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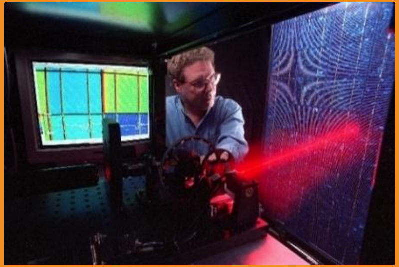


Goals of the workshop and targets for sCO2 power cycle integration with thermal energy storage

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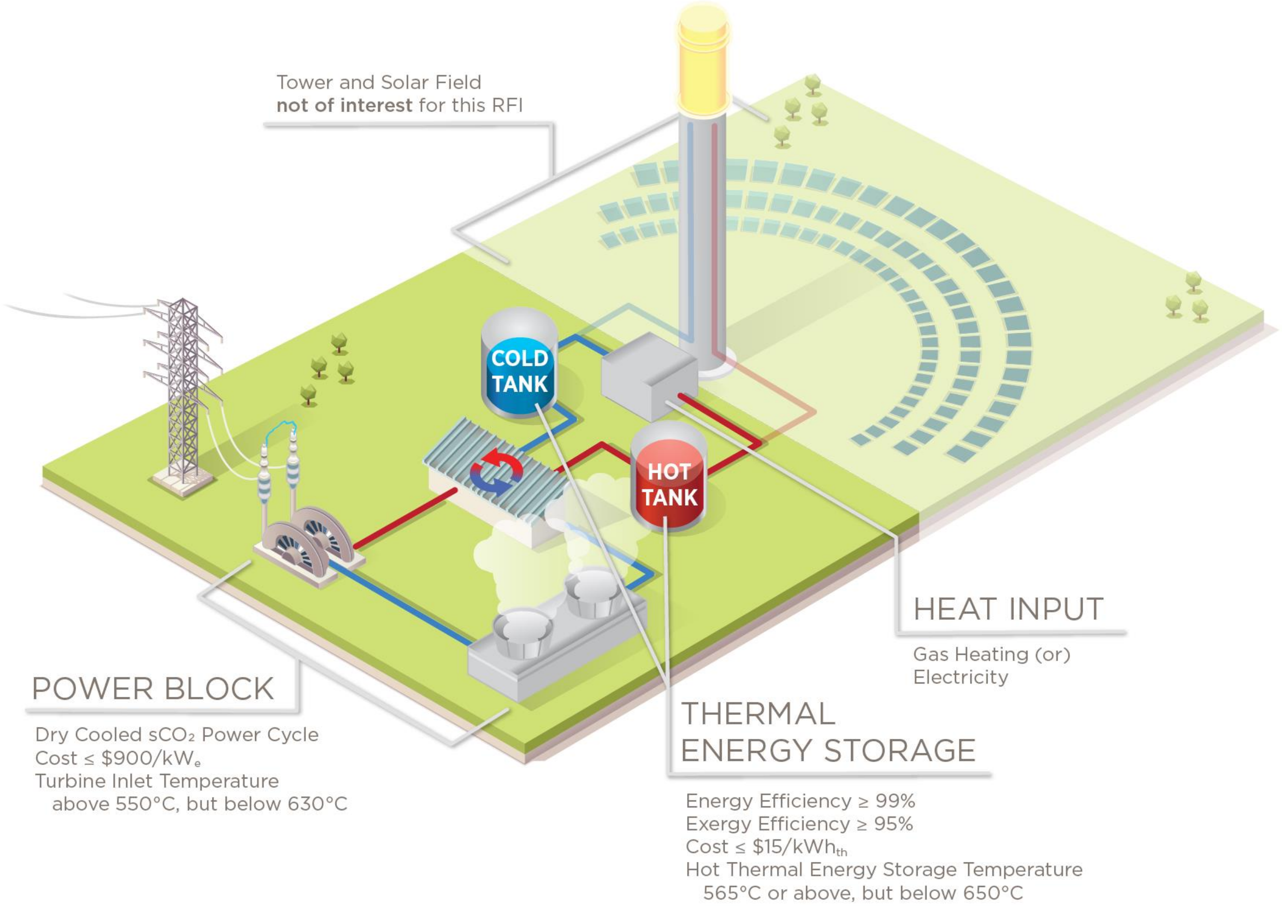
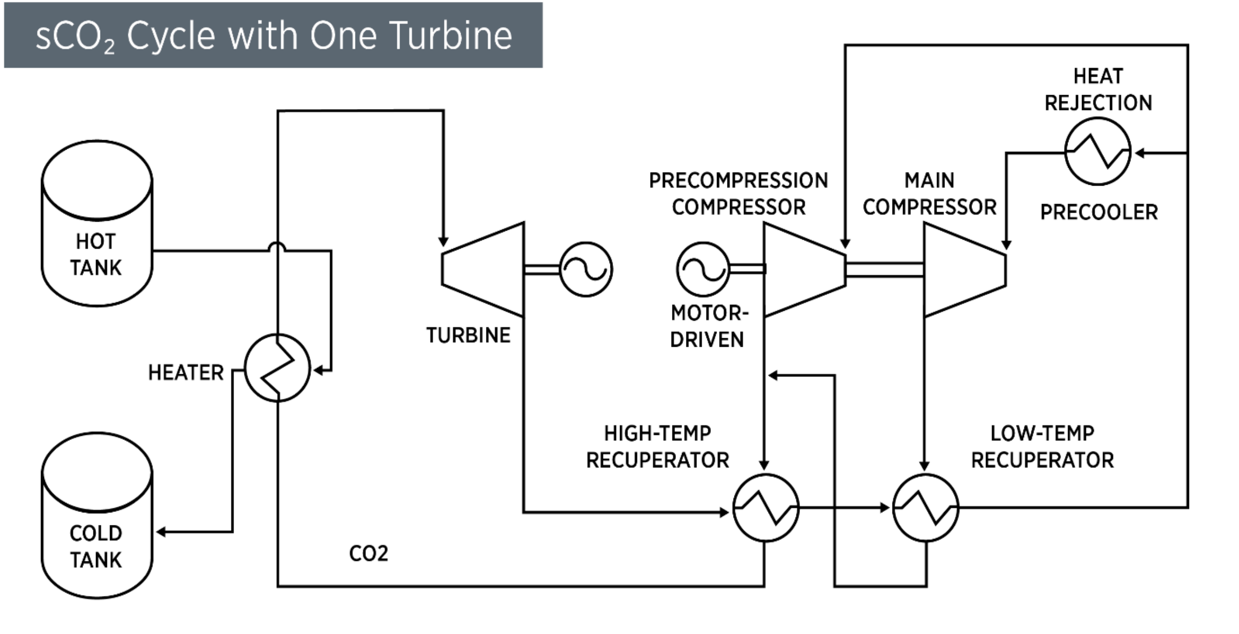
USDOE sCO_2 Workshop 2019

October 31, 2019

Focus: sCO_2 Power Block Integrated with TES



Example Power Block: RCBC



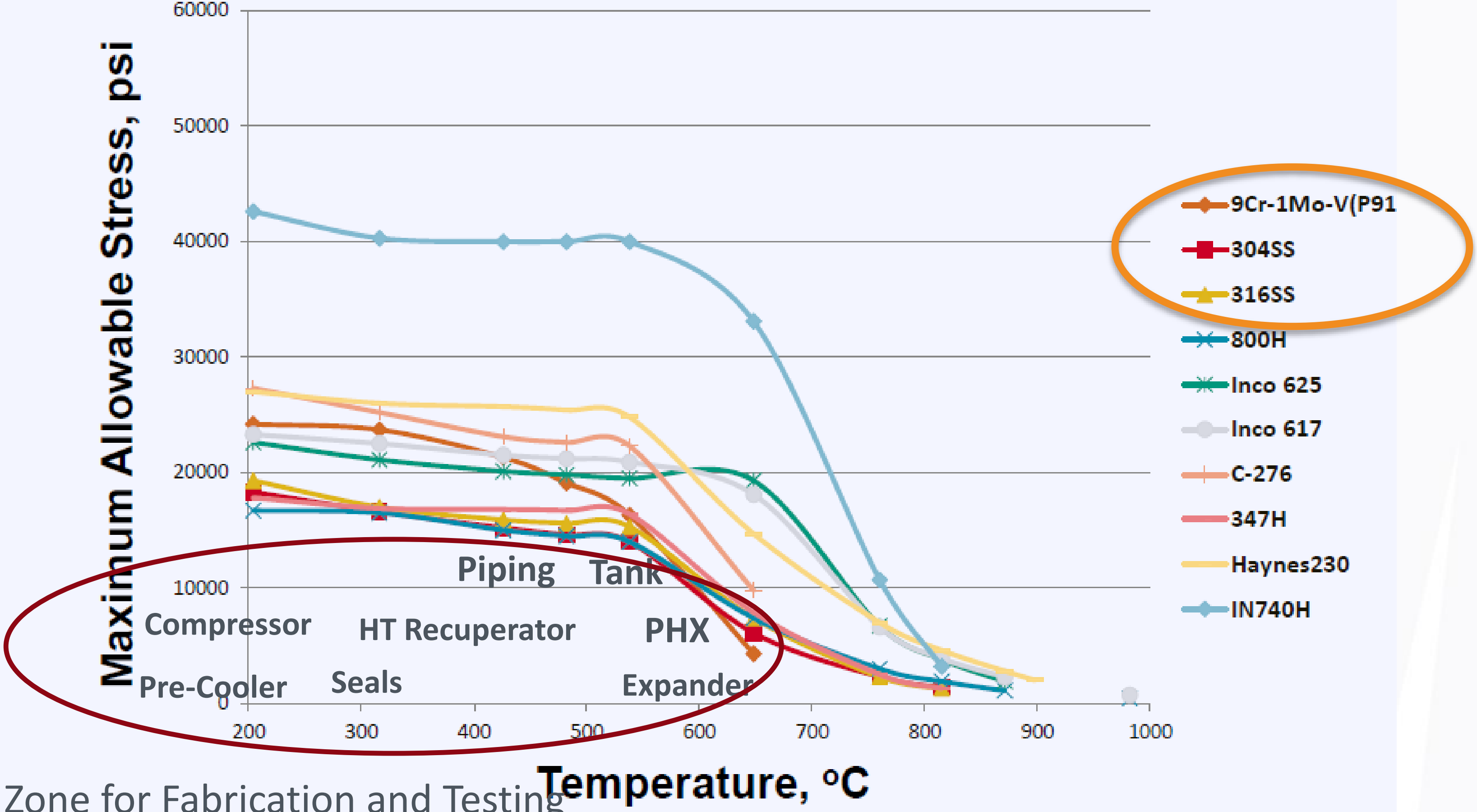
Commercialization Pathway for sCO2 Power Cycle

- Make Utility Operators Comfortable with sCO2 Power Block Integration with TES
  - TES is a Critical Feature that Decouples Energy Collection from Discharge to Grid, but no Operational Experience
  - Need to Gain Experience by Operating at Temperatures of Today's Plants
  - Overcome Operator O&M Concerns by developing an Integrated Power Block and Robust Control Strategy

sCO_2 Integration with Power Plants: Materials Issues

- While Working on 700°C, in order to gain experience:
  - Target TIT down to 550°C - 620°C (Piping not high-nickel alloy)
  - Materials for Piping, tanks, ready, available and not very costly
  - For turbomachinery, easier casing, impeller and seal design and fabrication
  - Focus on integrated operation of turbomachinery/heat exchangers and TES for ≥1,000 hours; utility operators comfort
  - Interaction of Materials, Temperature and SubComponent Design still to be resolved

Allowable Material Stress vs. Temperature



Comfort Zone for Fabrication and Testing

2010 ASME Boiler Pressure Vessel Code, Sec. II, from Tables 1A and 1B, July 1, 2010, New York, NY (compiled by Mark Anderson)

Thermal Energy Storage Fluid

- Current generation plants use Nitrates as TES
- 60-40 $NaNO_3/KNO_3$; not an eutectic
- Liquidus = 222°C
- Temperature Limit ~600°C
- Low Vapor Pressure
- Reasonable Specific Heat (1.545 kJ/kg°C) and Density (>1,700 kg/m^3)
- GEN3: Chloride Salt and Solid Particles for 700°C

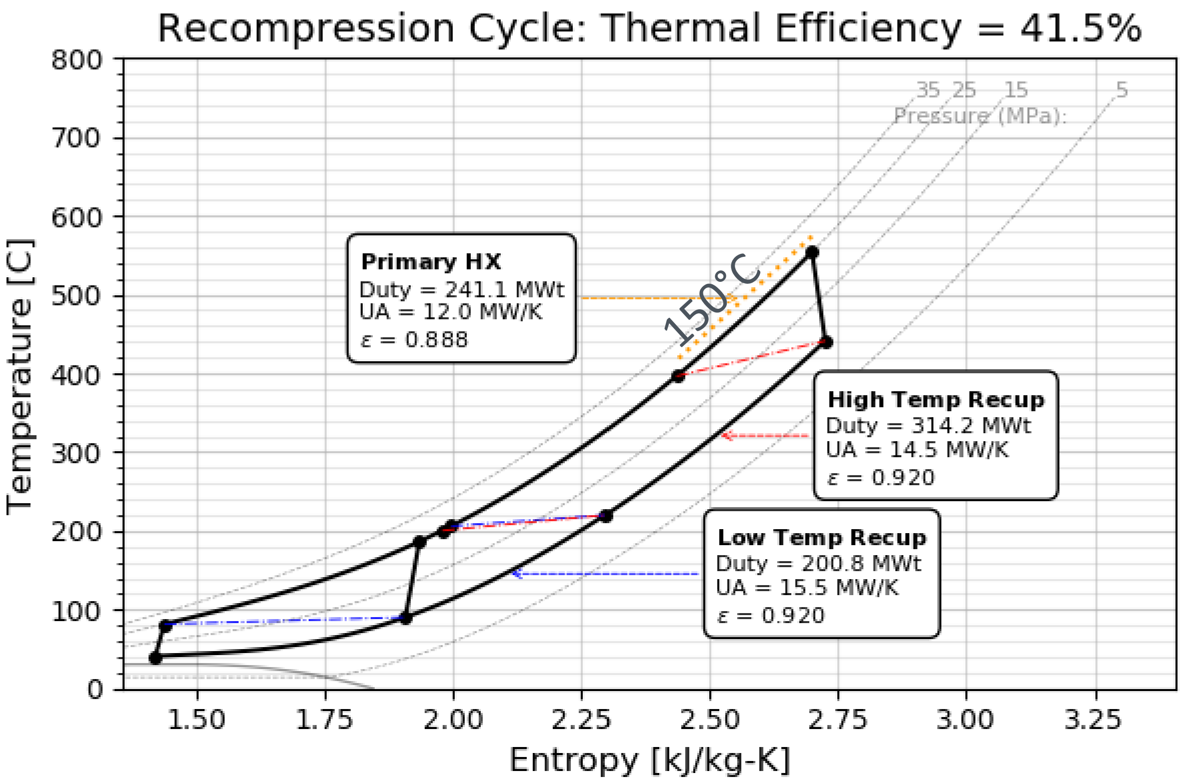
TES Tank Design for Nitrate Salt

- Similar for Parabolic Trough and Power Tower
- General Dimensions 120'(D) X 40'(H)
- getting bigger (Noor 153' X 46') ~18,000 m^3; 2,700 MWt
- Limits on H & D Set by Soil Bearing Load (for H) and by 1.5" thickness for Steel Plates, no Heat Treat (for D)
- Bruce counts 82 Tanks built so far
- 290°C Carbon Steel Cold Tank and 565°C Stainless Steel Hot Tank Operating Temperatures

Primary Heat Exchanger

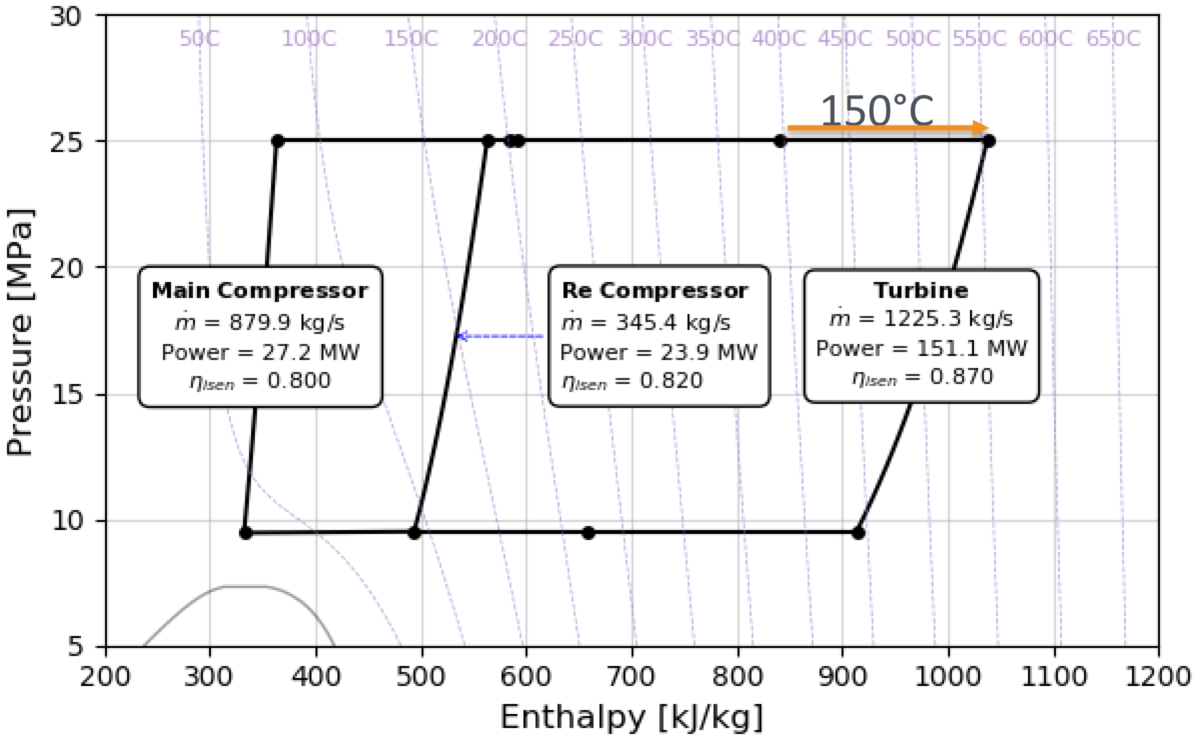
- Specific Requirement for CSP: Molten Salt->sCO_2
- Approach Temperatures of 15-20°C Indicated
- For ~250 MWT, Shell and Tube Heat Exchangers can be quite expensive
- MicroChannel Heat Exchangers Have Not been Developed to Even Facility Scale
- Differences Between Molten Salt and sCO_2 Channels for Pressure, Thermal Conductivity.

Major Issue for sCO_2 Power Block Integration with TES



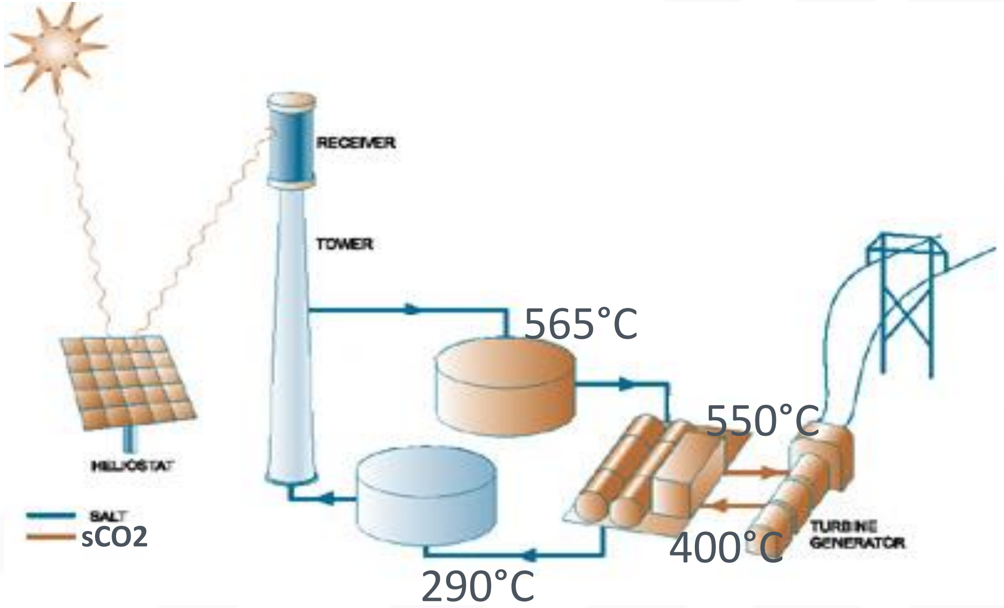
T-S Cycle Plot for Turbine Inlet temperature = 550 C

Major Issue for sCO_2 Power Block Integration with TES



P-h Cycle Plot for Turbine Inlet temperature = 550 C

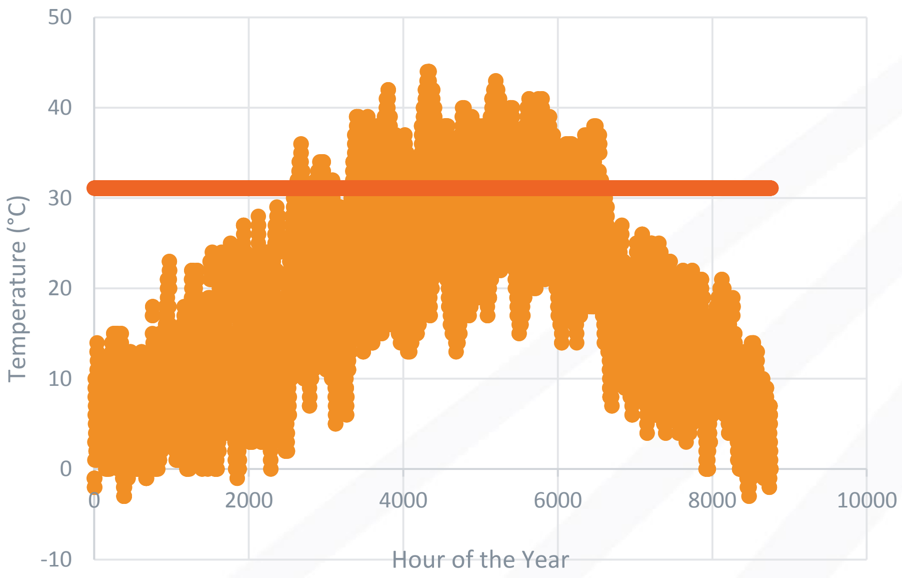
Major Issue for sCO_2 Power Block Integration with TES



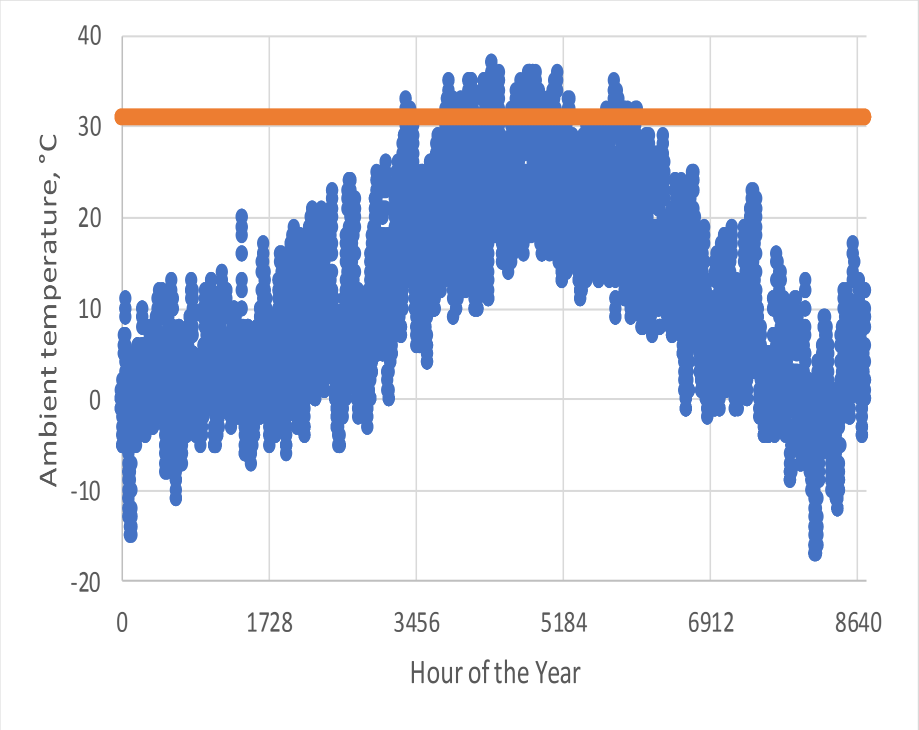
Mismatch between ΔT for TES and Optimized ΔT for sCO2 Cycle

Ambient Air Temperatures at Representative CSP Sites

- Dagget, CA



- Denver, CO

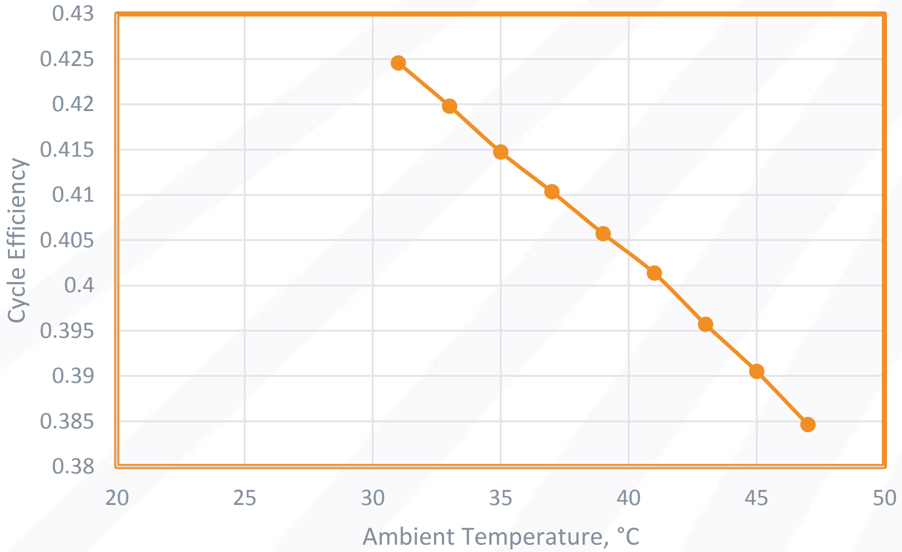


Operating sCO_2 Cycles with Air Coolers

- Ambient Temperature + PreCooler Design Sets Compressor Inlet Temperatures
- Large Swings in Ambient temperature, both, on a Daily basis and Seasonal Basis
- Traditional A-Frame Air Coolers: Can they Can Maintain Compressor Inlet Temperature in the 35-40°C?
- MicroChannel ACHEs have not Been Designed
- Reduced PreCooler approach Temperatures and ΔP Needed for Maximum Cycle Efficiency.

Ambient Air Temperatures at Representative CSP Sites

- Steady State Cycle Efficiency Decreases with Increasing Ambient Air Temperature
- Compressor Head Flow Curve and impact on wide range Performance

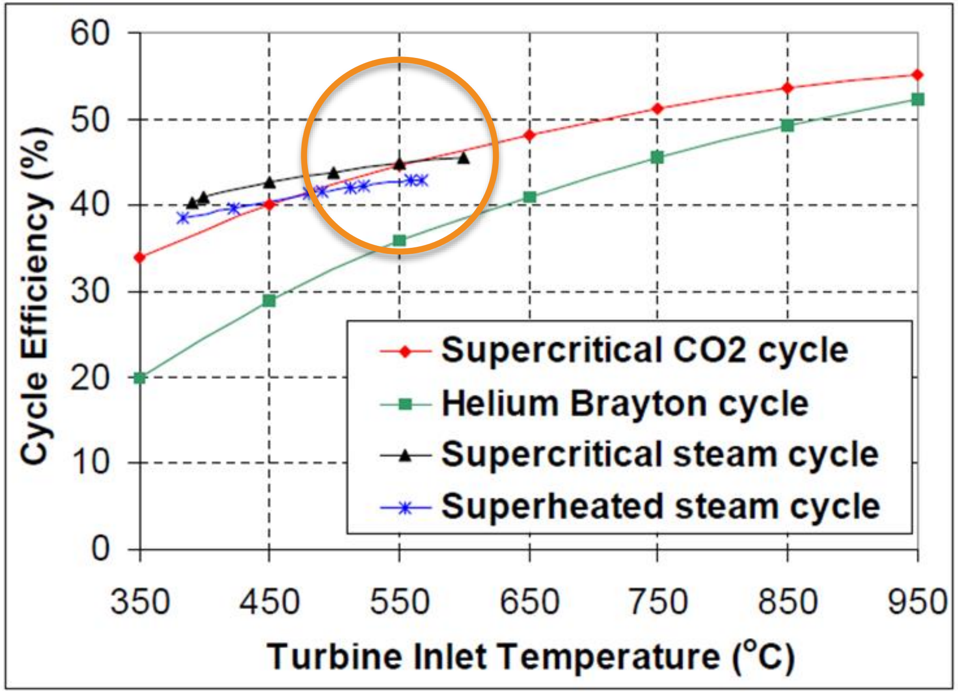


sCO_2 Cycles Need to be Competitive with Steam

- Realized that Cost Competitive sCO2 cycles will need to be at higher Turbine Inlet Temperatures
- Lower capital costs due to simplicity and smaller size; addressed by Nate in a following presentation
- Lower (or zero) use of water, due to compatibility with dry cooling
- 4X more compact design or footprint (permitting more operational flexibility, rapid startup and shutdown)

System	Temperature (°C)	Conversion Efficiency	Capital Cost ($/kWe)
Super-critical Steam	540 – 620	~40-45%	1,200
Super-critical CO_2	550 - 649	~41-46%	<900

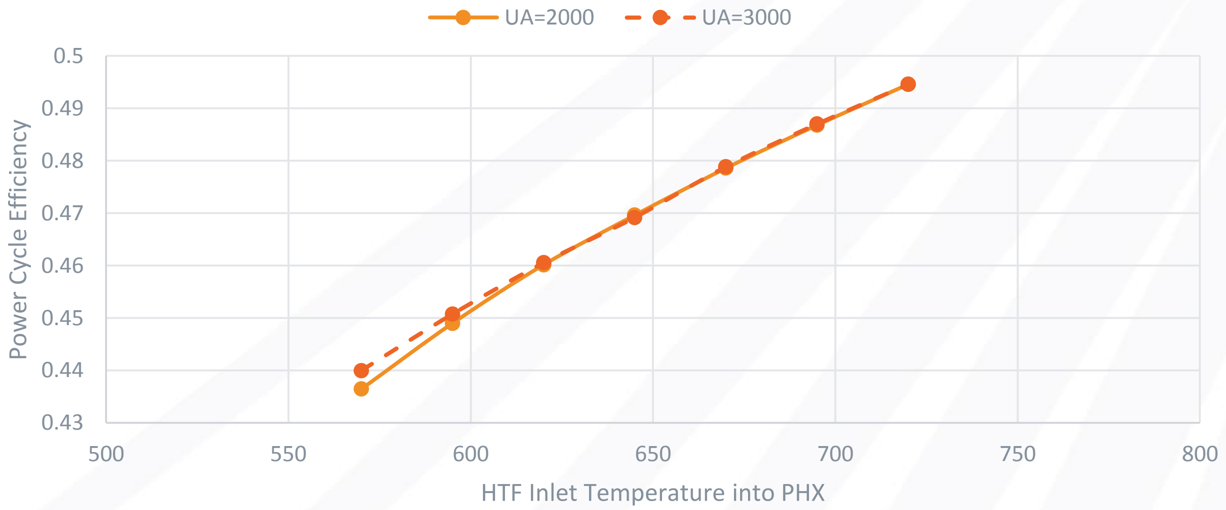
sCO_2 Cycles Need to be Competitive with Steam



Dostal V., Driscoll M. J., P. Hejzlar and N. E. Todreas, A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors, MIT-ANP-TR-100, March (2004).

Means to Higher Power Cycle Efficiency

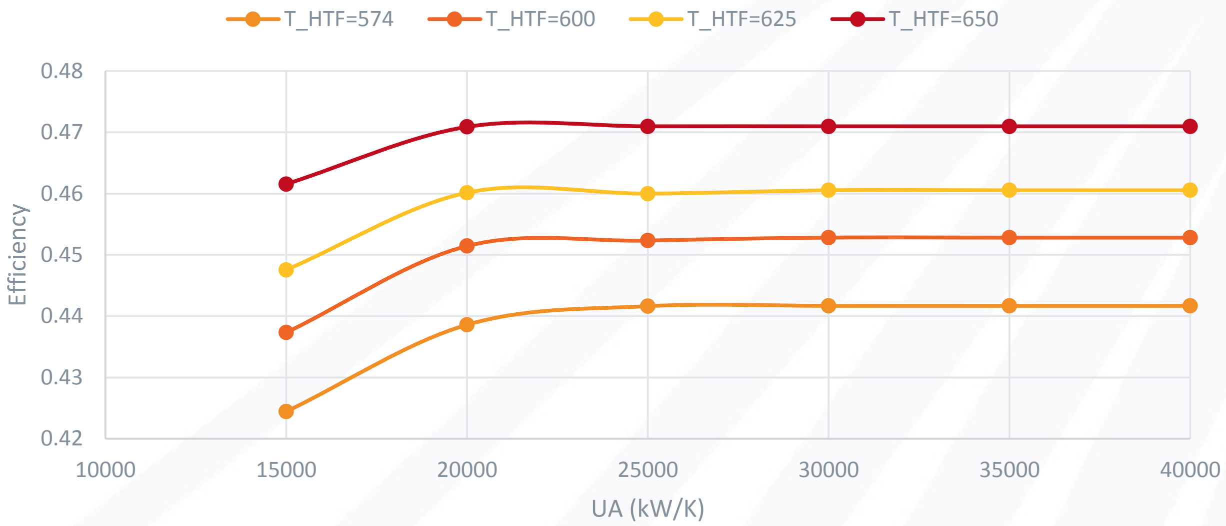
- Higher Turbine Inlet Temperature (Equivalent to Higher HTF Temperature)



Power Cycle Efficiency as a Function of HTF inlet Temperature, for Varying Recuperator UA; Compressor Inlet Temperature = 40°C; Turbine Efficiency = 91%; Main Compressor, Recompressor Efficiency = 85%

Means to Higher Power Cycle Efficiency

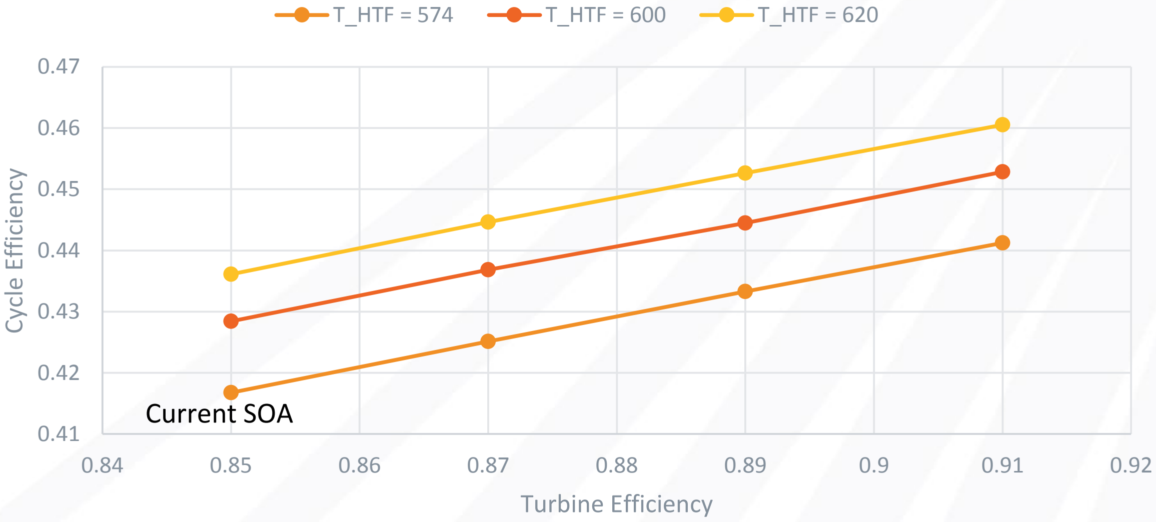
- Higher recuperation is Probably not as effective



Power Cycle Efficiency as a Function of Recuperator UA, for a range of HTF temperatures Compressor Inlet Temperature = 40°C; Expander Efficiency = 91%; Compressor(s) Efficiency = 85%

Means to Higher Power Cycle Efficiency

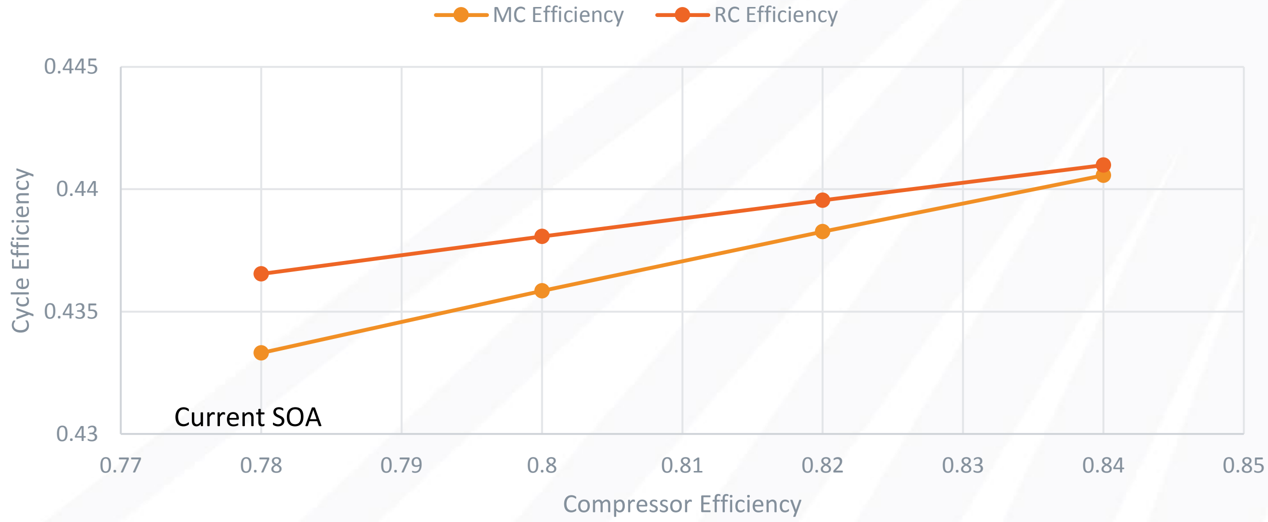
- Turbine Efficiency has a Significant Impact



Power Cycle Efficiency as a Function of Expander Efficiency, for Varying HTF Temperature; Compressor Inlet Temperature = 40°C; Main Compressor, Recompressor Efficiency = 85%; UA = 3,000 kW/K

Means to Higher Power Cycle Efficiency

- Compressor efficiencies somewhat Less So



Power Cycle Efficiency as a Function of Compressor Efficiency, for HTF Temperature of 574°C; Compressor Inlet Temperature = 40°C; Expander Efficiency = 91%; UA = 3,000 kW/K

Integrated Turbomachinery

- Higher Expander Efficiency requires Careful Turbomachinery Packaging and Reduced Expander Leakage
- Compressor and Expander development at a stage that Single Shaft/Single Casing Designs can Be Considered
- Packaging and reduction of seal count easier at 550 C than 700 C; give vendors breathing room
- Robust Control Strategy

Goals of the Workshop (1)

- Determine the scope of the Conceptual Research Effort
  - Size of the Power Block
  - Size of TES
  - Ultimate Heat Sink Definition: Air Cooling Only or Cold Storage to Allow a Broader testing Program
  - Turbomachinery Enhancements Considering the Narrowed Scope of Turbine Inlet Temperature (550-620°C)
  - Heating the TES Fluid: FiredGas Heater or Pumped Thermal or Electrical?
  - If a broader TIT (550-620 C) considered, methods for heating sCO_2

Goals of the Workshop (2)

- Turbomachinery Panel
- Breakout Panel Discussion discuss Steps beyond the current vendor efforts and STEP program
  - Expander and Compressor Design Improvements
  - Packaging Turbomachinery
  - Dry Gas Seals and Bearing Subcomponents
  - Power Block Size and testing hours in the Facility for Utility Operator Comfort
  - O&M Reduction
  - "Autonomous" Control Systems (?)

Goals of the Workshop (3)

- Heat Exchanger Panel
  - Panel discussions with Vendors in the morning
- Heat Exchanger Breakout
  - Recuperators
  - Primary heat exchanger design unknowns
  - Air Cooler design unknown
  - For Wide Range Testing Program of Compressor-Precooler Integration, look at Cold Storage?

Goals for this Workshop (4)

- Thermal Energy Storage
  - Presentation on CSP experience with TES
- Facilities
  - Experience in Existing Facilities Design and Operation
- Breakout Session on TES
  - Nitrate Salt or ?
  - Integration with sCO_2 cycle a big Question mark
  - How to heat the TES? Fired Heater or Grid-Heated?

Questions?

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