Fossil Fuels I

Sustainable Energy

Fall 2010

10/14/2010

Scope of this Session

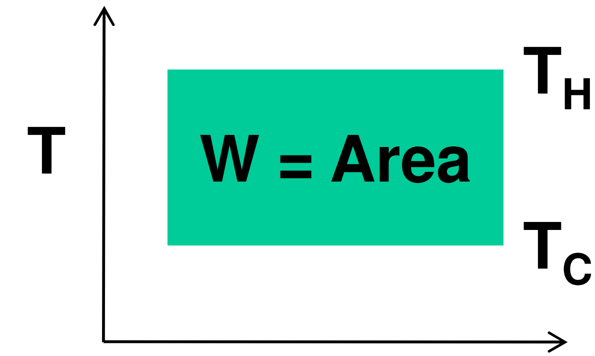
- Cover the major power cycles for conversion of fossil fuels to electricity
  - Steam Cycles
  - Steam Turbines
  - Brayton Cycle
  - Gas Turbines
  - Combined Cycles

Understanding Steam Cycles

- Start with Carnot efficiency as upper limit
- Use reality to chip away at the efficiency
- Use tricks to maximize efficiency

Carnot Efficiency

$$\eta_{\text{Carnot}} \equiv \frac{\dot{W}_{\max}}{\dot{Q}_{\text{H}}} = 1 - \frac{T_{\text{C}}}{T_{\text{H}}}$$



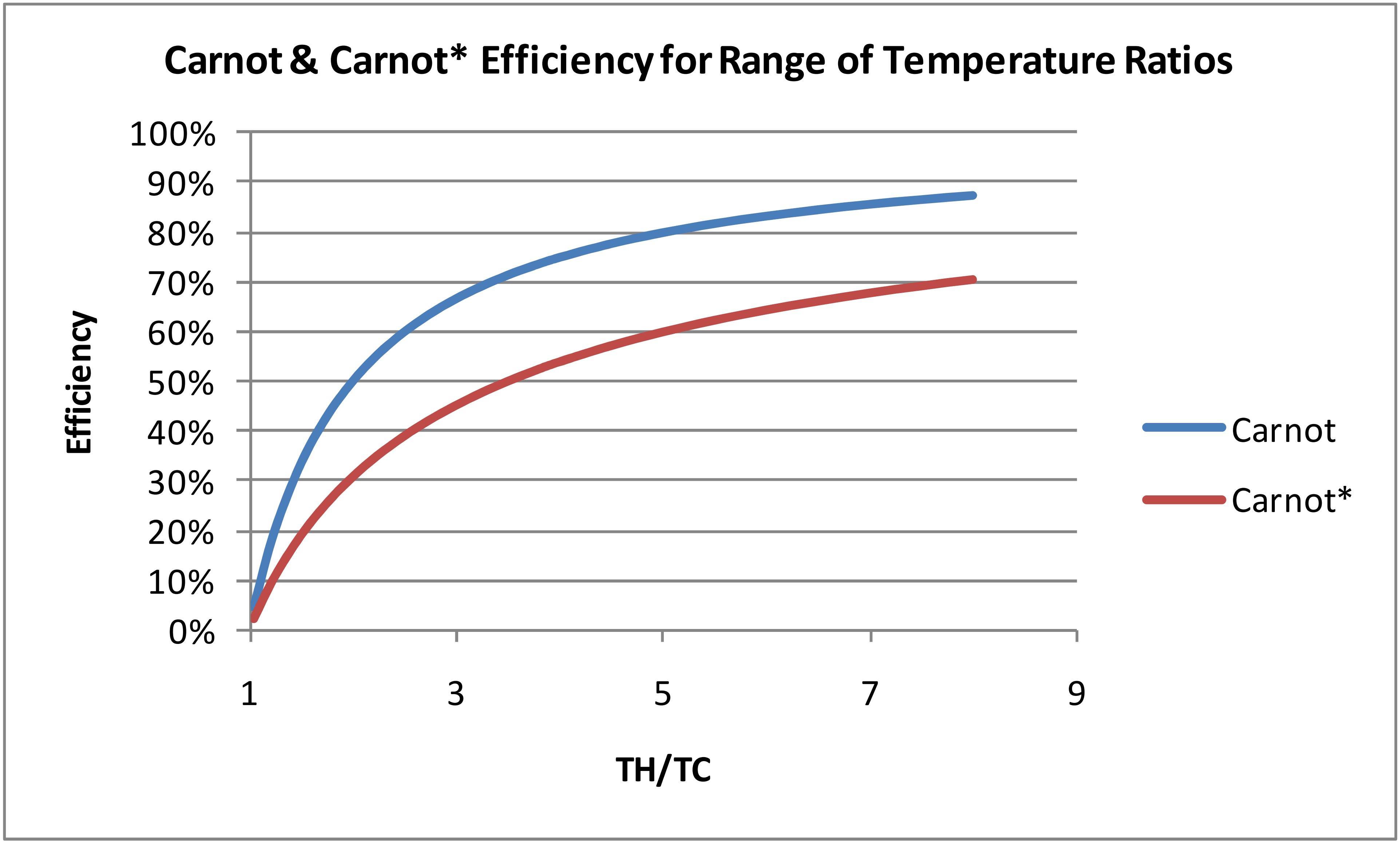
- Assumes Q_H is all available at T_H
- Assumes Q_C is all available at T_C
- Assumes Reversibility
  - No temperature driving force on heat exchangers
  - No pressure drops in exchangers or pipes
  - No entropy losses on turbines or pumps
- For T_H=1800 K, T_C=300 K, η_{Carnot}=83%

Reality 1
Heat Source Temperature not Constant

- Heat source may start at T_H but the temperature drops as heat is delivered
- Heat is maximized if hot medium exits at T_C
- Maximum work determined by integrating over this temperature profile (assume constant C_p)

$$\eta^*_{\text{Carnot}} = 1 - \ln\left(\frac{T_H}{T_C}\right) \Big/ \left(\frac{T_H}{T_C} - 1\right)$$

- For T_H=1800 K, T_C=300 K, η^*_{Carnot}=64%


Carnot & Carnot* Efficiency for Range of Temperature Ratios
Efficiency
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
1
3
5
7
9
TH/TC
Carnot
Carnot*

Rankine cycle

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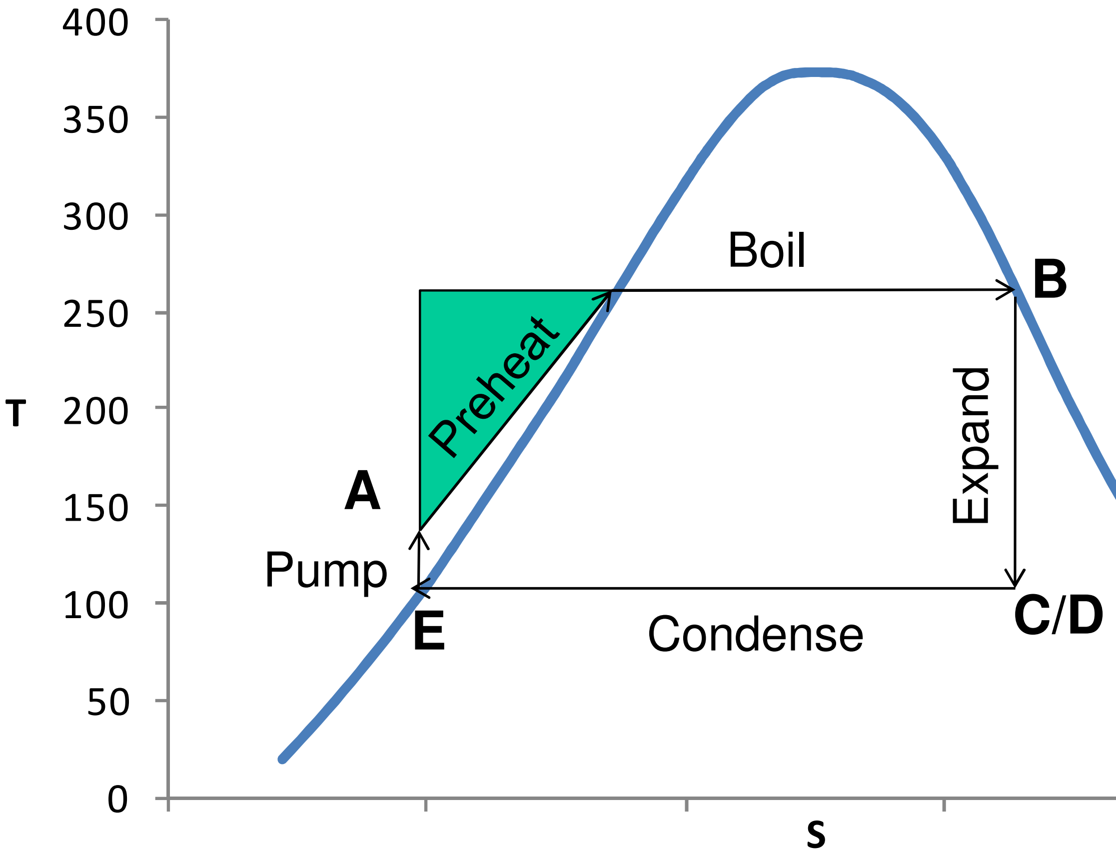
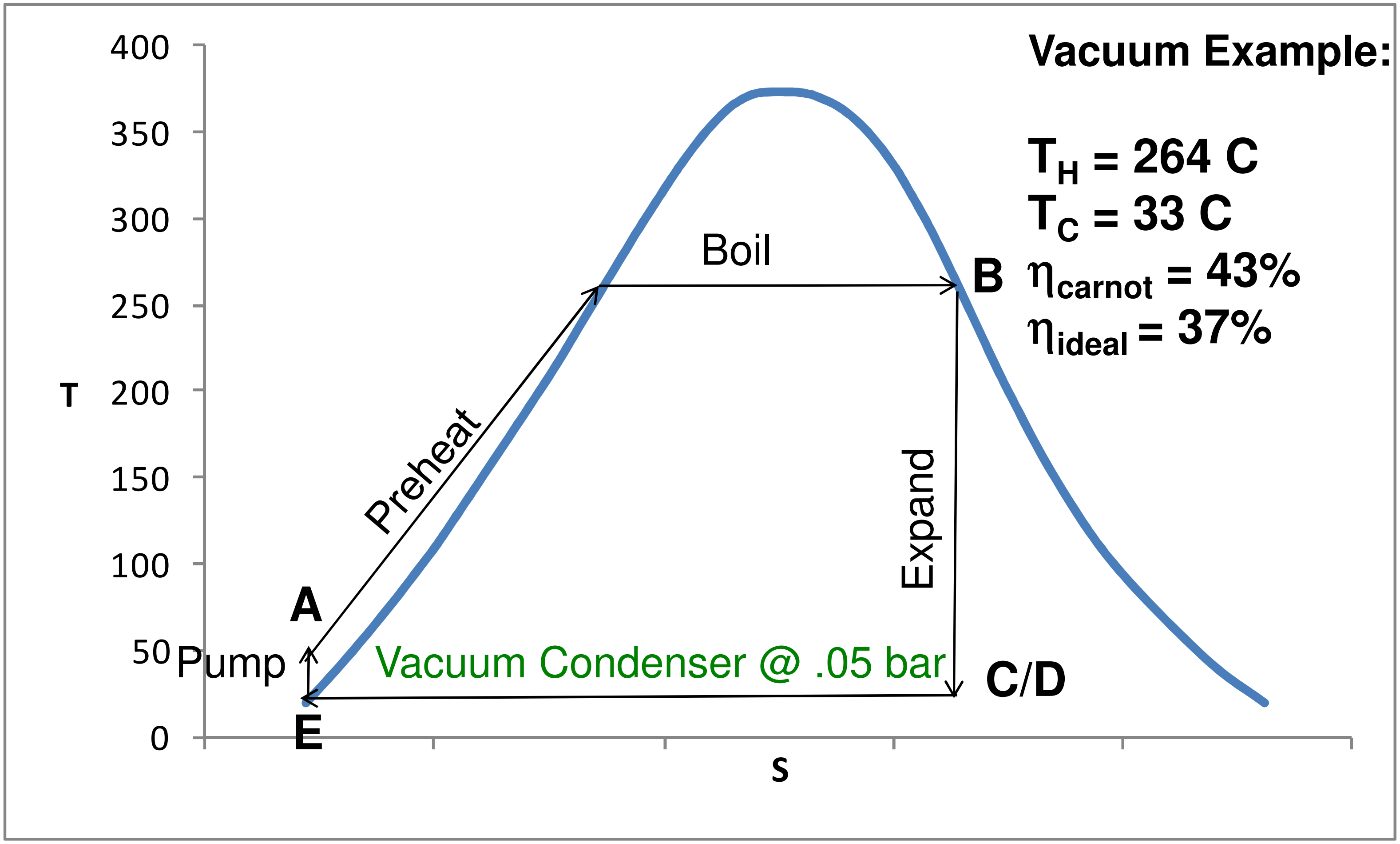
Reality 2
Working Fluid Phase Envelope Matters



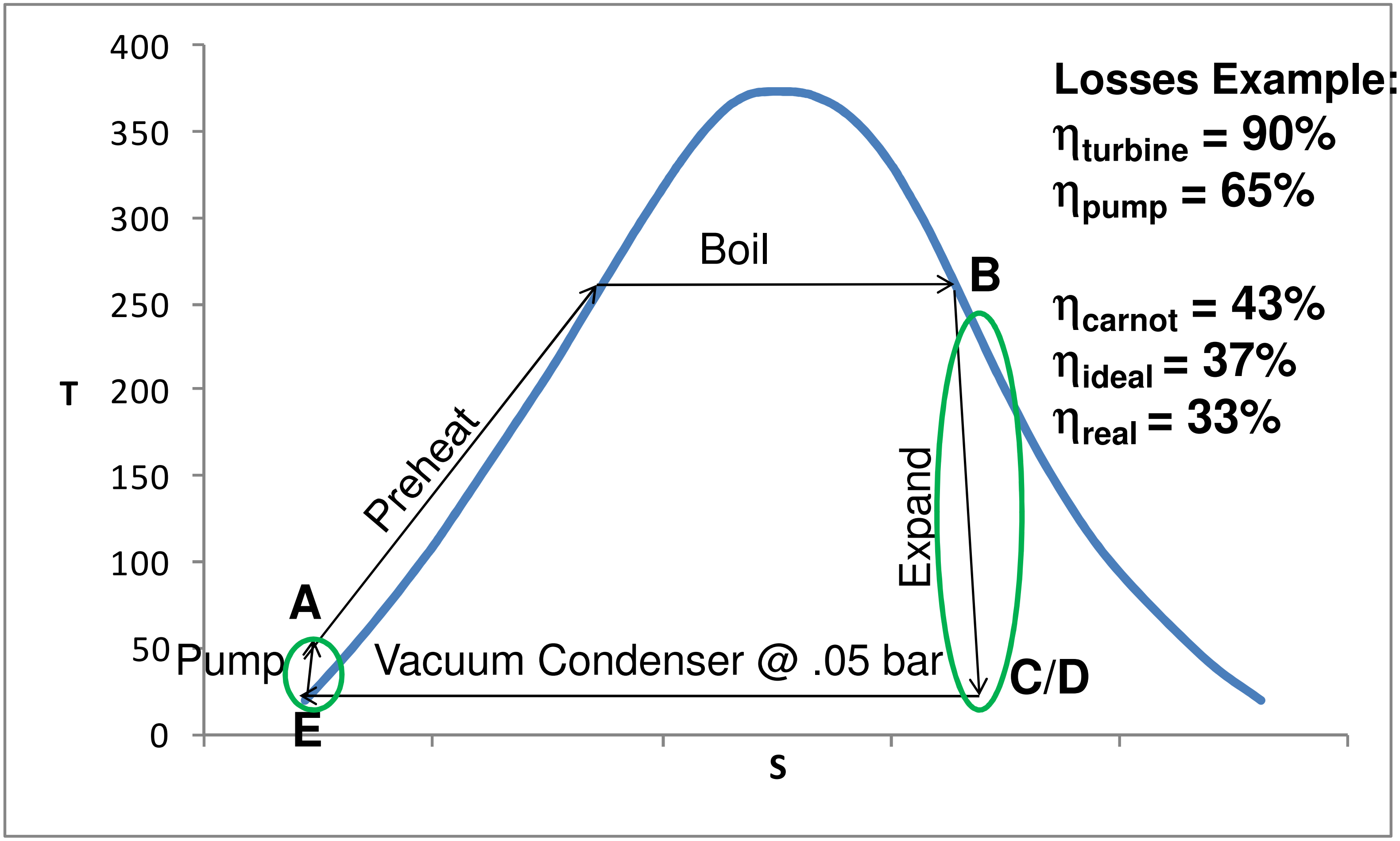
Steam Example:

T_H = 264 C
T_C = 100 C
η_{carnot} = 31%
η_{ideal} = 27%

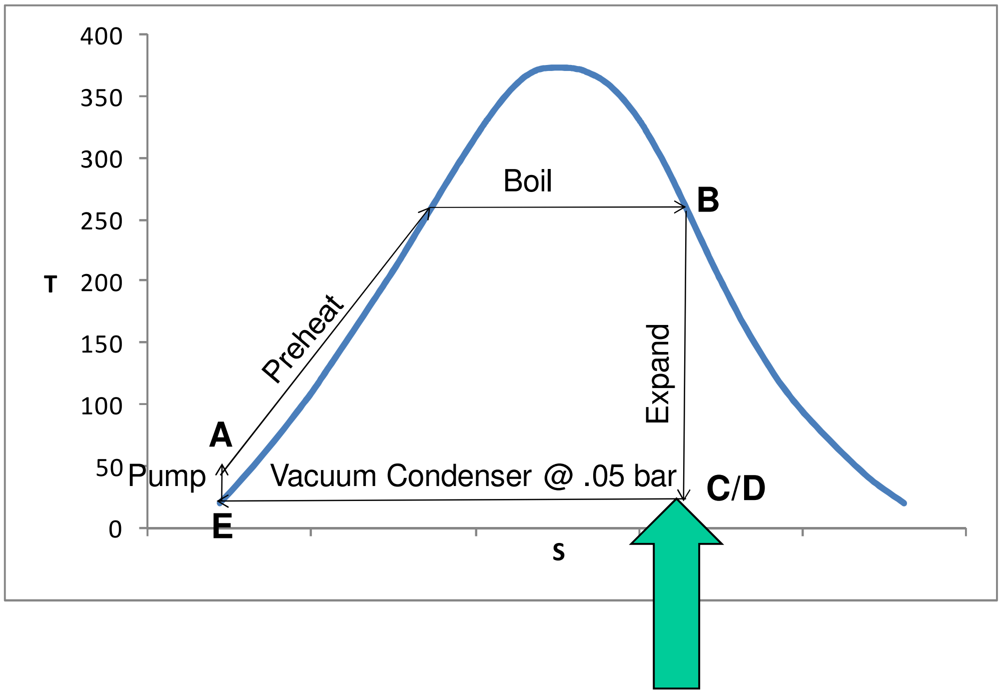
Reality 3
Ambient Pressure not Hard Limit For Closed Cycles



Reality 4
Real Pumps and Turbines have Entropy Losses



Reality 5
Expanding into Two-Phase Region is a Problem

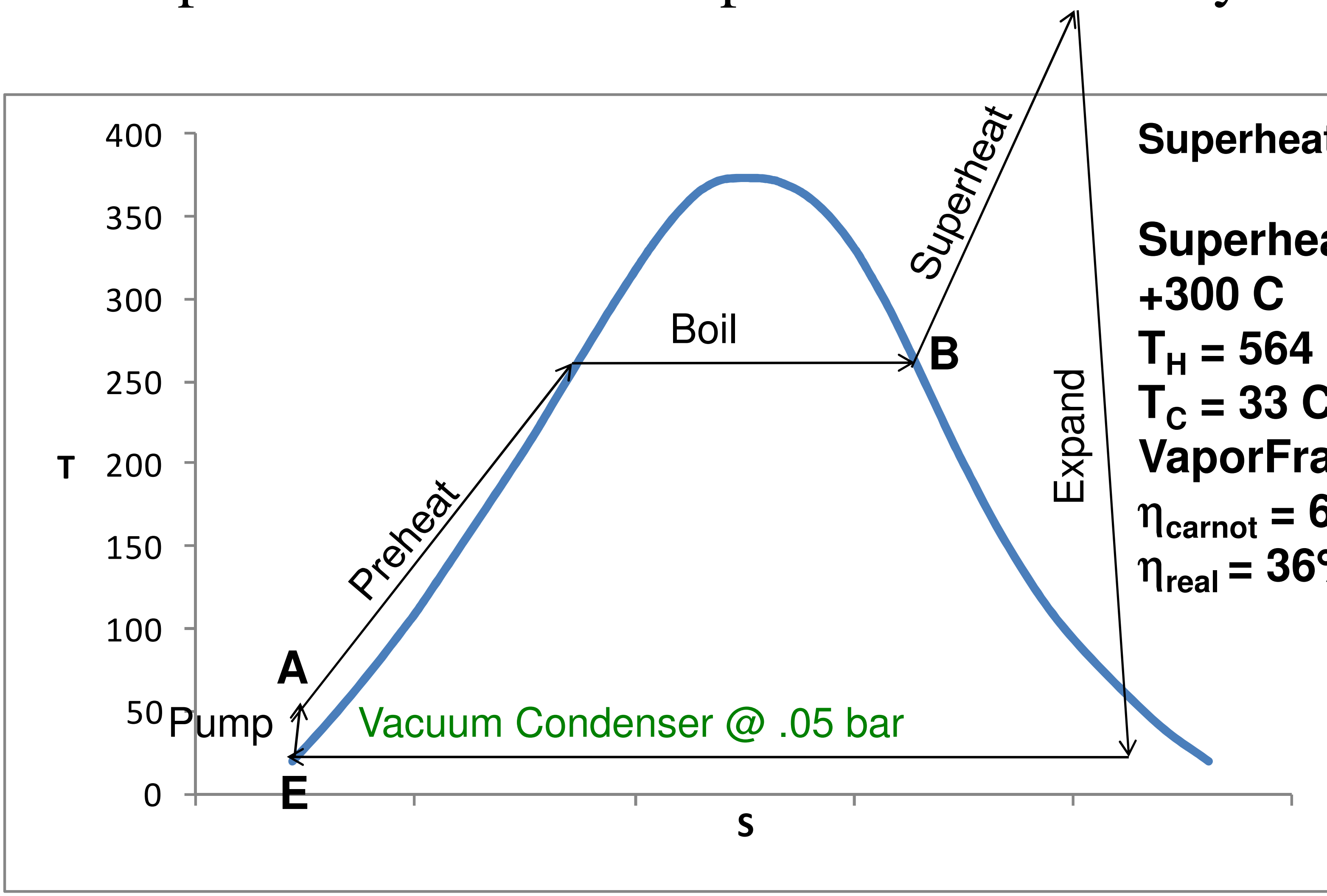


Turbine Exit Vapor Fraction is only 73%

Turbine Reality:
- **Vapor fraction must exceed 90%**
- **Efficiency diminished by condensation in turbine**

Superheat Cycles

Superheat Steam to Keep Turbine Relatively Dry

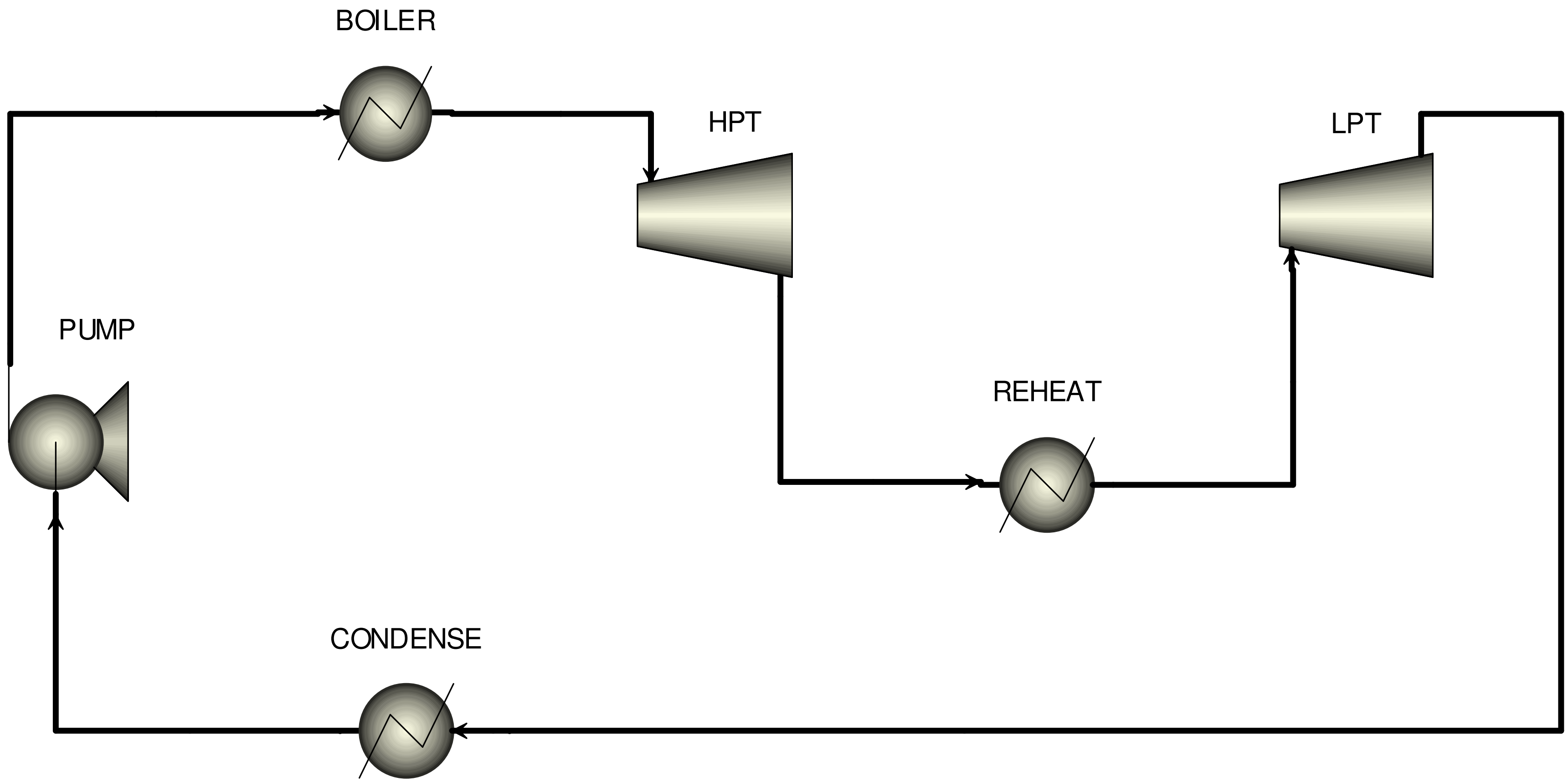


Superheat Example:

Superheat= +300 C
T_H = 564 C
T_C = 33 C
VaporFrac = 90%
η_{carnot} = 63%
η_{real} = 36%

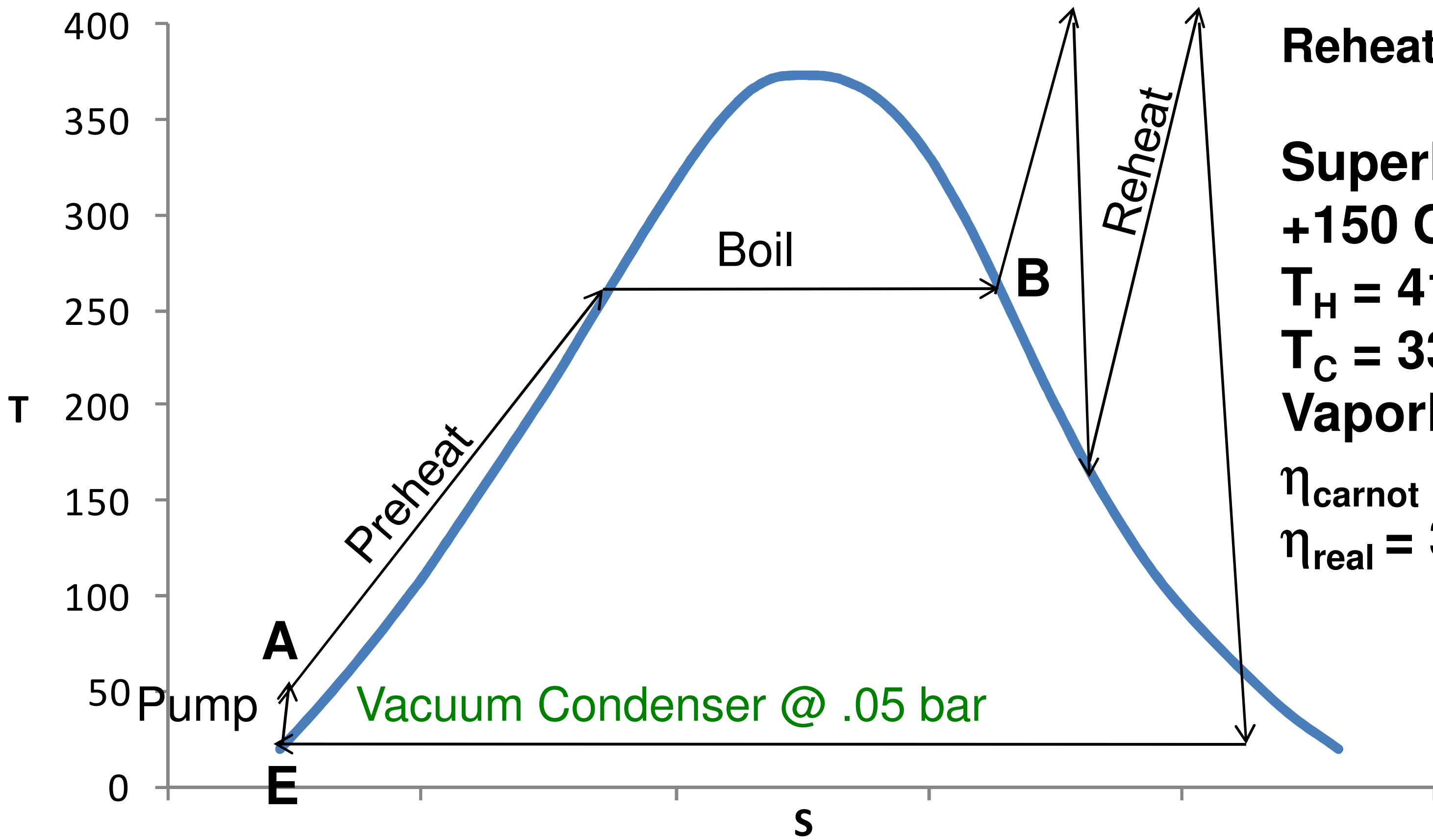
Reheat Cycles

Reheat between Turbines → More Power & Dry Turbines



Reheat Cycles

Reheat between Turbines → More Power & Dry Turbines

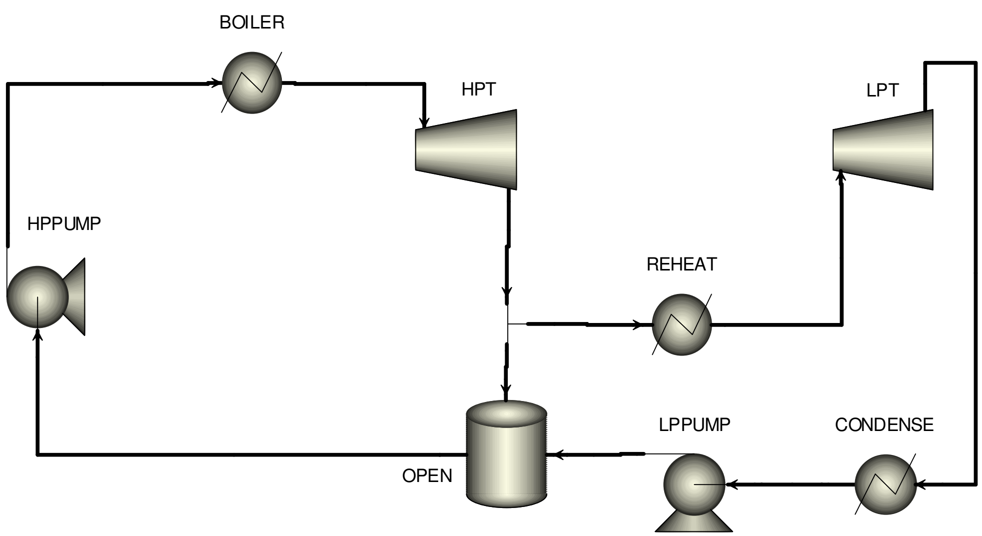


Reheat Example:

Superheat= +150 C
T_H = 414 C
T_C = 33 C
VaporFrac = 97%
η_{carnot} = 55%
η_{real} = 36%

Regenerative Cycles

- Preheat with lower quality heat
  - Extract steam from turbines
  - Feedwater heaters
    - Open (Direct contact)
    - Closed (Indirect)



Regeneration Example:

Extraction Factor = 12%

η_{carnot} **= 55%**

η_{real} **= 37%**

Real Steam Cycles

- Multiple steam pressure levels
- Multiple reheats
- Multiple extractions for feedwater heating
- Deaerator for oxygen removal
- Best performance at steam pressures > P_c
- Maximum steam temperature: ~ 600°C
- Economizer to recover heat from flue gas
- Fuel utilization is key metric for fossil fuel power

$$\eta_{\text{Fuel Utilization}} = \frac{W}{FuelFlow \times LHV}$$

Steam Rankine Cycle Summary

- Fuel flexible: works well with coal and other dirty fuels (closed cycle)
- Workhorse for nuclear and most solar thermal
- Low flow rate: thanks to high heat of vaporization
- Low pumping power
- But…
  - Limited by maximum steam temperatures due to material of construction constraints
  - High inertia: good for base load, not for load following
  - Requires cooling: a water hog for many power plants

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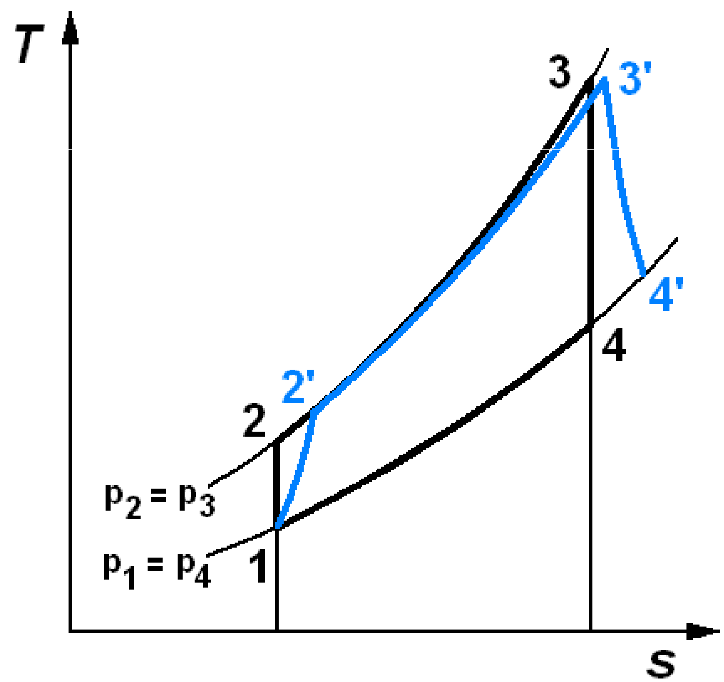
Siemens SST-500

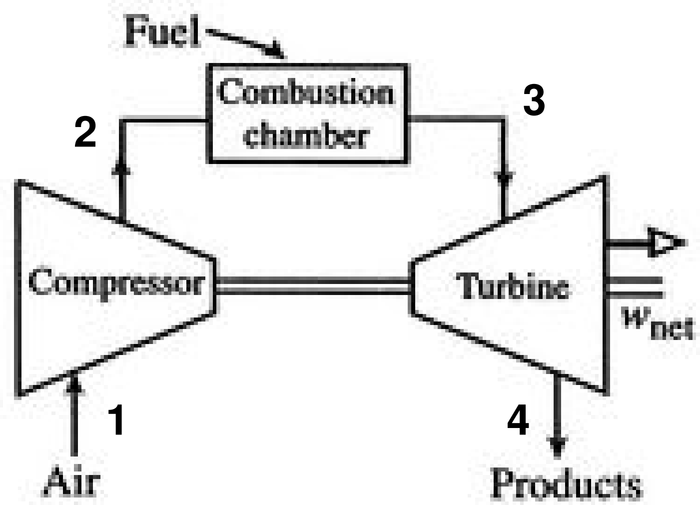
Photo of a Siemens SST-500 steam turbine removed due to copyright restrictions.

Power output: up to 100 MW
Rotational speed: up to 15,000 rpm
Inlet steam pressure: up to 30 bar
Inlet steam temperature: up to 400 °C
Bleeds: up to 2, at various pressure levels

Brayton Cycle

Brayton Cycle = Rankine Cycle – Boiling – Condensation





Evolution of Turbine Blade Technology

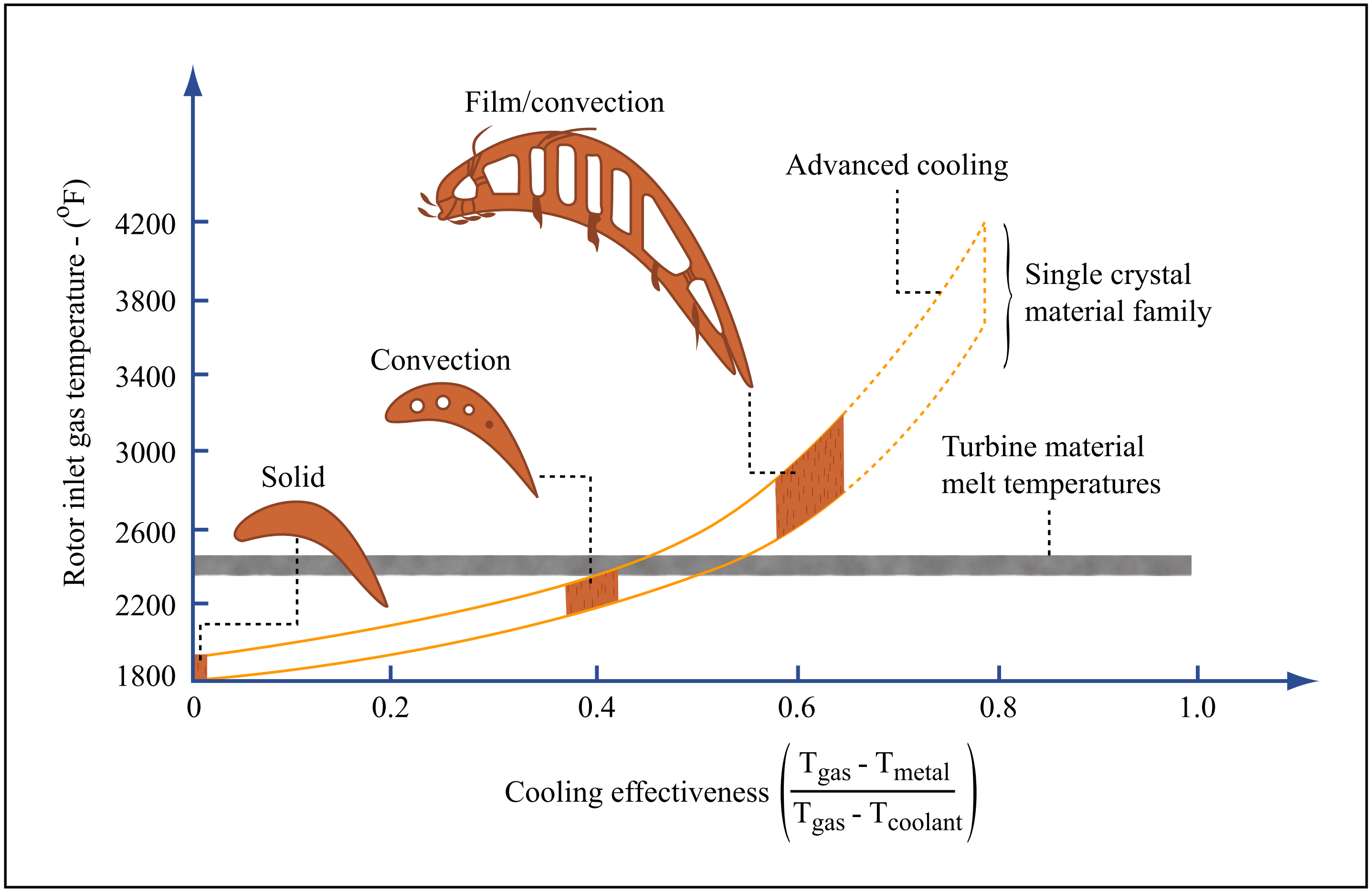


Image by MIT OpenCourseWare. Adapted from Pratt & Whitney.

Source: MIT Unified Engineering 16.003/16.004

Siemens Gas Turbine SGT5-8000H

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Power Output: 375 MW
Efficiency: 40%
Pressure Ratio: 19.2
Compression Stages: 13
Turbine Stages: 4

Brayton with Intercooling, Reheat and Regeneration

Gas Turbine Advantages

- Operate at high temperature → Utilize fossil fuel combustion
- Start, stop, turn-down easily → Load following and peaking
- Compact and easy to operate
- Operate at low pressures relative to steam turbines
- Internal combustion does not require heat transfer equipment
- Not as vulnerable to corrosion as steam turbines

Gas Turbine Disadvantages

- Open cycle limits exhaust pressure to ambient pressure
- Exhaust temperature well above ambient
- Efficiency limited by high compression work
- Cannot use dirty fuels (particulate & sulfur damage blades)
- Exhaust temperature well above ambient

Combined Cycle

Most common combined cycle = Brayton + Rankine

Efficiency ≈ 60%

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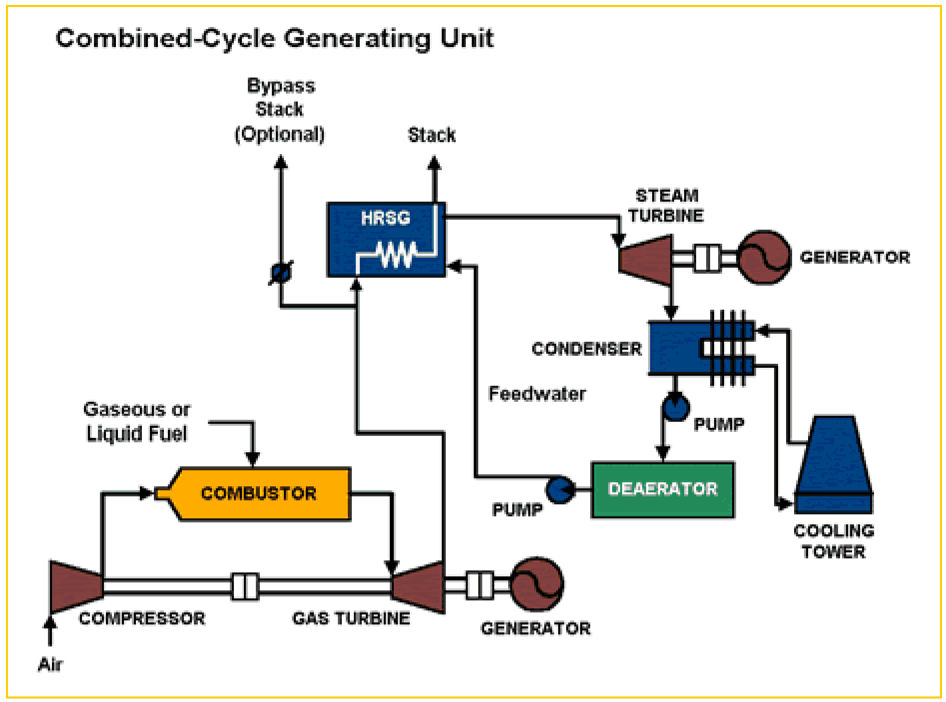
Figure at right from U.S. Department of Energy.



Sources: MIT Unified Engineering [Lee Langston]; US Department of Energy

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