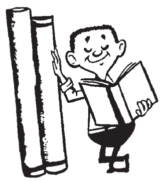
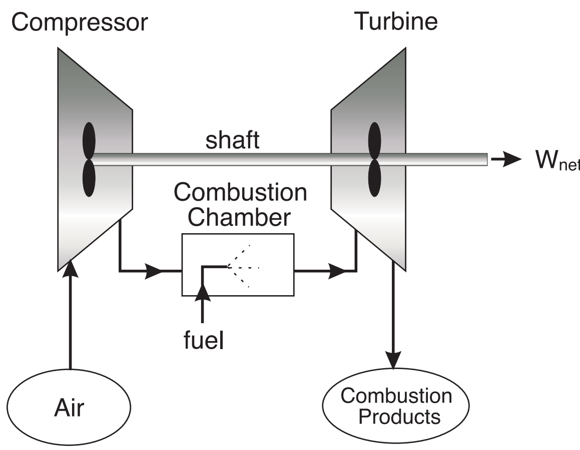
Brayton Cycle



Reading	Problems
9-8 → 9-10	9-78, 9-84, 9-108

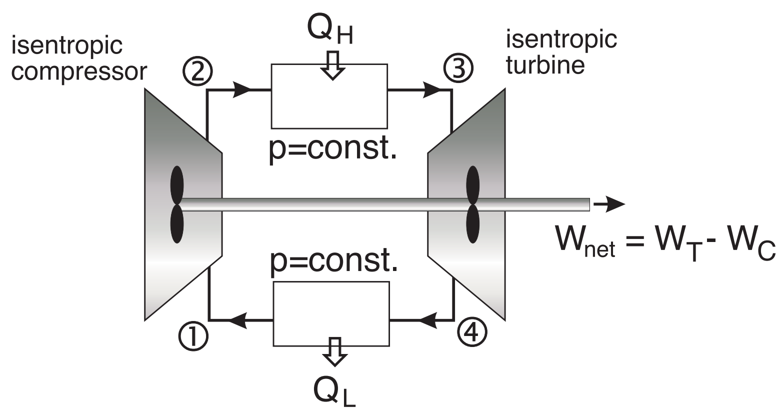
Open Cycle Gas Turbine Engines

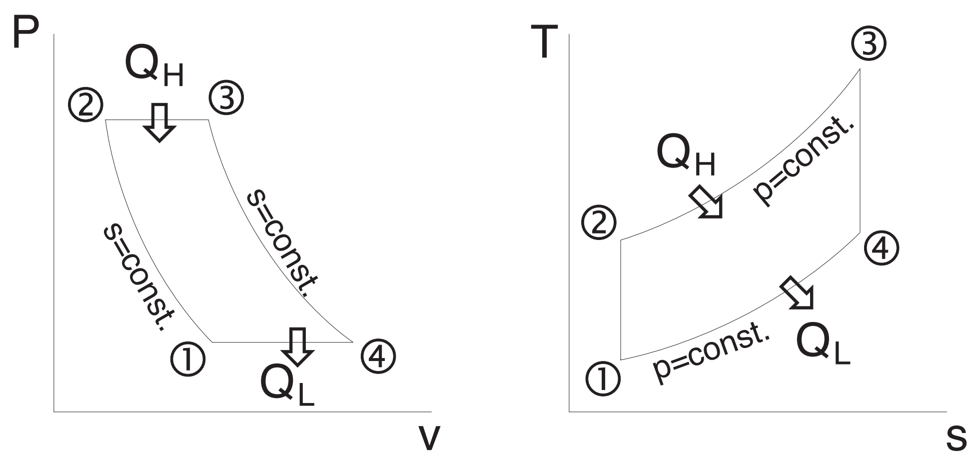


- after compression, air enters a combustion chamber into which fuel is injected
- the resulting products of combustion expand and drive the turbine
- combustion products are discharged to the atmosphere
- compressor power requirements vary from 40-80% of the power output of the turbine (remainder is net power output), i.e. back work ratio = 0.4 → 0.8
- high power requirement is typical when gas is compressed because of the large specific volume of gases in comparison to that of liquids

Idealized Air Standard Brayton Cycle

- closed loop
- constant pressure heat addition and rejection
- ideal gas with constant specific heats





Brayton Cycle Efficiency

The Brayton cycle efficiency can be written as

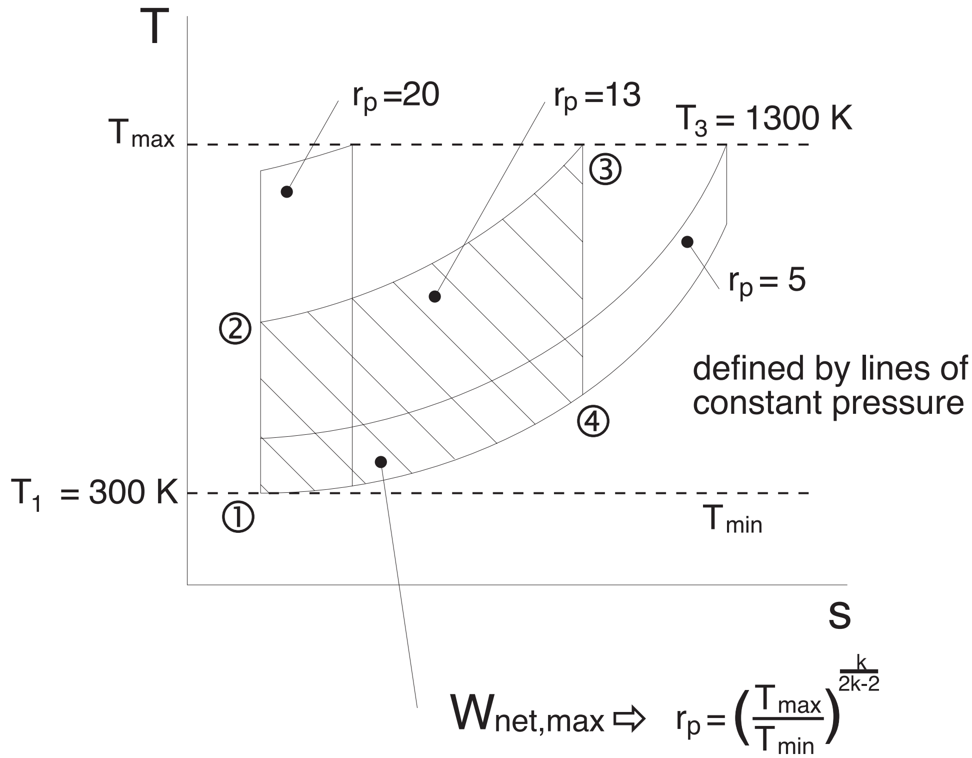
$$\boxed{\eta = 1 - (r_p)^{(1-k)/k}}$$

where we define the pressure ratio as:

$$r_p = \frac{P_2}{P_1} = \frac{P_3}{P_4}$$

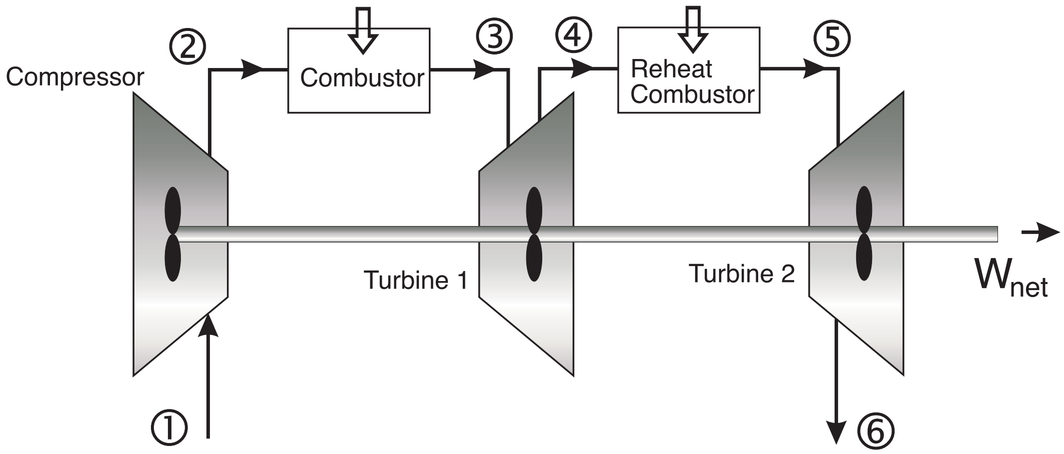
Maximum Pressure Ratio

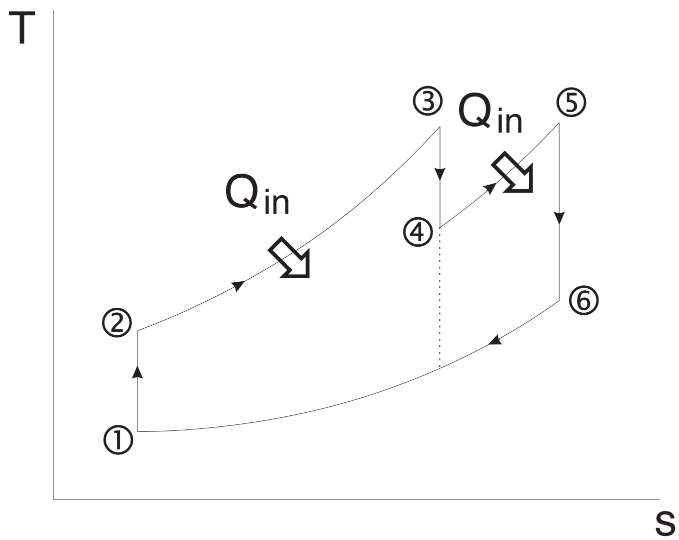
Given that the maximum and minimum temperature can be prescribed for the Brayton cycle, a change in the pressure ratio can result in a change in the work output from the cycle.



The **maximum temperature** in the cycle (T_3) is limited by metallurgical conditions because the turbine blades cannot sustain temperatures above 1300 K. Higher temperatures (up to 1600 K can be obtained with ceramic turbine blades). The **minimum temperature** is set by the air temperature at the inlet to the engine.

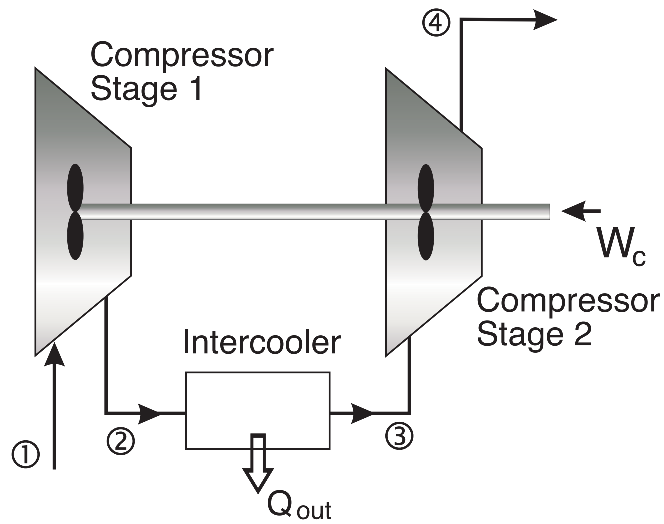
Brayton Cycle with Reheat

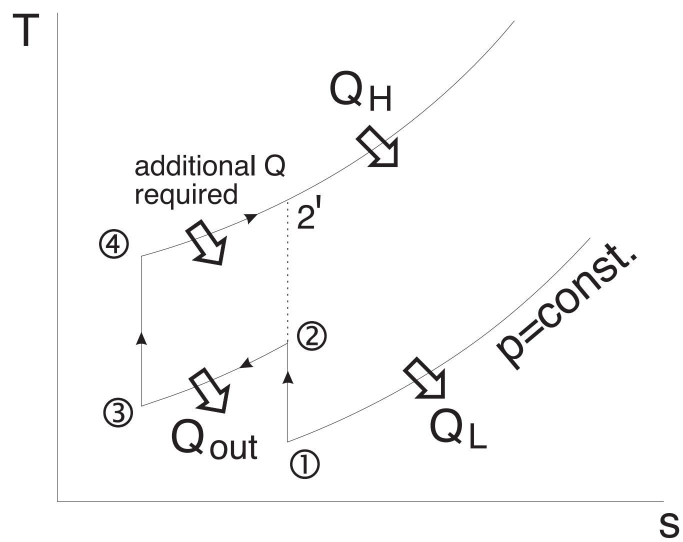




- T_3 is limited due to metallurgical constraints
- excess air is extracted and fed into a second stage combustor and turbine
- turbine outlet temperature is increased with reheat ($T_6 > T_4'$), therefore potential for regeneration is enhanced
- when reheat and regeneration are used together the thermal efficiency can increase significantly

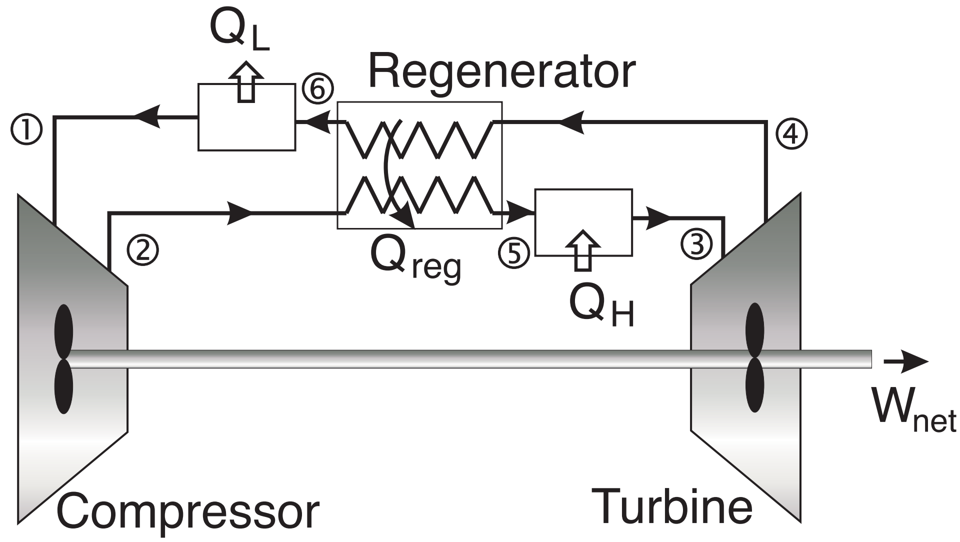
Compression with Intercooling

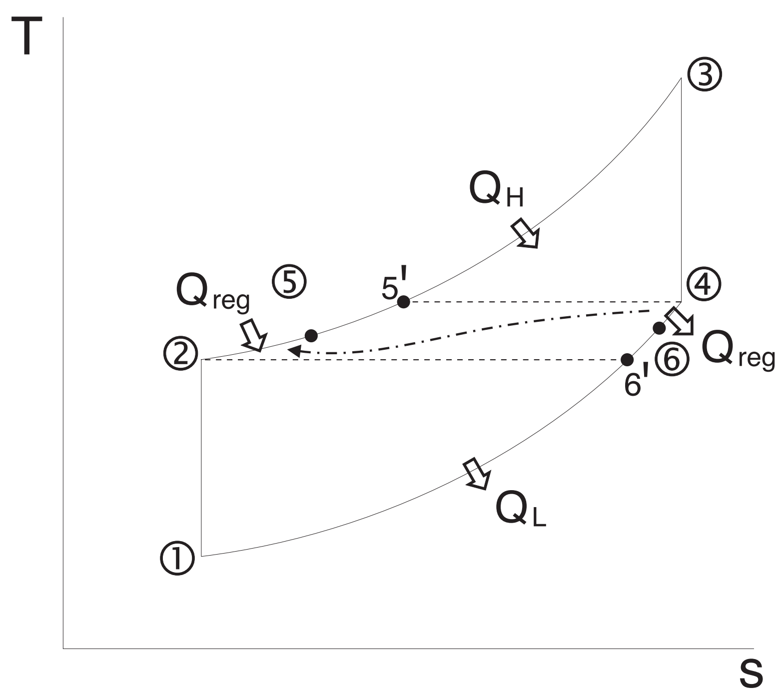




- the work required to compress in a steady flow device can be reduced by compressing in stages
- cooling the gas reduces the specific volume and in turn the work required for compression
- by itself compression with intercooling does not provide a significant increase in the efficiency of a gas turbine because the temperature at the combustor inlet would require additional heat transfer to achieve the desired turbine inlet temperature
- but the lower temperature at the compressor exit enhances the potential for regeneration i.e. a larger ΔT across the heat exchanger

Brayton Cycle with Regeneration





- a regenerator (heat exchanger) is used to reduce the fuel consumption to provide the required $\dot{Q}_H$
- the efficiency with a regenerator can be determined as:

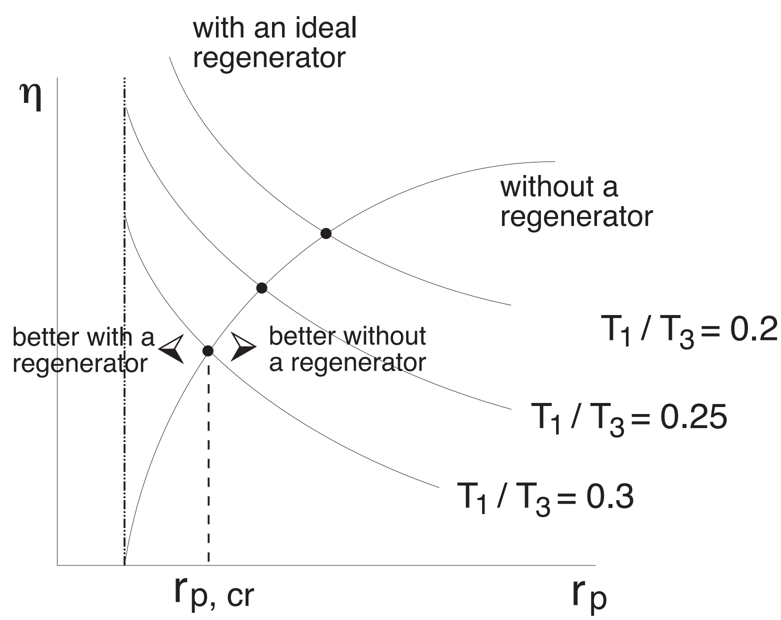
$$\eta = \frac{\dot{W}_{net}}{\dot{Q}_H} \quad = \quad 1 - \frac{\dot{Q}_L}{\dot{Q}_H}$$

$$
\begin{aligned}
&= 1 - \frac{c_p(T_6 - T_1)}{c_p(T_3 - T_5)} \Rightarrow (for\ a\ real\ regenerator) \\
&= 1 - \frac{c_p(T_6' - T_1)}{c_p(T_3 - T_5')} \Rightarrow (for\ an\ ideal\ regenerator) \\
&= 1 - \frac{c_p(T_2 - T_1)}{c_p(T_3 - T_4)}
\end{aligned}
$$

and

$$
\boxed{\eta = 1 - \left(\frac{T_{min}}{T_{max}}\right)(r_p)^{(k-1)/k}}
$$

- for a given T_{min}/T_{max}, the use of a regenerator above a certain r_p will result in a reduction of η



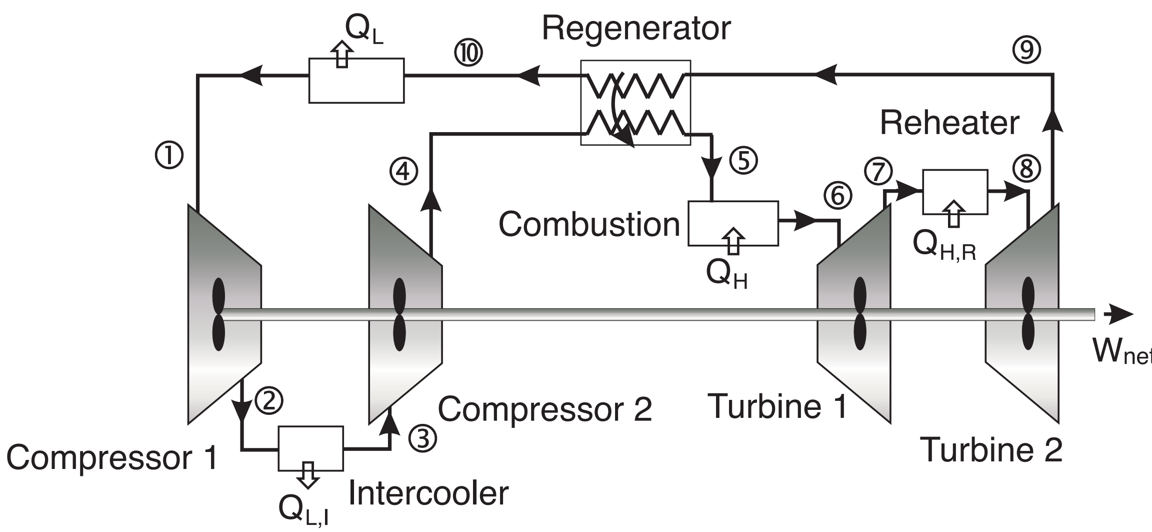
Regenerator Effectiveness

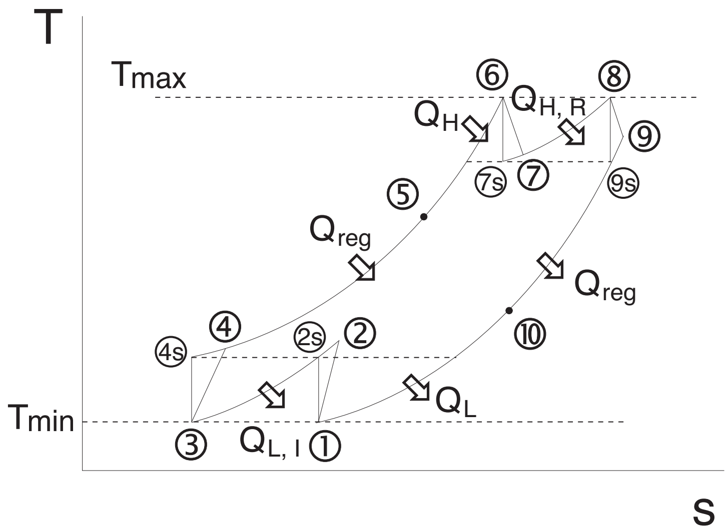
$$\epsilon = \frac{\dot{Q}_{reg,actual}}{\dot{Q}_{reg,ideal}} = \frac{h_5 - h_2}{h'_5 - h_2} = \frac{h_5 - h_2}{h_4 - h_2} = \frac{T_5 - T_2}{T_4 - T_2}$$

Typical values of effectiveness are ≤ 0.7

Repeated intercooling, reheating and regeneration will provide a system that approximates the Ericsson Cycle which has Carnot efficiency $\left(\eta = 1 - \frac{T_L}{T_H}\right)$.

Brayton Cycle With Intercooling, Reheating and Regeneration





Compressor and Turbine Efficiencies

Isentropic Efficiencies

(1) $$\eta_{comp} = \frac{h_{2,s} - h_1}{h_2 - h_1} = \frac{c_p(T_{2,s} - T_1)}{c_p(T_2 - T_1)}$$

(2) $$\eta_{turb} = \frac{h_3 - h_4}{h_3 - h_{4,s}} = \frac{c_p(T_3 - T_4)}{c_p(T_3 - T_{4,s})}$$

(3) $$\eta_{cycle} = \frac{W_{net}}{Q_H} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{c_p(T_4 - T_1)}{c_p(T_3 - T_2)}$$

Given the turbine and compressor efficiencies and the maximum (T_3) and the minimum (T_1) temperatures in the process, find the cycle efficiency (η_{cycle}).

(4) Calculate T_{2s} from the isentropic relationship,

$$\frac{T_{2,s}}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k}.$$

Get T_2 from (1).

(5) Do the same for T_4 using (2) and the isentropic relationship.

(6) substitute T_2 and T_4 in (3) to find the cycle efficiency.