Investigation of a Dry Air Cooling Option for an S-CO_2 Cycle

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Background

- Traditionally, (nuclear) power plants use water for ultimate heat sink
  - Restricts plant location choices
- At the same time, the water restrictions are becoming more important
- If dry air cooling could be shown to be feasible for an S-CO_2 cycle, it will basically eliminate any water use by the plant
- Goal: investigate what it takes to apply dry air cooling to an S-CO_2 cycle

Why water?

- Much better heat transfer medium than air
  - 1000 times higher density
  - 4 times higher specific heat
  - 20 times higher thermal conductivity

} 4,000 times lower volumetric flow and pumping power

	Units	Water (at 1 atm, 30 °C)	Air (at 1 atm, 30 °C)	CO_2 (at 7.4 MPa, 40 °C)
Density	kg/m^3	998.2	1.196	224.1
Specific heat (C_p)	kJ/kg-K	4.184	1.005	3.160
Thermal conductivity	W/m-K	$598.5*10^{-3}$	$25.5*10^{-3}$	$33.4*10^{-3}$
Viscosity	Pa*s	$1.0*10^{-3}$	$18.3*10^{-6}$	$20.2*10^{-6}$

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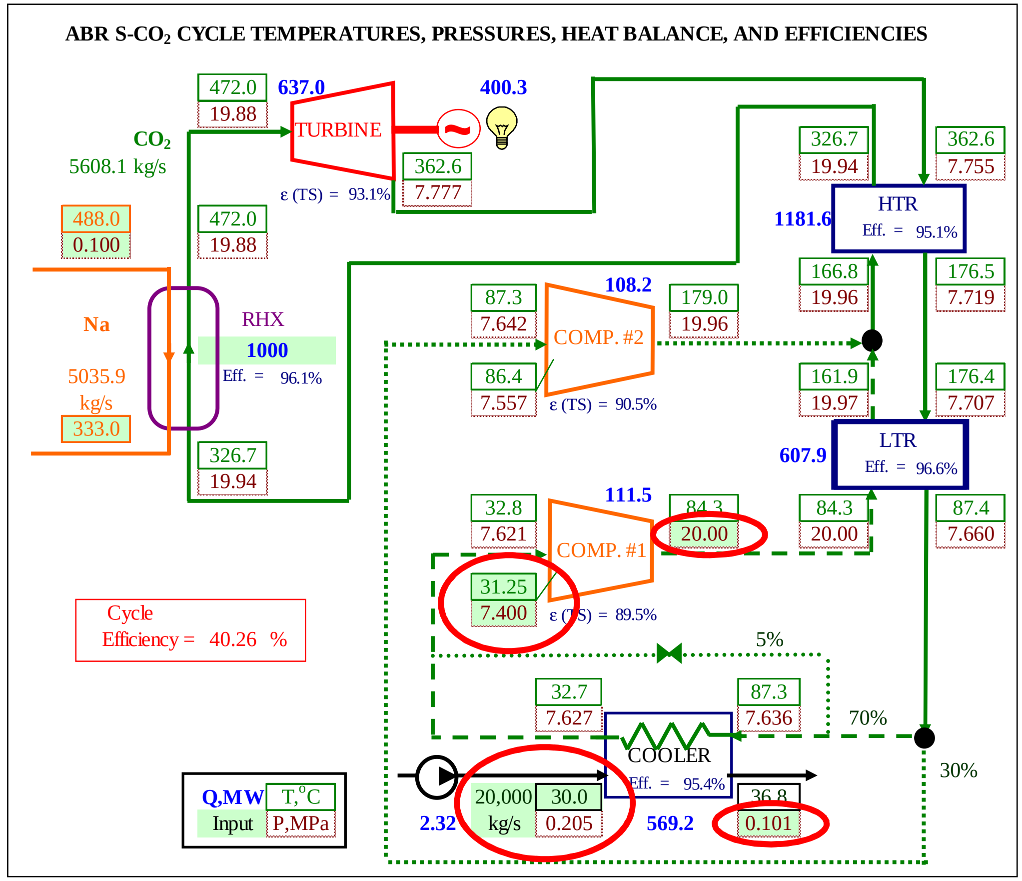
Reference Conditions and Assumptions

- 1000 MWt (400 MWe) S-CO_2 cycle for a Sodium-Cooled Fast Reactor (SFR)
  - 40.3% cycle efficiency
- 31.25 °C minimum cycle temperature
  - 0.25 °C margin over critical temperature
  - 32.7 °C cooler-outlet temperature
- 7.4 MPa minimum and 20 MPa maximum cycle pressures
- 30 °C inlet water temperature
  - Assumed same for air
  - Atmospheric pressure
- Realistic cooler analysis
  - CO_2 properties
  - Multi-nodal treatment
  - PCHE or shell-and-tube

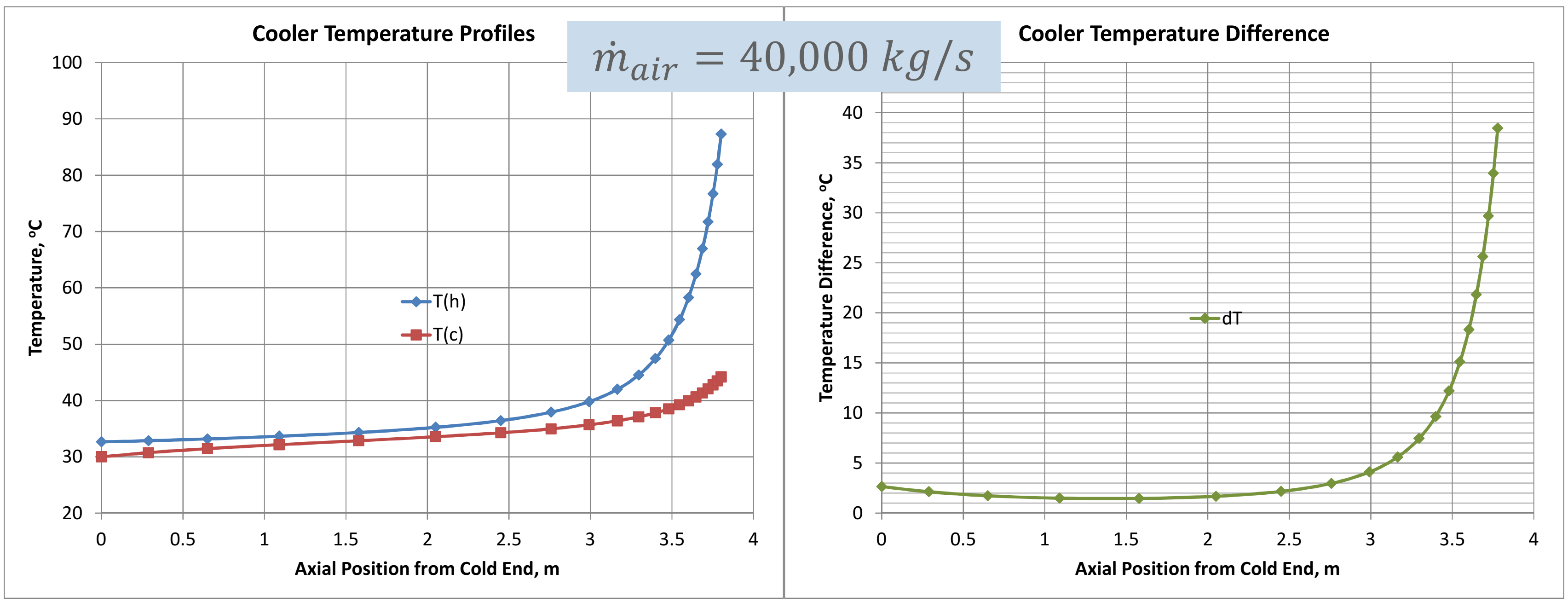


Selection of Air Flow Rate

- Pumping (fan) power is expected to be very high for air
  - 4,000 time higher volumetric flow rate
  - Low flow rate is better

$$W_{pump} = \frac{1}{\varepsilon_{pump}} \frac{\dot{m}}{\rho_{in}} \Delta p$$

- Flow rate is limited by pinch point in cooler
  - Condensation-like temperature profile on CO_2 side near the critical point



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Air Cooling at Reference Conditions

- 32.7 °C CO_2-outlet temperature
- Same cooler design as for water

- Air flow rate is practically limited by 40,000 kg/s
  - 2 times higher than for water
  - 2,000 times higher volumetric flow rate
    - Huge pressure drop
    - Huge pumping power (>1000 MW)

Air Flow Rate, kg/s	Temperature Approach, °C	Cooler Heat Transfer Length, m
80,000	2.5	1.7
60,000	2.0	2.0
40,000	1.3	3.8
30,000	1.0	9.6
Water @ 20,000	2.5	0.73

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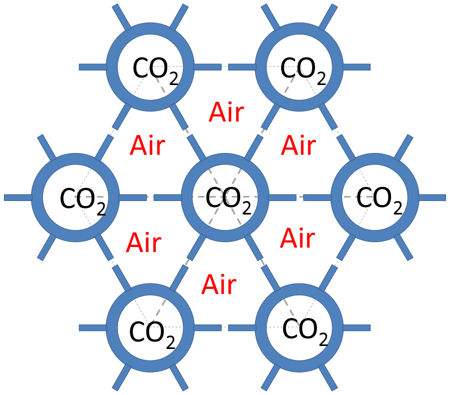
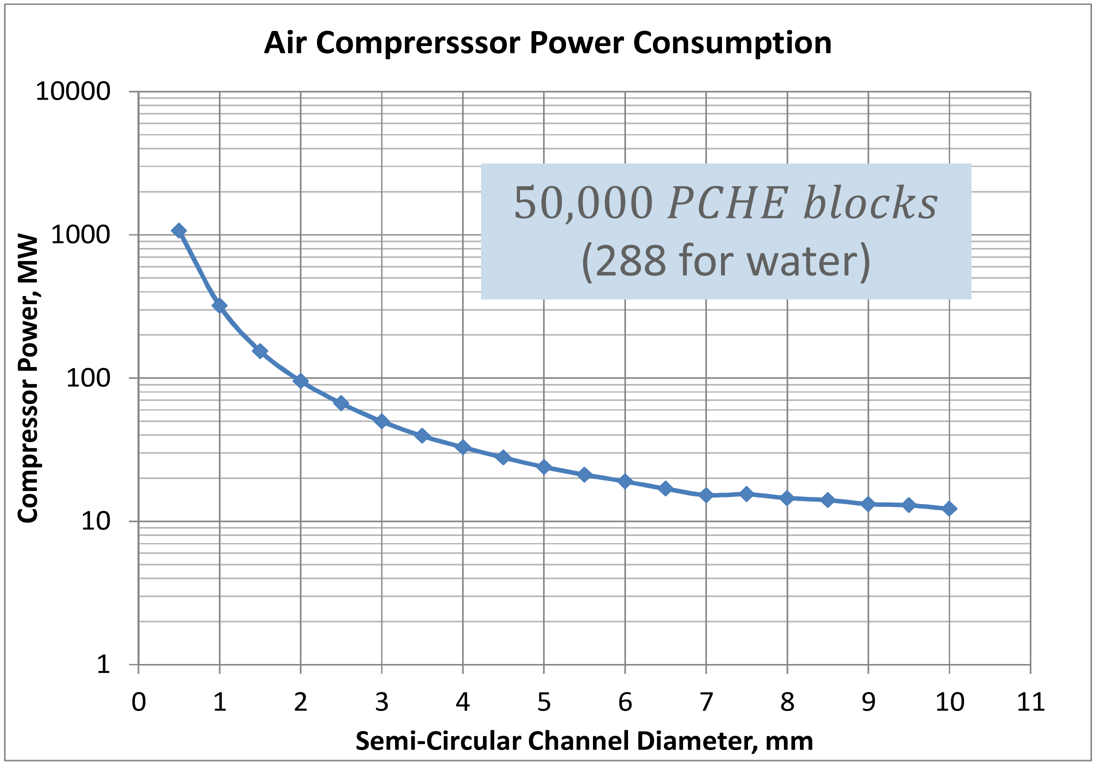
Better Cooler Design?

- Some of these issues can be offset by changing cooler design
  - Larger channel
  - More HX units
  - Shell-and-tube HX





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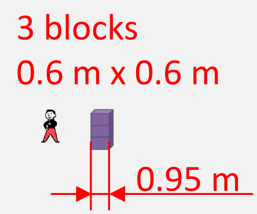
Cooler Size Comparison - Reference Conditions

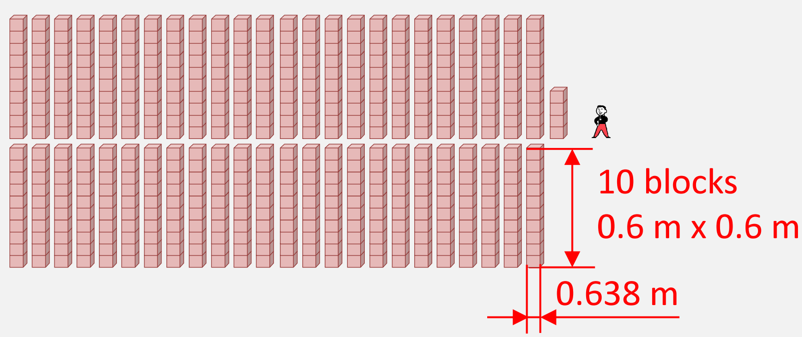
- Figures show 1% (1/100) of the HX

<u>1/100 Water Cooler PCHE – 288 blocks total</u>



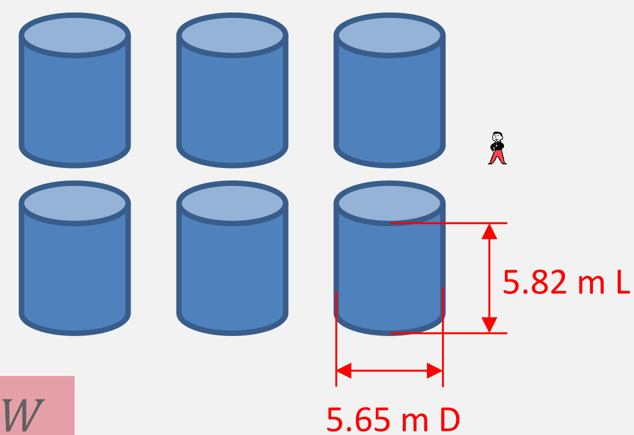
$W_{pump} = 2.3\ MW$

<u>1/100 Air Cooler PCHE – 48,350 blocks total</u>



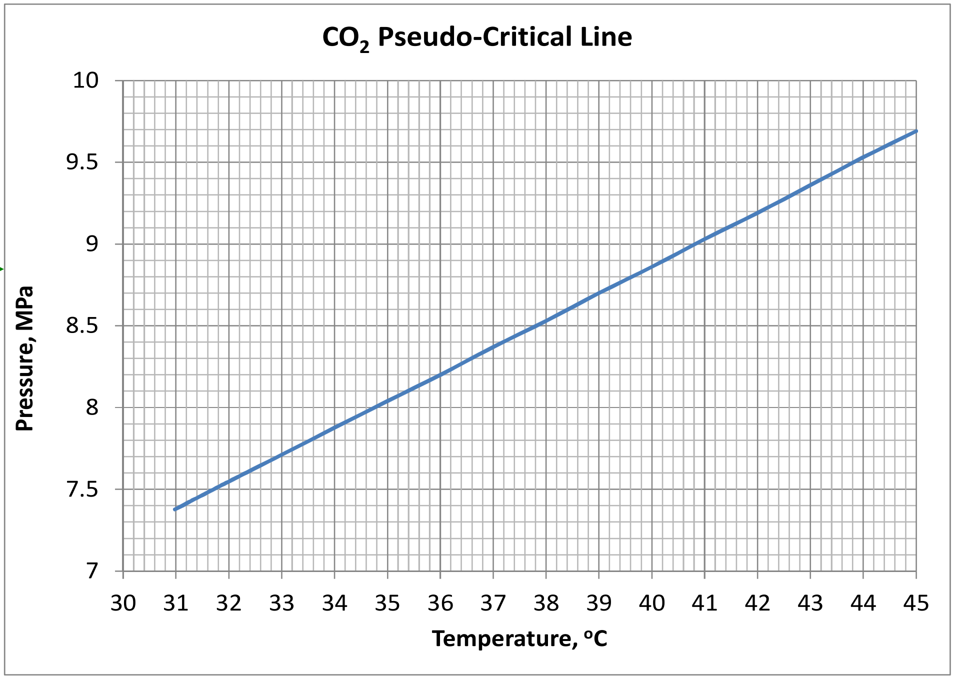
$W_{pump} = 20\ MW$

<u>1/100 Air Cooler Shell-and-Tube – 600 units total</u>



Effect of Air Cooling on Cycle Conditions

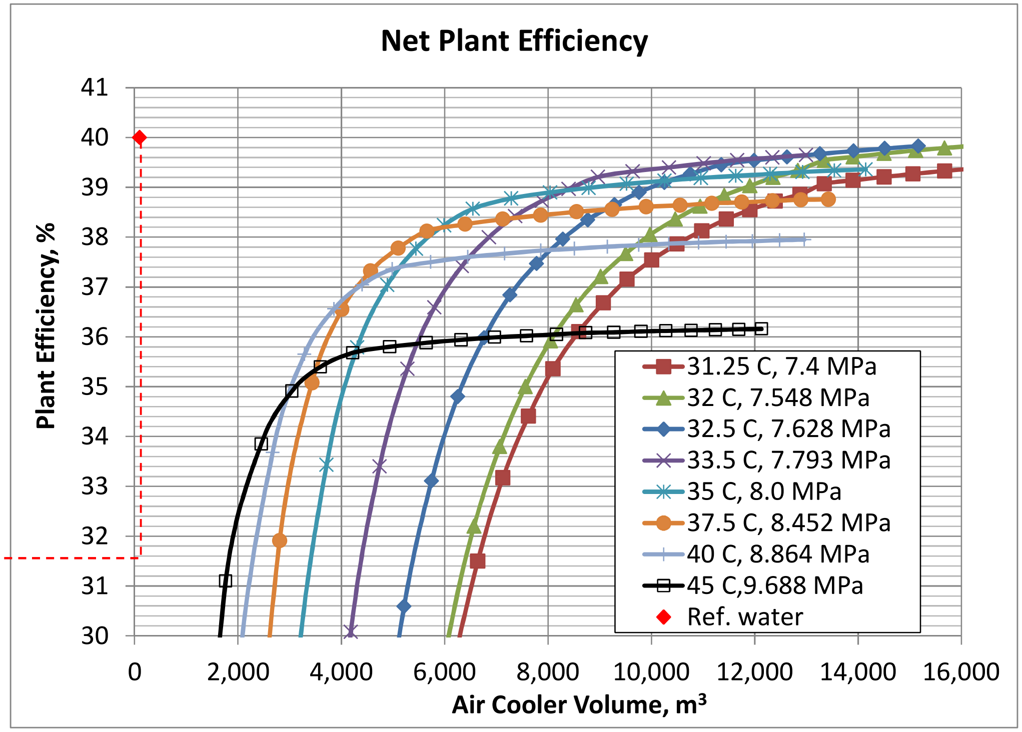
- Previous results clearly show that dry air cooling at reference conditions (31.25 °C CO_2) will be too expensive
  - Huge HX and 4.4% reduction in net output
- Both HX size and power consumption can be reduced by increasing CO_2 temperature
  - Of course, at the expense of lower cycle efficiency
- Optimization calculations found that the optimal design is obtained at or close to the pseudo-critical line at the compressor inlet



- At each point:
  - Air flow rate is selected to avoid excessively low temperature approach in cooler
  - CO_2 flow split between compressors is selected to maximize cycle efficiency
  - HX volume (number of units) is varied parametrically
  - Rest of the plant design is fixed (reactor conditions, 20 MPa high pressure, other HX designs,…)

Selecting Optimal Cooler Design

- At each condition, there is a trade-off between the cooler size and the cycle efficiency
  - Efficiency is also affected by the air circulation power
- These two characteristics cannot be compared in TH analysis
  - Only in **cost** analysis



- Notice also still significant penalties in **both** cooler size **and** cycle efficiency compared to the reference water cooler

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Cost-Based Optimization

- The technique was previously developed to optimize other S-CO_2 cycle components
  - Heat exchangers and turbine
  - Provides direct comparison between the HX size (cost) and the cycle performance (efficiency)
- Based on comparing the plant cost per unit electrical output
  - Good measure for nuclear plants, where most of the cost is in capital

HX Cost

$$[\$/kWe]_{new} = \frac{[Plant\ Cost]_{new}}{[Plant\ Power]_{new}} = \frac{[Plant\ Cost]_{ref} - [HX.Cost]_{ref} + [HX.Cost]_{new}}{\eta_{cyc,new} * Q_{Rx}}$$

Cycle efficiency

1000 MWt

$$[Plant\ Cost]_{ref} = [\$/kWe]_{ref} * \eta_{cyc,ref} * Q_{Rx}$$

Cost-Based Optimization: Assumptions

- Reference capital cost of the plant is 4800 $/kWe
  - Excluding (water) cooler
  - 1,920 M$ for 400 MWe
- Cooler cost = Material Cost + Fabrications Cost
  - Material Cost = 7.64 $/kg (316 stainless steel)
  - PCHE fabrication cost is estimated at $44,000 per block based on similar earlier vendor quotes
  - ***An optimistic assumption of 50% reduction in total cooler cost (both material and fabrication) is made for the air cooler***

Not for CO_2-air HX

- Additional cost and cost variation of air compressor are ignored

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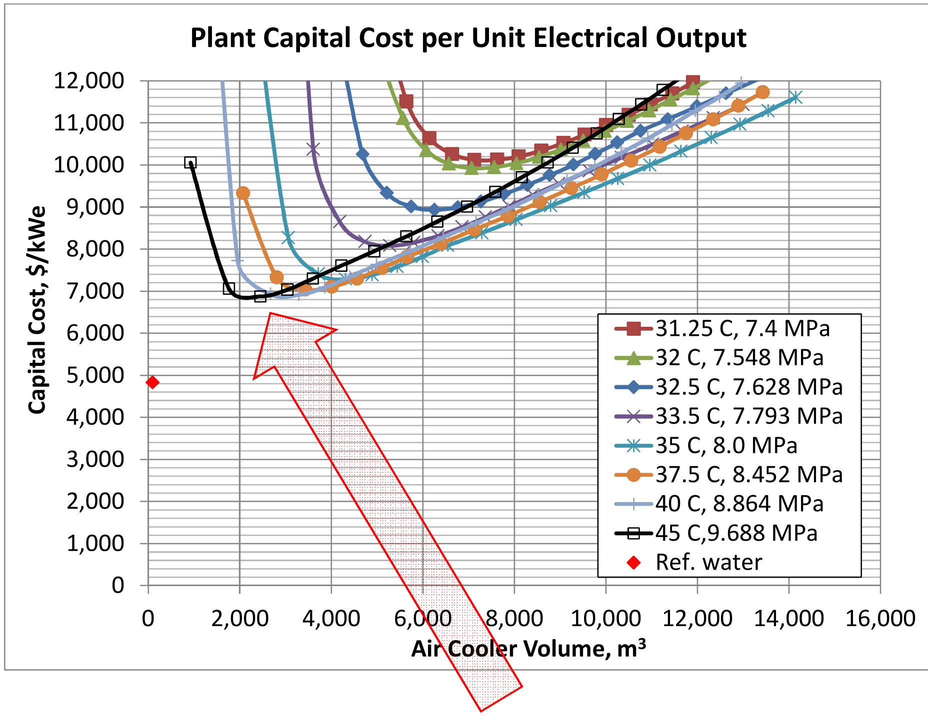
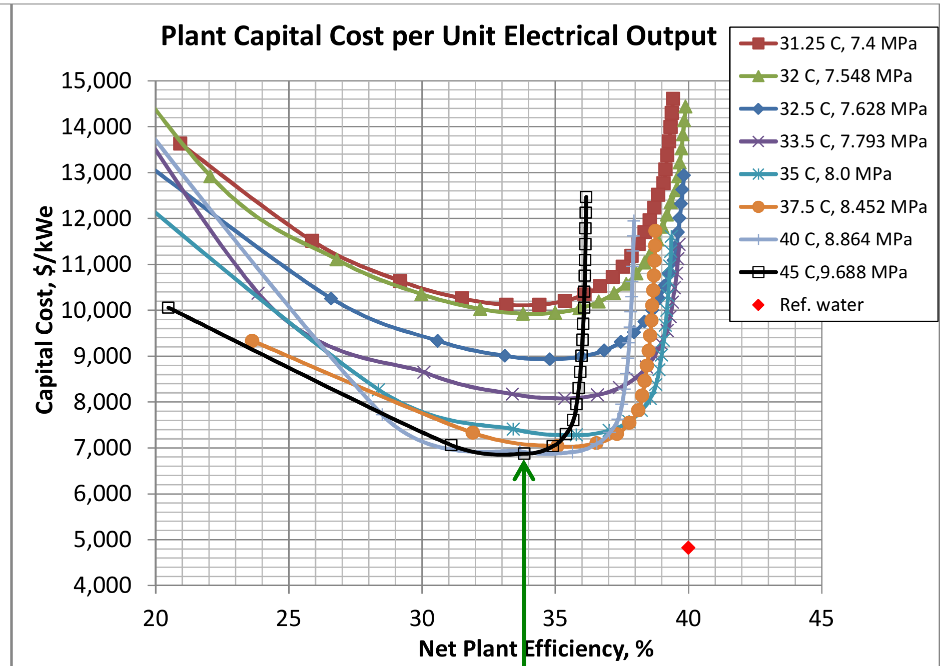
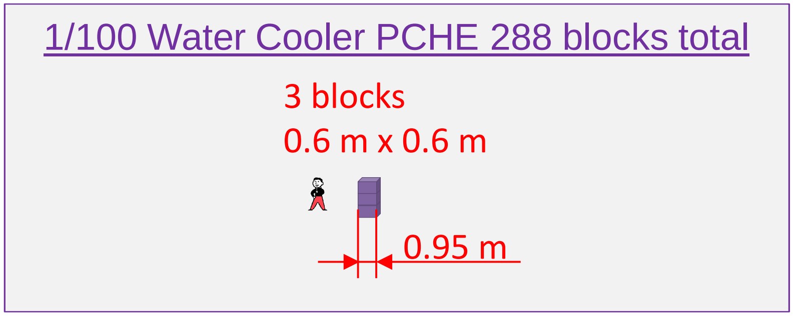
Cost-Based Optimization: Results

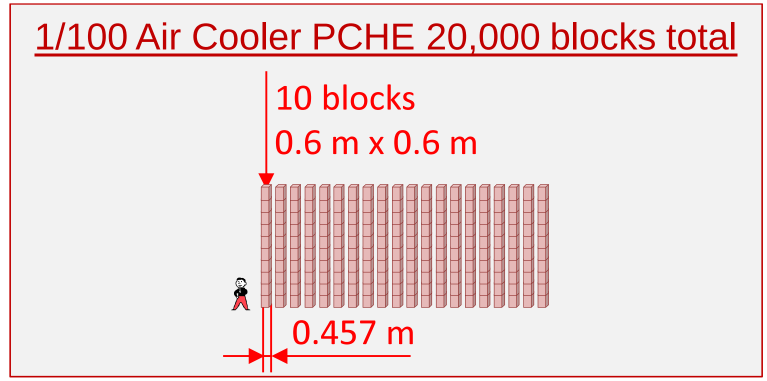


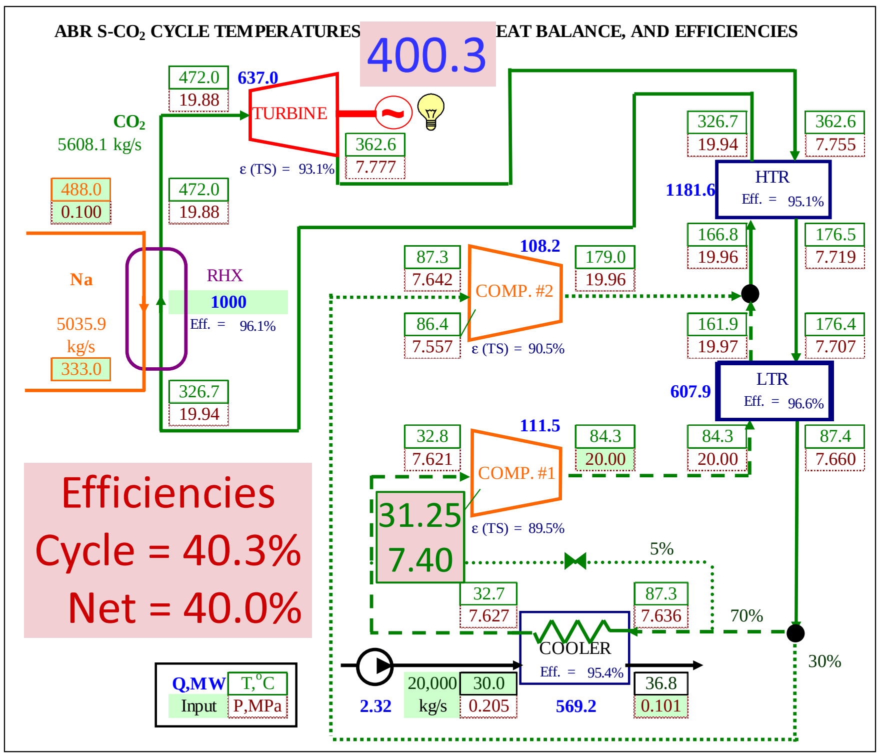


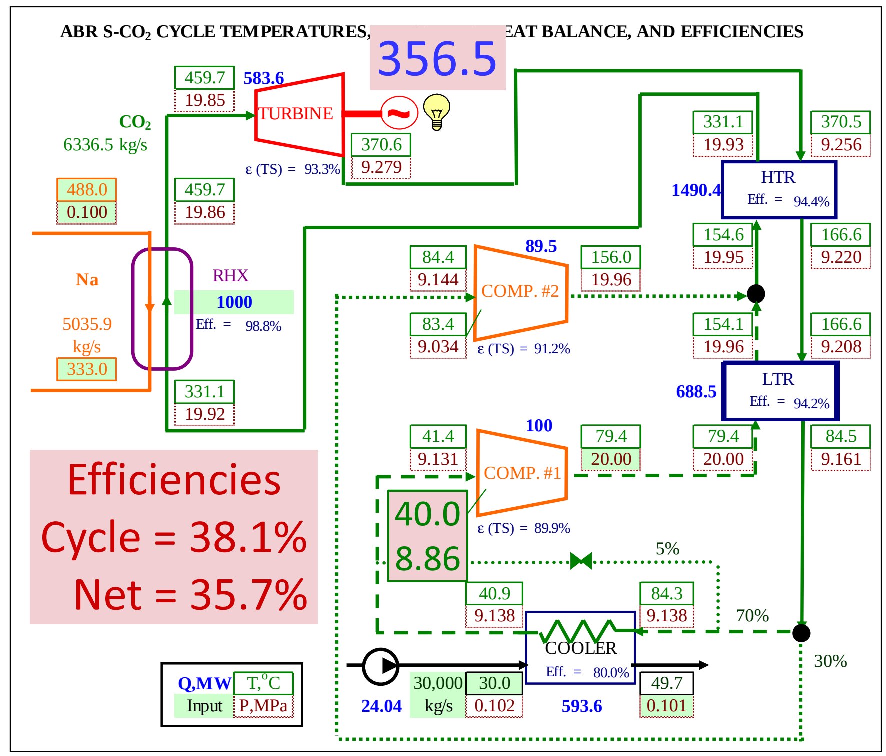
- Lowest cost is at 40-45 °C compressor-inlet temperature
  - It is beneficial to accept reduction in cycle efficiency
    - But reduce HX cost
- Plant capital cost per unit electrical output increases ~40% compared to water cooler
  - Even with an optimistic cooler cost assumption

Water vs Dry Air Cooling – Optimal Designs









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Summary

- Dry air cooling would be beneficial for S-CO_2 cycles
  - More choices in plant location and water resources management
- Water has much better heat transfer medium properties
  - Pumping power
- Air cooler at optimal S-CO_2 cycle conditions is huge
  - 100 times bigger for PCHE, 900 times bigger for S&T HX, compared to water PCHE
- Air cooler size could be decreased by increasing CO_2 compressor-inlet temperature
  - Optimal designs are found along the CO_2 pseudo-critical line
- Cost-based optimization is used to characterize trade-off between the cooler size and cycle efficiency
  - Air cooling results in both larger cooler and lower cycle efficiency
  - At least 40% increase in plant capital cost per unit electrical output is calculated
    - Compared to water cooler
    - *Even with optimistic cooler cost assumptions*

➢ ***Overall, the results of the air cooling analysis for the S-CO_2 cycle have demonstrated that even though this option might be feasible (provided that significantly larger heat exchangers can be accommodated), this approach would not be competitive with water cooling***

- Consider only if water is not available, very restricted, or expensive

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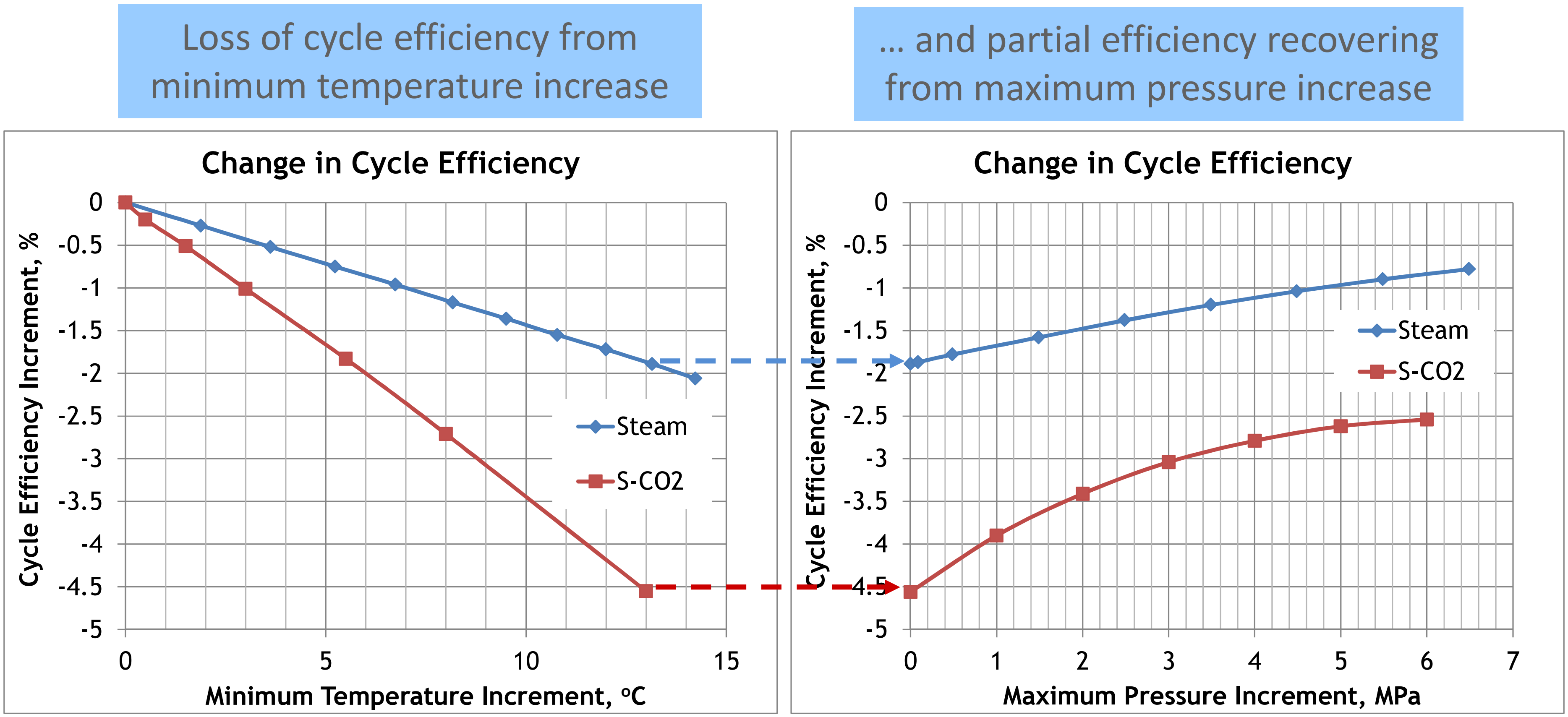
S-CO_2 vs Steam Cycle for Dry Cooling



- Application to an SFR (ABR-1000)

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