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Workshop on New Cross-cutting Technologies for Nuclear Power Plants

Session 2: Supercritical CO_2 cycle for advanced NPPs

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Can we increase the efficiency/utilization? YES

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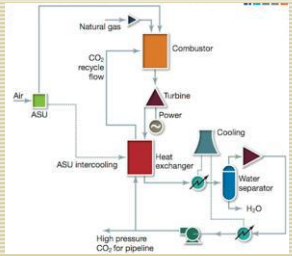
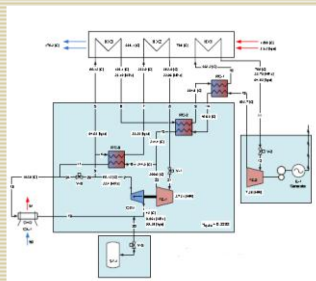
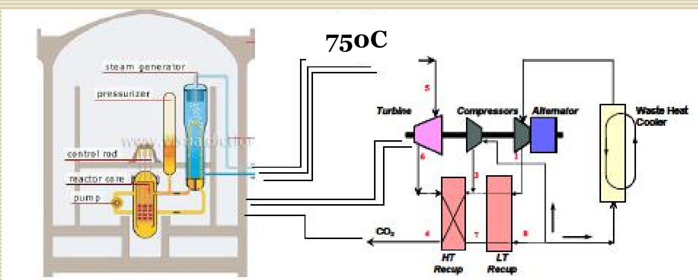
The sCO_2 power cycle allows for high temperature heat and waste heat recovery, carbon capture. (Significant Market Potential)

Potential for Natural Gas/Coal with CO_2 Capture Oxy-Fuel Combustion Cycle (This is already being done by NetPower) 50MWth system

Advanced High Temperature CSP Energy Generation



Advanced High Temperature Nuclear Energy Generation

Increasing from 39% Eff to 50-55%
Provides an LCOE = 6 – 7 ¢/kWh


Energy Generation from Waste Heat, NG-Compression, Industrial

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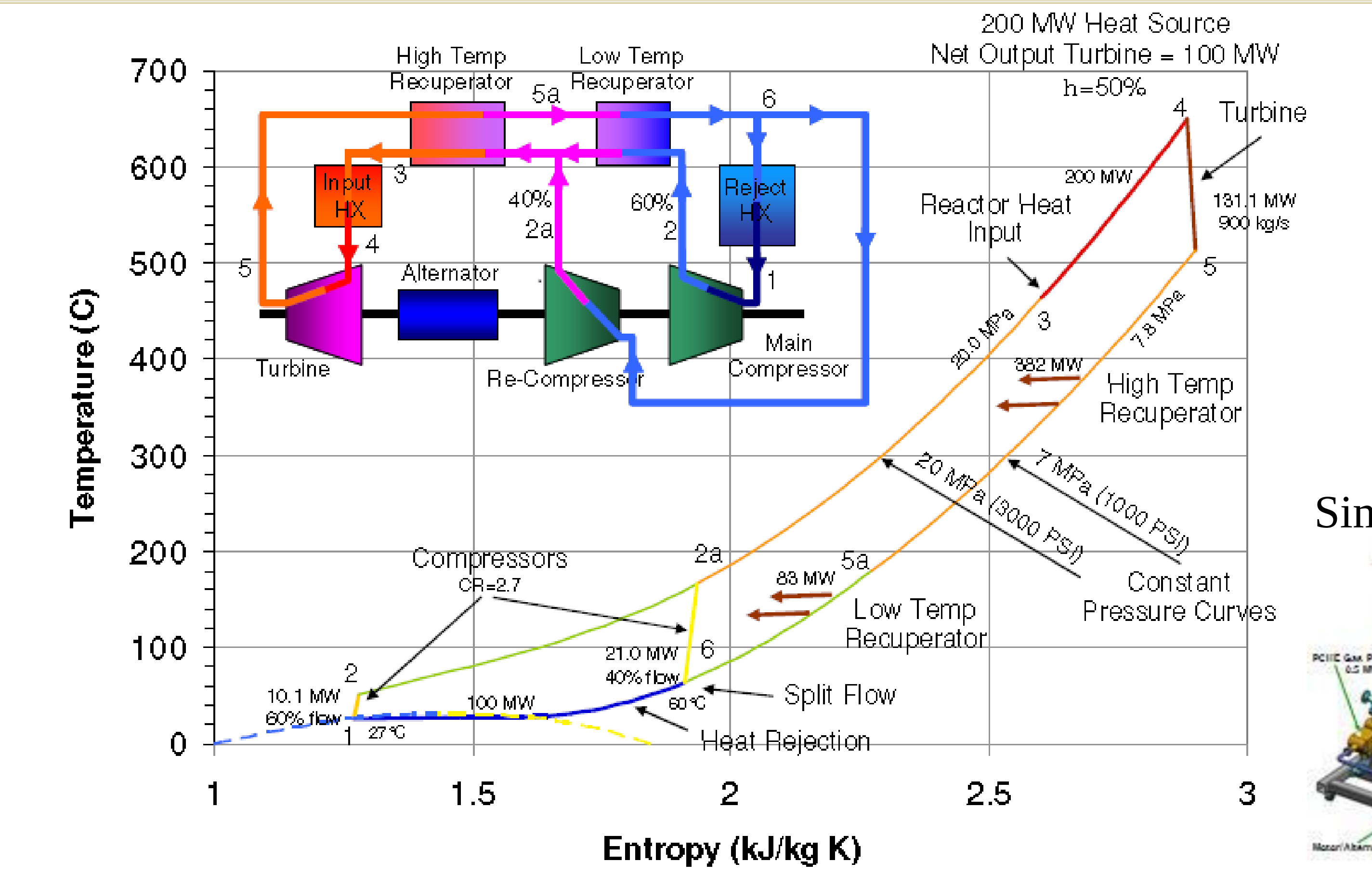
T-S diagram for Split flow s-CO2 cycle "Recompression" Cycle

PC =7.3 Mpa (1070psi), TC=31C (88F)

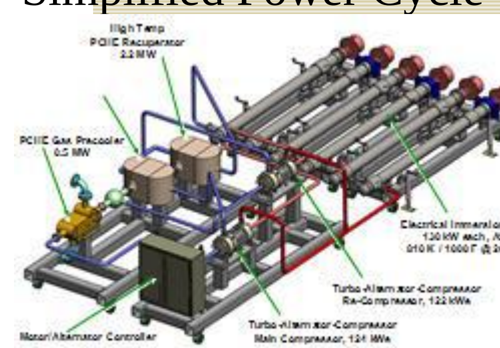


Higher operating temperature

Higher thermal efficiency

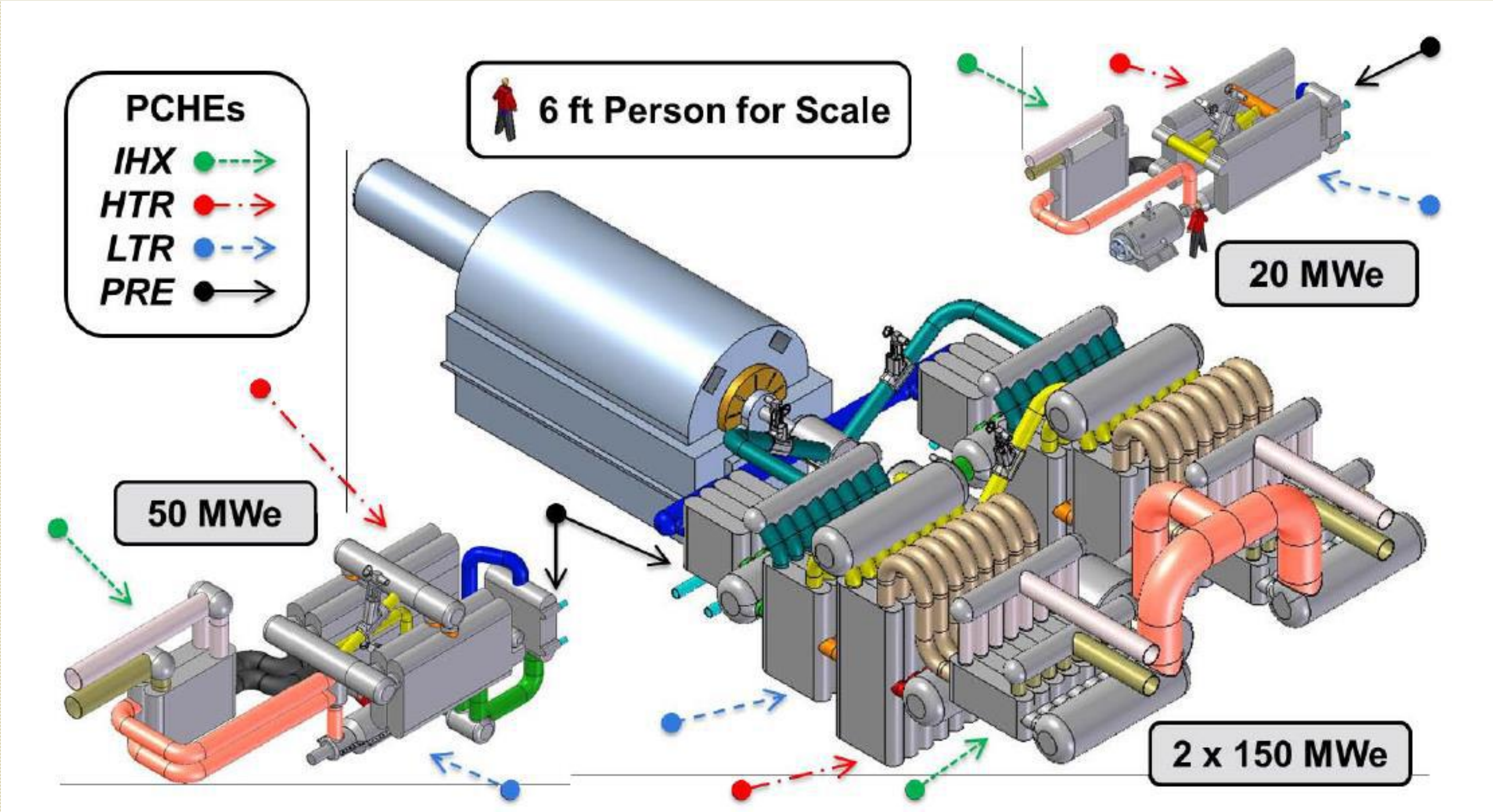
Single Phase

Simplified Power Cycle



SuperCritical Technologies

Larger Scale SCO2 Recompression Cycle



J.P. Gibbs, P. Hejzlar, & M.J. Driscoll. (2006). *Applicability of Supercritical CO2 Power Conversion Systems to GEN IV Reactors* (Topical Report No. MIT-GFR-037) (p. 97). Cambridge, MA: Center for Advanced Nuclear Energy Systems MIT Department of Nuclear Science and Engineering.

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What is Supercritical Carbon Dioxide? Inert Abundant Gas

- Use of carbon dioxide (CO_2) above its critical point.
  - Critical temperature is 31.1°C (88°F).
  - Critical pressure is 7.39 MPa (1,072 psi).

Low temperature acts like a liquid – High temp acts as a gas

- Currently used extensively as a solvent and occasionally as a refrigerant.
  - Dry cleaning, decaffeinating coffee, etc.

- Ideal for use in a power cycle---closer to the ideal Carnot Cycle --- could displace the use of steam -> $10's of billions/year in potential technology.
  - With Condensation Efficiencies increase. "Transcritical Cycle"
  - Cascaded cycles are good for Sensible Heat (WHR, and Fossil)

Abundant – Inexpensive, Non-toxic, GWP=1

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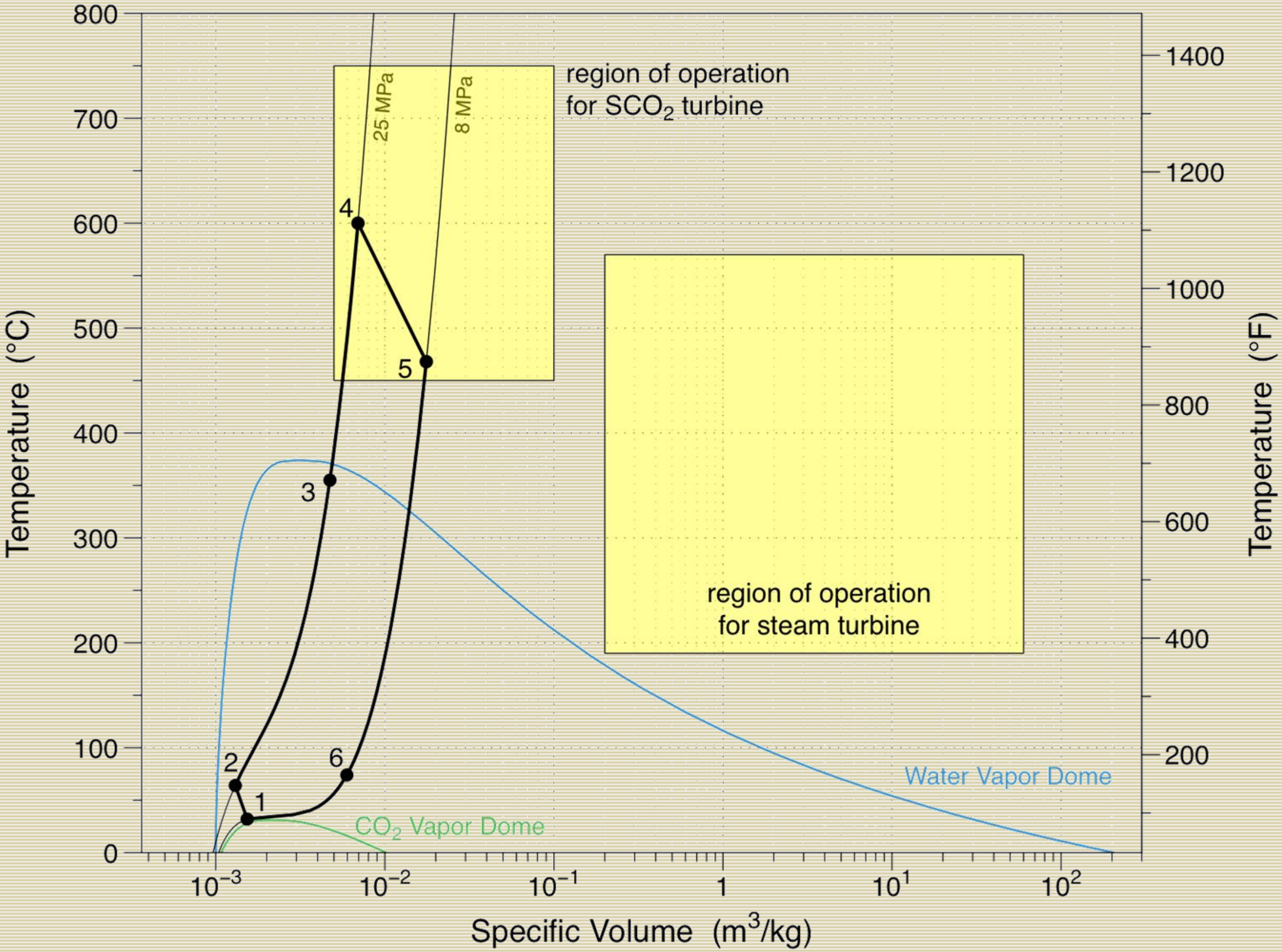
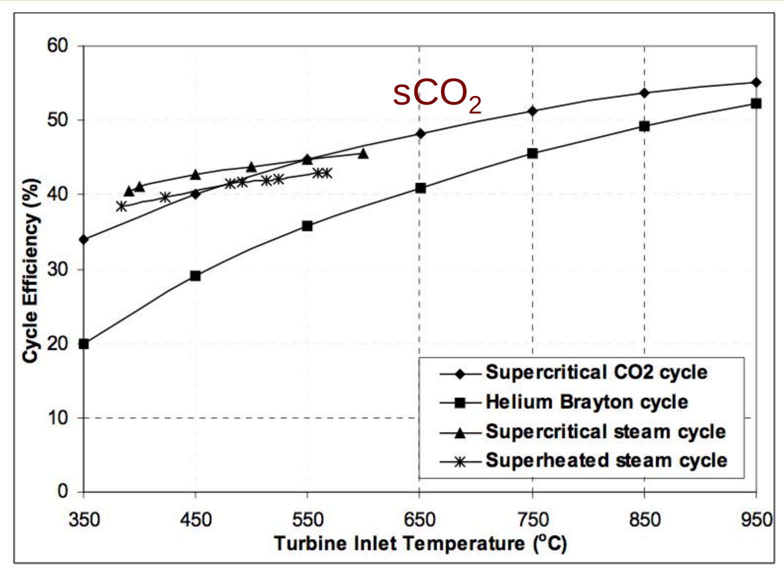
How is this cycle different from Rankine?

sCO_2 Turbine Region of Operation

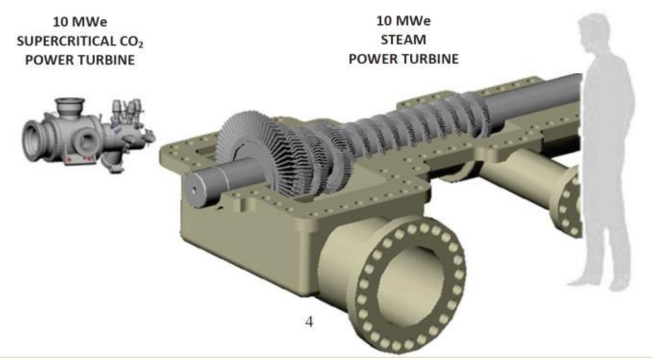


What about capital costs?

The sCO2 cycle is much smaller – less material



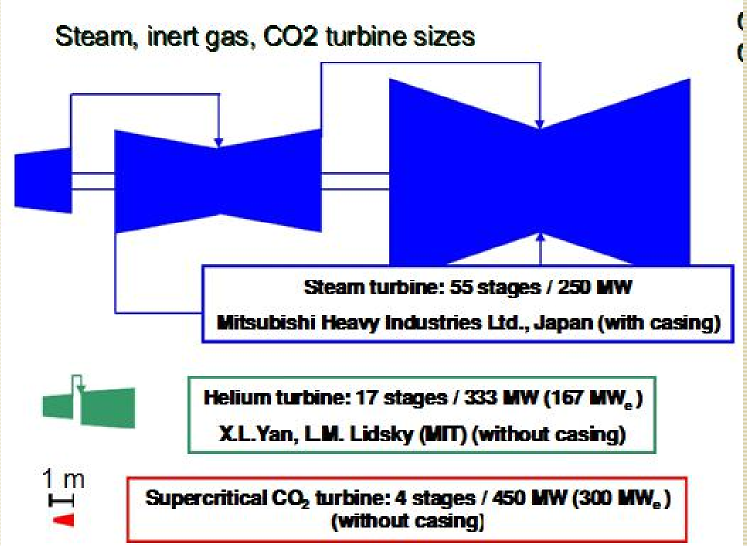
V. Dostal, "A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors," Ph.D. Thesis, pg. 304, MIT, 2004.



10MWe size comparison

sCO2 has high power density

- sCO_2 cycle has potential for thermodynamic performance > steam Rankine
- Potential for improved capital cost saving
  - Turbine size : S-CO2 < He << Rankine
  - Compressor size: S-CO2 <<< He
  - Total pipe volumes: S-CO2<< He
  - Cost of working fluid: S-CO2<< He



Paul Pickard (SNL), 2004

50 kW (67 horsepower) compressor

Wright et al., "Operation and Analysis of a Supercritical CO2 Brayton Cycle," Sandia Report, SAND2010-0171, pp. 1-101 (2010)

Is it more complicated? No

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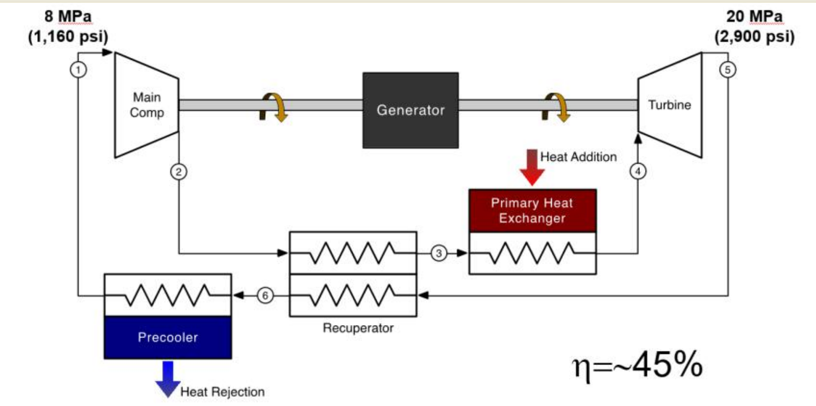
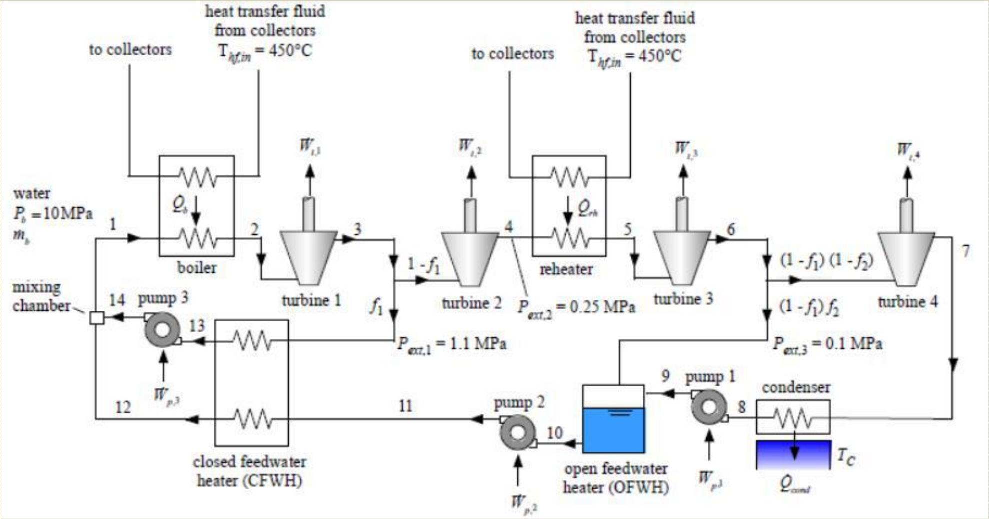
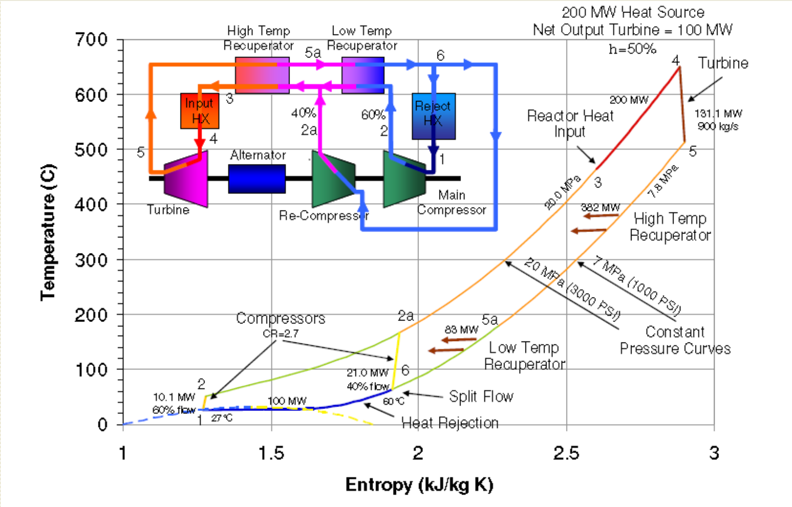
The sCO2 cycle is also actually much simpler

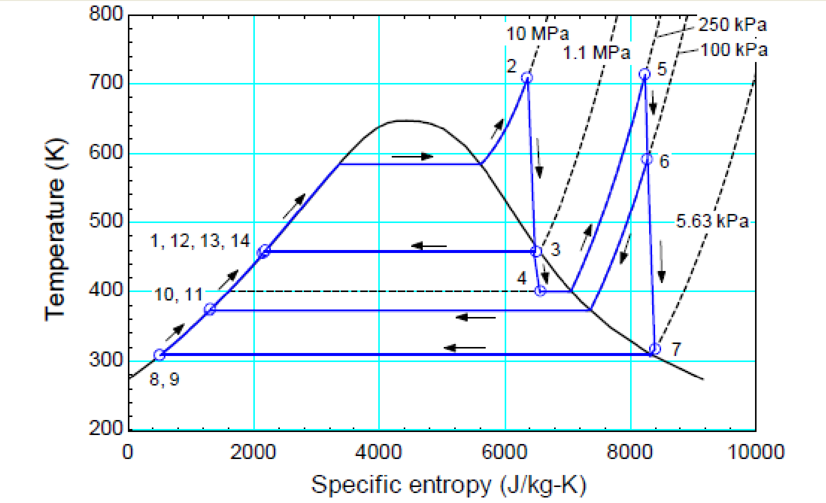




$\eta_{plant} = 45\%$

$\eta_{plant} = 39.8\%$





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There are Lots of SCO_2 Power Cycles

WISCO2

Cycles Appropriate for Heat Flux Based Heat Sources
Nuclear and Concentrated Solar Power (High Efficiency Cycles)

Simple closed recuperated Brayton cycle

SRBC

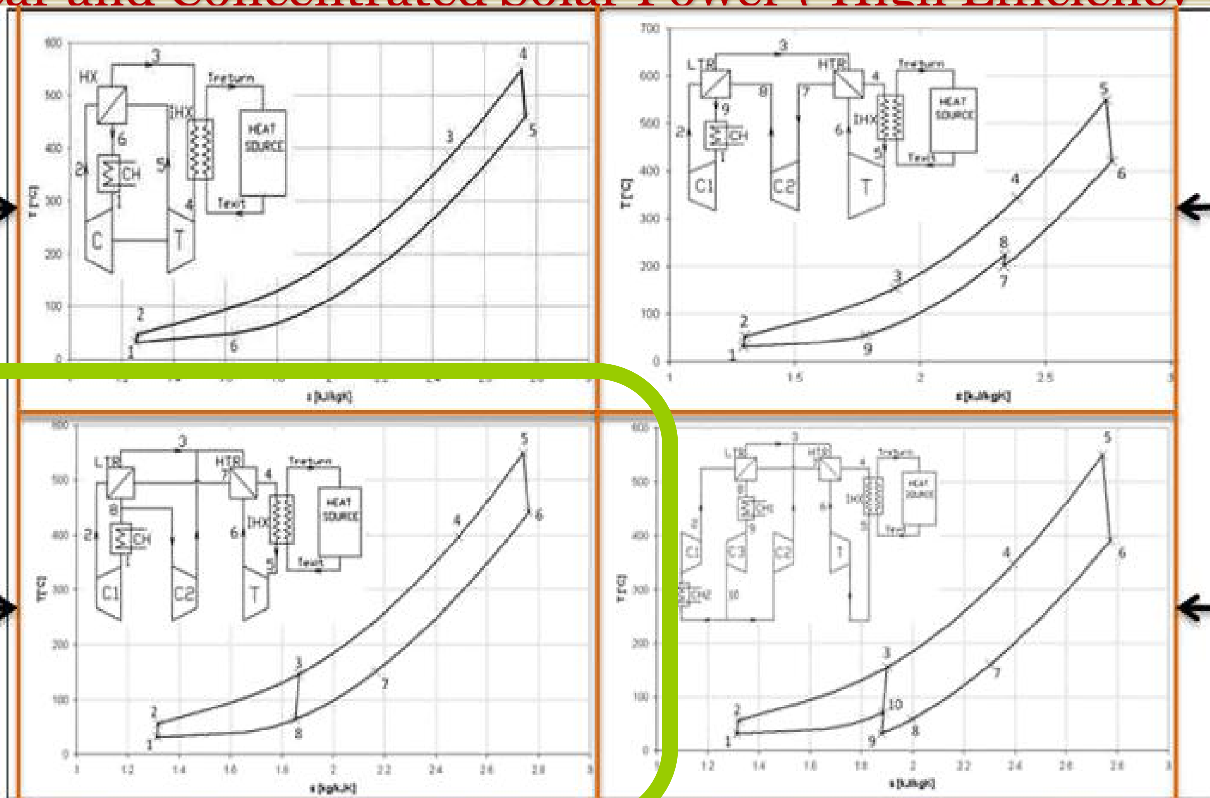
Precompression cycle

Nuclear & CSP

Recompression cycle

RCBC

Partial cooling cycle



Source: Kulhanek M., Doshermtal V., Todynamic Analysis and Comparison of Supercritical Carbon Dioxide Cycles. Supercritical CO2 Power Cycle Symposium, May 24-25, 2011

Recompression Cycle has Highest Efficiency
Variations such as Condensing, Inter-Cooling, Reheating improve efficiency
Other Cycles available for Sensible Heat Power Systems

SuperCritical Technologies

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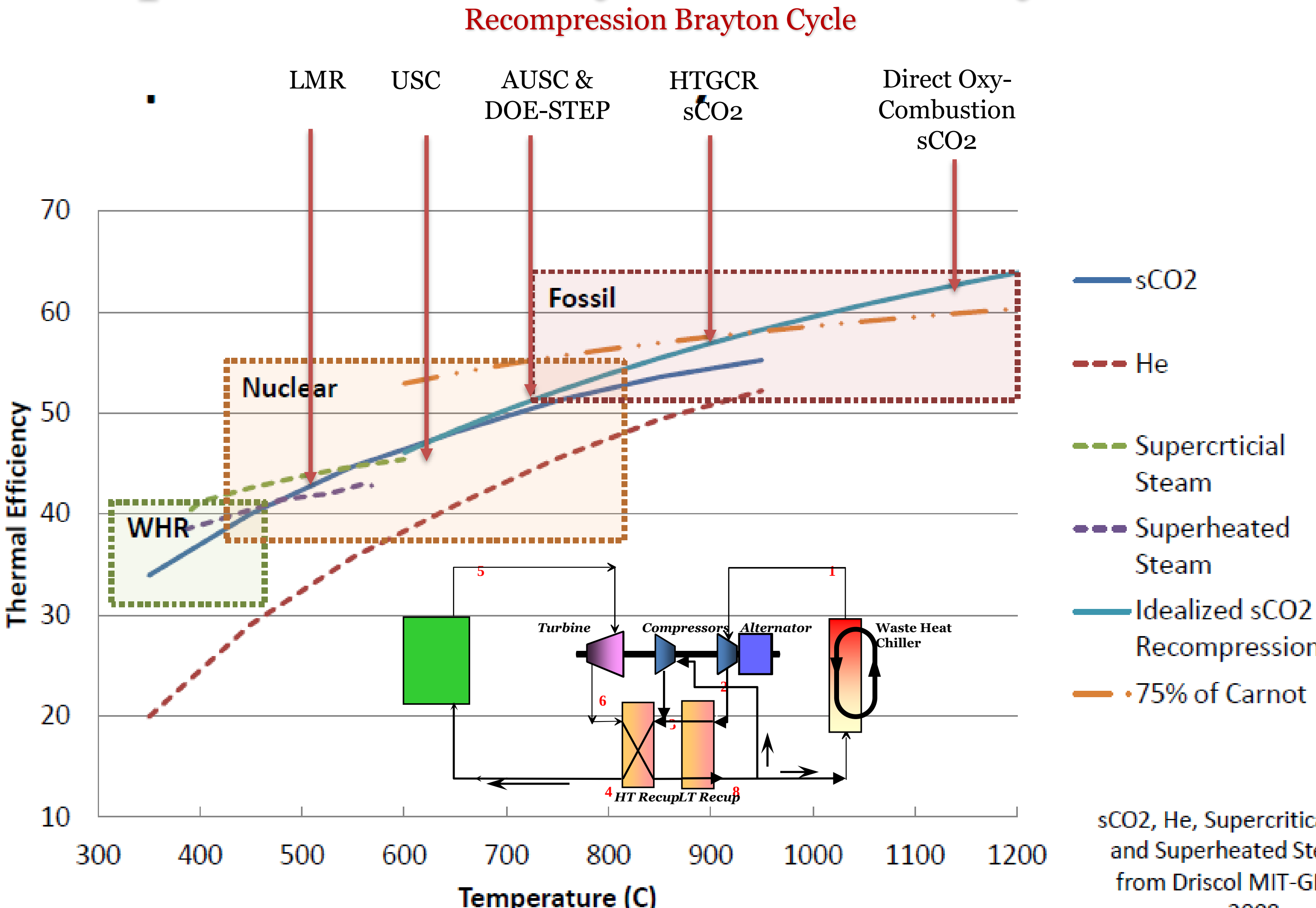
Representative Cycle Efficiency (from McClung 2015)



sCO2, He, Supercritical Steam, and Superheated Steam are from Driscol MIT-GFR-045, 2008

sCO_2 Power Cycle: Advantages & Disadvantages

Advantages

1. 2-4 Percentage Points more Efficient than Steam Plants at same Turbine Inlet Temperature (Re-Compression Cycle is closer to the Ideal Carnot Cycle)
2. Small Turbomachinery (due to low pressure ratio => Lower Costs)
3. Operates well with Dry Cooling (Larger dT, Pinch Point is less Challenging, Benefits for CHP)
4. Operating Pressure is Same or Lower as in Steam
5. Integrates well with all Heat Sources + New Opportunities (Bulk Energy Storage)
6. Potential for Very High Temperature Operations (750-1200 C) (Eff 50-60%)
7. Oxy-Combustion Enables Fossil Fuels with Near Zero Emissions

Disadvantages

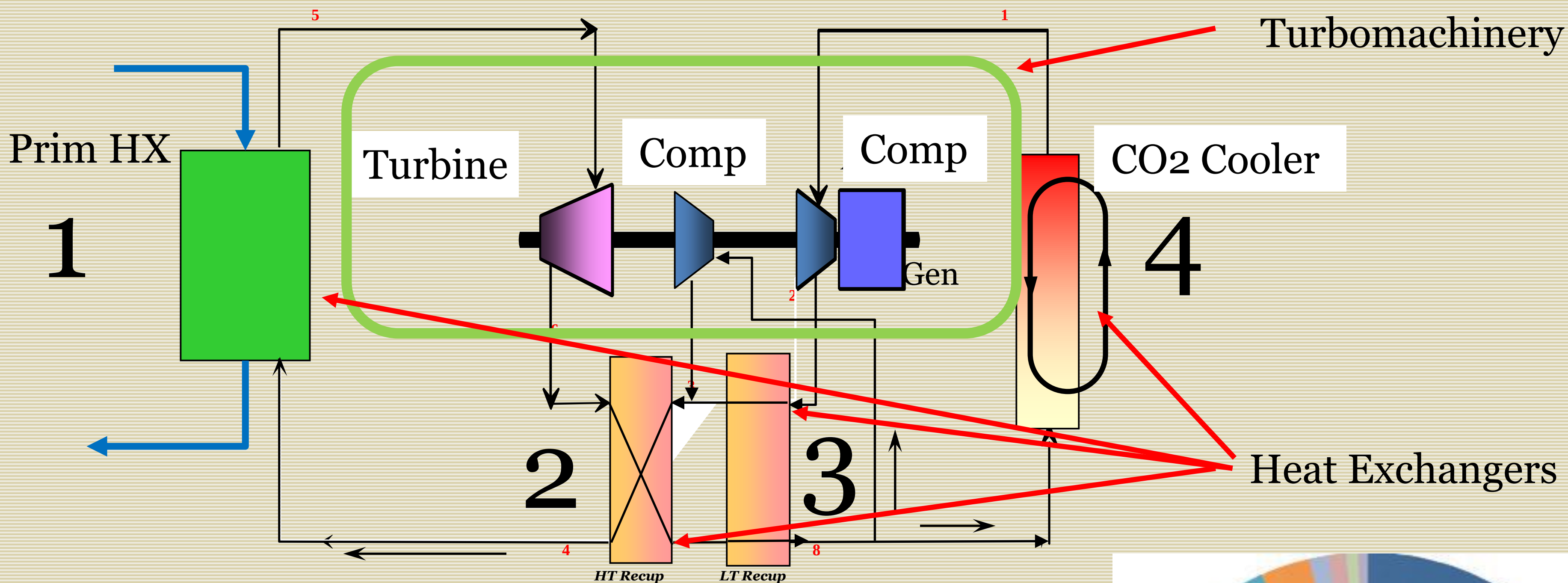
1. Added Capital Costs Due to Recuperation and High Temp. Heat Exchangers & High Nickel Steels
2. Very High Power Density in Turbine (Reliability needs Proving + New Design Req.)
3. Generally Needs Higher Mass Flow Rates than Steam (may limit size to 300-600 MWe)
4. Costly Materials at High Temperature
5. New Technology for Oxy-Combustion and High Power Density Turbines

CROSS CUTTING TECHNOLOGIES

Small Turbomachinery
Turbomachinery Support Hardware
Heat Exchangers
Materials

Supercritical Oxy-Combustion
sCO_2 High Temperature Reactors

Turbomachinery is Small but High Risk
Heat Exchanger Costs Can Be Large (~50% depending on design)



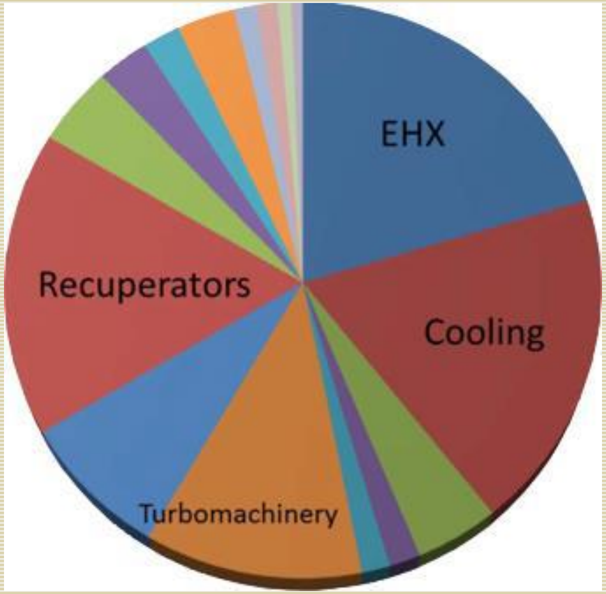
SCO2 RCBC: 4 Heat Exchangers

Steam Rankine: 2 Heat Exchangers

Gas Turbine: 0 Heat Exchangers

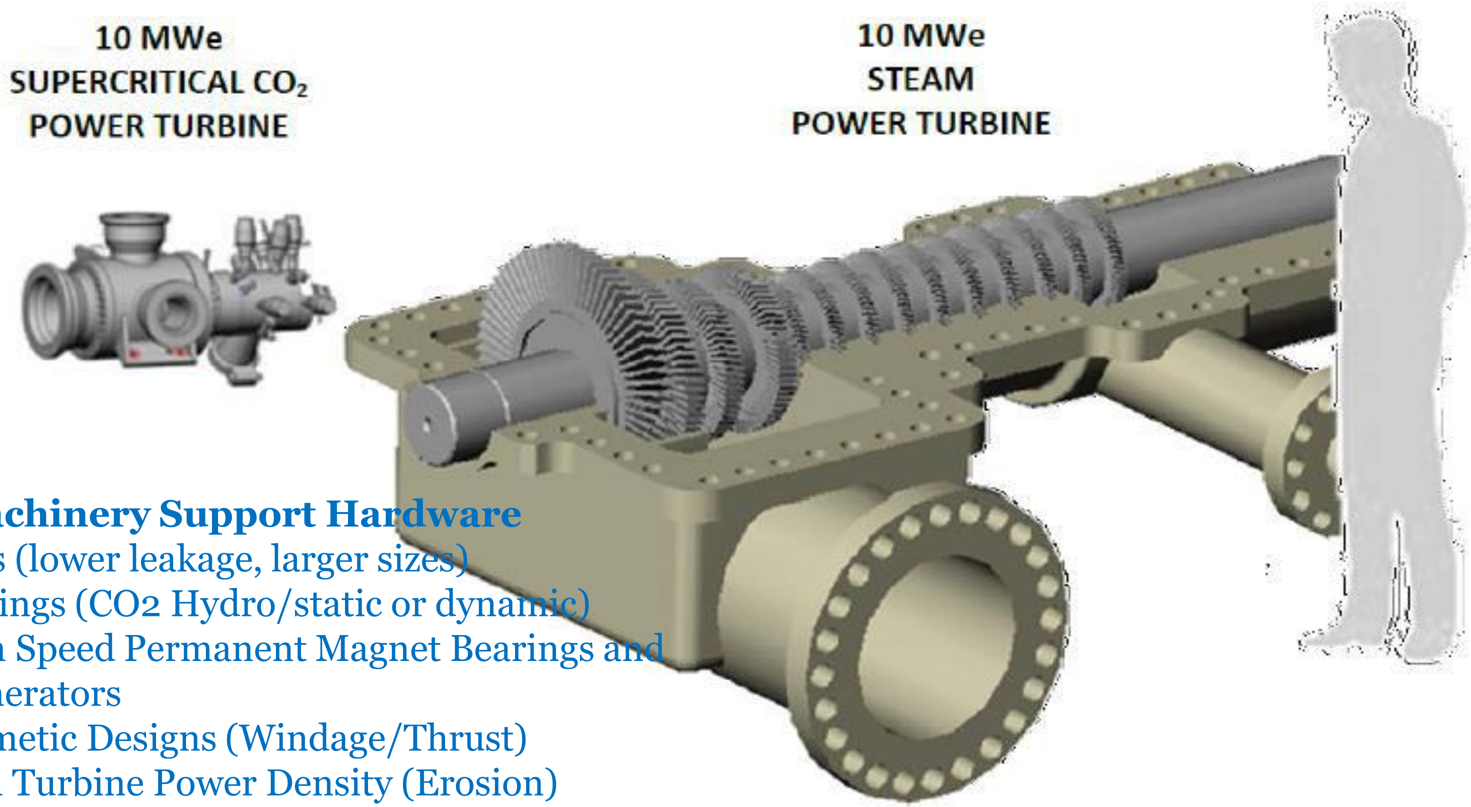
Cost Break down

Tim Held Echogen



WISCO2

Example: 10 MWe Turbine Comparison



Turbomachinery Support Hardware

- Seals (lower leakage, larger sizes)
- Bearings (CO2 Hydro/static or dynamic)
- High Speed Permanent Magnet Bearings and Generators
- Hermetic Designs (Windage/Thrust)
- High Turbine Power Density (Erosion)
- Small Size complicates thermal management

SwRI

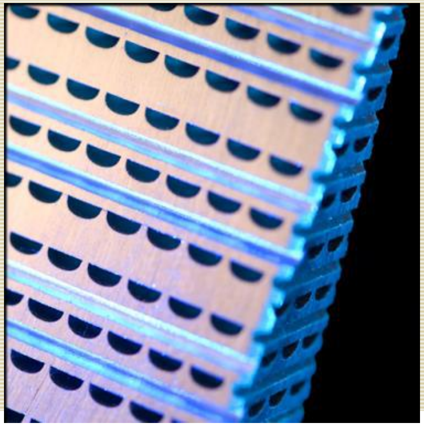
Source (Musgrove, et al: Fundamentals: SWRI

Source: Persichilli et al. (2012)

Advanced Compact Heat Exchangers

Channel D_h 1-2 mm : 1000-4000 m^2/m^3 High Pressure Capable

Micro Channel Diffusion Bonded Heat Exchanger MCHE



U Stamp
Multiple Vendors
1-2 mm Width

MICRO TUBE HX

5 tonnes

Meets ASME Design Specs.

Tube and Shell Standard Welds Inspectable

Ustamp & Nstamp Capable

Less Material …

Lower Cost

Robotic Assembly

Corrosion Resistance Issues?

Tubes & Headers $^1/_{16}$" to ¼"

Microtube HXs Lead to Cost Reductions
30%-100% for SS300 series steels
Factors of 2-4 for Advanced Alloys

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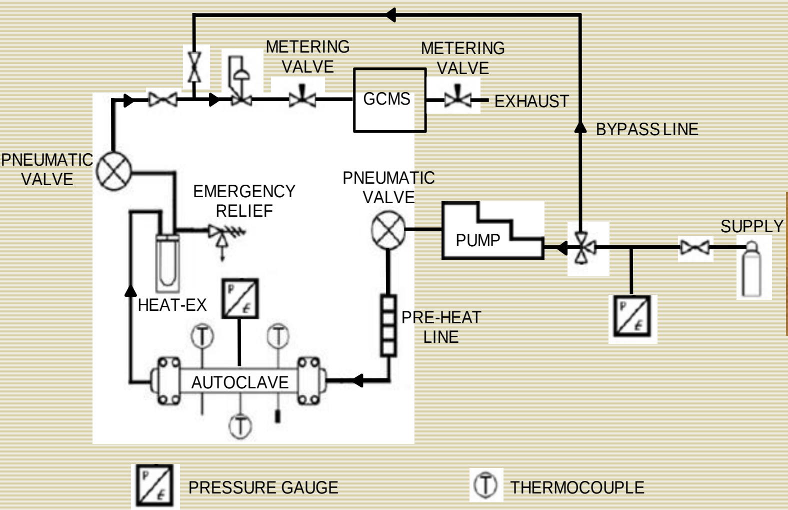
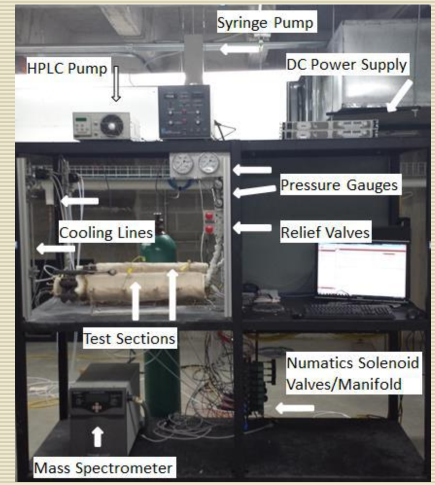
sCO_2 Materials Research

Several groups, vendors and world wide are looking at corrosion in CO2 and there is a lot of collaboration in this area.

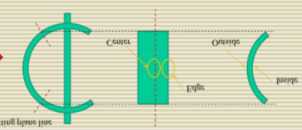
$S\text{-}CO_2$ Static autoclave testing





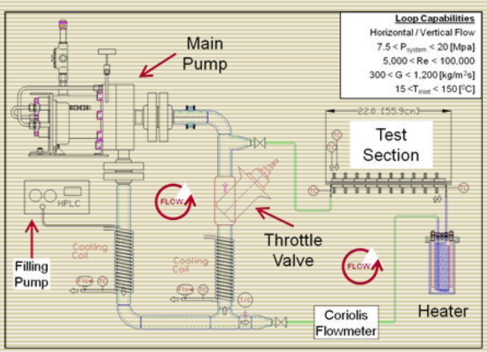
Flow

Applied stress



Component testing

$S\text{-}CO_2$ Flow testing (corrosion/erosion)



Low speed HX test facility

Valve, seal, high speed flow test facility

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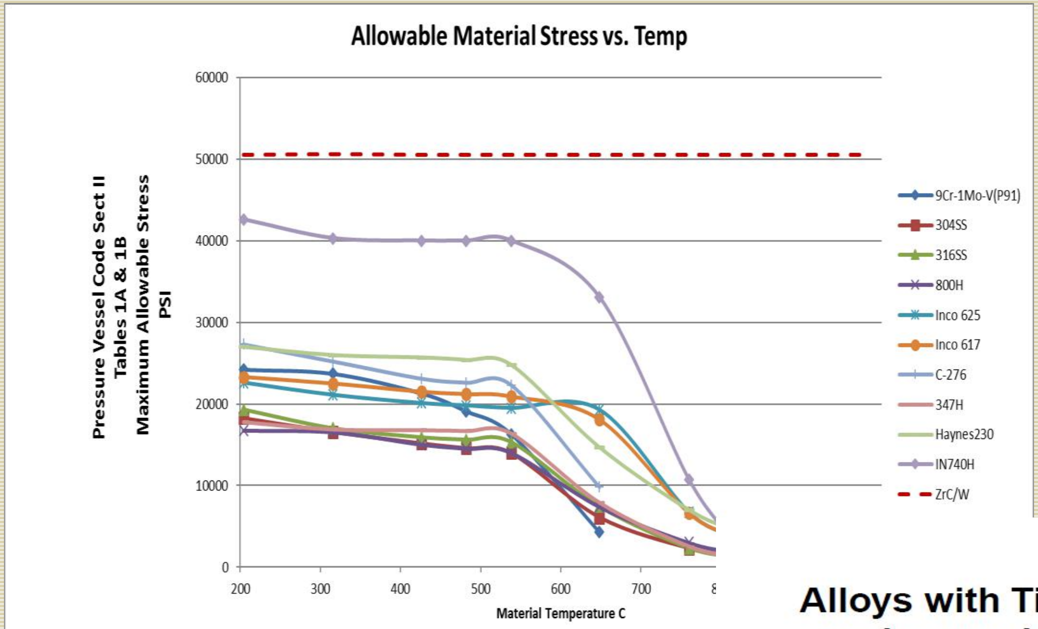
Current Status of materials



Higher Creep Strength at Elevated Temperatures

Lower Corrosion at Elevated Temperatures

Alloys with Ti, Ni, Al, and high Cr typically have good corrosion resistance

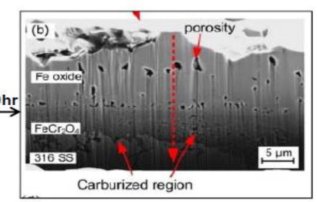
Alloys with high amounts of Cr and Ni and trace amounts of Ti and Al build a stable oxide layer to resist corrosion

Steel alloys with low amounts of Cr typically build up a duplex layer with a thick iron oxide layer

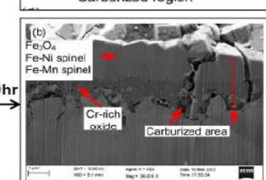
Decreasing corrosion resistance

ODS	Nickel	Austenitic	Martensitic
Cr ~ 20%	Cr > 16%	Cr > 16%	Cr < 12%
PM2000	IN625	304SS	T91
MA754	IN617	310SS	F91
MA956	PE-16	316SS	HCM12A
MA957	Haynes 230	AL-6XN	HT9
		UNS S30815	
		800H	

3000hr



3000hr



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[Cao 2012]

SwRI

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Alloys	Oxide	Number Density	overall corrosion rate	Comments
Haynes 282	Elongated Nb-Ti rich oxide cluster (50um)	Low	(~1um-2um)/year@750C	Excellent corrosion resistnace/ good strength at temp
	Cr rich oxide (<1um)	High		
IN740	Elongated Nb-Ti rich oxide cluster (50um)	Low	(~1um-2um)/year@750C	Excellent corrosion resistnace/ good strength at temp
	Cr rich oxide (<1um)	High		
Haynes230	Elongated W rich oxide cluster (30um)	Medium	450C - <1um/year 550C - <1um/year 650C - 5um/year	Good corrosion resistance. Needs to be looked at for higher temps.
	Cr rich oxide (<1um)	High		
IN800H	Ti oxide cluster (20um)	Low	450C - 1-2um/year 550C- 5 um/year 650C - 30 um/year	Performed similar to 347 but cost is considerable higher
	Cr-Mn rich oxide (<1um)	High		
	Octahedral Fe oxide cluster (30um)	Medium		
347SS	Nb oxide (<1um)	Medium	450C - 5um/year 550C- 5um/year 650C - 35um/year	Alloy performed pretty well at most temps - started to fall off at 650 not suitable for higher temps
	Needle Cr-Mn rich oxide scale	Whole surface with some spallation		
	Octahedral Fe oxide cluster (20um)	High		
316L	Octahedral Fe oxide scale	70% of surface	450 C - 10um/year 550 C - 30-50um/year 650 C- 100 um/year	Ok for lower temperatures 347 performed much better
	Octahedral Cr-Mn rich oxide scale	30% of surface		
AFA-OC6	Nb oxide (<10um)	High	450C - 1-2um/year 550C- 5-10um/year 650C - 200um/year	Ok for low temperatures/ alloy somewhat unstable
	Cr-Mn rich oxide (<1um)	Very high		
	Fe oxide (<10um)	Low		
P91/T122	Magnetite and spinel layers	100% coverage high corrosion rate	>1000mu/year	not suitable for 450+

There is currently also work looking at impurities and coatings

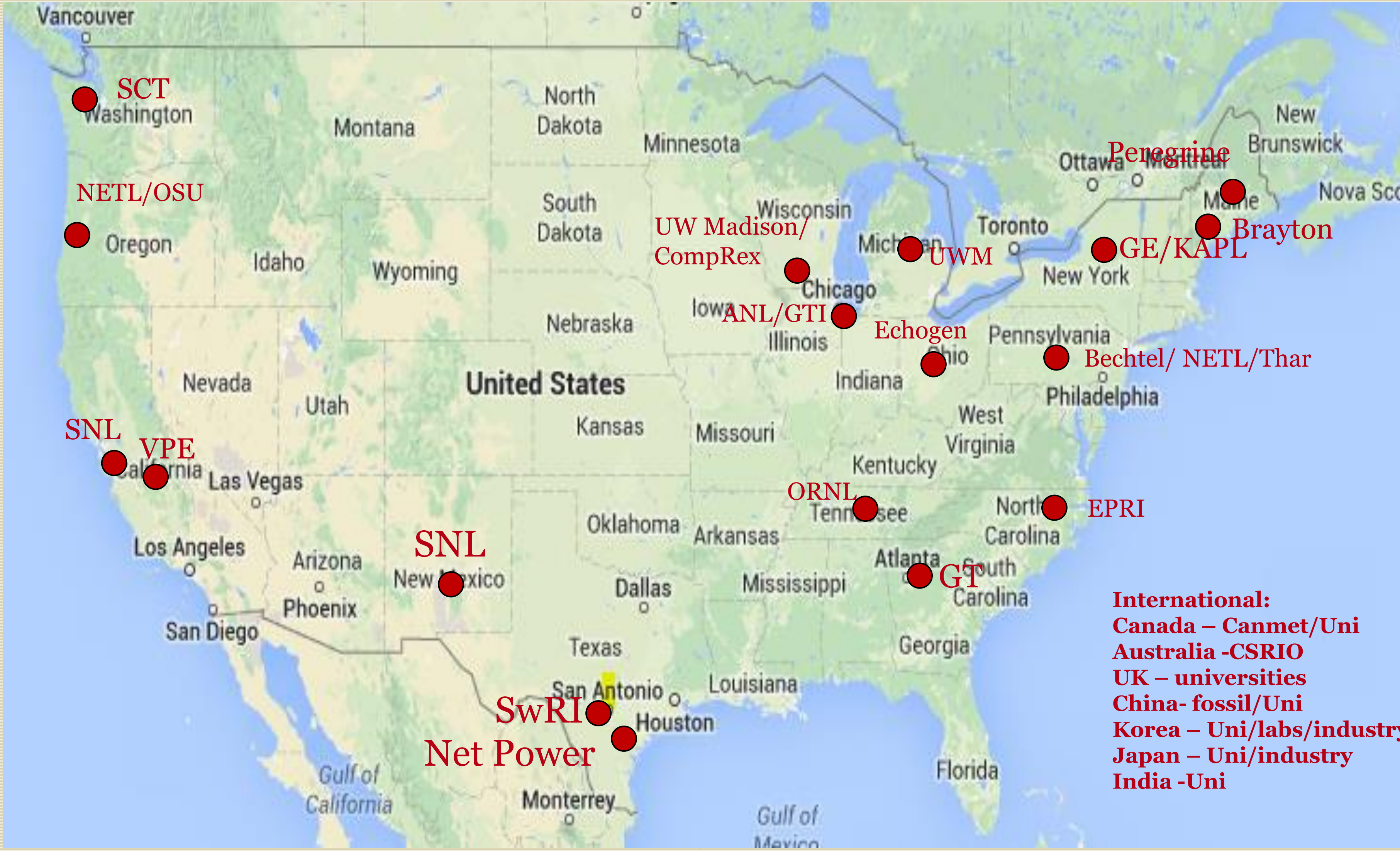
Dostal V., Driscoll MJ, Hejzlar P.,

Cross Cutting Technology Conclusions

- **MIT Study on sCO2 Power Conversion for Nuclear Reactors : Cross Cut Success**
  - **Fostered a New sCO_2 Power System Industry (Nuclear, CSP, WHR, Fossil) (see map)**
  - **Enables Burning of Fossil Fuels with Zero Emissions at Affordable Costs**
  - **Cross Cutting Support within DOE (EERE, FE, NE)**

  - **Turbine is high risk component, but small and affordable**
  - **Micro-tube Heat Exchangers offer low mass, small size and lower costs**
  - **New Materials (Alloy 740 has high creep strength and low corrosion)**

Current sCO2 work sites



International:
Canada – Canmet/Uni
Australia -CSRIO
UK – universities
China- fossil/Uni
Korea – Uni/labs/industry
Japan – Uni/industry
India -Uni

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sCO_2 Power and Reactors

Eff increase from 39% to 50% -55% Lowers Cap Cost and LCOE

Direct sCO2 Reactors Lower Capital Costs and Lower LCOE Costs

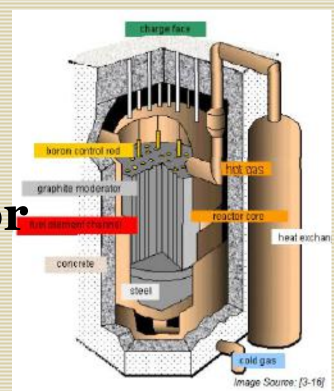
- No prim HX, No 2ndary HX,
- Smaller Reactor and Turbine Hall
- Natural Circulation for Decay Heat Removal
- Much higher efficiency (55%) at 850-900C

Indirect Cooled Reactors

- Focus on Lower Cap. Costs
- High Temp 700-750C and high 50% efficiency

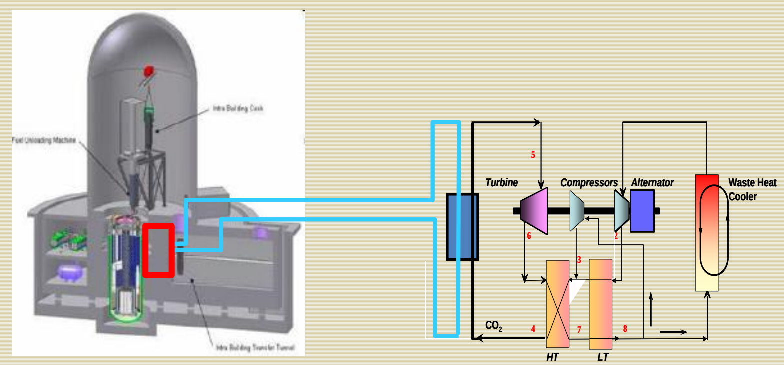
Direct

sCO2 Gas Cooled Reactor



Indirect

Molten Salt
Pb
Sodium



Primary Loop 2 ndary sCO2 Power Cycle

$$\mathrm{LCOE} = \left(\frac{\text{Project Cost } - \text{PV Tax Shield} + \text{PV Lifetime Operating Costs} + \cdots}{\text{Lifetime Electric Production}}\right)$$

sCO2 Power System Costs

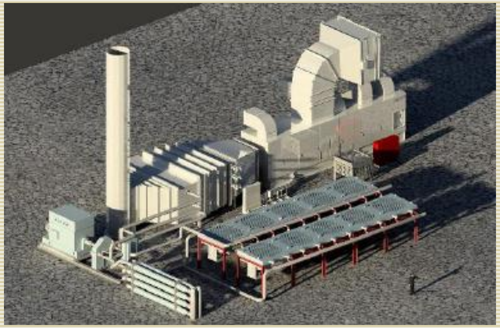
Gas Turbine	15 MWe
sCO2 Plant	5 MWe
Efficiency	47-48%

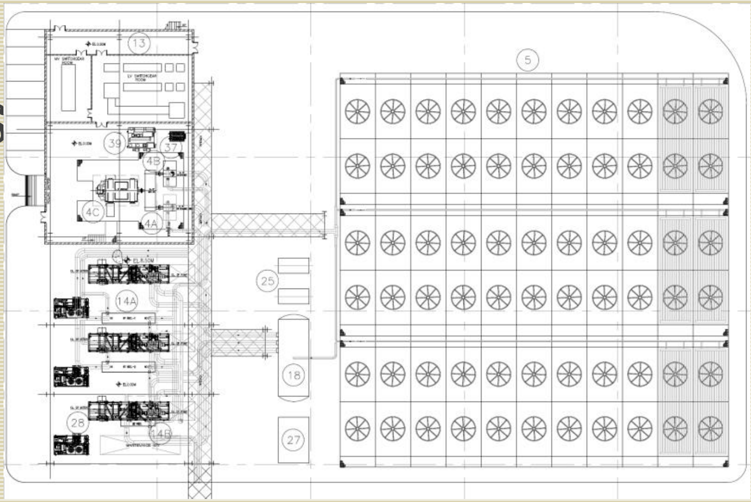
SCT 5-10 MWe sCO2 WHR

- Plant Costs WHR 1.2-1.5 $/We n^th^ of a kind

GE-(Dash et al. 2013) sCO2 Demo

- Net Power : 137.5 MW
- Efficiency : 49.31 %
- Plant Cost (10th unit) : 146.6 M$
- Plant Specific Cost: **1070 $/kWe**
- No DM Water Plant, less O&M
- Suitable for remote operation & fast start





Future: Advanced sCO2 Power System

Green = Zero Emissions
Blk = NGCC like Emissions

COST SUMMARY				
Plant Type	Cap Cost		LCOE	eff
	Overnight Cost $/kWe	Fuel Cost $/mmBTU	Base Case ¢/kWh	
sCO2 System Estimates				
Nuclear				
Gen IV HT-Nuclear	tbd		tbd	50% - 55%
[8]Adv. GEN-III+	**5945**		**9.97**	**39%**
[9]NuScale LWR-SMR	**5078**		**10**	**24% est**
sCO2 HTCGR eff-55% no HX *****	**4000 -5400 est**		**6.4 est**	**55%**
NGCC				
[8]NGCC (2016)	978	3 est	5.64	52% (est)****
[7]NGCC CCS (2010)	**1637**	**6.55**	**11.0**	42.2%
[7]Oxy-CES(Steam)	3146	6.55	14.2	44.7%
Coal Oxy-sCO2				
[10]PC Coal-CO2 Indirect SWRI	5600			
[12]PC Coal-CO2 Indirect BAH			11	
[13]Coal-Gas CO2 Direct NetPwr		1.73	6.5	
NG Combustion Gas Turbine or sCO2 Turbine				
[8]Advanced Gas Turbine	678		9.36	36-40%(est)
[11]NG-sCO2 GE Feasibilty	1100		6.0 est	49.30%
NG Direct Oxy-sCO2				
[13]NG-NetPower Allam (2016)		**3**	**4**	**52%-60%**
Oxy-CO2 Direct (2016) ***	1800-2800 (est)	3	7 (est)	**52-60%**

Gen III + with 10% Reduct Cap X Eff Increase to 55%

NG with 52-55% Net Ef

1) **Adv sCO_2 Nuclear Competitive to NGCC**
2) **Existing Nuclear Competitive to NGCC – CCS**
3) **Oxy-Combustion Competitive to NGCC**

SuperCritical Technologies

WISCO2

sCO2 Development Path

Next Step in sCO_2 Evolution

- *Multiple 5-10 MWe or Greater Pilot Plant Systems (WHR or Biomass)*
- *Commercial (Echogen& Affiliates, SuperCritical Technologies, Peregrine Turbines)*

sCO_2 Systems High Temperature System

- *Systems having: Zero Emissions using Fossil Fuels*
  - *Commercial Net Power, Toshiba, CBI, Exelon*
- *Systems having High Temp, High Efficiency for Reactors & CSP*
  - *US Government STEP Program + Other Nation States*

Call for proposals for a 6 year $100M program (20% required cost share) to develop and test components of a 10MWe sCO2 cycle that operates at 700C

Oct 17, 2016 DOE announced a $80M STEP initiative project award led by GTI with GE and SWRI as major team partners. Contract Negotiations are still in progress.

*Caution: All early systems are **Developmental***

SuperCritical Technologies

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Conclusion: sCO_2 Reactor Business Model

- ***Proposal***
  - *US or International Corporation*
  - *Develop High Temperature, High Efficiency Reactor with sCO_2 Power Conversion (target 50-55% efficiency 50%)*
    - *Use known fuel cycle and fuel fabrication (oxide, coated particle)*
    - *Target Lower Specific Capital Costs to ~ $4000-5400/kW)*
  - *Investment Funding*
    - *Focus on Volume Sales, with preset PPAs, Contractual Sales Agreements if performance targets are met in a Pilot Plant*
    - *Operation of Pilot Plant Pays for the Demonstration Testing*
  - *Design Focus*
    - *Single loop, small foot print, natural circulation decay heat removal, 50-55% Efficiency, with known fuel processing capabilities*
    - *Factory Built SMR 100-250 MWe*
    - *Licensed via Nation State (US, Canada, UK, S. Korea, India, Indonesia, etc.)*
    - *Focus Markets on High Growth Regions (Africa, India, S.E. Asia, Pacific Nations)*
  - *Deal with Policy Issues*
    - *Fuel Fabricated in West, and Returned to West*
    - *Requires a Licensed Waste Repository*