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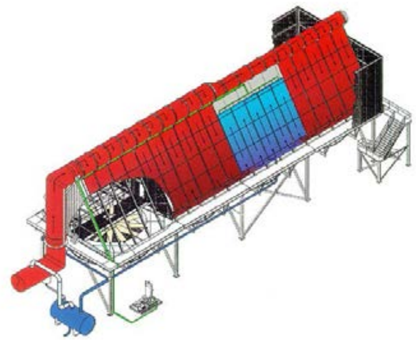

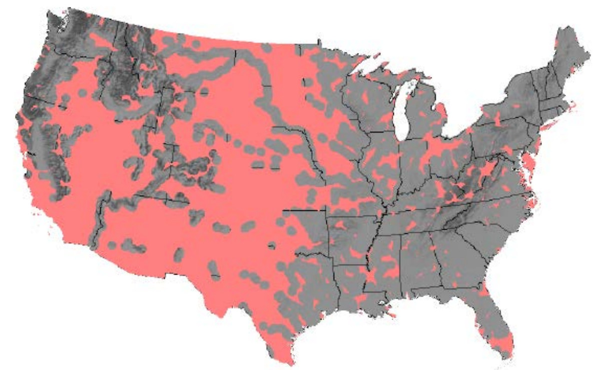

DRY-COOLED SUPERCRITICAL CO_2 POWER FOR ADVANCED NUCLEAR REACTORS

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Overview – Dry-Cooled SCO2 SMRs

- The water-energy nexus is a critical challenge for power plants
  - Current nuclear, coal, and concentrating solar plants require cooling
  - 39% of U.S. freshwater withdrawal is used for cooling power plants
  - Supply is decreasing while demand is increasing

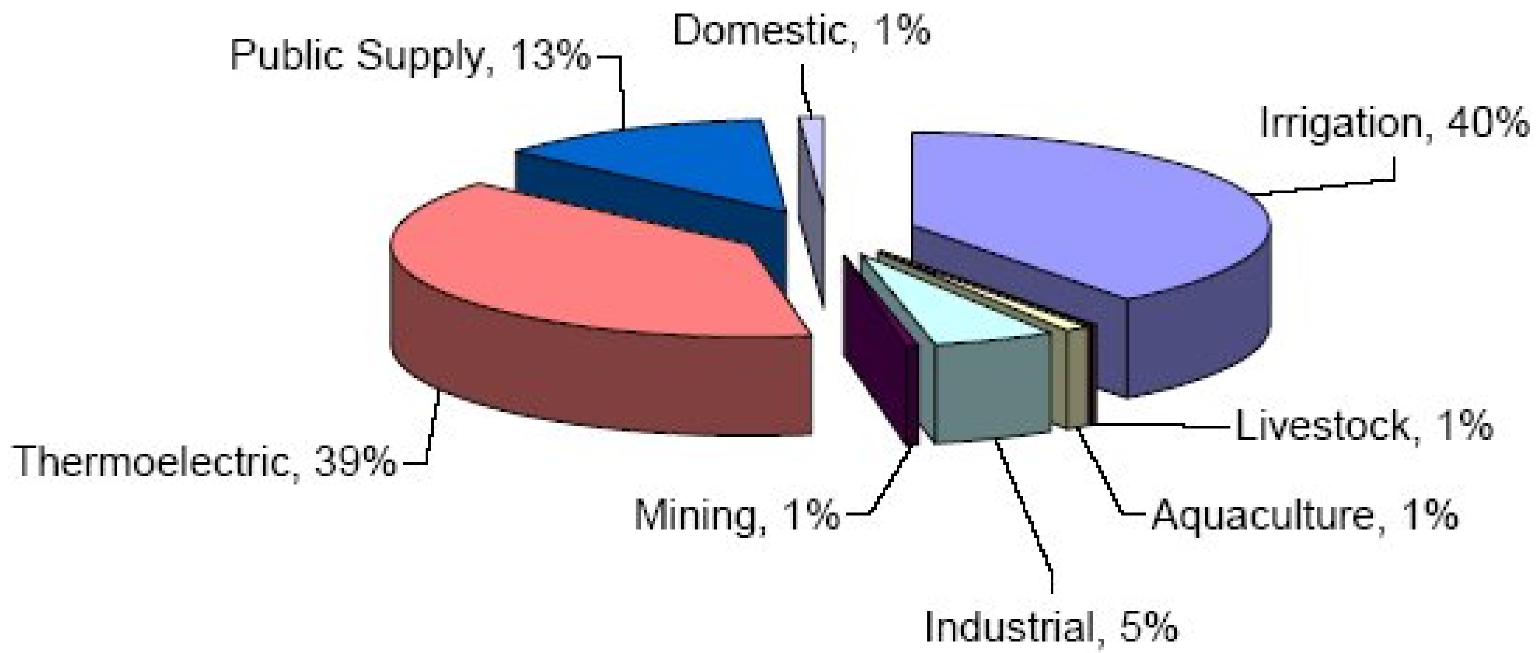
- Supercritical CO_2 (s-CO_2) power cycles offer many advantages
  - Proposed as an alternative to steam and organic Rankine systems
  - Offer high efficiency, compact turbomachinery, fluid compatibility

- s-CO_2 power cycles are well suited for use of dry-air cooling
  - Maintain good efficiency at high heat sink temp
  - Allow for closer average temperature differences
  - Less capital in building, operating cooling towers.

- Benefits of dry-cooled s-CO_2 cycle could aid the rise of next-generation nuclear systems, and could redraw the map for siting of new nuclear

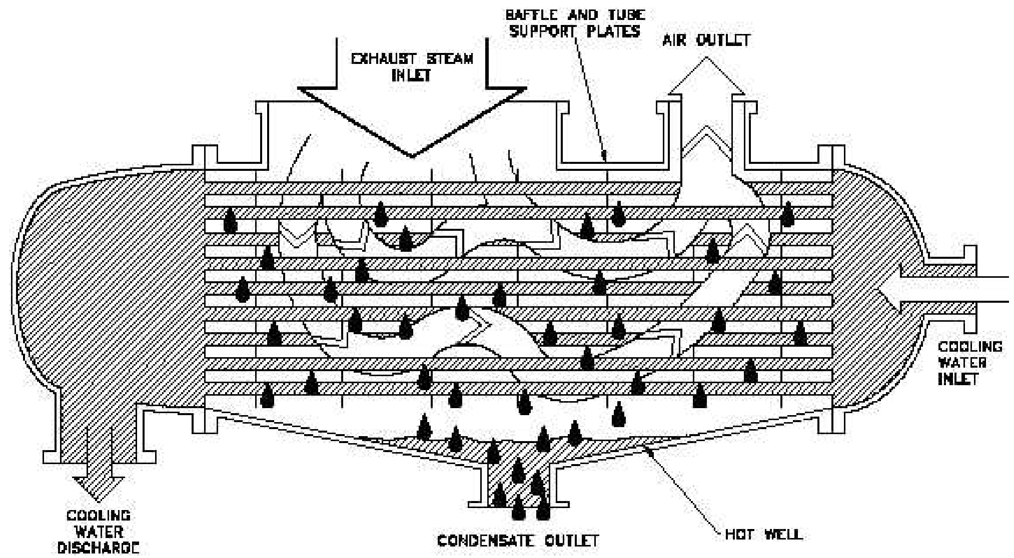
Introduction – U.S. Water Use

39% of U.S. withdrawal is for power plant cooling



Nuclear Steam Condensers

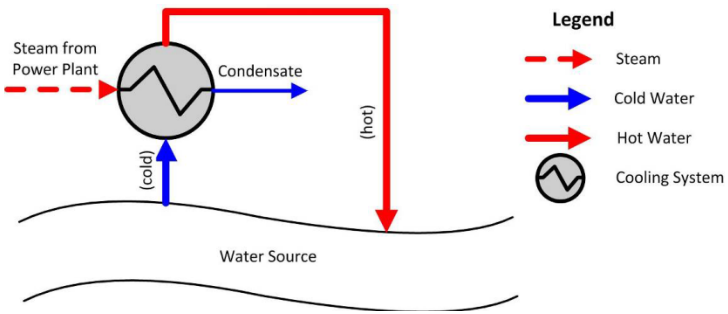
- Most U.S. electricity is generated by 33% efficient steam turbines, with the remaining ~67% of the thermal source energy rejected to the environment
- Steam condensers are a critical component for safety and performance
- Currently shell & tube, with tube-fin, wet, dry, and hybrid options possible
- Operate at sub-atmospheric turbine back pressure
- Performance can be hampered by the build-up of non-condensable gasses



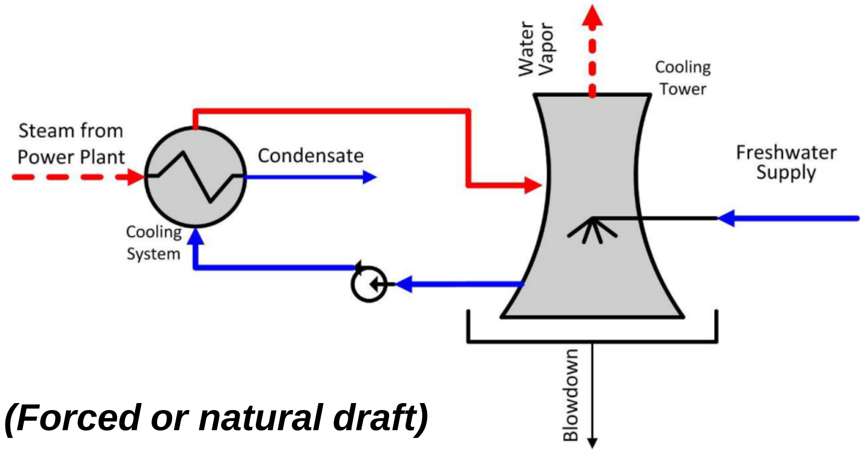
Heat Sink Options:

Each has advantages and disadvantages

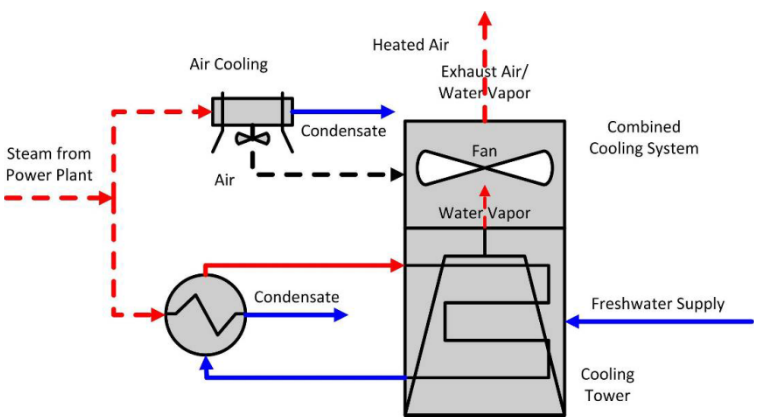
Once-through, wet



Indirect wet cooling tower

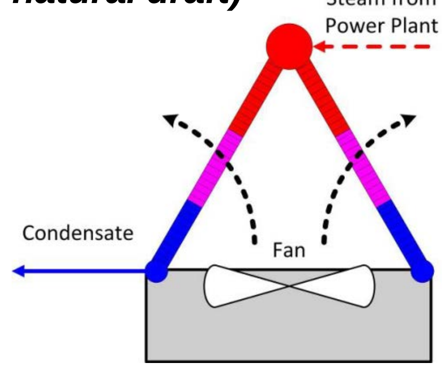


(Forced or natural draft)



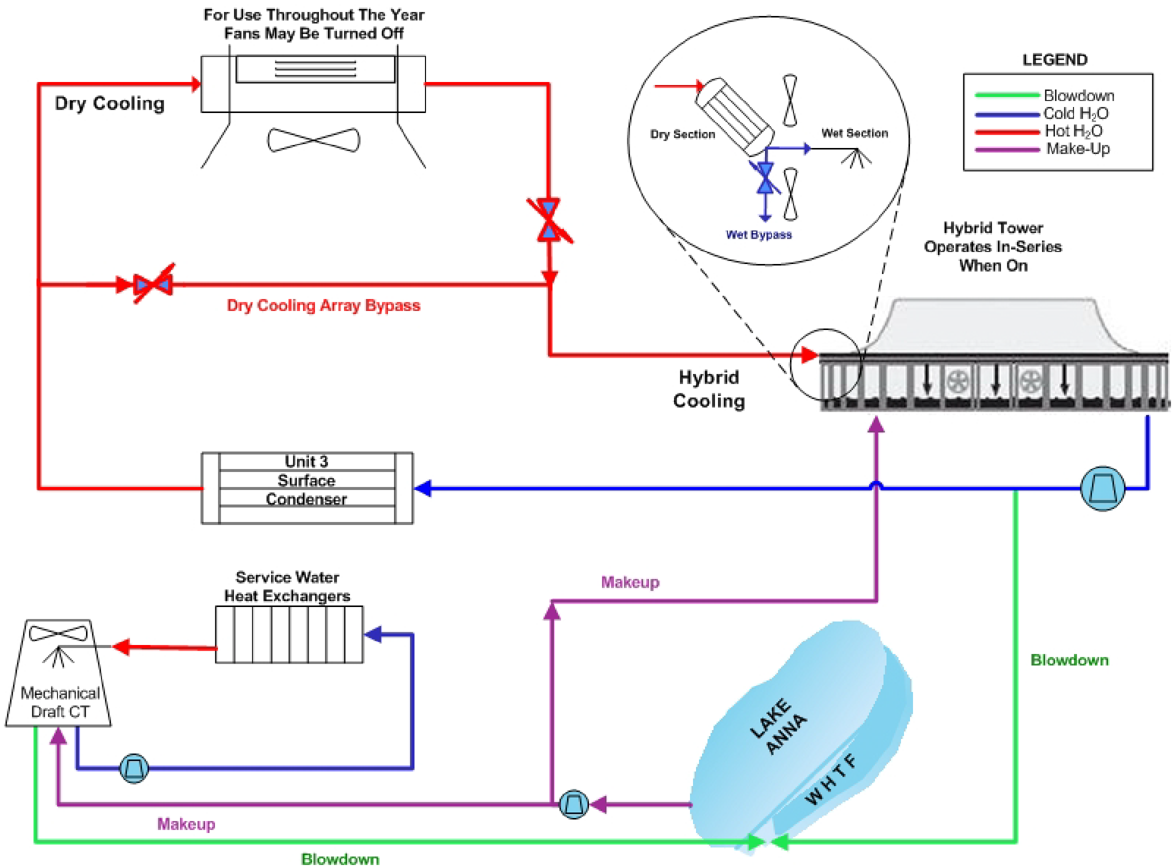
Hybrid cooling tower

(Forced or natural draft)



Dry cooling tower

Cooling in the news at nuclear plants



North Anna Unit 3 (proposed BWR)
-COL submitted

- **Oyster Creek (NJ) agrees to shut down a decade early rather than build cooling towers at cost of $1-2B**
- **Legal action to force cooling towers at Millstone (CT) , Salem 1 and 2 (NJ), and Indian Pt (NY)**
- **North Anna (VA) new build proposes use of hybrid cooling after water concerns**
- **etc**

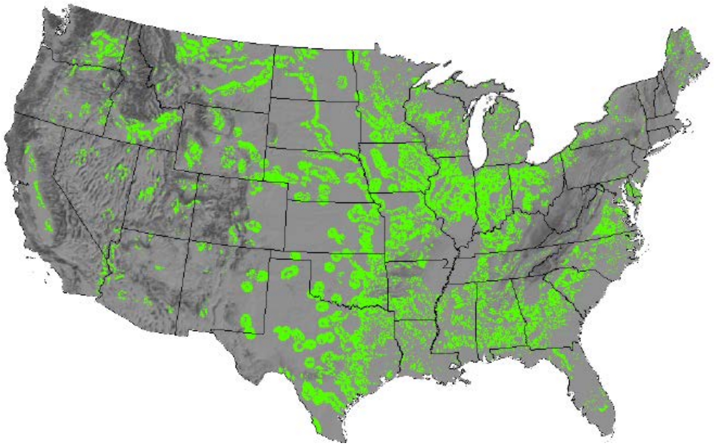
Nuclear siting

Factors considered in nuclear plant siting:

- Local population density
- Proximity to faults, protected lands, slopes, flood terrain
- Wide open free space around the site (500+ acres)
- **Cooling water**
  - **50,000 gpm for 300MWe SMR**
  - **200,000 gpm for 1000+ MWe**

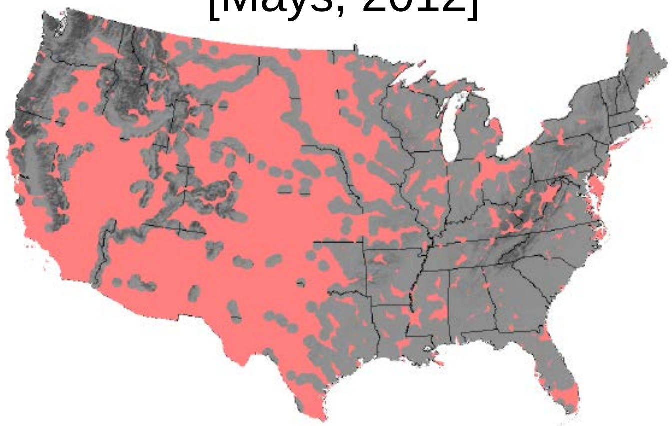
Study at ORNL in 2012 considered all of these factors and more, scanned spatial map of US for potential sites

Much of Western US is excluded from consideration because of cooling water requirements



Green: areas of sufficient water

[Mays, 2012]

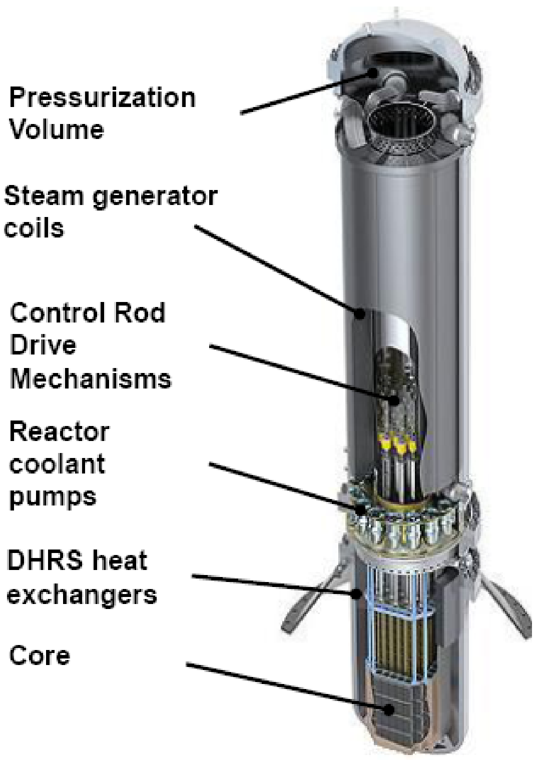


Pink: areas excluded from nuclear siting

Dry cooling in nuclear?

Generation mPower

- Developed by Babcock & Wilcox
- 125 MWe capacity
- Integral PWR configuration
- Forced circulation of primary coolant
- Standard 17x17 pin fuel assemblies with 4.5-yr refueling cycle
- Once-through straight tube steam generator
- 3.6-m-dia by 22-m-tall reactor vessel



- advertises 31% efficiency in dry cooling [WNA, 2013]
- Still requires large volume of water on site for 7 day emergency cooling

Current dry-cooled steam plants

- 1% of installed steam plants are dry
- Because of limitations, its only economic when water is prohibitively expensive
- Even then, gas turbines or solar PV can be used

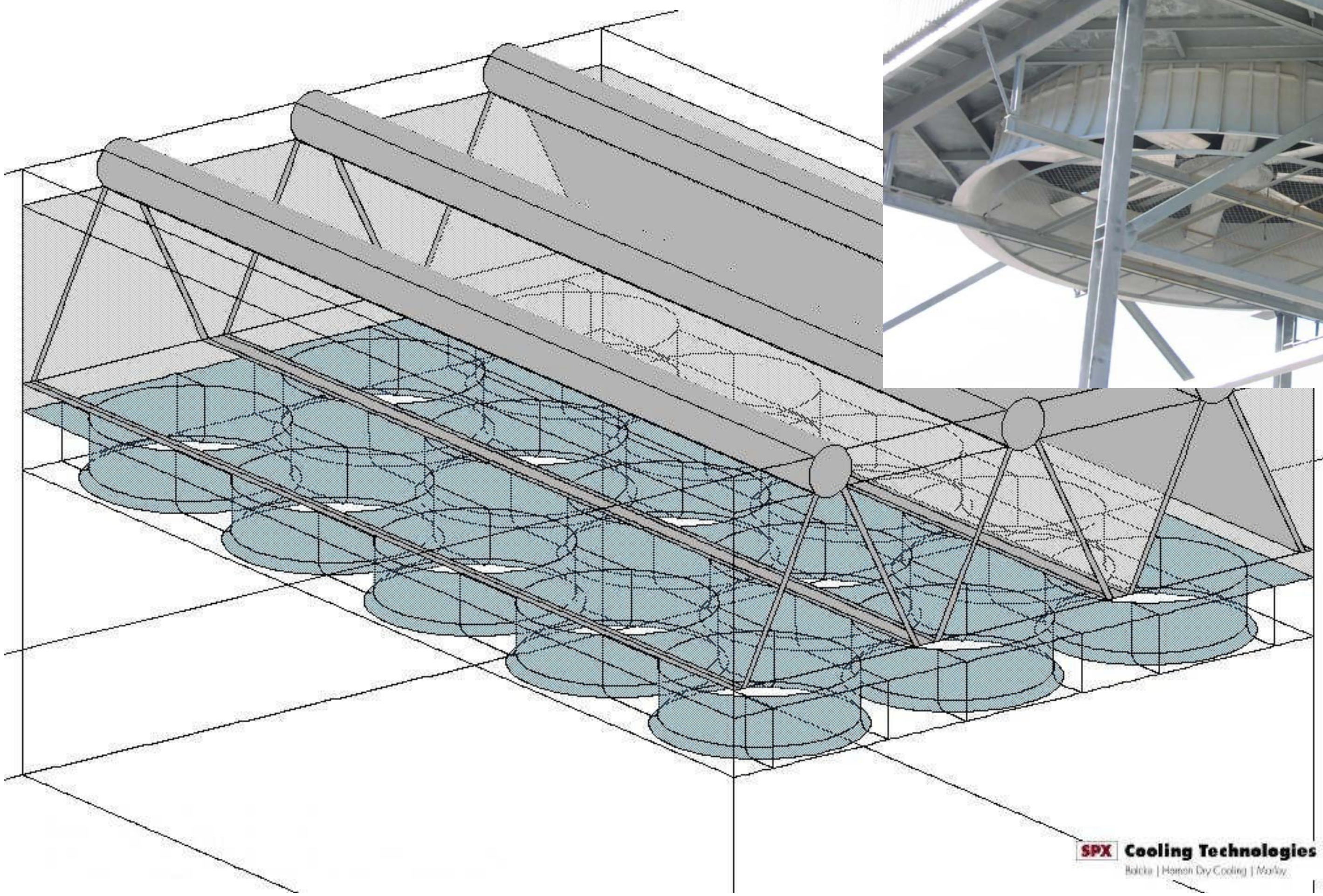
- **Higgins Generating station (NV)**
  - *550MWe combined cycle*
  - *Forced mechanical dry cooling*

- **Kendal Power Station (South Africa)**
  - *6 x 686MWe coal plant*
  - *Natural draft dry cooling plant*

Generally operate at backpressure of 14-17kPa (T_{sat}=55.8C) instead of 6kPa (T_{sat}=36.2C)

- **Ivanpah (under construction)**
  - *372MWe CSP (concentrating solar)*
  - *Forced mechanical dry cooling*
  - *Solar drives much of dry cooling technology today*

Cooling fans at Higgins Station



Challenges for dry-cooled condensers

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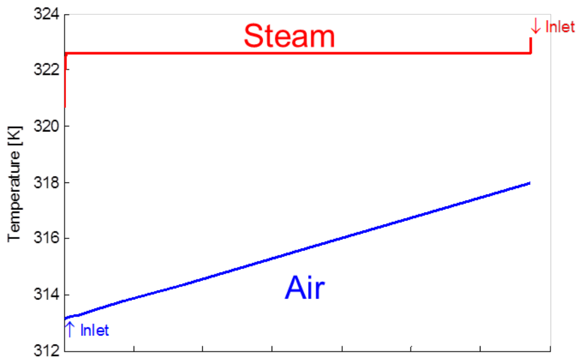
- **Dry heat rejection is attractive in**
- **theory, use on commercial steam**
- **is rare despite obvious advantages**



- **Difficulties include:**
  - *Limited by constant temp of condensing fluid*
  - *Poor heat flow profile match, exergy loss*
  - *Bounded by dry-bulb temp, instead of wet-bulb*
  - *3-5x as expensive to build [NEI]*
  - *10x as expensive to operate [NEI]*
  - *10% efficiency penalty when using dry cooling*
  - *Water is needed anyway for emergency cooling (nuclear)*

- **These issues are fundamental physical limits**
- **Much of ongoing research is looking at novel hx surfaces such as conducting polymers, metal foams, nanostructures [See FOAs: NSF/EPRI 2013, ARPA-E 2012]. Relevant on large scale?**

- ***Use of alternative working fluid is relatively unexplored solution***

What is a SCO2 Brayton Cycle?

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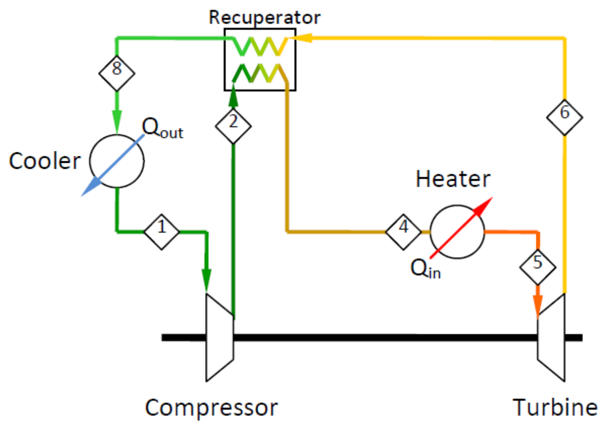
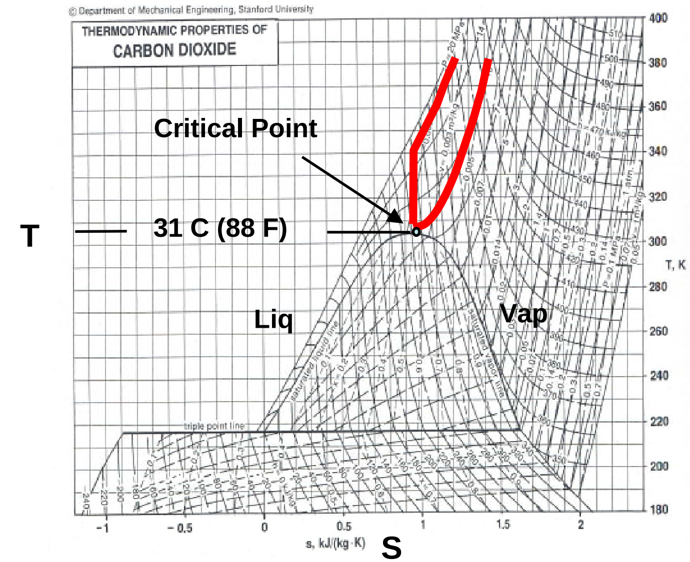
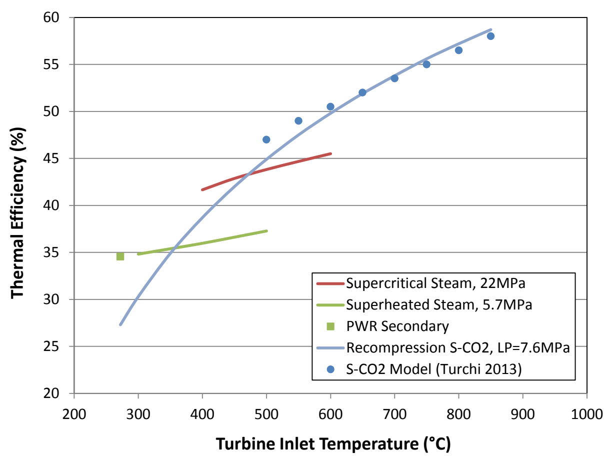


Liquid like Densities with CO_2
Very Small Systems,
High Efficiency due to Low Pumping Power

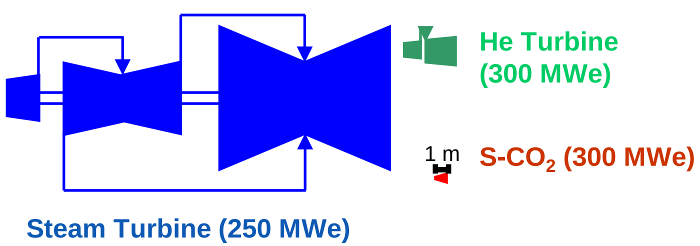


Rejects Heat
Above Critical Point
High Efficiency ***Non-Ideal Gas***
Sufficiently High for Dry Cooling

Critical Point
88 F / 31 C
1070 psia / 7.3 MPa



High Efficiency at Lower Temp
(Due to Non-Ideal Gas Props)



High Density Means Very Small Power Conversion System
Non-Ideal Gas Means Higher Efficiency at Moderate Temperature

Nuclear Applications of s-CO_2 Power

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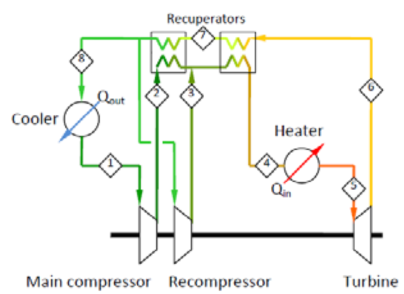
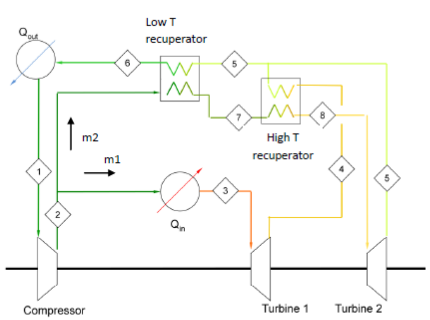
- *s-CO_2 Brayton cycle first rose to prominence in 1960s*
- *Decades later, revived by Gen-IV Forum and work at MIT (2002-2006)*
- *Earlier work served as theoretical basis for ongoing demo projects at SNL (2007-present)*
- *Many studies have been published on use of s-CO_2 in different reactor types*
- *Cycle should be chosen to match ΔT_{rise} with desired ΔT_{rise} across core*
  - *Liquid metal reactors ΔT~150C, gas reactors ΔT~400-500° C*

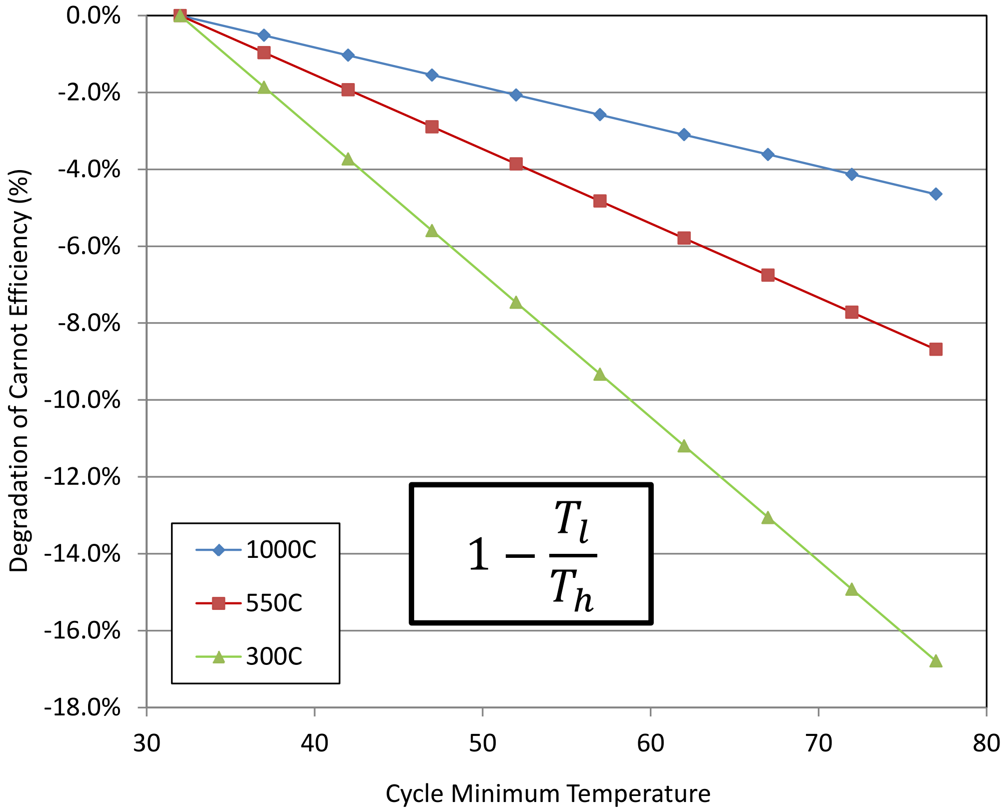




Reactor type	Coolant	Neutron spectrum	Peak Temp.	Optimum S-CO_2 Cycle	
SFR	Na	fast	550°C	Recompression	[Moisseytsev, 2009, etc]
LFR	Pb-Bi	fast	800°C	Recompression	[Moisseytsev, 2008, etc]
GFR-indirect	He	fast	850°C	Cascaded/ Series	[Wright, 2010]
GFR-direct	CO_2	fast	650°C	Recompression	[Parma, 2011; Handwerk 2007]
LWR	H_2O	thermal	300°C	Simple Cycle	[Yoon, 2011; Kao, 2011]
VHTR	He	fast	1000°C	Cascaded/ Series	[Wright, 2010]
MSR	fluoride salt	fast/ thermal	1000°C	Recompression	[Forsberg, 2012]

Dry Cooling Power Cycle Efficiency

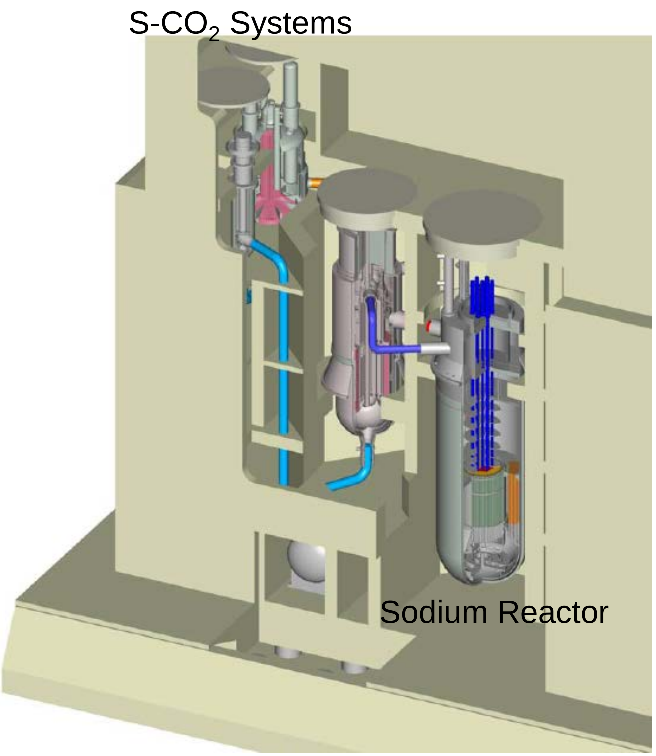
- *Power cycle lower limit is hostage to ambient air conditions*
- *May result in elevated compressor inlet conditions*
  - *negatively impacts cycle efficiency*
- *Certainly introduces increased variability (day/night, seasonal, etc)*
- *Effect is reduced for high temperature cycles*



Case Study: SFR at 550C turbine inlet temperature

- *Intermediate temperature SFR at 550°C chosen as example for further study*
- *Currently baseline concept for DOE-NE ARC Program*

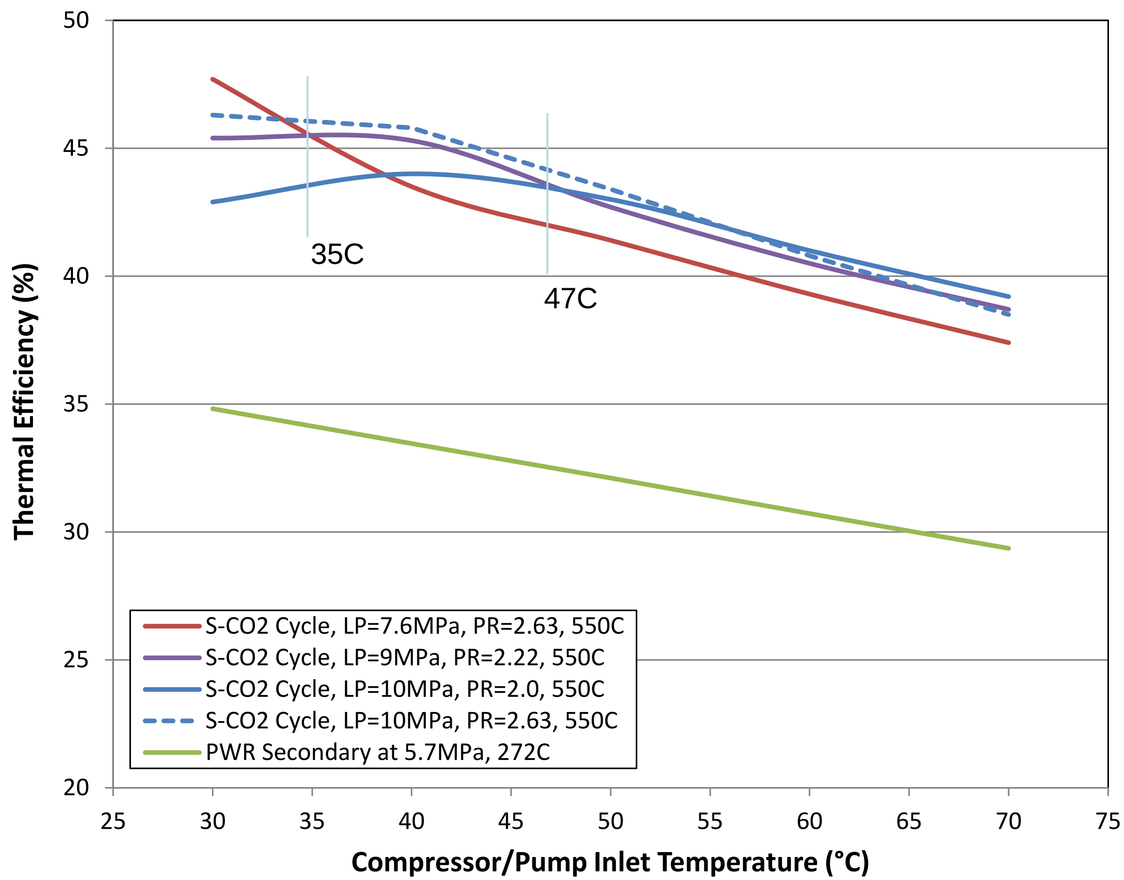
- *SFRs have operated 550°C+ (Phenix, etc)*
- *Metal corrosion with CO_2 well understood (AGRs, lab-scale tests)*
- *Hot enough to reach 48% thermal efficiency, Cool enough that materials risks are minimal*
- *Design condition 150°C temperature rise [Sienicki 2007]*
- *Use of SS316 and other standard materials*
- *Na-CO_2 coupling removes Na-steam interaction, eliminate intermediate Na system?*



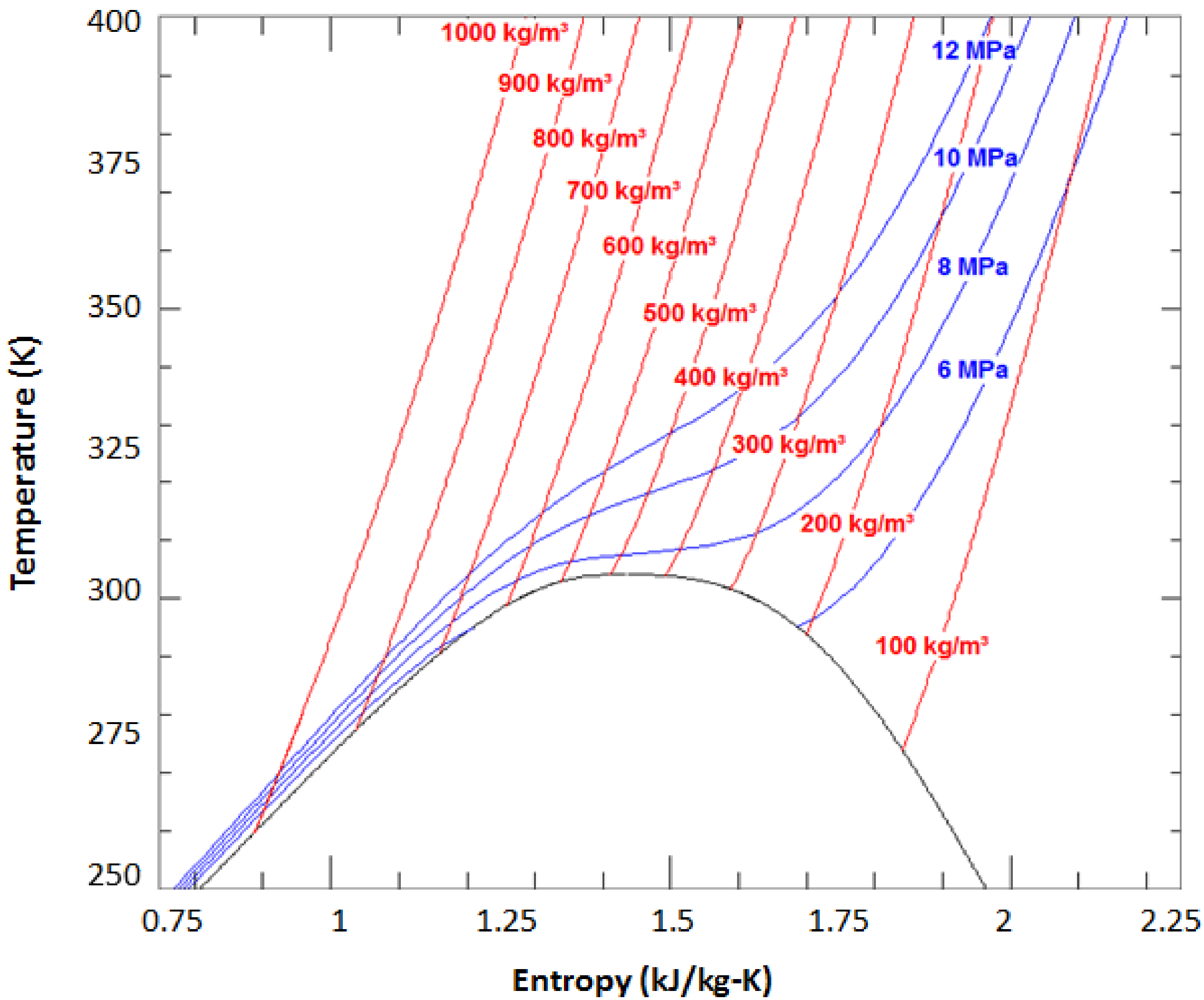
[ANL, 2005]

S-CO_2 cycle efficiency vs. compressor inlet temp

- *Simulates temperature rise due to change in ambient conditions, ie dry cooling*
- *Near critical point, efficiency is very sensitive to change*
- *Results show that increasing pressure helps, even if max pressure is fixed*

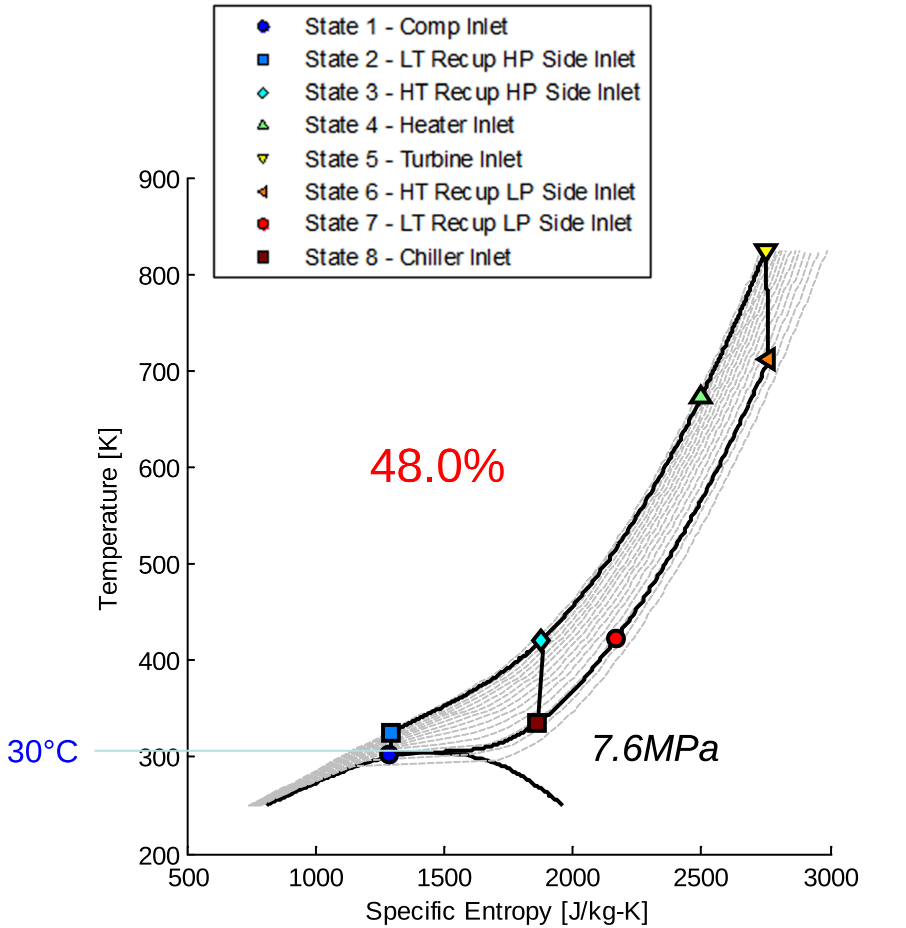


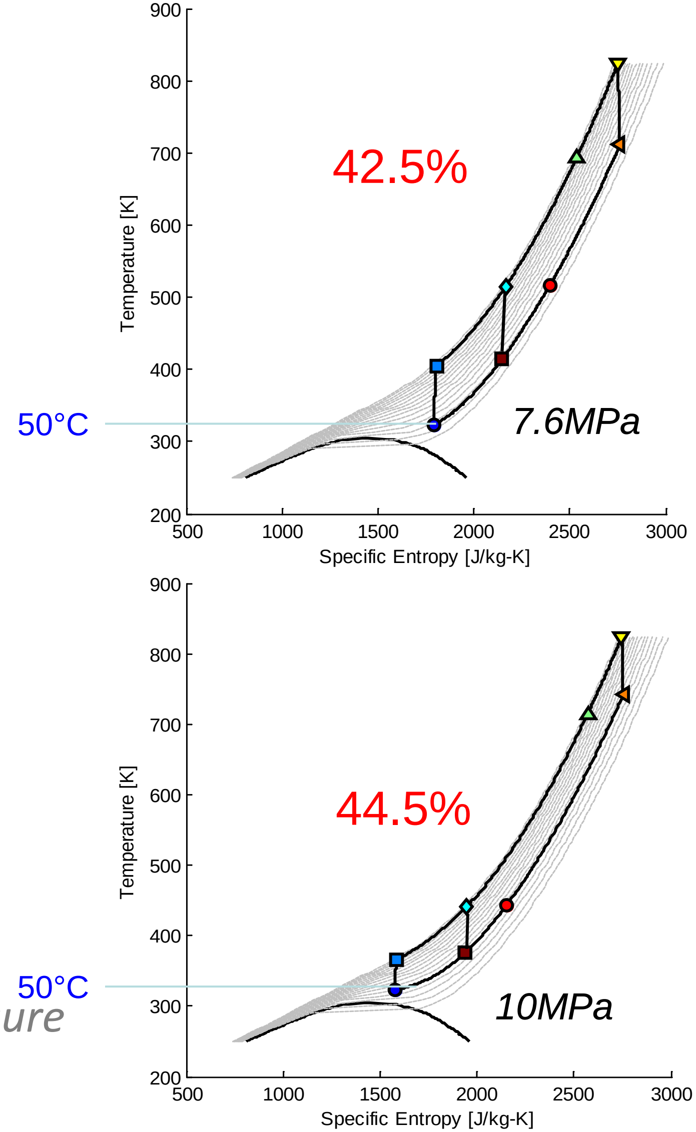
CO_2 Equation of State



- *s-CO_2 cycle relies on low compressibility, high density of fluid during compression for reduced pumping power*
- *Density increases for a constant temperature by increasing pressure*
- *Analogous chart can be drawn to show CO_2 compressibility*
- *As temp rises, CO_2 conditions are adjusted for min. work*

s-CO_2 cycle optimization





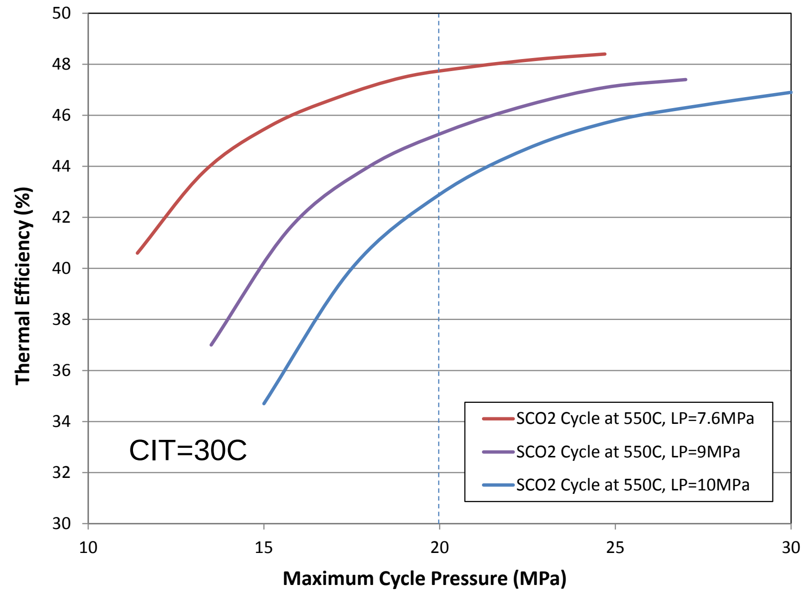
- *Unlike steam system, cycle min temp and pressure can be controlled independently, as ambient conditions change*

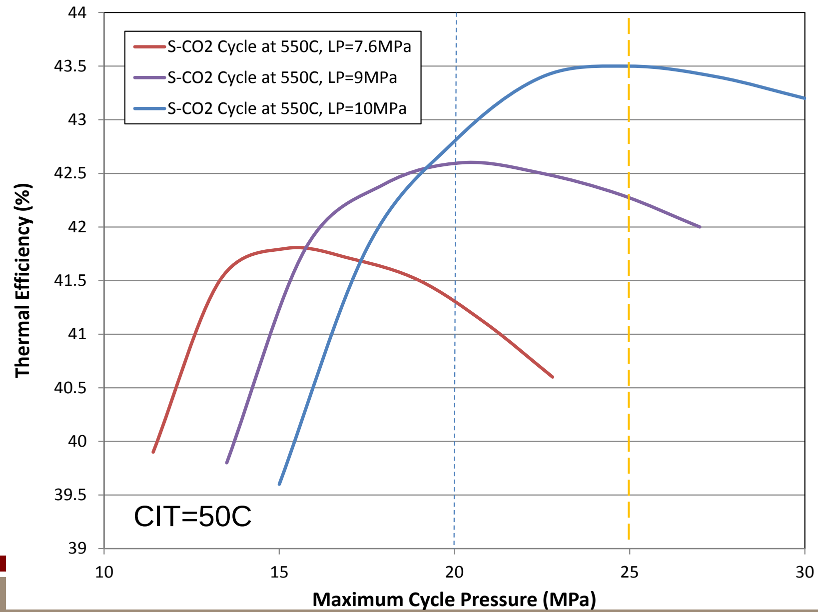
$s\text{-}CO_2$ cycle optimization

- ***Studies show that for a standard $s\text{-}CO_2$ case (T_{min}=30C), pressure ratio should be increased as much as is feasible***

- ***Baseline high pressure ~20MPa, max for present fossil systems ~25MPa***

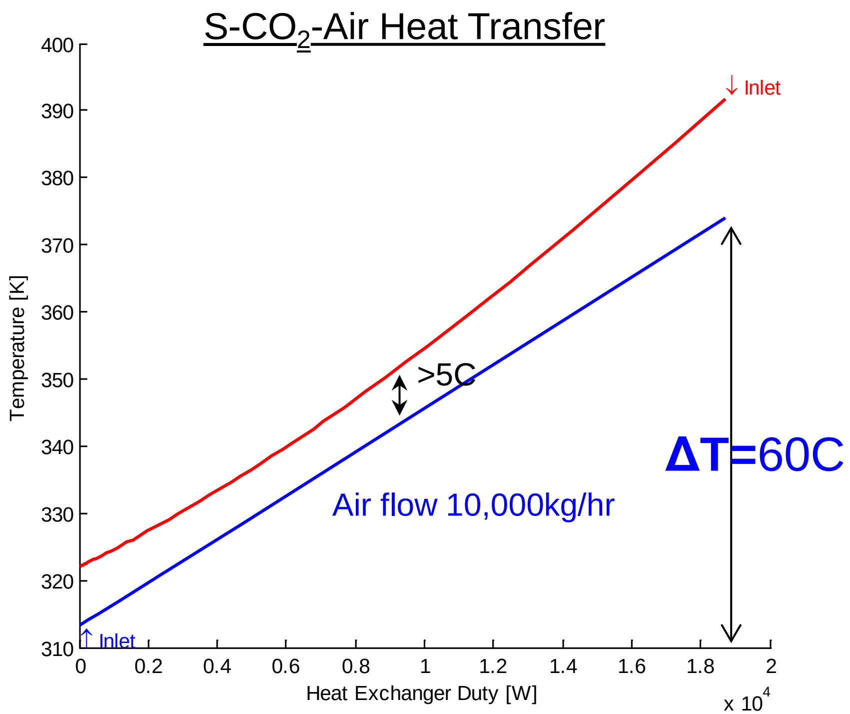
- ***For a warmer 'dry-cooled' $s\text{-}CO_2$ case (T_{min}=50C), a distinct peak occurs, high min pressures show clear benefits***

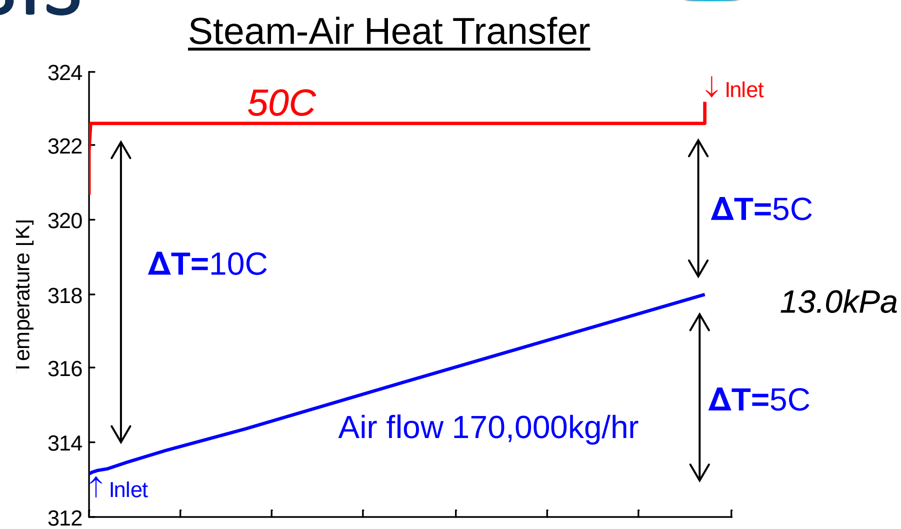




Air-Cooled HX Analysis

- ***Assumes ambient air at 40C, no pinches <5C***
  - *Plots generated using SNL HX design tool [Carlson, 2013]*

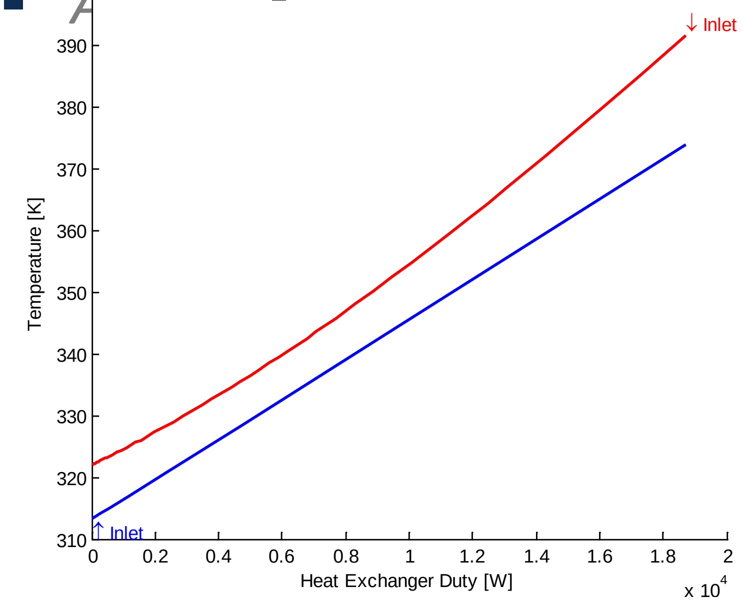




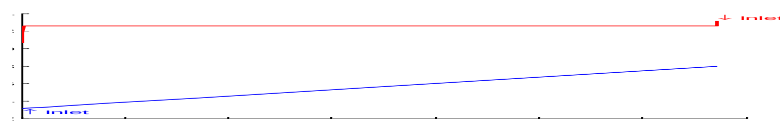
- ***Two cases:***
  - ***To achieve same heat transfer***
  - ***Air temp = 40C***
  - ***CO_2 inlet temp = 50C***
  - ***same UA value,***
  - ***17x air flow is needed***
- ***Not optimized; in practice steam pressure is increased***

Air-Cooled HX Analysis

S-CO_2-Air Heat Transfer



Steam-Air Heat Transfer

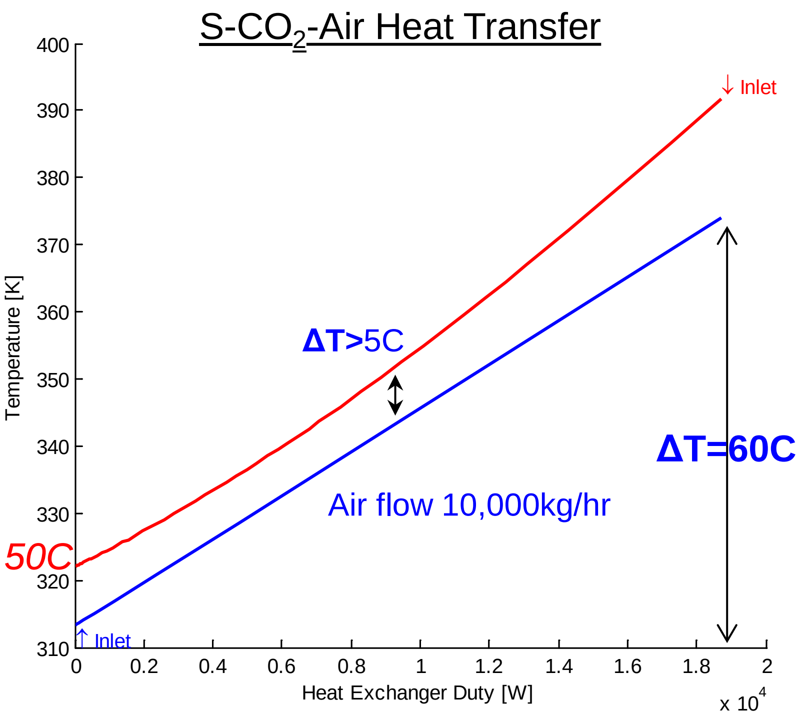


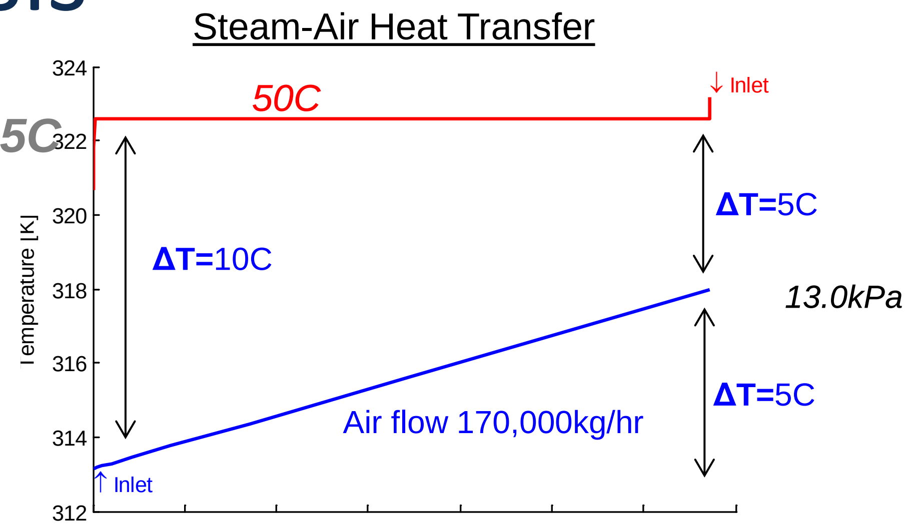
- *Two cases:*
  - *achieve same heat transfer*
  - *Air temp = 40C*
  - *CO_2 inlet temp = 50C*
  - *same UA value,*
  - ***17x air flow is needed***

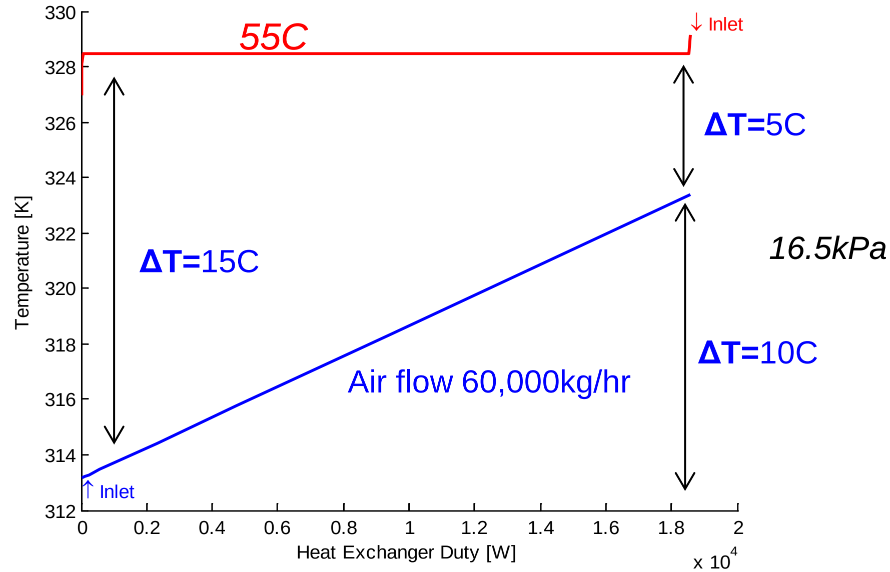
- ***Not optimized; in practice steam pressure is increased at cost of efficiency***

Air-Cooled HX Analysis

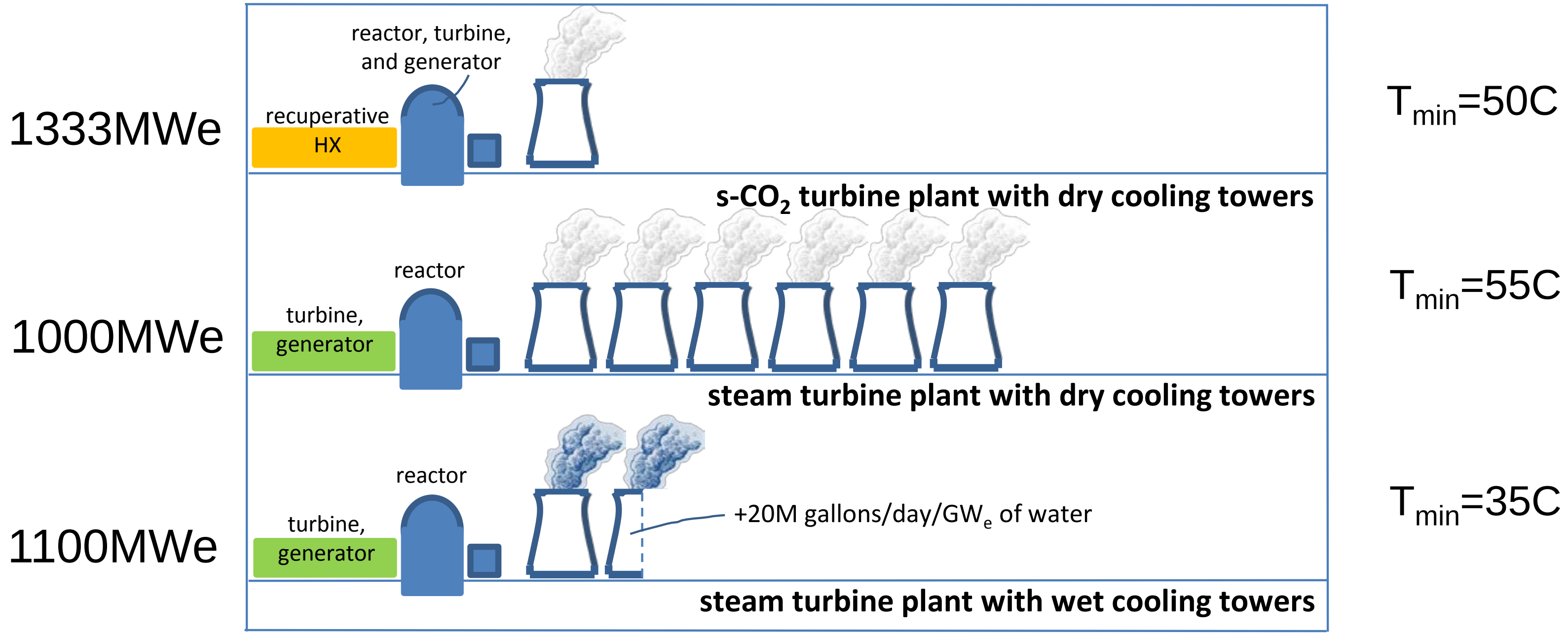
- ***Assumes ambient air at 40C, no pinches <5C***







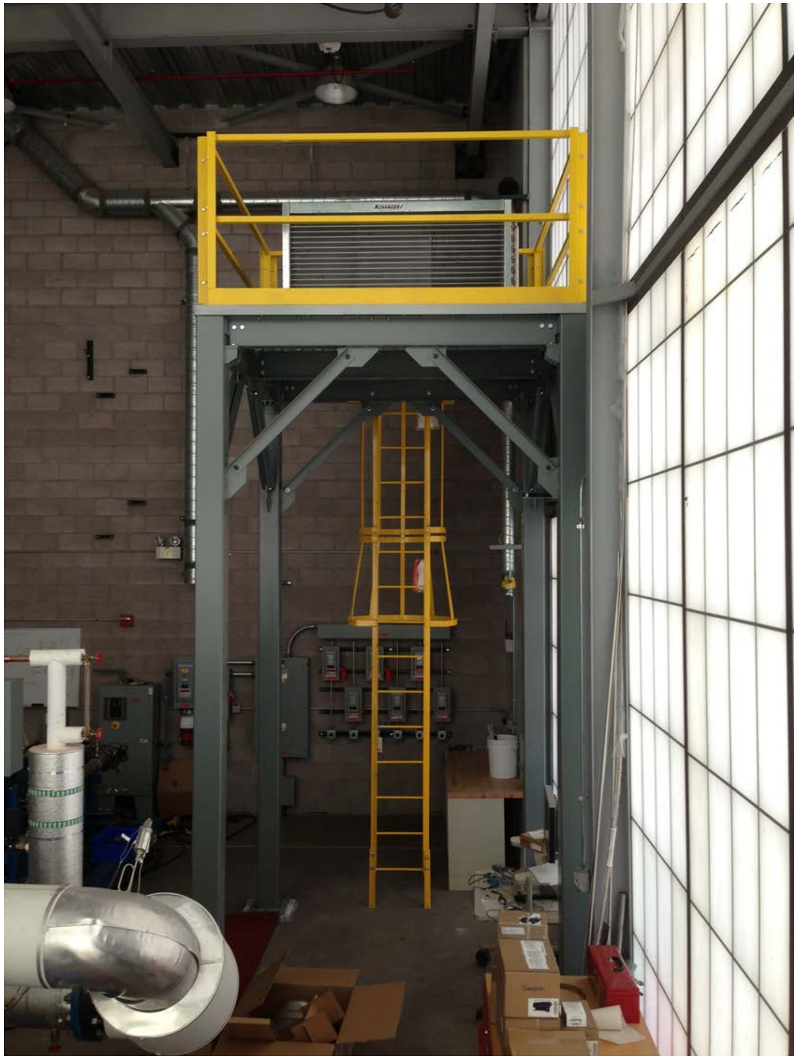
s-CO_2 allows reduction in dry cooling costs



- *'Artist's conception' of dry-cooled s-CO_2 plant as compared to steam*
- *Assuming dry natural draft units, s-CO_2 needs 1/6th cooling towers of steam-- therefore **cooling tower costs for dry-cooled s-CO_2 may be competitive with wet cooled steam plants, + higher thermal efficiency***

Experimental Work: Passive, Air-Cooled Supercritical CO_2 Test Loop

- **Loop has been designed and constructed, testing not yet begun**
  - Dry cooler operation, dry cooler heat exchanger profile temps
  - Passive decay heat removal
  - S-CO_2 inventory control operations
  - S-CO_2 based mixtures
  - Air-cooler surface coatings and advanced geometry for reduced size.
  - High pressure sight-glasses allow for two-phase visualization
  - S-CO_2 pumping power at alternate inlet conditions



S-CO_2 natural circulation

- Increased reliance on passive emergency cooling using natural circulation is a major goal of next generation SMRs
- Natural circulation is driven by gravitational head resulting from elevation and density differences in a closed loop.
- Supercritical CO_2 is ideally suited for establishing natural circulation flow
  - Large density variations are achieved for only small elevation in temperature
  - This allows natural circulation to occur earlier in the emergency transient, provide increased flow throughout
  - Viscous-to-buoyancy forces of a given fluid are a good indicator of natural circulation potential (Grashof number);
  - At conditions of SCO_2 heat rejection system, the Grashof number is 4 orders of magnitude higher than water for a 10C temperature rise (1)

$$Gr = \frac{g \beta \rho^2 L c^3 \Delta T}{\mu^2}$$

Parameter	Units	CO_2	Water
Bulk Temperature	K	300	300
Pressure	MPa	7.69	7.69
β	1/K	0.039	0.00037
ρ	kg/m^3	275.6	996.7
μ	Pa-s	2.21e-5	6.94e-4
Gr		5.9e14	7.5e10

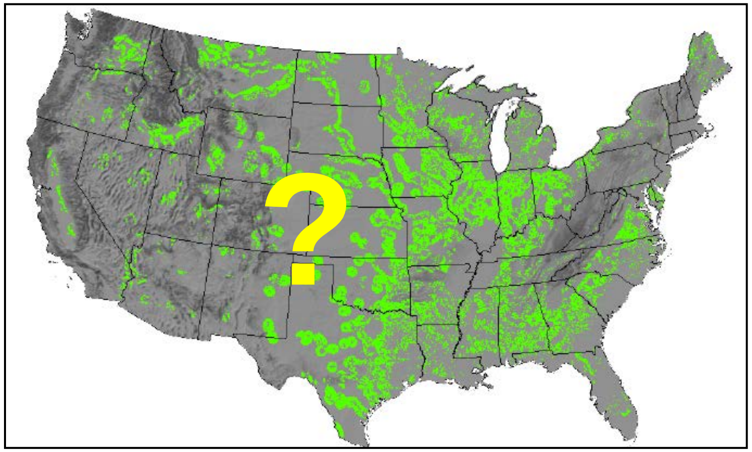
*Parameters were evaluated at conditions typical of an SCO_2 power heat rejection system.

(1) Parma, et al, (2011)

Conclusions

- ***Dry cooling has not penetrated commercial steam plants because of economics, fundamental limits of air-cooled condensation***
- *For LWRs, water needs extend beyond the cooling tower*

- *S-CO_2 power cycles can achieve **higher efficiency** with elevated inlet temps, but this alone **is not enough to make the case***
- *For a number of reasons, s-CO_2 can be well matched with air-cooling, **cooling tower costs for dry-cooled s-CO_2 appear to be similar to wet-cooled steam***
- *More detailed analysis is needed*
- *Experiments underway*



- *Siting map should be reconsidered*
- *Safety and regulatory issues*
- ***Application to many different reactor types could help fuel the rise of all Gen-IV systems***