THERMODYNAMICS OF CONVENTIONAL AND NON-CONVENTIONAL SCO_2 RECOMPRESSION BRAYTON CYCLES WITH DIRECT AND INDIRECT HEATING

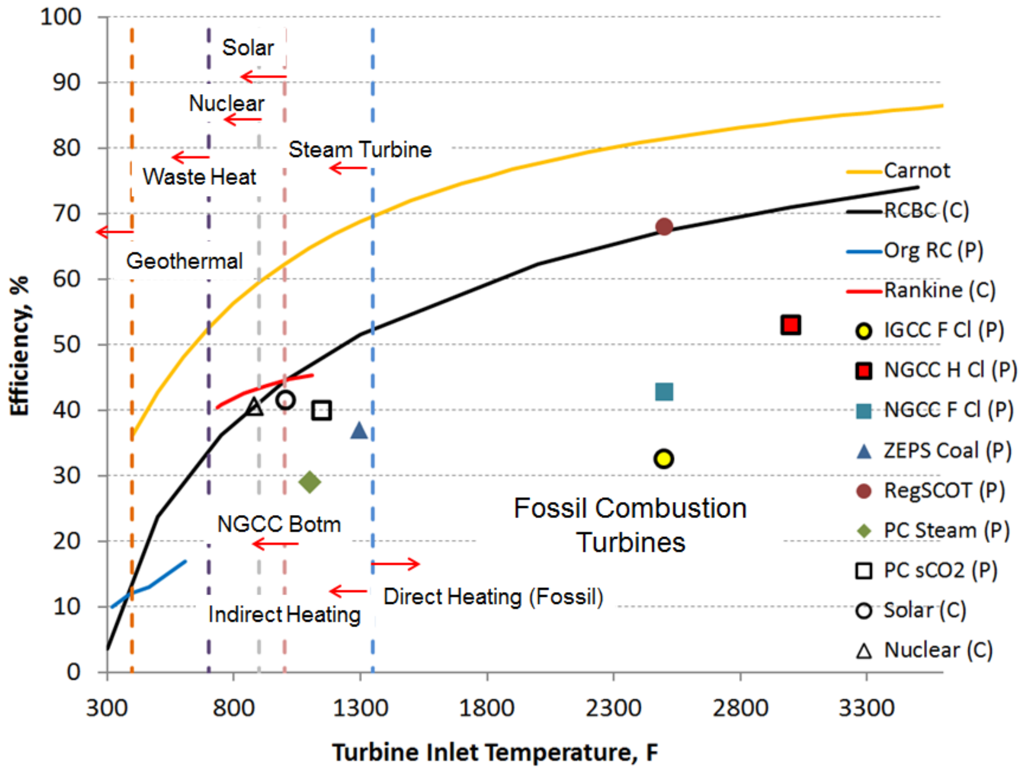
September 10, 2014

Megan Huang*
& Dr. Chandrashekhar Sonwane

Agenda

- Efficiency of Various Systems
- Steam Rankine Cycle
- Natural Gas Combined Cycle (NGCC)
- Recompression Brayton Cycle (RCBC)
- RCBC System Analysis Results
- Conclusion

Cycle and Plant Efficiencies of Various Systems

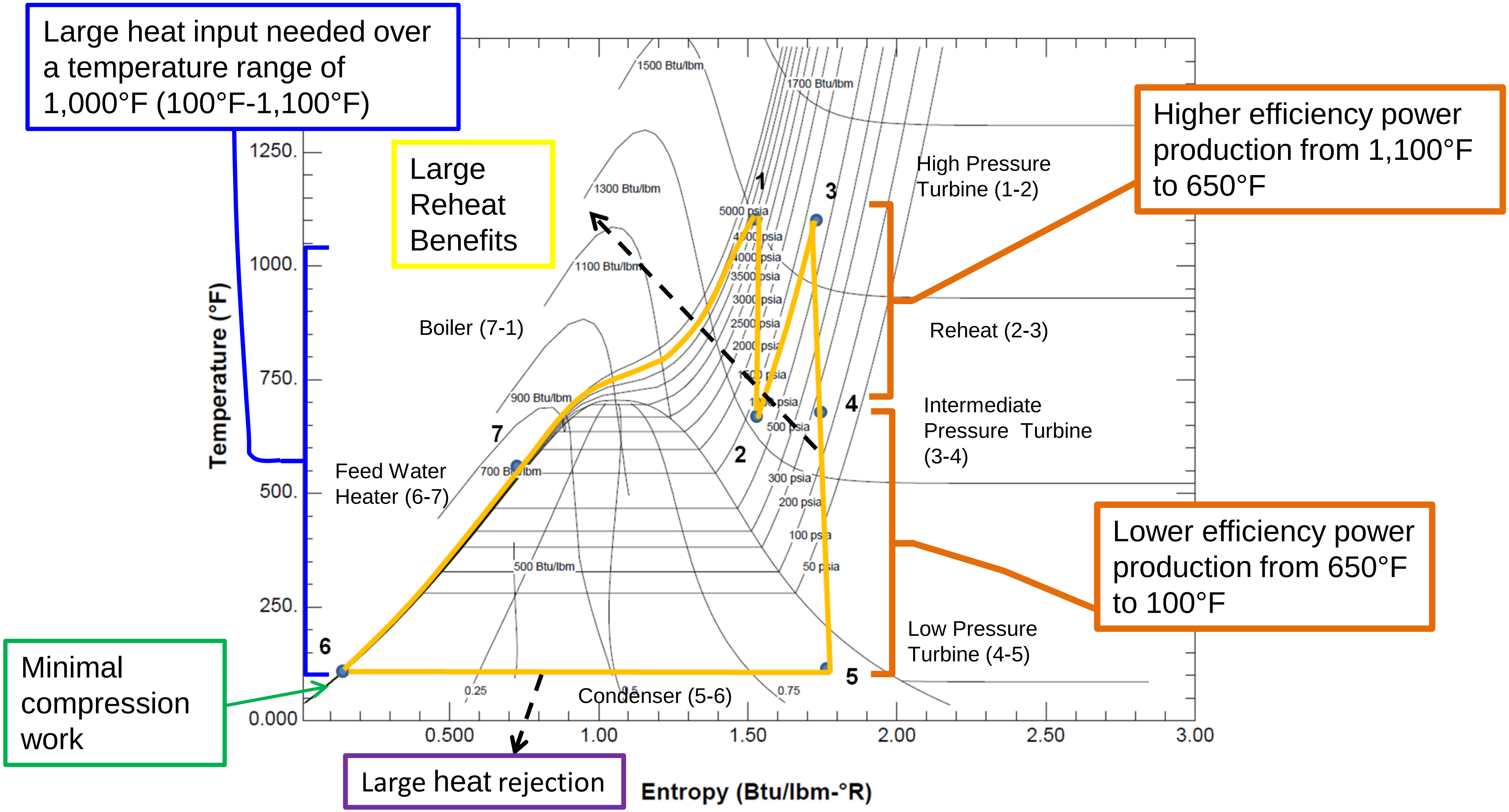


Cycle and plant efficiencies noted by C or P in legend

- **Both indirectly heated and directly heated system performance shown**
  - Modeled cycle efficiencies depicted for indirectly heated systems
  - Modeled plant efficiencies (HHV) depicted for directly heated systems
- **1,300°F (704°C) defines upper limit of indirectly heated systems**
- **Higher turbine inlet temperature leads to higher cycle or plant efficiency**
- **For <1,000°F (<538°C), Brayton cycle is not expected to show efficiency benefits over Rankine cycle**
- **For >1,000°F (>538°C), Brayton cycle is expected to show significant efficiency benefits over Rankine cycle**

Steam Rankine Cycle

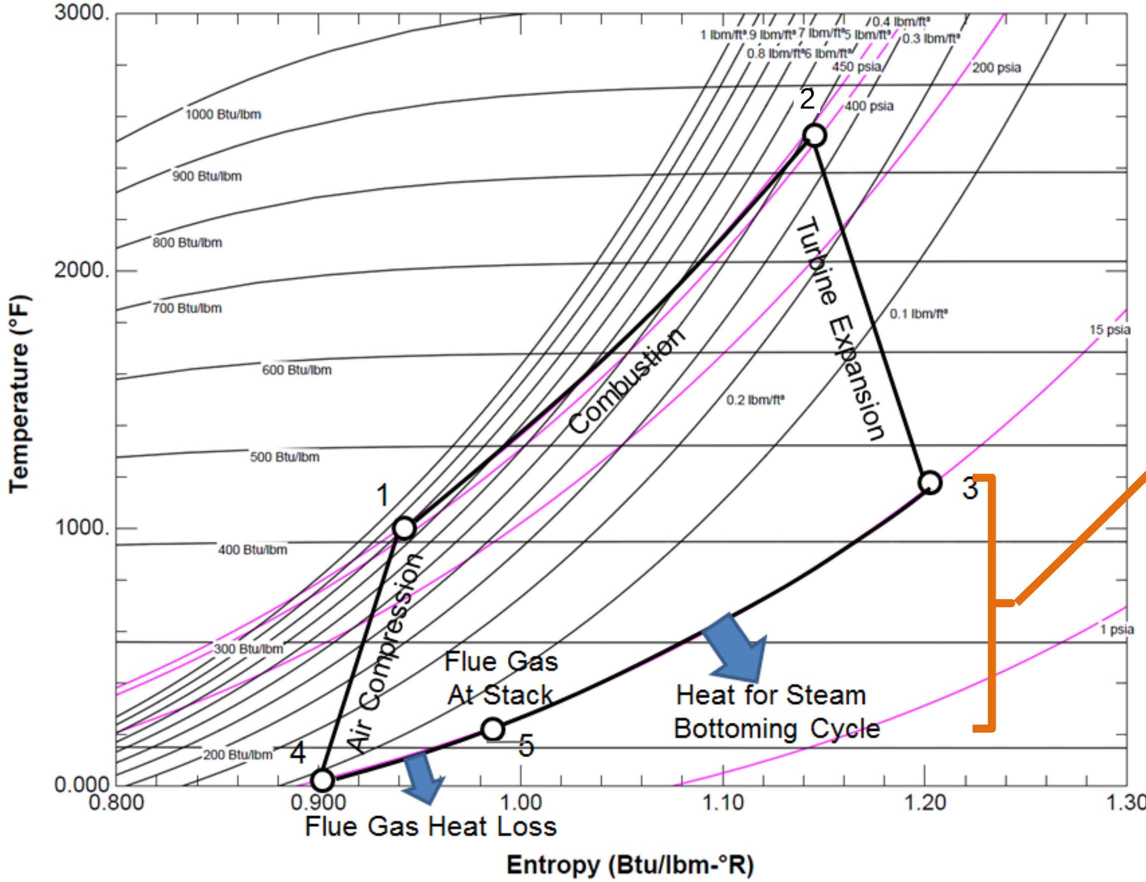
Temperature-Entropy Diagram



- **Turbine inlet temperature ranges from 800 – 1,100°F (427-593°C) for Supercritical systems (up to 1,300°F (704°C) for Advanced Ultra Supercritical plants)**
- **Cycle efficiency range from 40-45% for Supercritical systems**

Natural Gas Combined Cycle F Class Turbine

Temperature-Entropy Diagram



In NGCC turbine exhaust flue gas **sensible heat** available over temperature range of 950°F (over 1,162°F to 220°F – some high quality but mostly low quality heat)

- **Typical turbine inlet temperature and pressures ~2,750˚F (1,510°C) and 300 psia (2.1 MPa) for F class**
- **42% plant efficiency for F class turbine system**
- **Up to 57% expected efficiency for H and J class turbines**
- **Heat recovered in Heat Recovery Steam Generator (HRSG) at low efficiency**
- **Lower pressure of system = lower density of fluid → larger equipment units**

AEROJET ROCKETDYNE

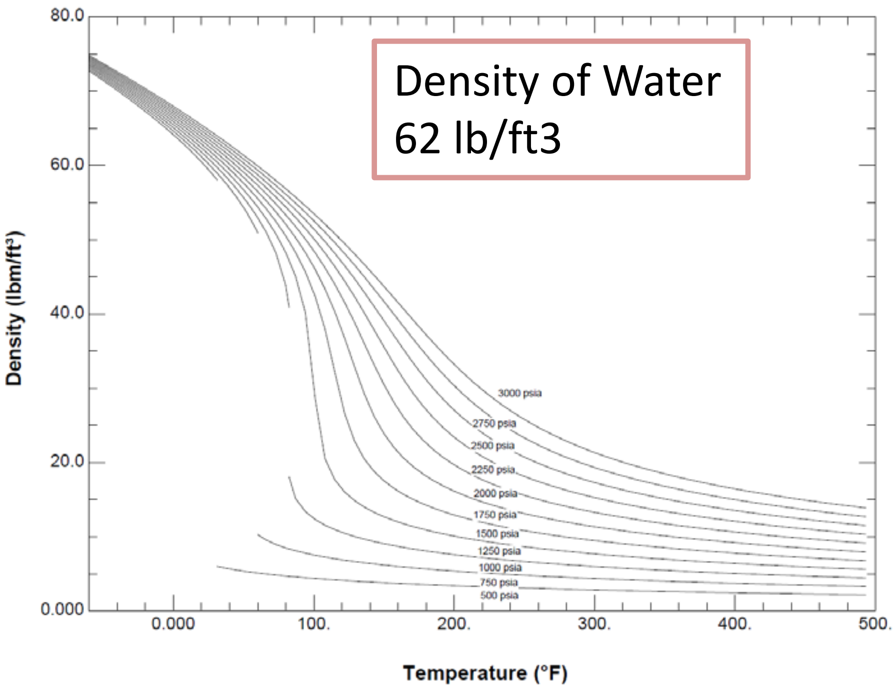
sCO_2 Recompression Brayton Cycle

- **Below 1,300°F (704°C): closed loop indirectly heated**
  - Heat sources include geothermal, nuclear, solar, etc.
  - Expected to have lower efficiency than Steam Rankine but higher efficiency than Organic Rankine cycle
- **Above 1,300°F (704°C): open loop directly heated with recycled CO_2**
  - Heat sources include Natural Gas, coal, etc.
  - Expected to have higher efficiency than NGCC or IGCC
- **Benefits**
  - Higher density of sCO_2 may lead to reduction in turbomachinery size and compression costs
  - Corrosion and H_2 embrittlement not an issue allowing for higher turbine inlet temperatures

Expected Benefits of sCO_2 vs H_2O

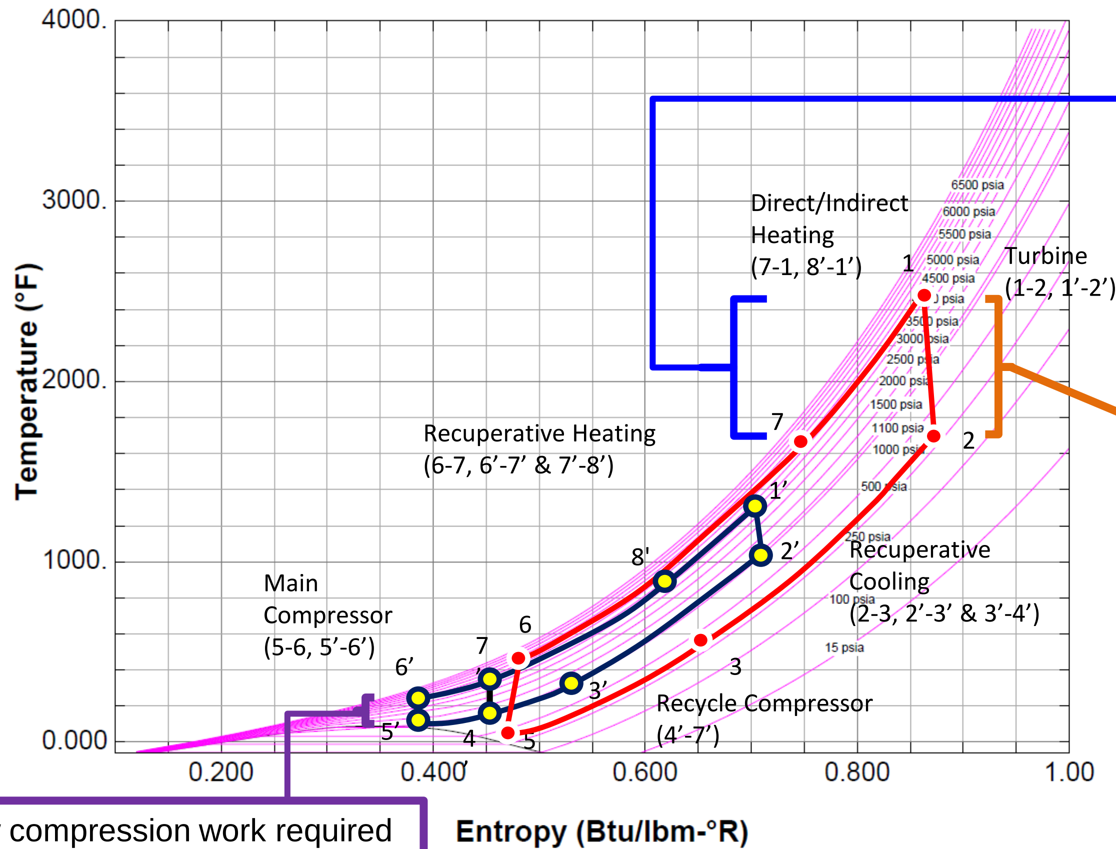
- **CO_2 critical temperature and pressure: 88°F, 1070 psia**
- **CO_2 not as corrosive as H_2O**
- **At turbine inlet conditions**
  - Density of CO_2 is twice that of H_2O → allows for compact turbines
  - Specific heat of CO_2 is half that of H_2O → less heat lost

Fluid	T (°F)	P (psia)	ρ (lb_m/ft^3)	C_p(Btu/lbm°R)
Turbine Inlet				
H_2O	1,100	3,514	4.3	0.71
CO_2	1,100	3,514	8.8	0.30
CO_2	1,300	3,000	6.7	0.31



sCO_2 Recompression Brayton Cycle

Temperature-Entropy Diagram



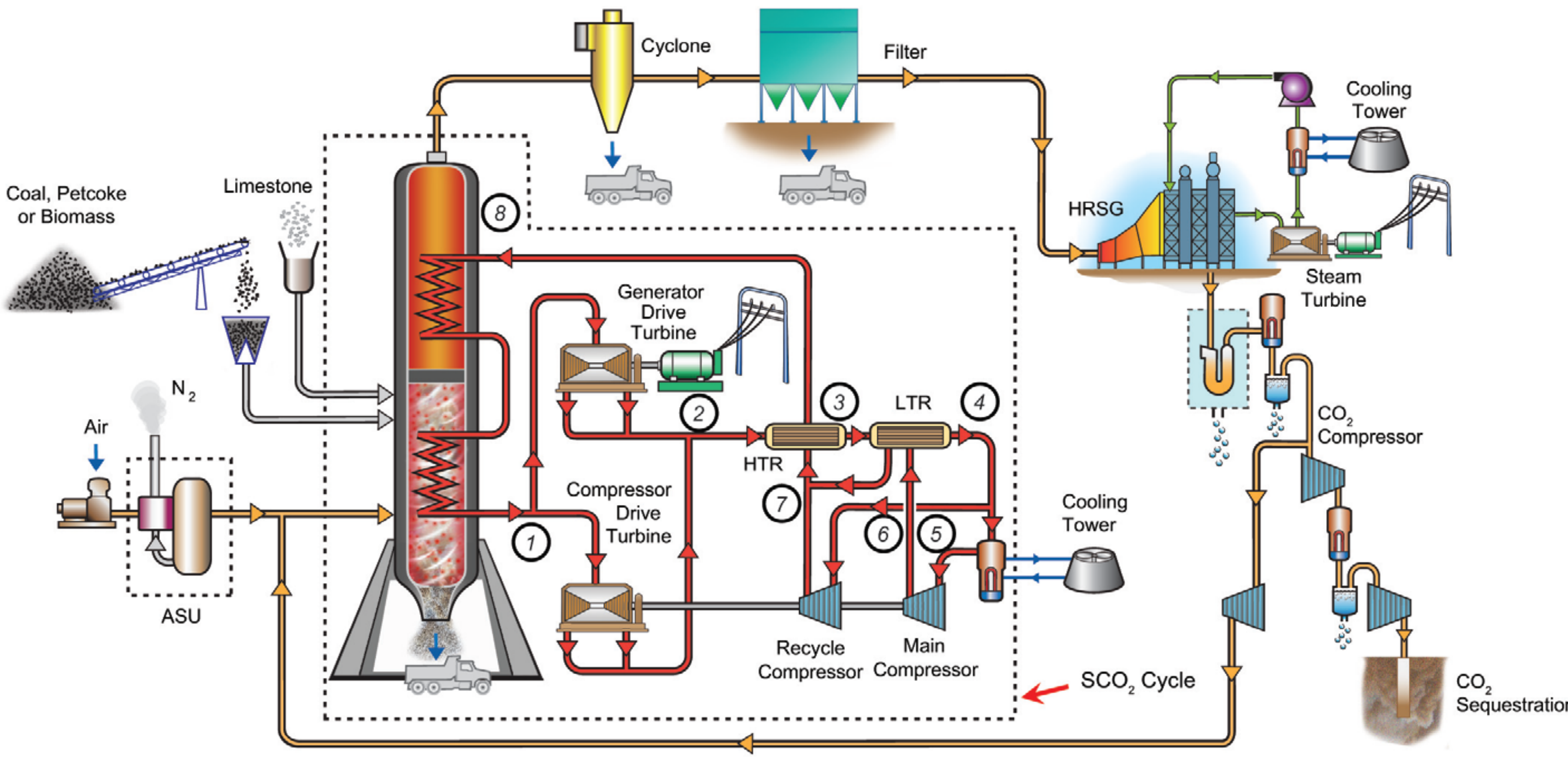
Small heat needed over a temperature range of 200°F (800°F -1,100°F, All high quality heat)

Very high efficiency power production over 1,300°F – 1,000°F

Low compression work required

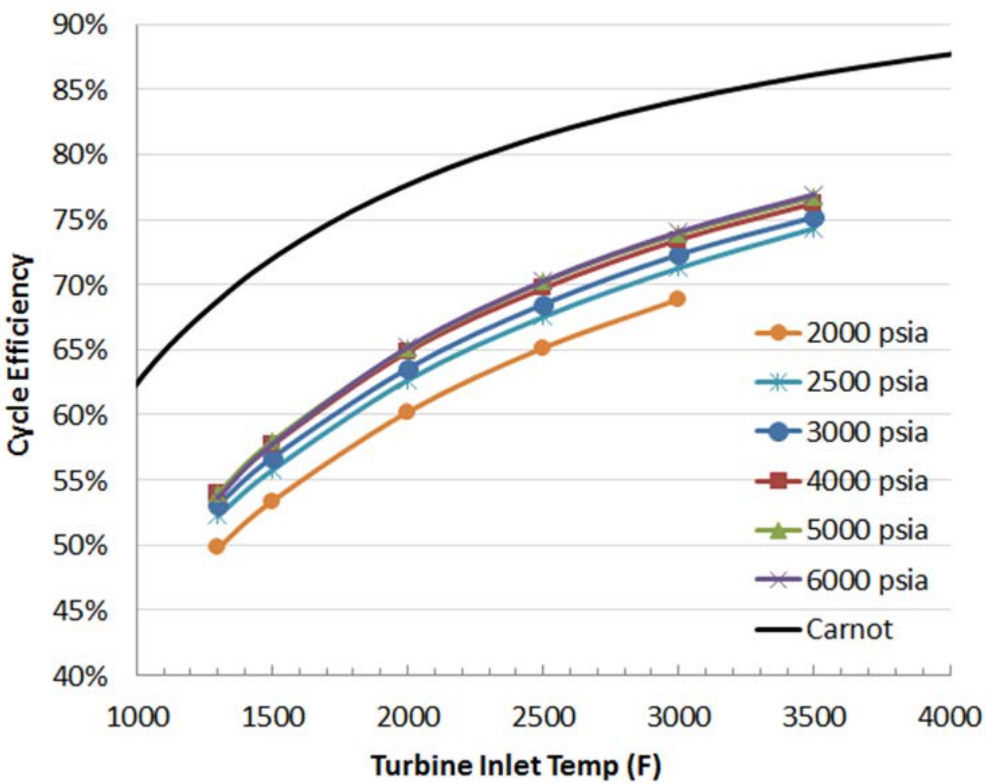
- **Both low temperature (black) and high temperature (red) recuperation cycles depicted**
  - Low temperature cycle is a double recuperation cycle
  - High temperature cycle is a single recuperation cycle
- **Significant efficiency gains at high turbine inlet temperatures based on simulated analysis**
- **Recuperated heat used more efficiently when incorporated back into the system as opposed to in HRSG**
- **Higher pressure of system = higher density of fluid → may lead to smaller equipment units**

Zero Emission Power and Steam (ZEPS™) Oxy-Coal Power Plant with Supercritical CO_2 Cycle



sCO_2 Recompression Brayton Cycle

Turbine Inlet Temperature and Pressure Effects on Cycle Efficiency

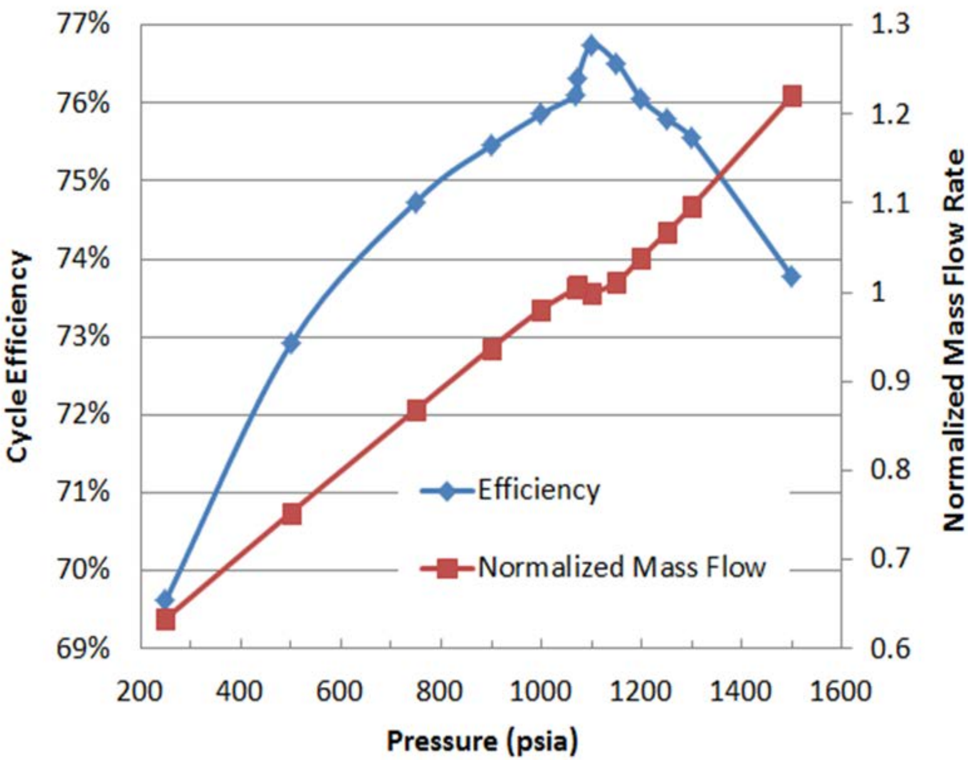


- **Temperature is a stronger driver than pressure on system performance**
- **General trend for RCBC similar to Carnot**
  - each increment of 500°F (260°C) yielding an efficiency benefit of ~5%
- **Performance gain diminishes with increasing pressure**
  - For lower pressures of 2,000-4,000 psia (13.8-27.6 MPa), there is ~2-3% efficiency gain per 1,000 psia (6.9 MPa) increase
  - For pressures >4,000 psia (27.6 MPa), there is little efficiency benefit

- **Efficiency and performance analysis based upon a closed loop, double recuperation recompression Brayton cycle simulated in Aspen Plus.**

sCO_2 Recompression Brayton Cycle

Turbine Outlet Pressure Effects on Cycle Efficiency and Mass Flow Rate

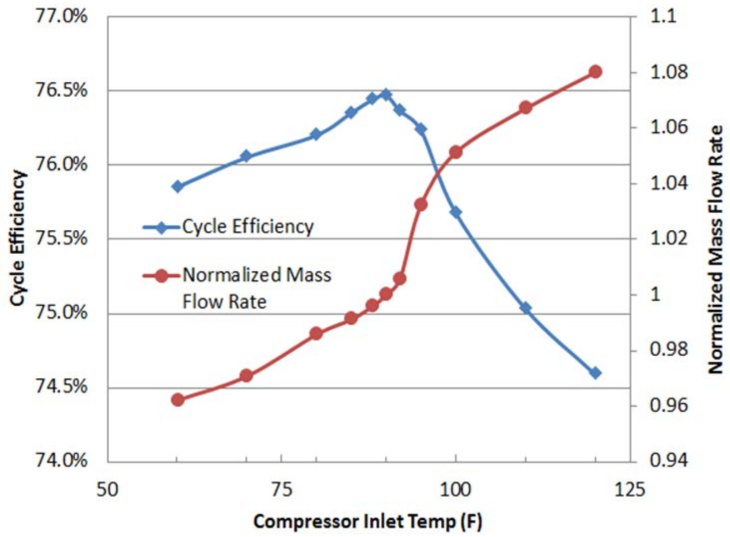


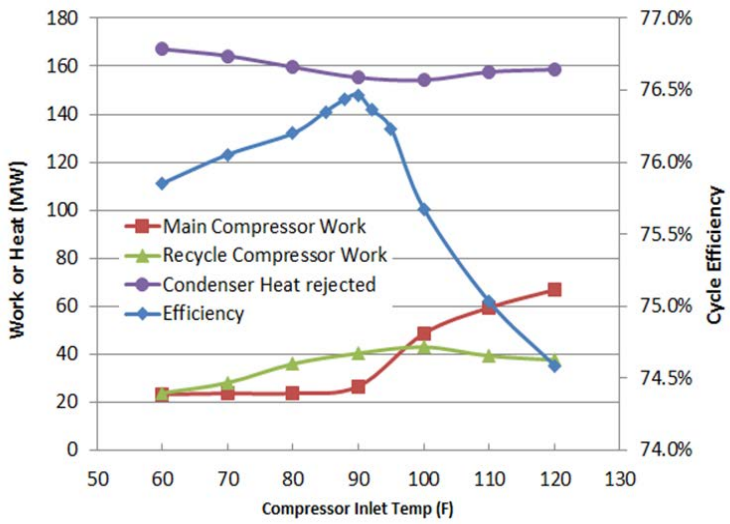
- **Outlet pressure of 1,100 psia (7.6 MPa) shows highest efficiency**
- **Increasing exit pressure results in an increase in system mass flow rate**
- **Penalty for slightly subcritical conditions is small**
  - Minor efficiency drop but a significant mass flow rate decrease which allows for smaller ducts, turbomachinery, and heat exchangers → smaller footprint and capital cost
- **Reducing outlet pressure reduces inlet temperature to the recuperator → limits material challenges**

- **Efficiency and performance analysis based upon a closed loop, double recuperation recompression Brayton cycle simulated in Aspen Plus.**

sCO_2 Recompression Brayton Cycle

Main Compressor Inlet Temperature Effects on Cycle Efficiency and Mass Flow Rate





- **Highest efficiency with inlet temperature of 90°F (32°C)**
- **Rapid efficiency drop for temperatures > 90°F (32°C)**
  - Due to drastic increase in main compressor work
- **Slower efficiency drop for temperatures < 90°F (32°C)**
  - Compression work decreases
  - Heat rejected in the condenser increases
  - The increase in the amount of heat rejected is larger than the decrease in compression work
- **Lower inlet temperatures result in lower system mass flow**

- **Efficiency and performance analysis based upon a closed loop, double recuperation recompression Brayton cycle simulated in Aspen Plus.**

Conclusion

- **Higher turbine inlet temperatures lead to higher efficiency**
- **Expected significant efficiency gains for the Brayton cycle at inlet temperatures >1,000°F (<537°C) as compared to other systems**
- **sCO2 recompression Brayton cycle offers many advantages**
  - Higher density of sCO2 may reduce turbomachinery size and compression costs
  - Limited corrosion issues at higher turbine inlet temperatures
- **Analysis results of a double recuperation RCBC based on simulations in Aspen Plus**
  - Turbine inlet temperature is expected to be a stronger driver of cycle performance than pressure
  - Cycle efficiency is optimal for turbine exit pressures near the critical pressure of CO_2, although slightly subcritical conditions may still be considered due to other system benefits such as mass flow rate
  - Main compressor inlet temperature around the critical temperature is optimal for system performance.

Contact information

Megan Huang

Megan.Huang@rocket.com

818-586-5254