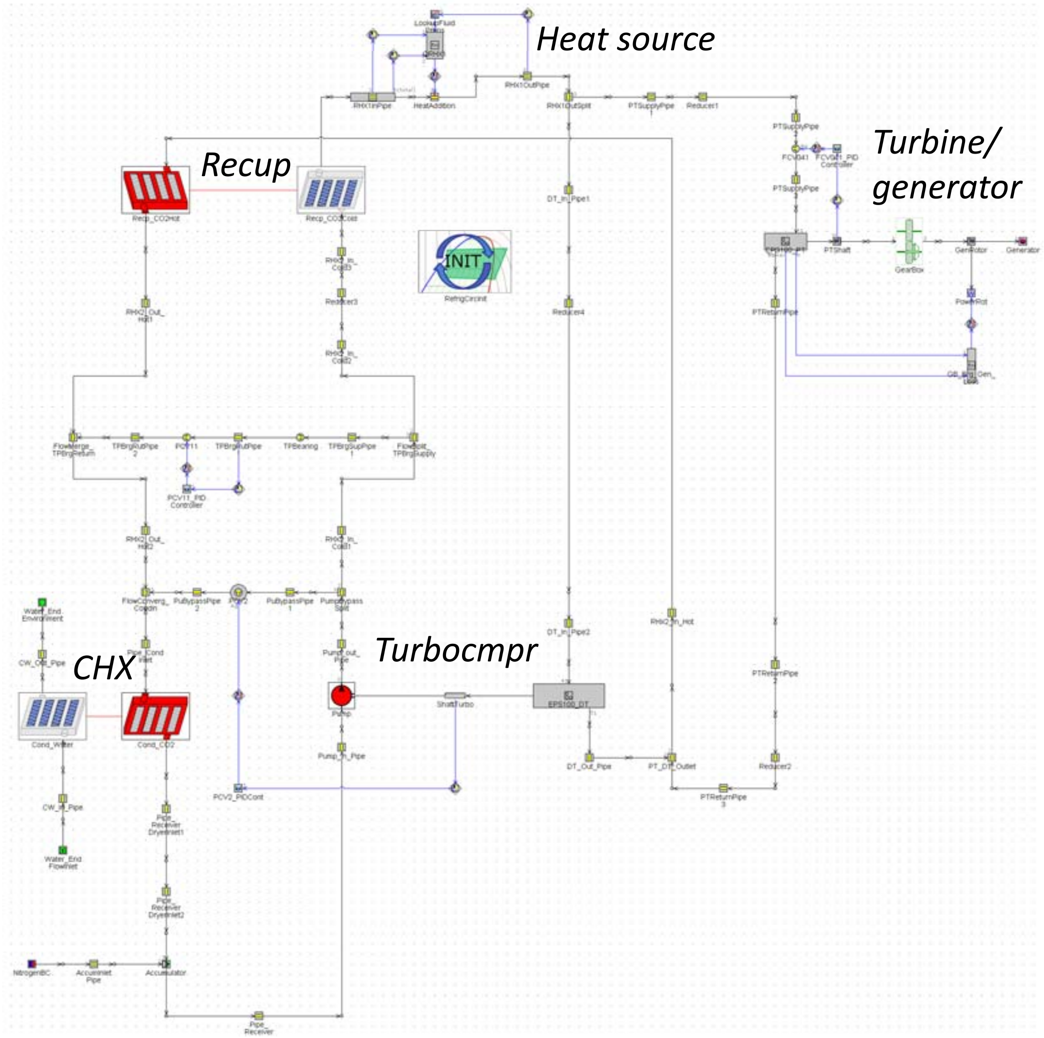
Turbine performance vs NASA TP-1730 curve. Note that TP-1730 curve ends at approximately Ut/C0=0.9.

Steady-state cycle model validation

- Detailed cycle model
- Includes off-design component performance submodels
- Inputs:
  - Compressor inlet and outlet pressures
  - Heat source temperature & flow
  - Cooling water temperature and flow
  - PT speed
- Outputs:
  - TP speed
  - All other cycle points
  - Power output



Transient system model



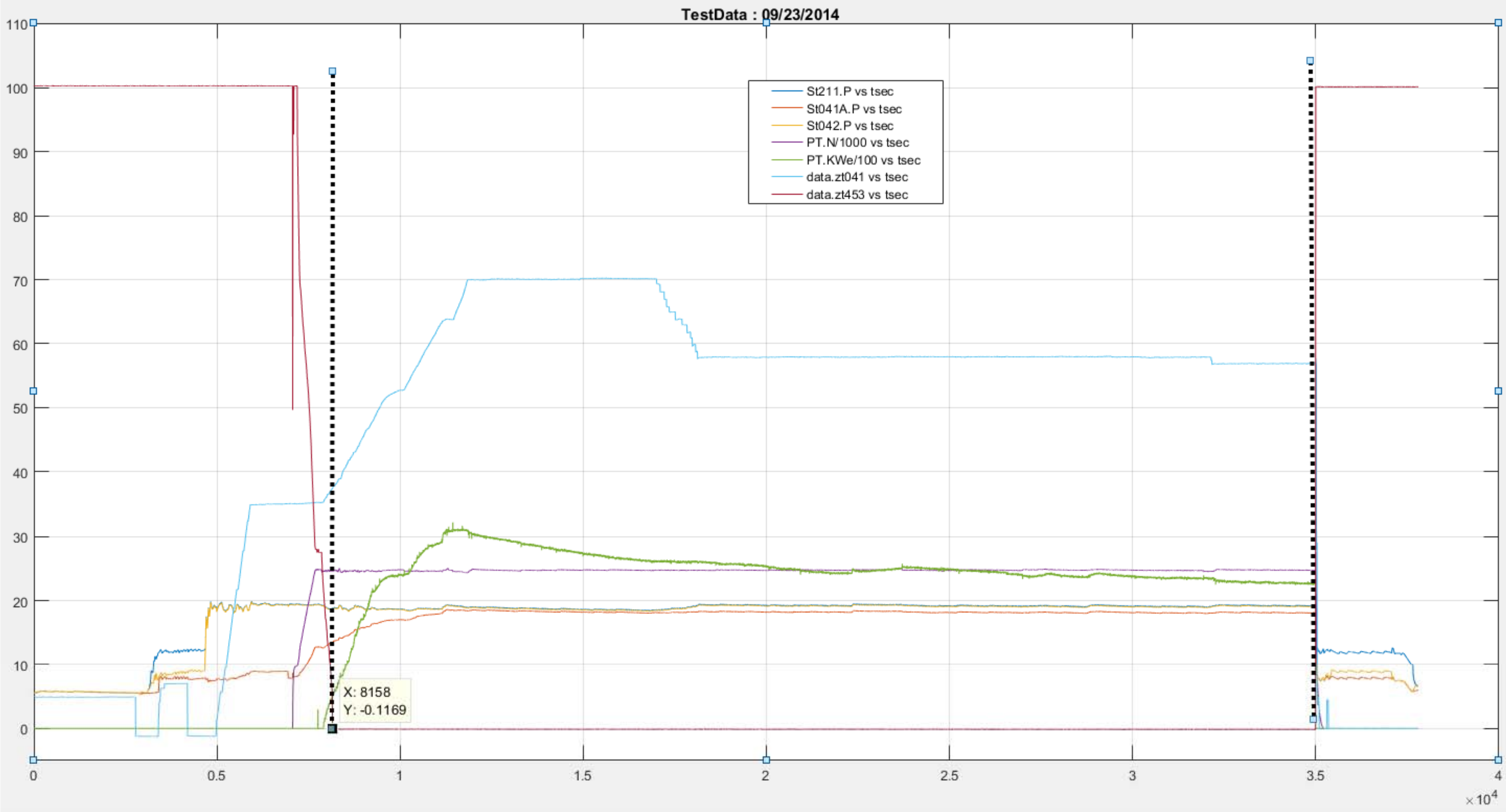
Boundary conditions:

- Cooling water flow rate & temperature
- Heat source input
- Generator load

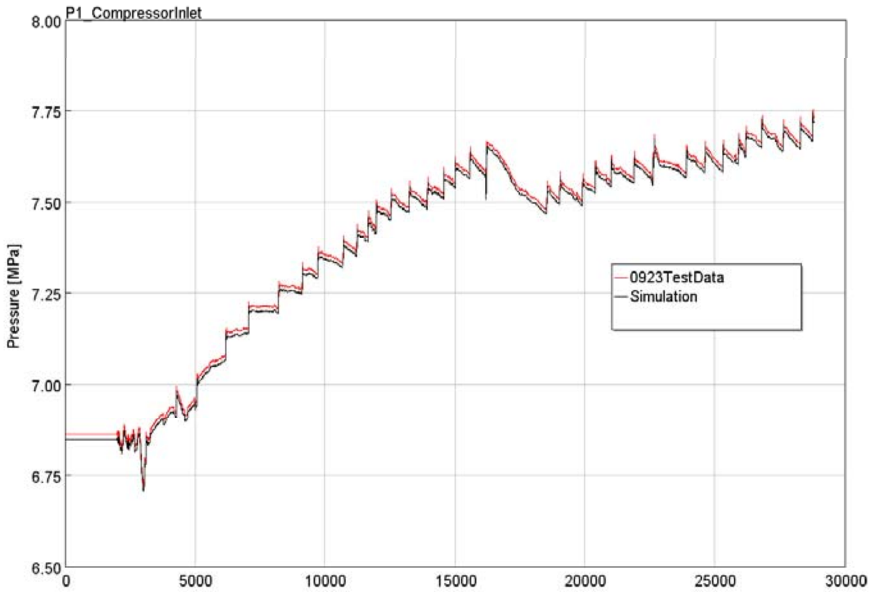
PID loop controls:

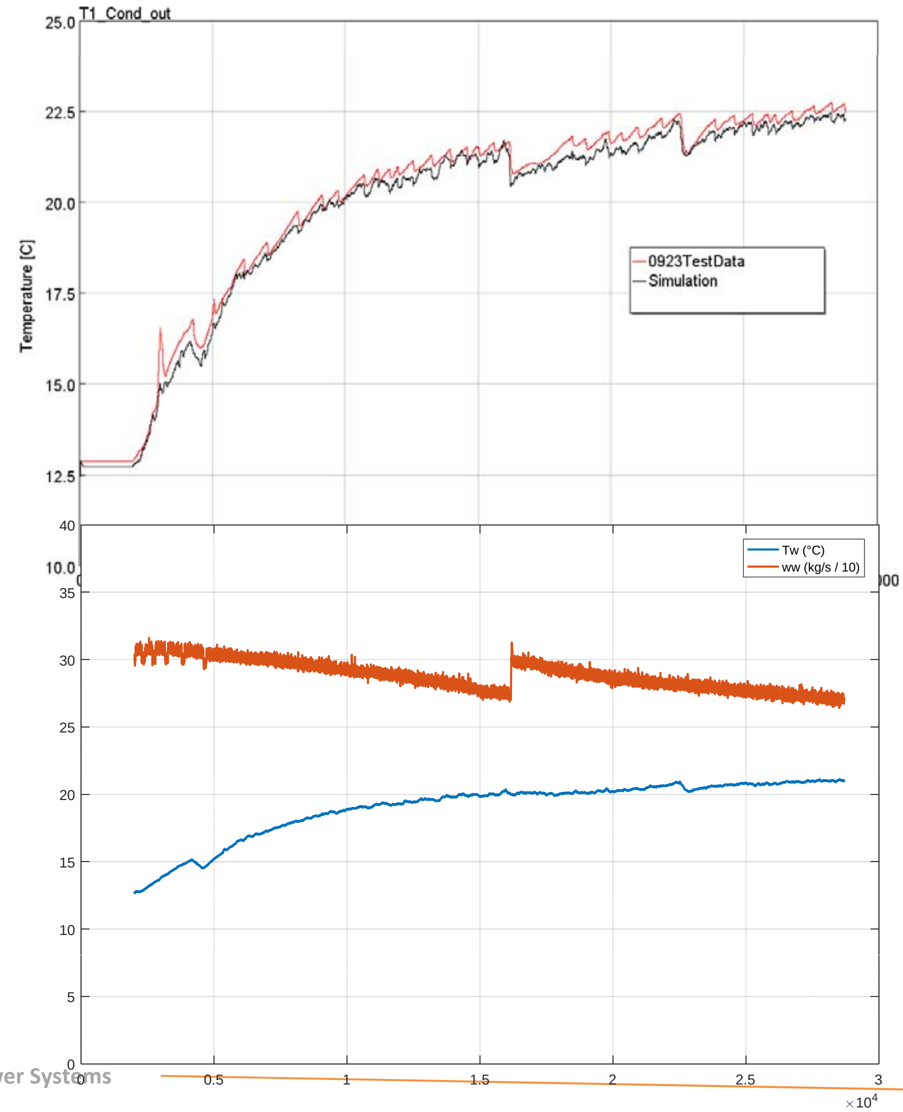
- Turbocompressor speed
- Power turbine speed
- Compressor inlet pressure

Test Data Considered for System Simulation



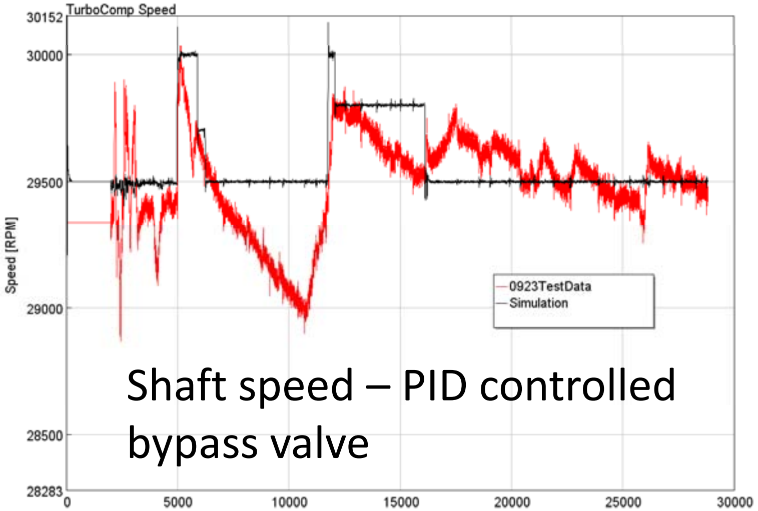
HRHX performance

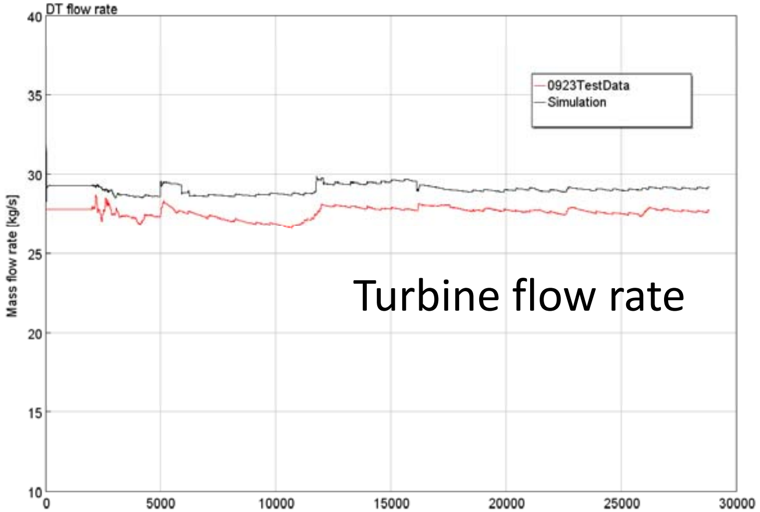


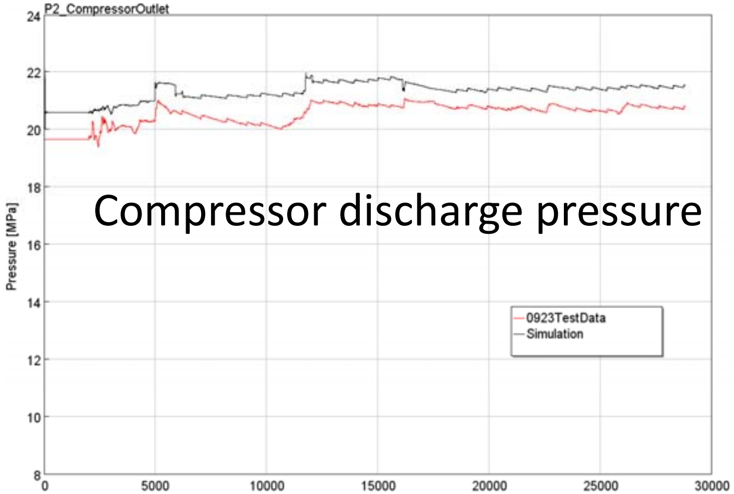


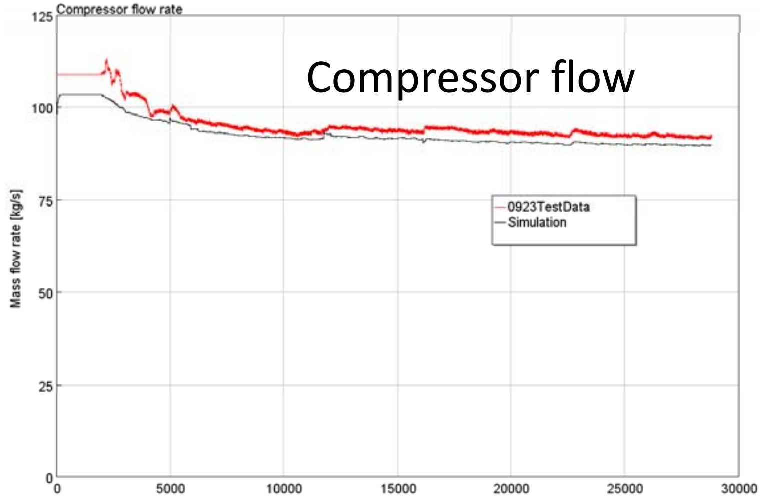
- Pressure controlled by inventory management
- Temperature varies based on cooler performance, water temperature and flow rate, CO_2 flow rate, temperature and pressure, etc.

Turbocompressor control & performance

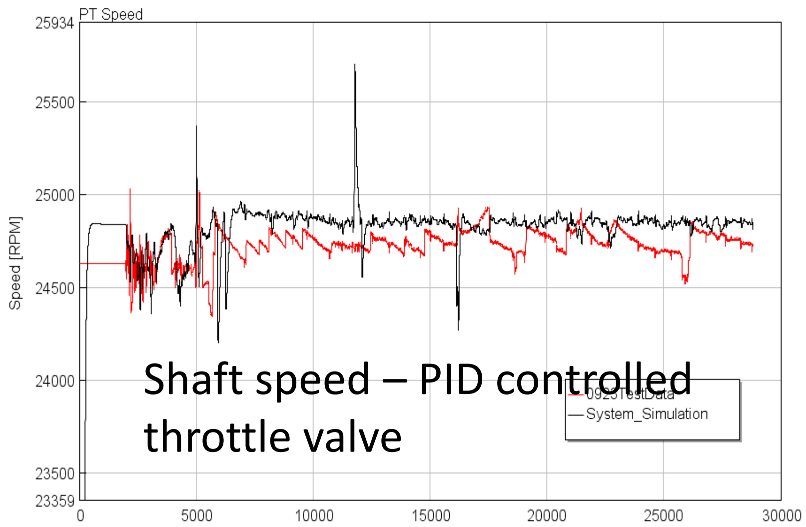


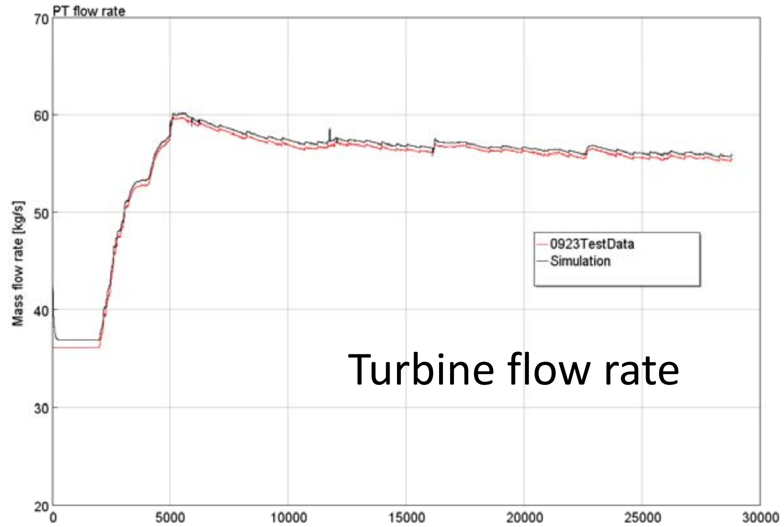


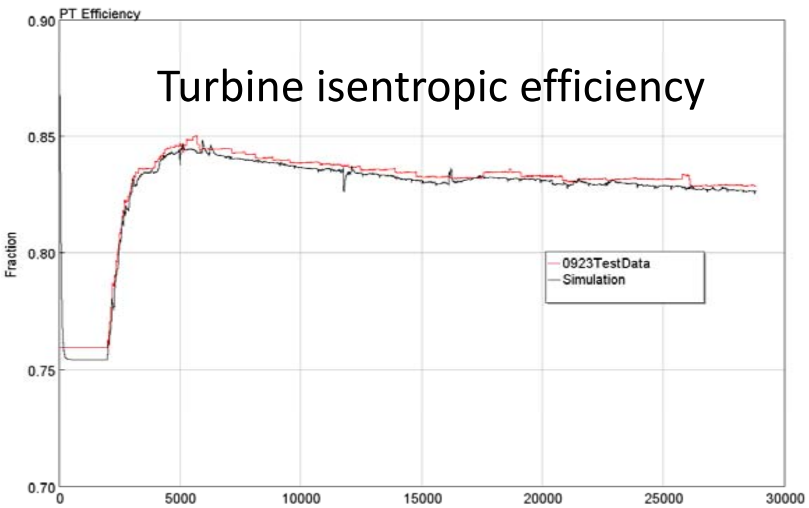




Power turbine control & performance





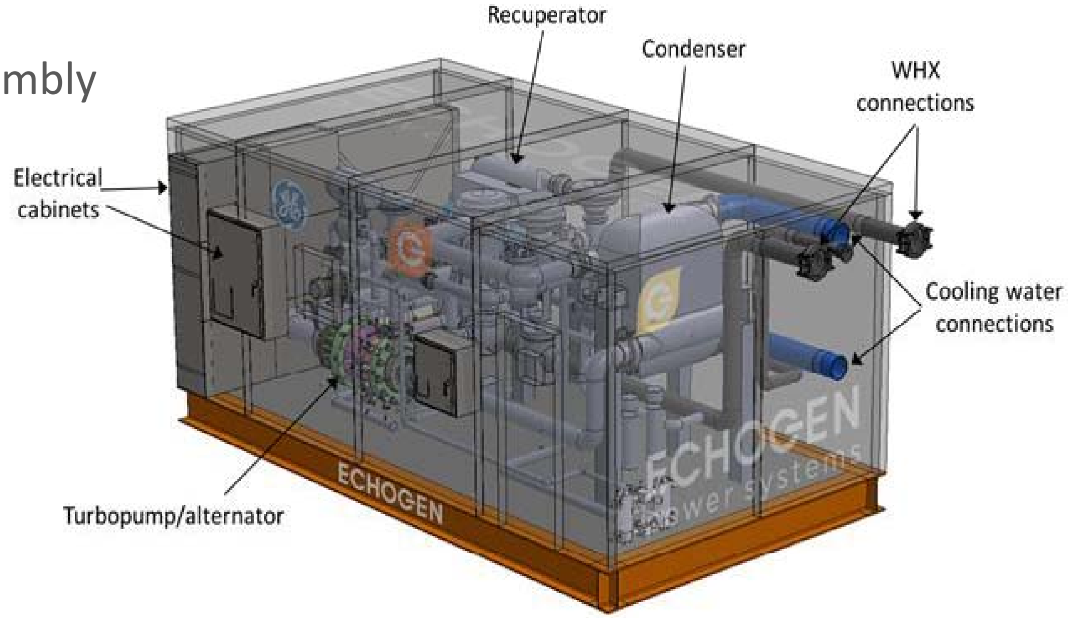


EPS100 Testing – Key Accomplishments

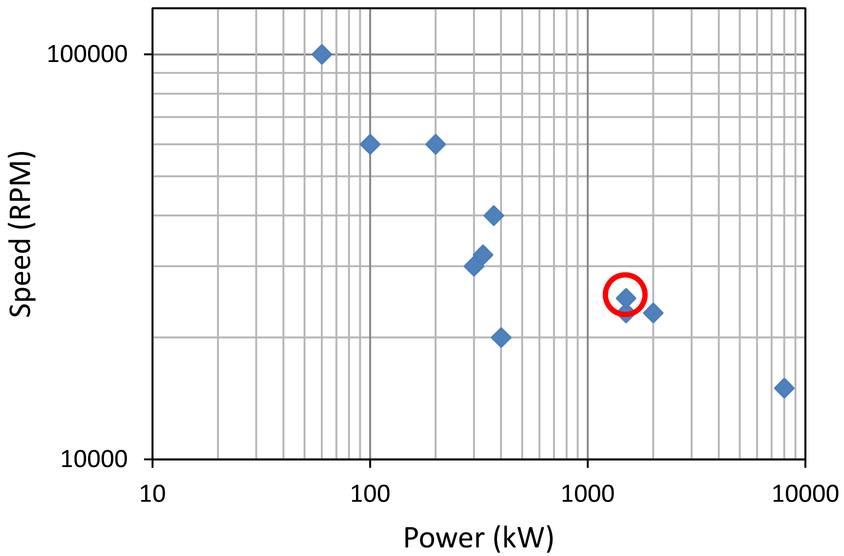
- System control and stability fully demonstrated
- Component performances meet or exceed expectations
- Turbocompressor run to max power (3.0 MW shaft)
- Generator speed control stability demonstrated
- Power turbine electrical output = 3.10 MWe
  - Limited by available heat on test stand
- 310 hours turbocompressor run time
- 151 hours power turbine run time

Echogen's EPS30 System

- Multi-platform solution currently in final design stage
  - 1.35 MW rated output (net)
  - Commercial availability late 2016
  - Compatible with medium-speed diesels and small gas turbines
- Builds on prior Echogen technology development
  - Single-shaft, dual-coil HX architecture
  - Advanced hermetically-sealed turbine/compr/alternator assembly
  - Water cooled (1,800 gpm)
  - 60 Hz, 480V output
- Designed for marine installations
  - Easily adapted for land-based applications as well
  - Can replace water cooling with air cooling
- Designed for remote operation and minimal maintenance

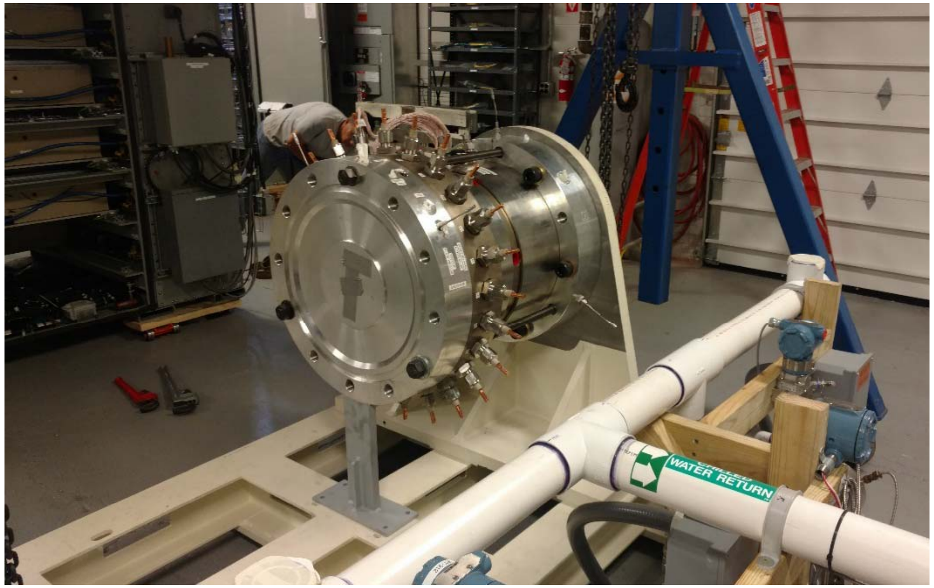


High speed alternator – EPS30M product



- Motor-generator test in preparation
- Full speed, full load
- Test of windage & cooling models

- 1500kW permanent magnet alternator
- 25,000 RPM
- Combination water-cooled stator, CO_2 cooled rotor & stator



Summary

- sCO_2 offers significant advantages in numerous heat conversion applications
  - Waste/Exhaust heat technology offers a path to technology introduction in a market that is available today
  - Primary power opportunities limited at small scale, but can offer path to utility-scale
- Echogen sCO_2 heat engine technology delivering on the predicted system performance
- Test program provided key learnings, and insight into the challenges and opportunities of sCO_2 technology
  - Current test facility limited operational envelope
  - Working toward full power demonstration facility
- On the path to commercialization