# Initial Test Results of a Megawatt-Class Supercritical $CO_2$ Heat Engine

Timothy J. Held

ECHOGEN
power systems

# Exhaust & waste heat recovery

- Covers broad range of potential application (size, temperature, "special circumstances")
  - Gas turbine exhaust – 450-600°C, accessible thermal energy from 100-200% of GT output
  - Recip engines – 250-450°C, ~ 40-70% of engine output
  - Steel, cement, glass, other industrials > 300°C, size widely variable, often contain condensable / corrosive materials

- $sCO_2$ cycles offer several key advantages
  - Power output comparable to steam systems at lower cost, smaller footprint
  - Direct in-stack heat transfer (no thermal loop), single-phase
  - Fluid is low-cost, widely available, low toxicity, thermally stable and generally non-corrosive below ~ 550°C

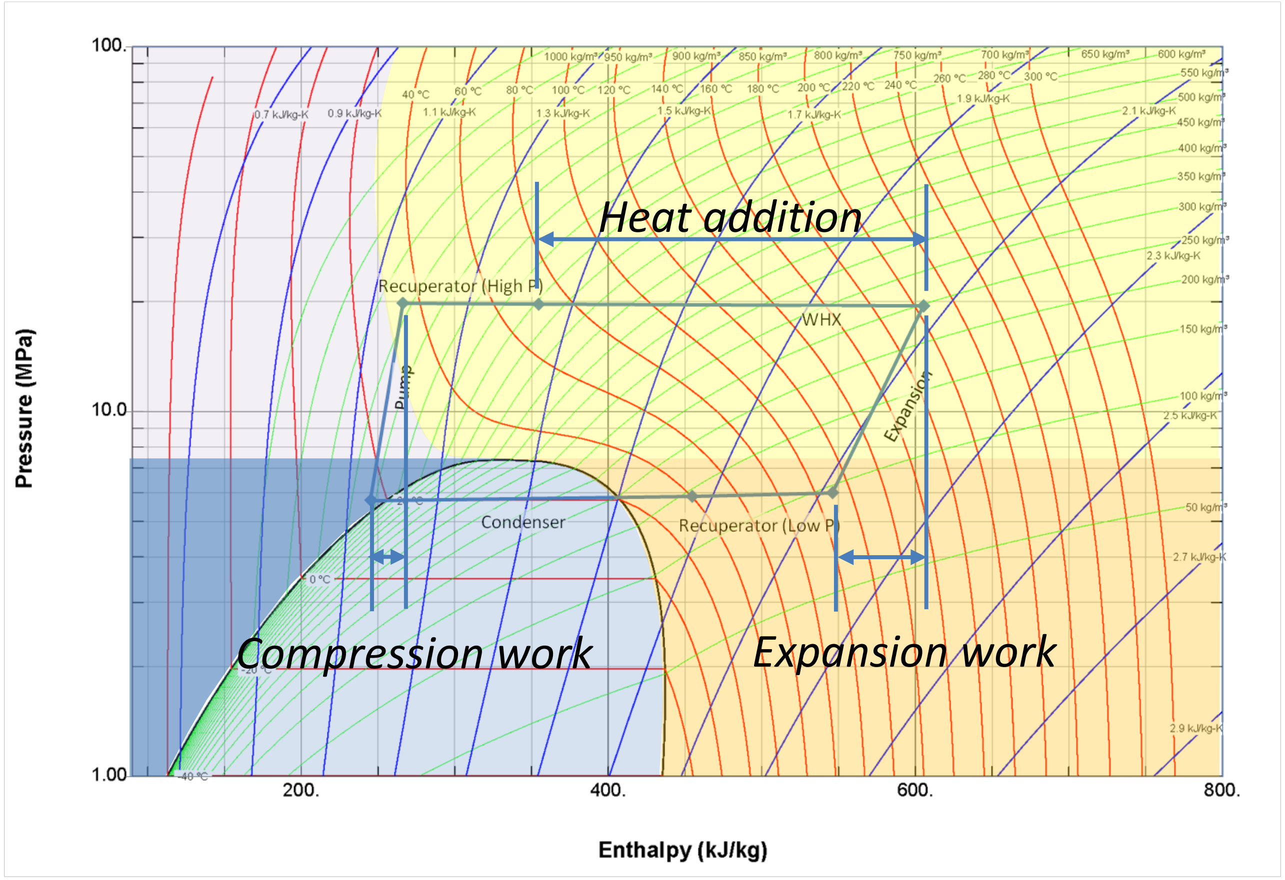
# EPS100 - description

- Waste heat recovery system
- Targeted to ~ 20-25MW gas turbine exhaust or equivalent (500-600°C, 60-75kg/s)
- Sized for $T_4$ ~ 450°C, 100kg/s total $CO_2$ flow rate
- Process skid = heat exchangers, controls, turbopump
- Power skid = Power turbine, gearbox & generator
- $CO_2$ service systems = Storage tank, transfer pump and auxiliaries

# The EPS100

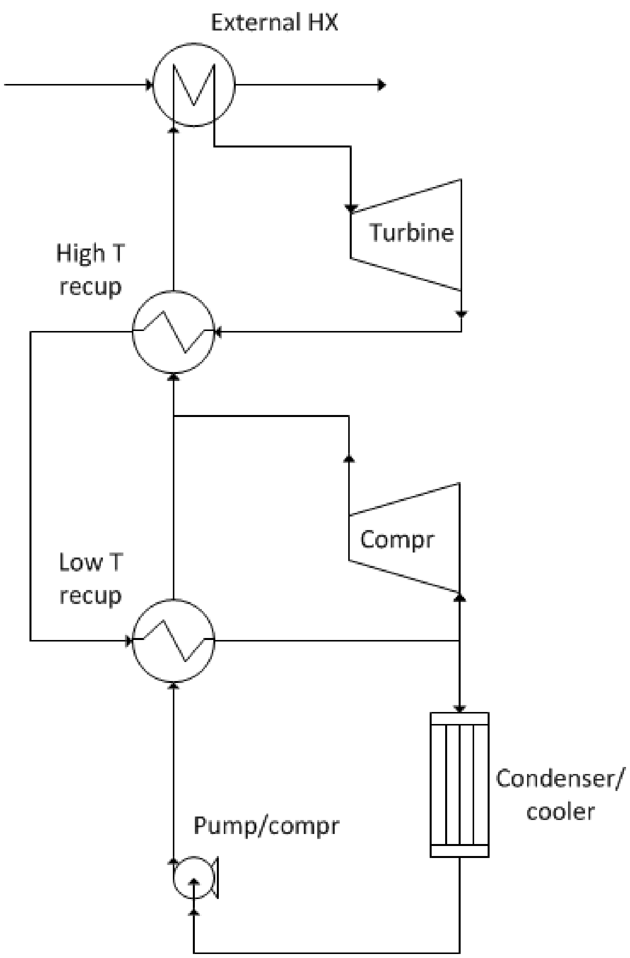
- Designed for GE LM2500 exhaust
  - 8 MW gross, 7.3 MW net
- Physical Configuration
  - Process Skid (right)
  - Power Skid (above)
  - MCC
  - CO2 storage tank and transfer system
  - Cooling system, air or water

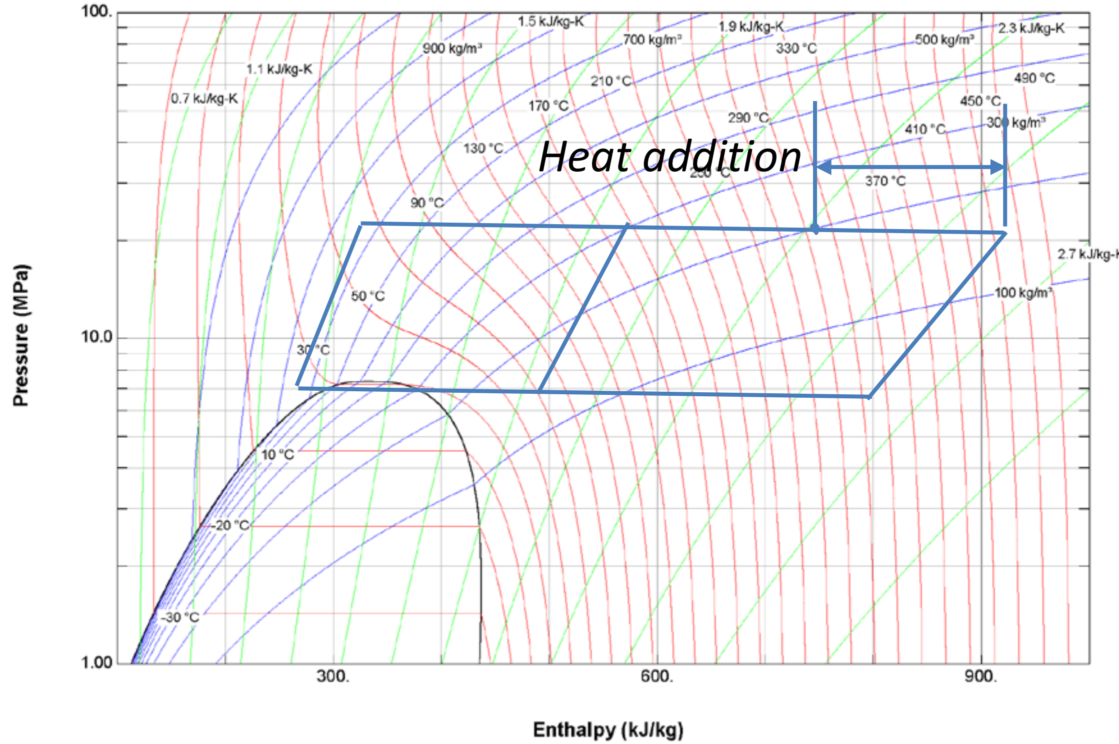
# Cycle architectures - Simple recuperated




*Low pressure ratio cycle => recuperation => can limit ΔT of heat addition*

# Cycle architectures – Recompression

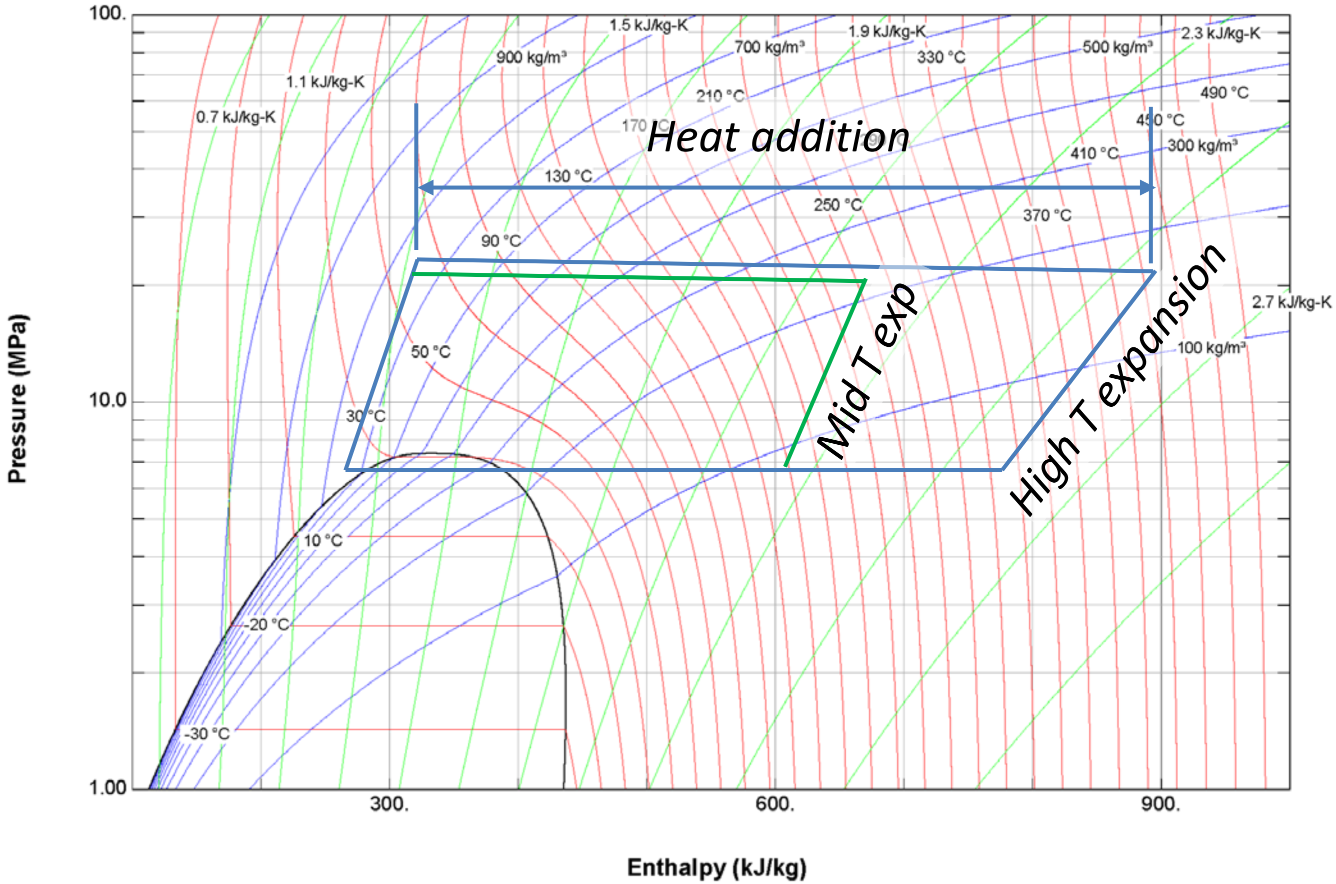



*Recompression cycle designed for low ΔT*

*Not a good solution for WHR*

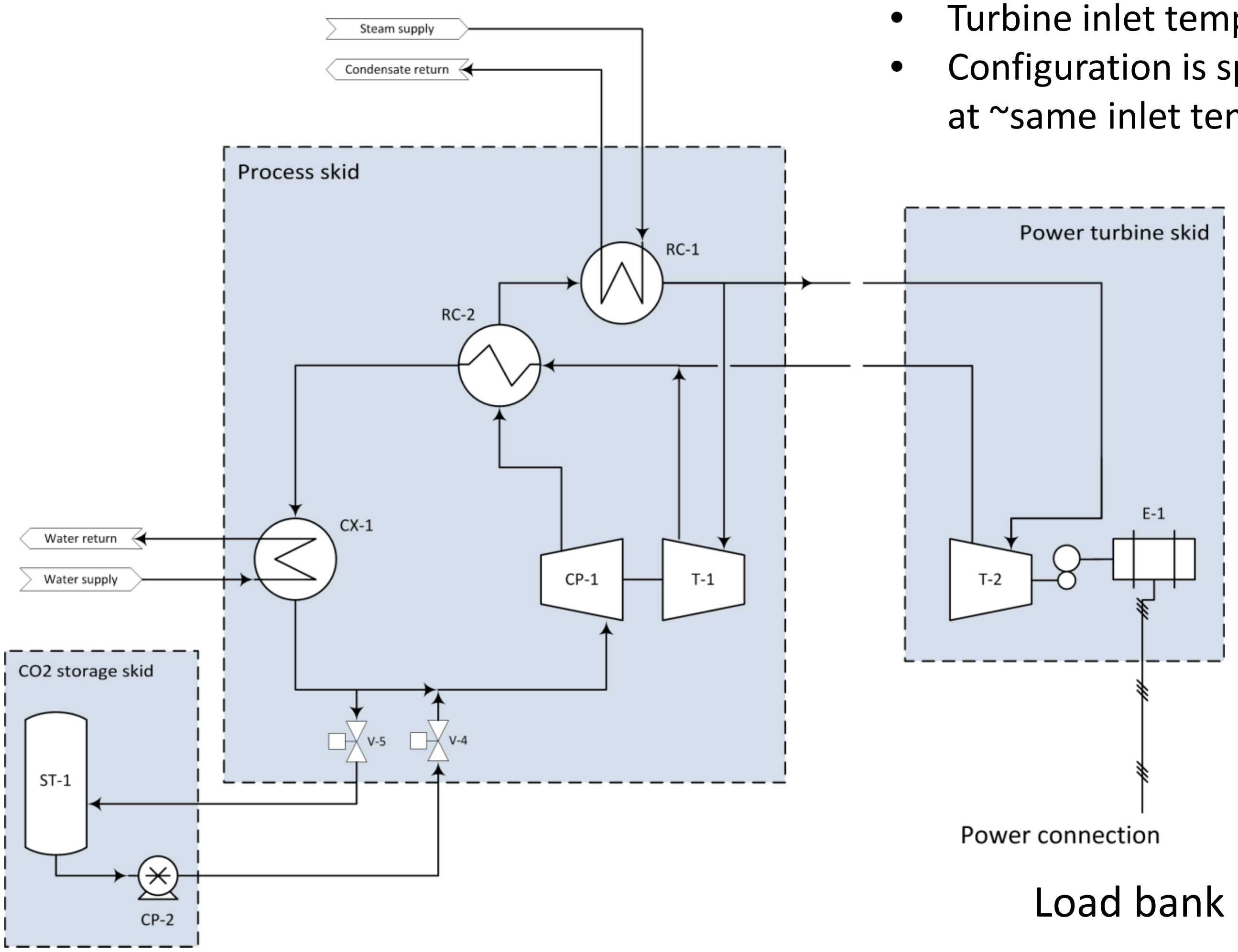
# Cycle architectures - WHR




*Multiple stages of heat transfer and expansion used to maximize power output for a given heat source $mc_p\Delta T$*

# Test configuration at Dresser-Rand

- Facility steam used as heat source
- Turbine inlet temperature is limited to ~ 270°C
- Configuration is split recuperated – both turbines at ~same inlet temperature




Load bank

# EPS100 Test Program

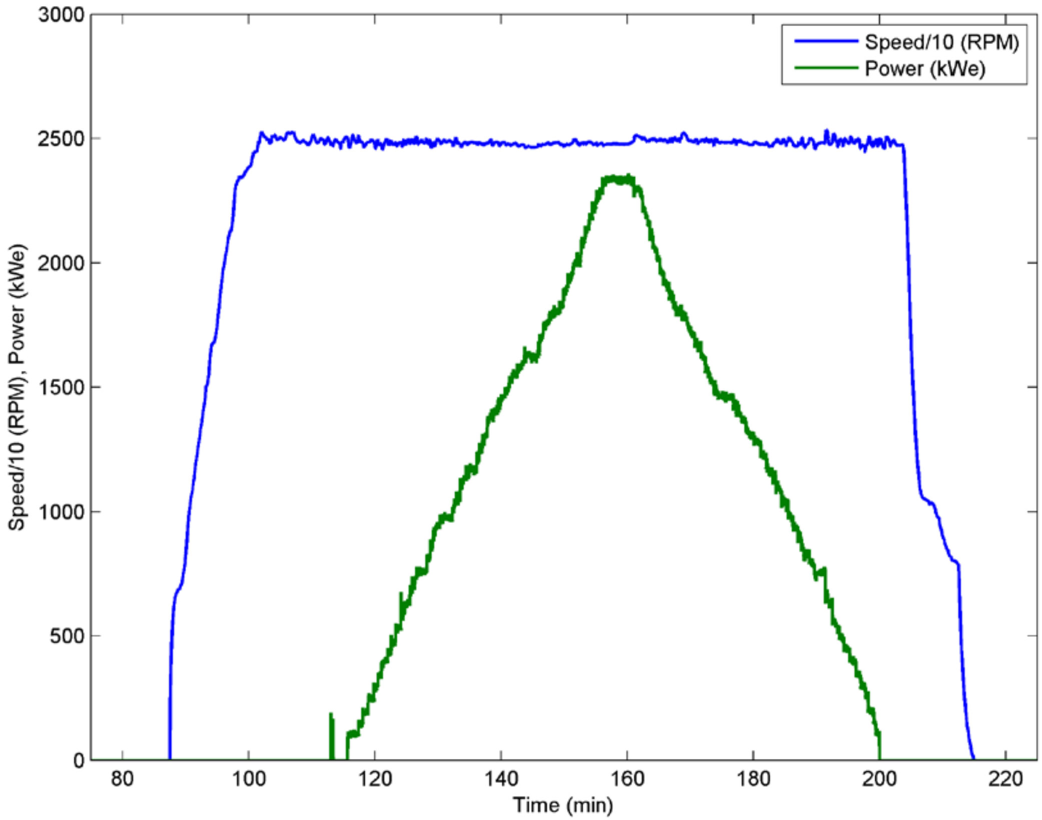
- Multi-phase test program (✓=complete):
  - ✓Phase 1: Process Skid
    - ✓Validation of components and controls
  - ✓Phase 2: Power Skid
    - ✓Full speed no load testing of powertrain
    - ✓Demonstration of ability to synchronize to the grid
  - ✓Phase 3: Process Skid Durability
    - ✓Validate operation at operating extremes
  - Phase 4: Endurance Testing at Part-Load
    - Run to facility limits
    - Ongoing

# EPS100 testing at Dresser-Rand


## Key accomplishments

- Completed Phases I-III of testing
- System control and stability fully demonstrated
- Component performances meet or exceed expectations
- Turbopump run to max conditions
- Generator speed control stability demonstrated
- Power turbine electrical output = 2.35MWe max to date
- 218 hours turbopump run time
- 68 hours power turbine run time

# PT power and speed summary

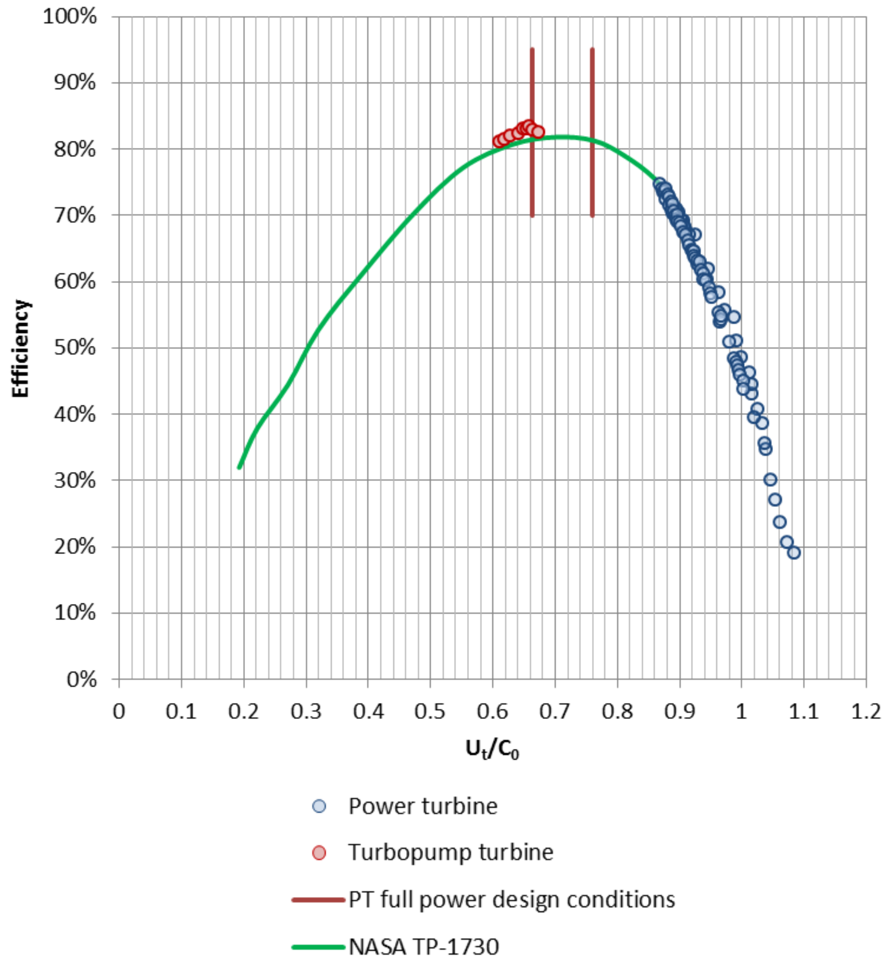



- Running in “island mode” due to load banks
- Speed and load ramp rates improving as controls refined

# PT max power run

# Turbomachinery Validation

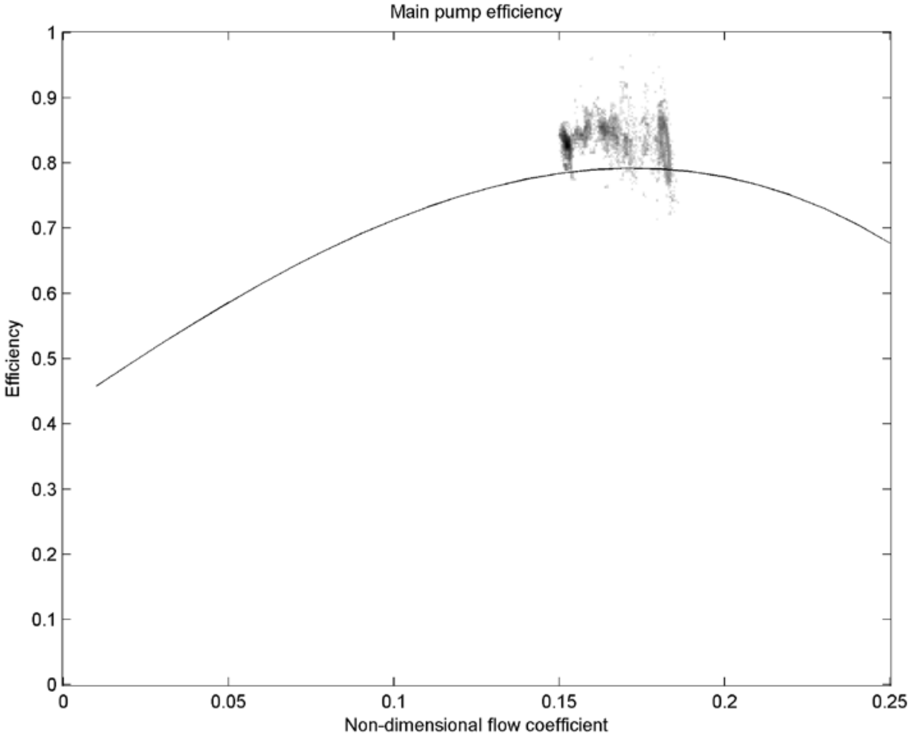
- Power turbine and turbopump efficiencies demonstrate excellent agreement with reference curve derived by NASA.
- Turbopump test data represent operation near full power
- Power turbine data represent significantly off-design conditions of the test cycle configuration. At full power conditions efficiency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




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

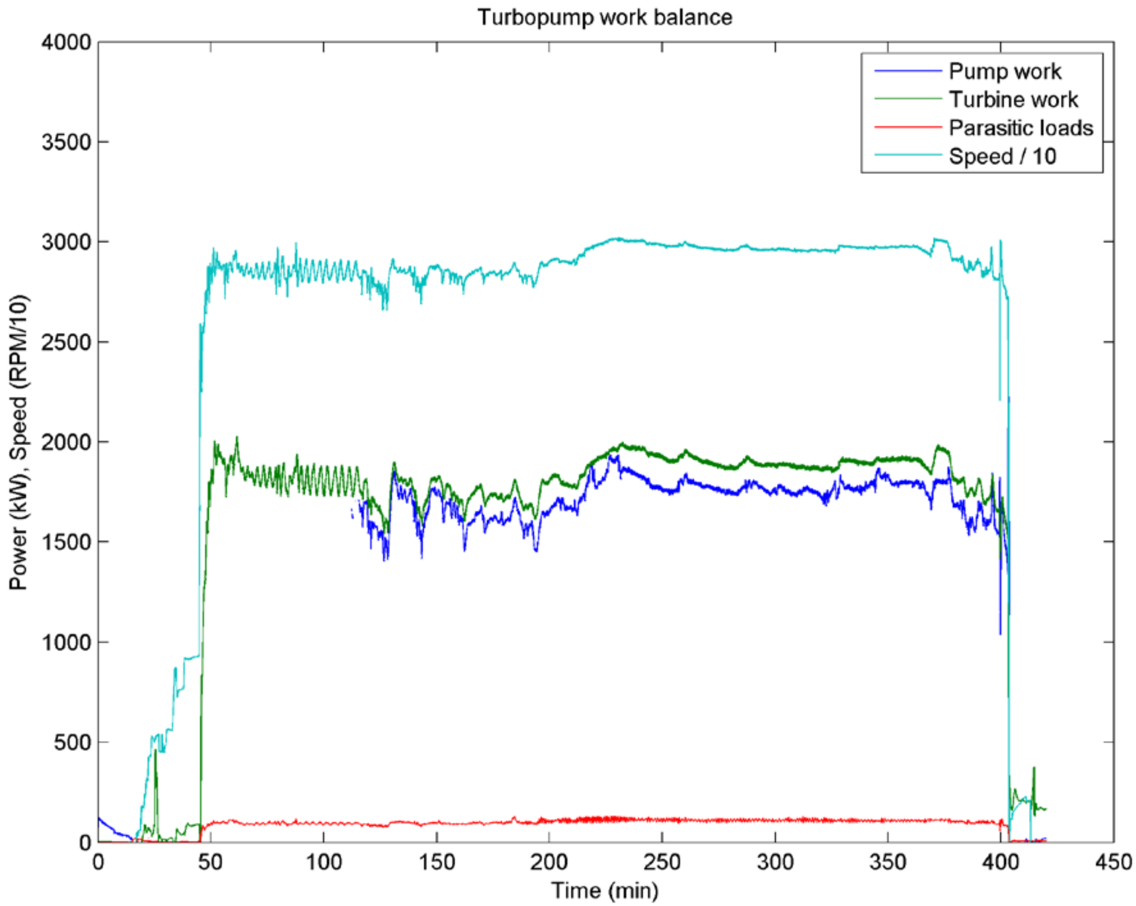
# Turbopump Validation

- Measured pump efficiency is somewhat higher than predicted value.




Measured pump efficiency vs flow coefficient. Note that this is a "cloud plot" of the density of approximately 25,000 data points - the gray scale indicates the density of data points that fall within a given x,y coordinate set.

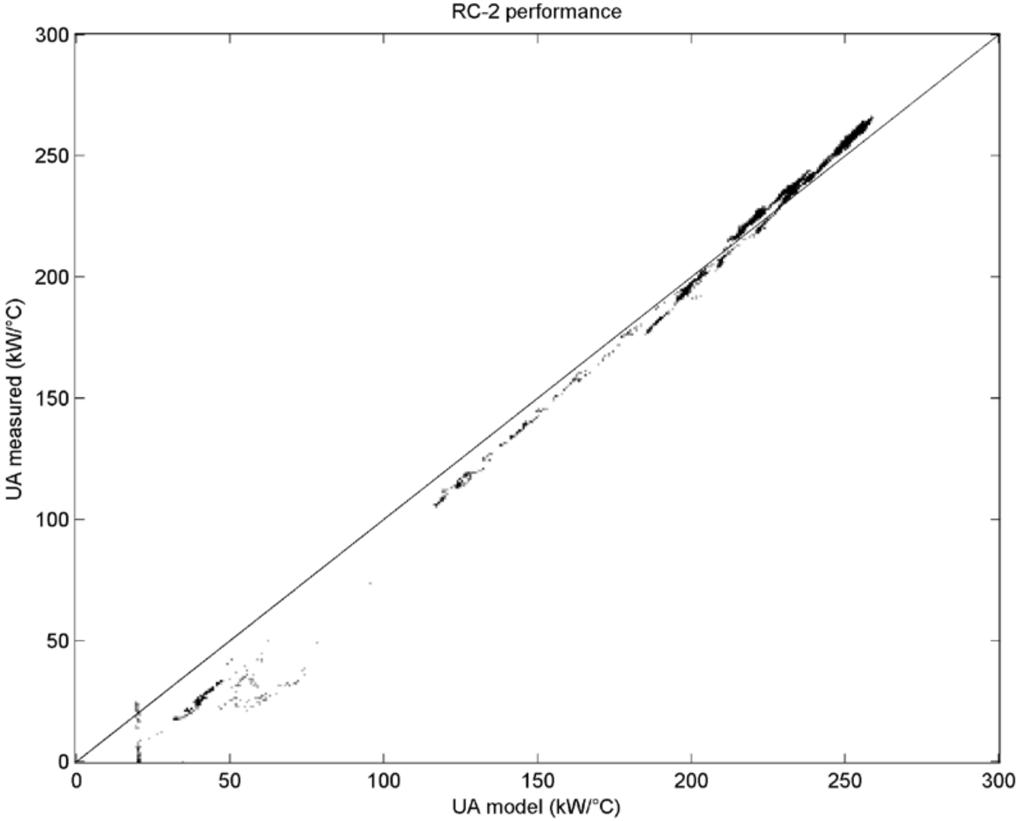
# Turbopump work balance




- Difference between pump and turbine work equals expected bearing and heat losses

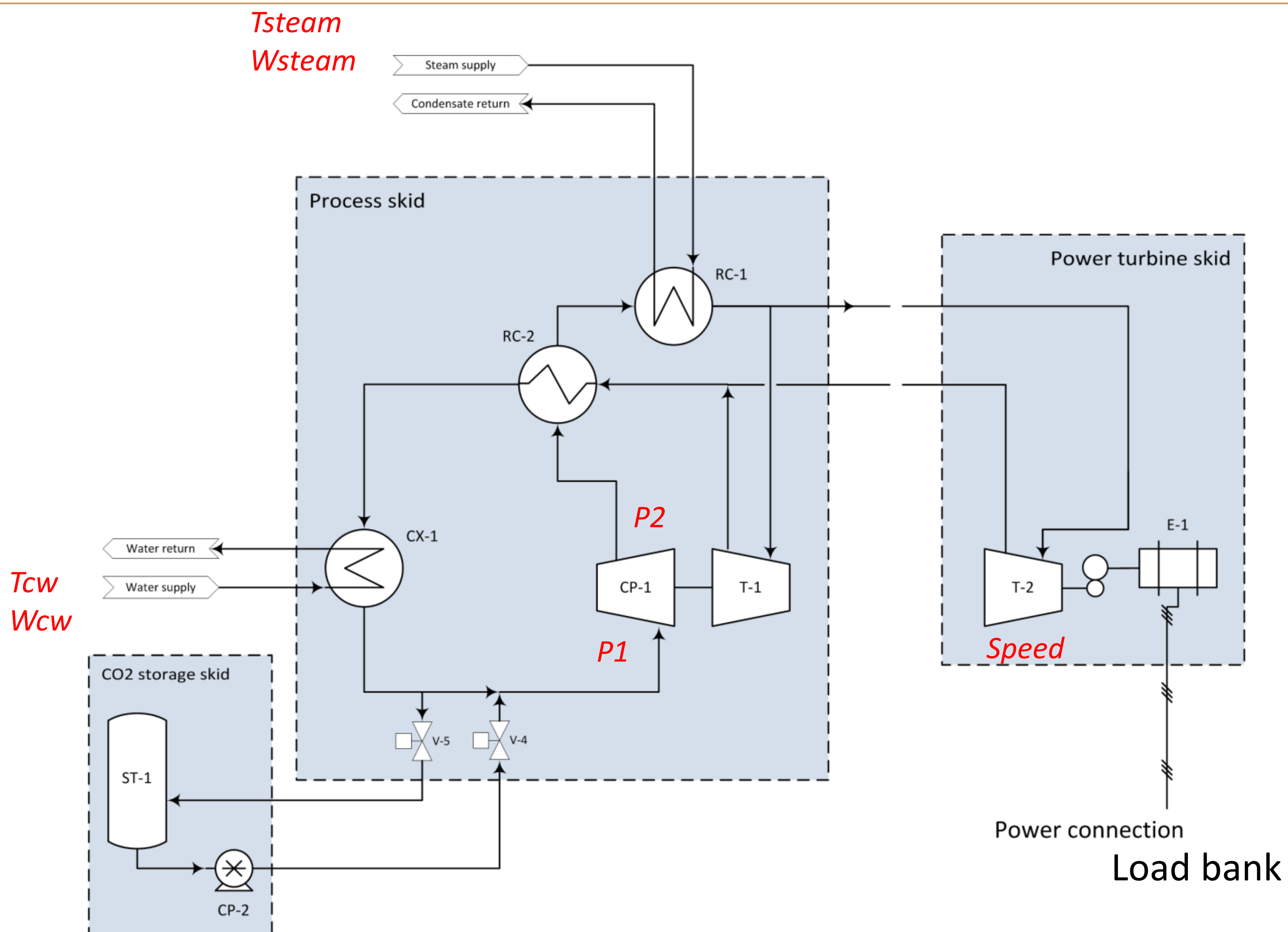
# Heat Exchanger Validation

- Discretized heat exchanger model
  - Geometric details inferred from design point performance
  - Scaling to other conditions based on detailed heat transfer model
- Good agreement between model and data over a broad range of operating conditions.



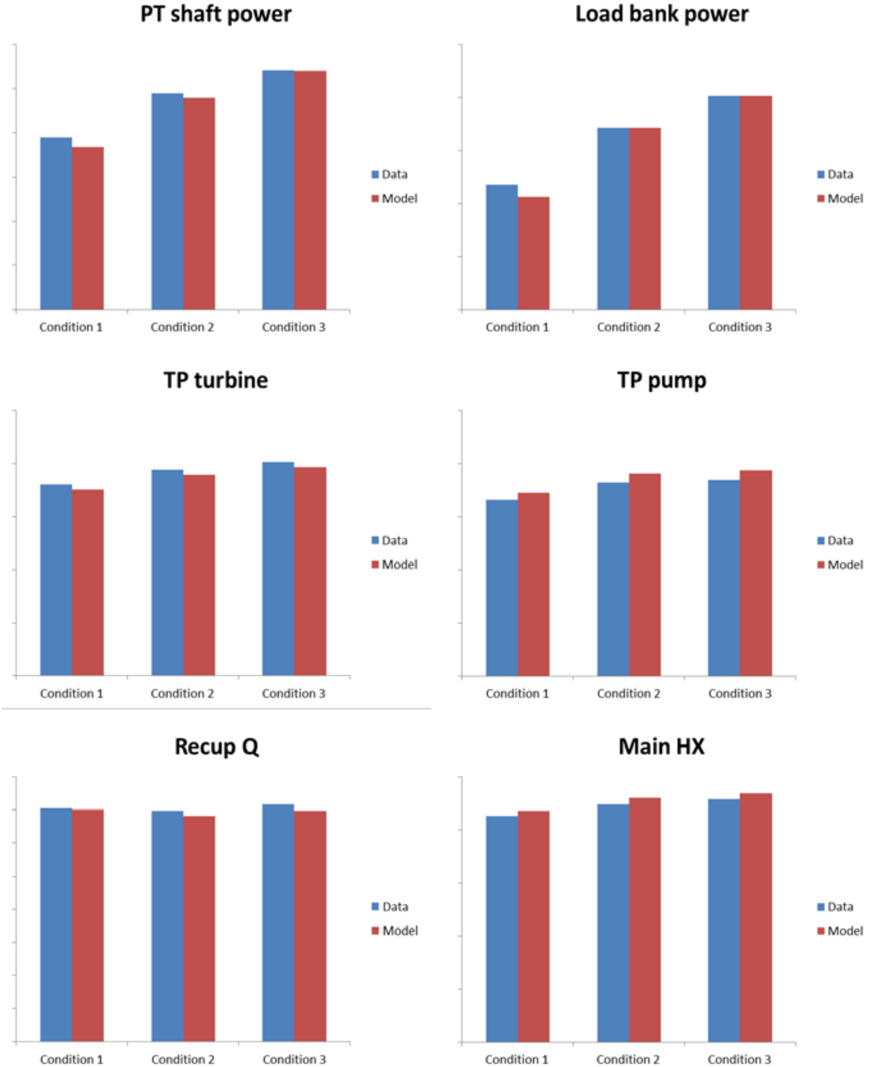

Cloud plot of recuperator (RC-2) performance, actual vs predicted.

# Test configuration



# Heat and Mass Balance Cycle Model

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



# EPS100 test program

- First commercial-scale $sCO_2$ heat engine operational in test environment
- Completed baseline performance and controls testing
- Component and system performance meets expectations, cycle model validated
- Endurance testing in process, will be followed by detailed system inspection