Heat Engines & Second Law of Thermodynamics

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ME 203: Engineering Thermodynamics
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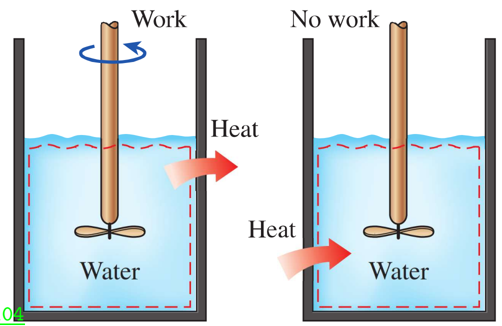
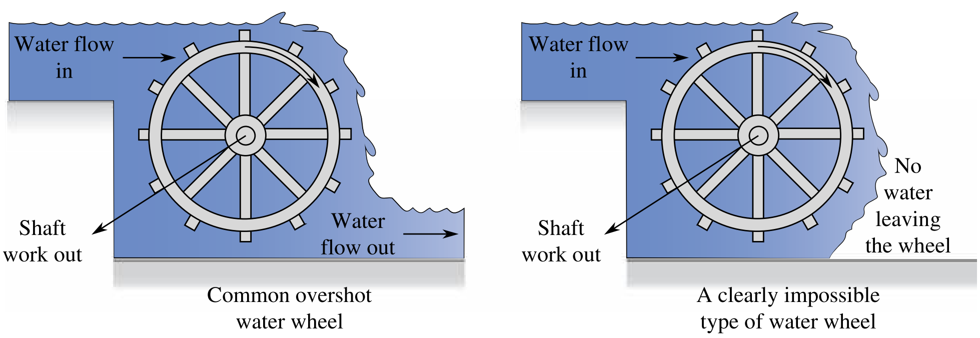
Some Observations in Work & Heat Conversions

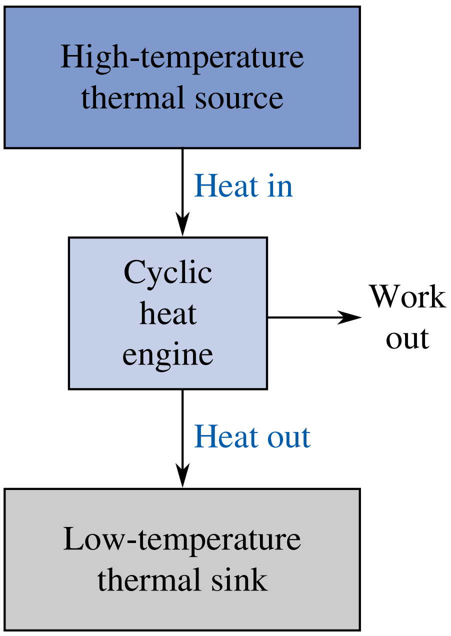


T104

Work can always be converted to heat directly and completely, but the reverse is not true.

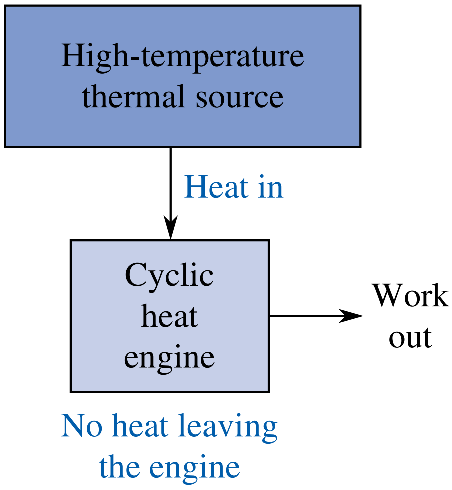


T054



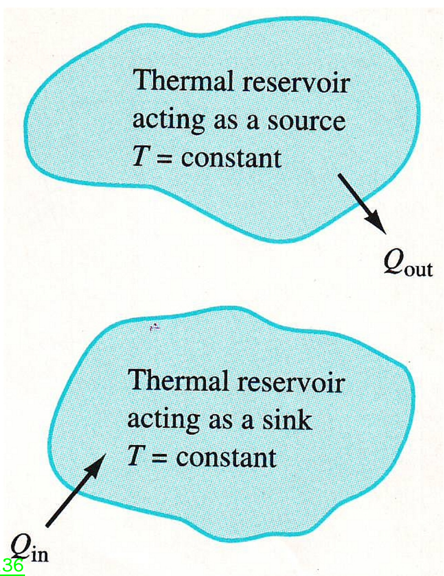
A common continuously operating heat engine

T055



An impossible type of continuously operating heat engine

Thermal Reservoir



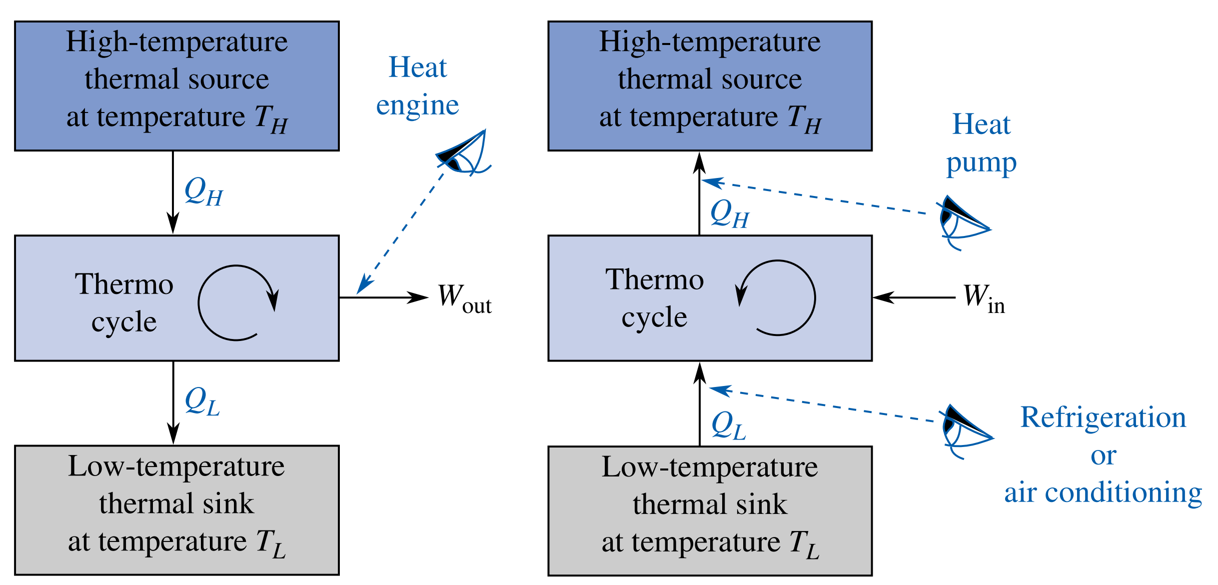
T136

A thermal reservoir is a closed system with the following characteristics:

- Temperature remains uniform and constant during a process.
- Changes within the thermal reservoir are internally reversible.
- Heat transfer to or from a thermal reservoir only results in an increase or decrease in the internal energy of the reservoir.

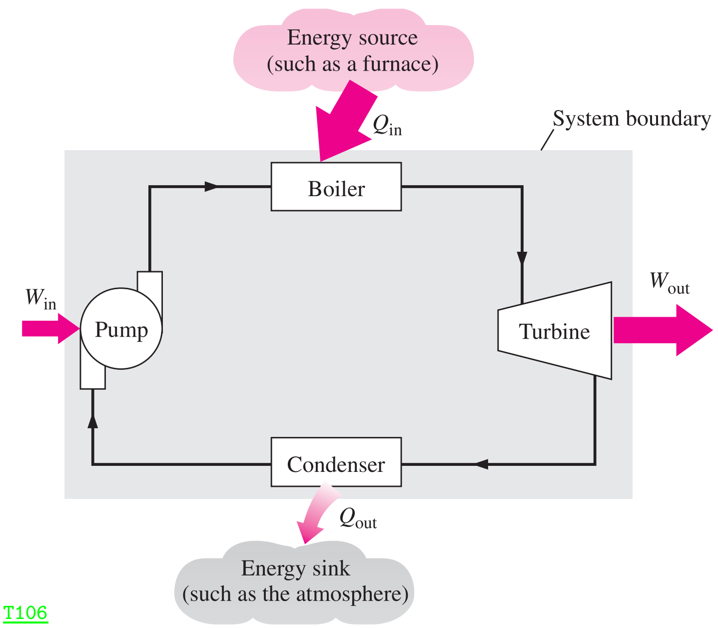
A thermal reservoir is an idealization which in practice can be closely approximated. Large bodies of water, such as oceans and lakes, and the atmosphere behave essentially as thermal reservoirs.

Heat Engine: Classifications

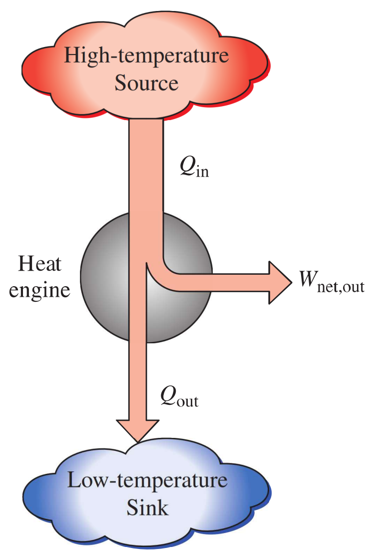


T058 (a) (b)

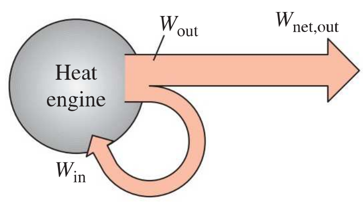
(Heat) Engine



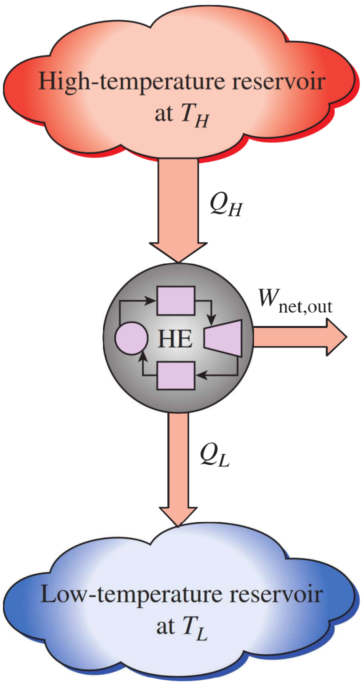
T106



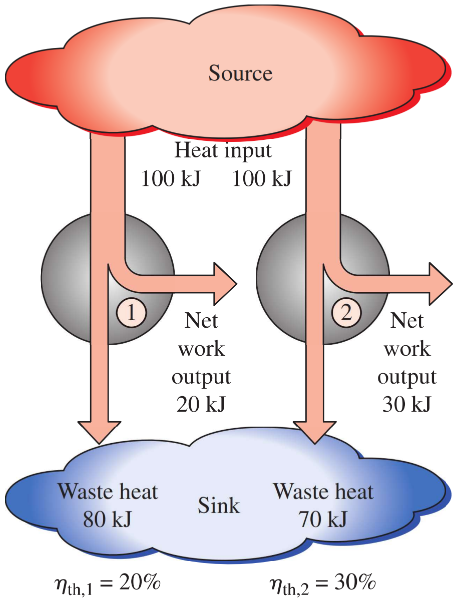
T105



T107



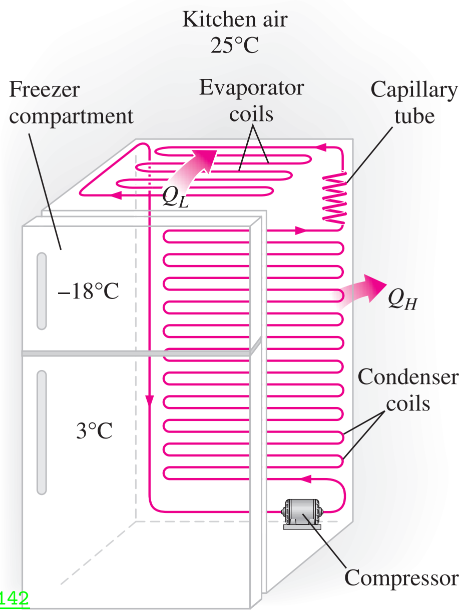
T109



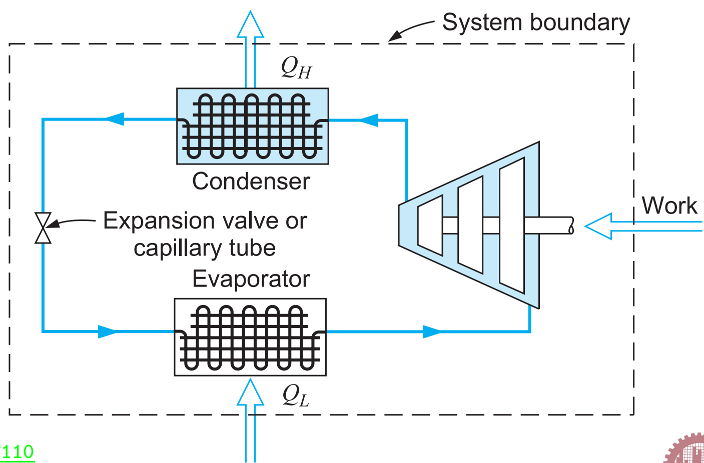
T108

$$\text{Thermal Efficiency, } \eta_{th} \equiv \frac{W_{net,out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{Q_L}{Q_H}$$

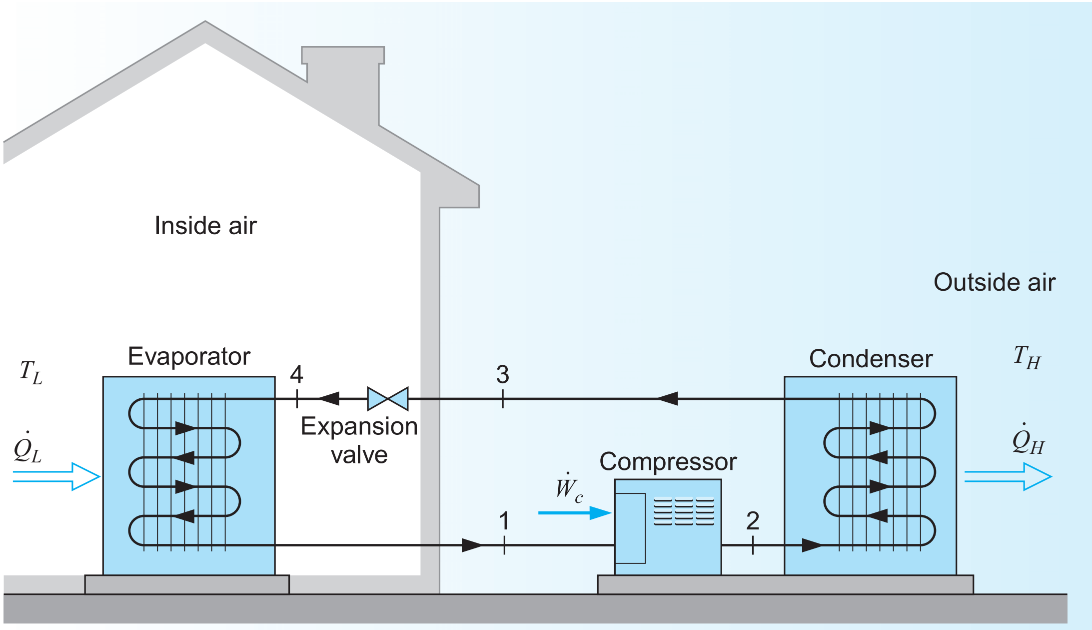
Refrigerator/Air-conditioner



T142

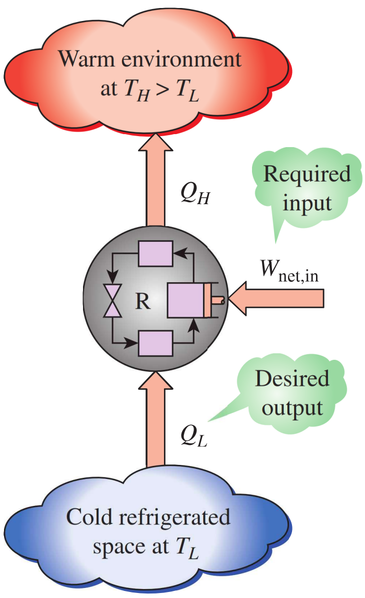


T110

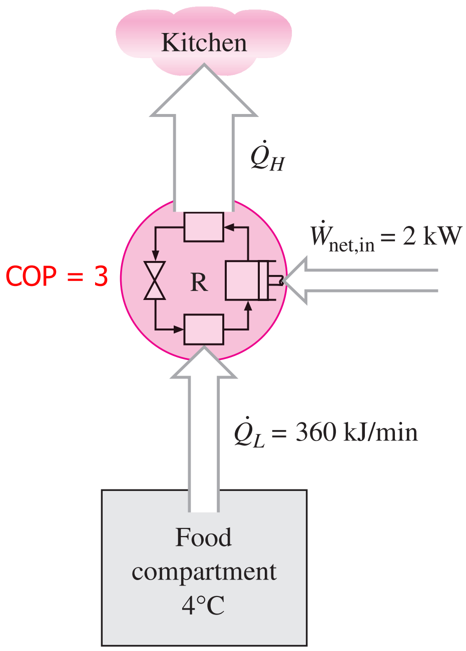


An air conditioner in cooling mode

T144



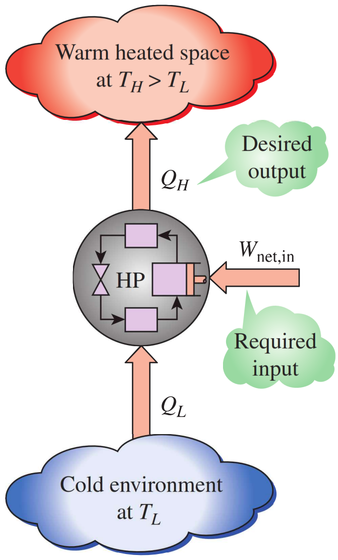
T111



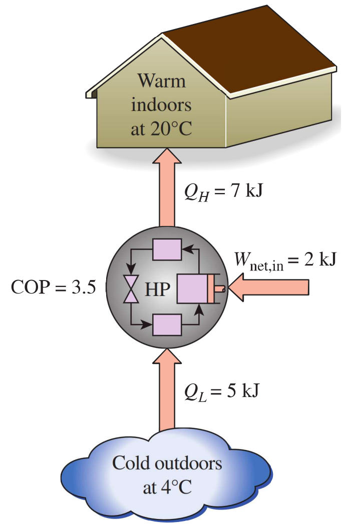
T138

$$\boxed{\text{Coefficient of Performance, } COP_R = \frac{\text{Desired Output}}{\text{Required Input}} = \frac{Q_L}{W_{net,in}}}$$

Heat Pump



T112

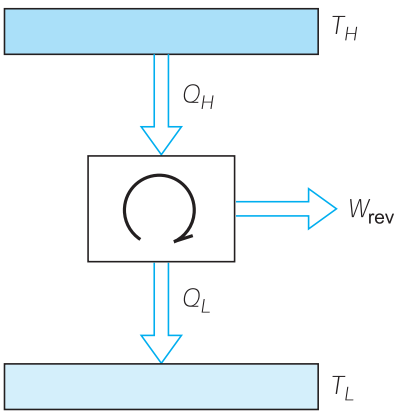


T137

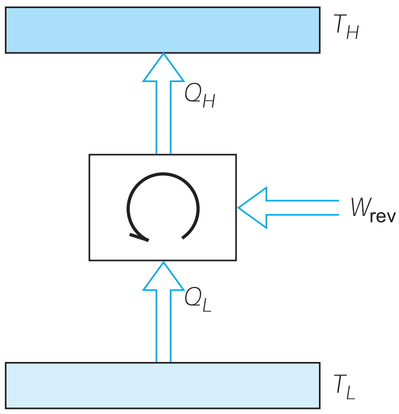
$$\boxed{\text{Coefficient of Performance, } COP_{HP} = \frac{\text{Desired Output}}{\text{Required Input}} = \frac{Q_H}{W_{net,in}}}$$

$$\boxed{COP_{HP} = \frac{Q_H}{W_{net,in}} = \frac{Q_L + W_{net,in}}{W_{net,in}} = COP_R + 1}$$

Reversible Engines



T035



T036

- A reversible process for a system is defined as a process that once having taken place can be reversed and in so doing leave no change in either the system or the surrounding.
- A reversible power cycle can be changed to a reversible refrigeration cycle by just reversing all the heat and work flow quantities.

Kelvin-Planck (KP) Statement

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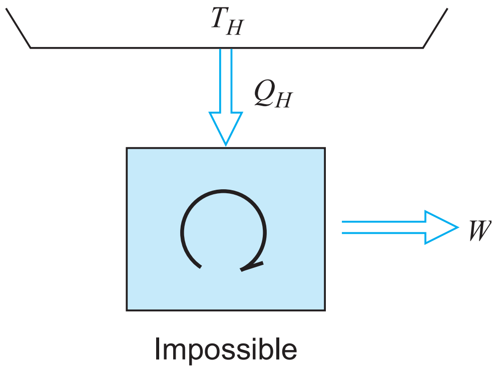
It is impossible to construct a device that will operate in a cycle and produce no effect other than the raising of a weight and the exchange of heat with a single reservoir.



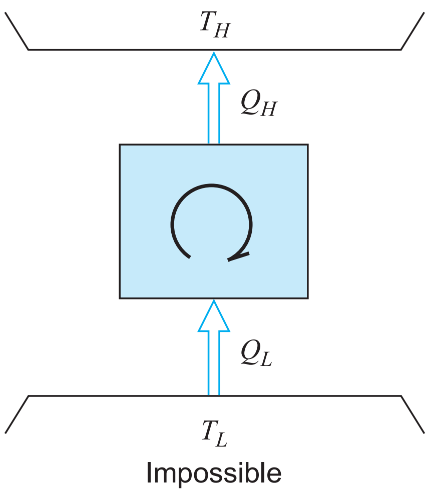
T028

$$\boxed{\oint \delta W \leqq 0 \quad \text{for single reservoir}}$$

Clausius Statement

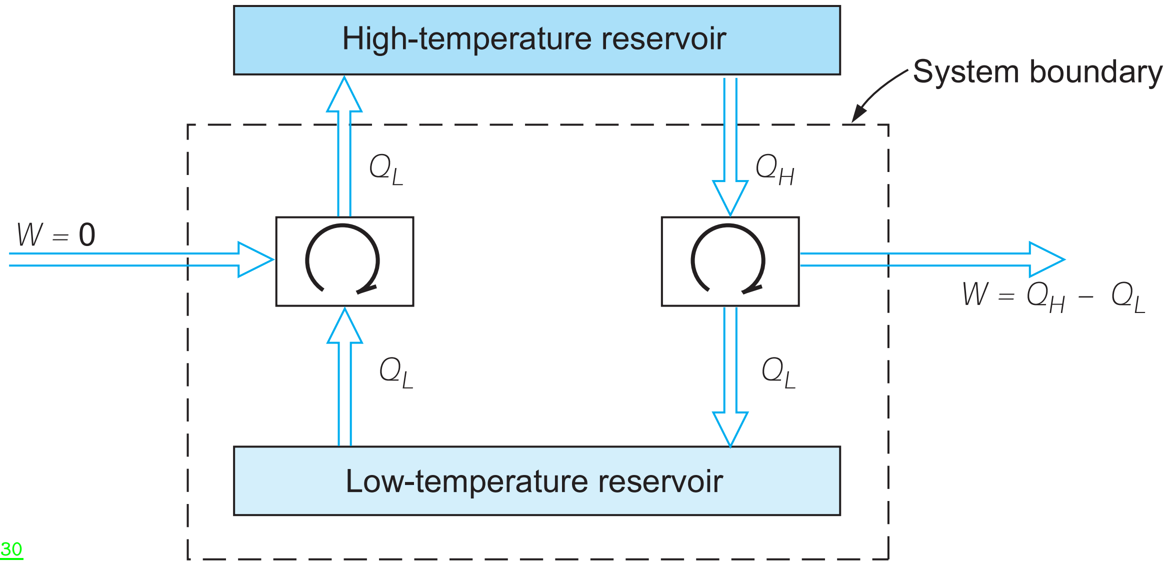
Clausius statement

It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a cooler body to a hotter body.

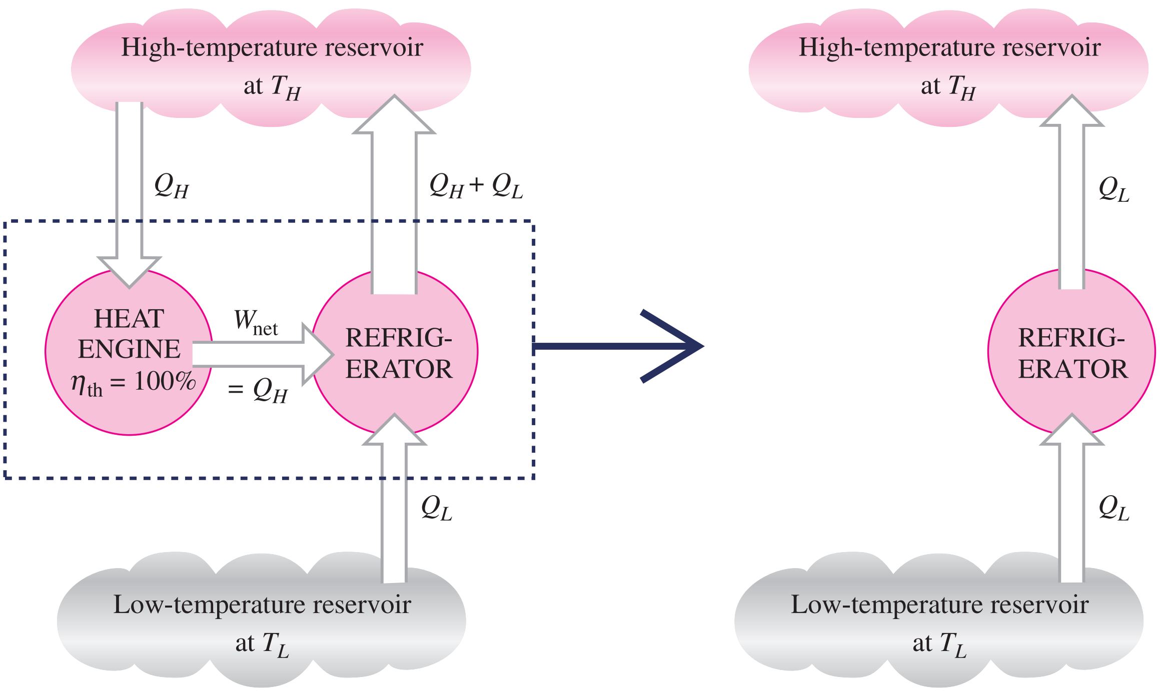


T029

Equivalence of Statements



Violation of Clausius (C) statement ⇒ violation of Kevlin-Planck (KP) statement.



T113 (*a*) A refrigerator that is powered by a 100 percent efficient heat engine

(*b*) The equivalent refrigerator

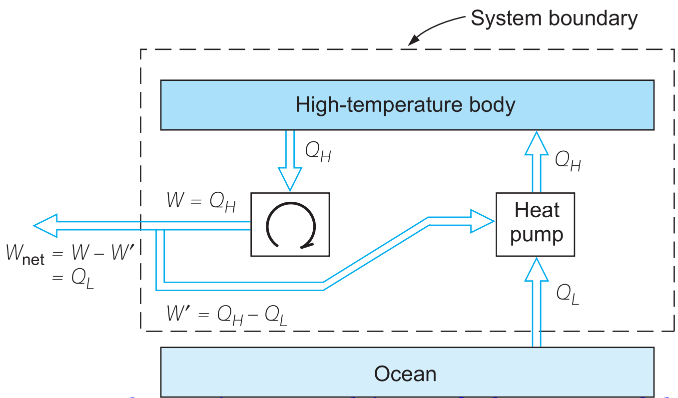
Violation of Kevlin-Planck (KP) statement ⇒ violation of Clausius (C) statement.

3 Observations of Two Statements

1. Both are negative statements; negative statements are impossible to prove directly. Every relevant experiment that has been conducted, either directly or indirectly, verifies the second law, and no experiment has ever been conducted that contradicts the second law. The basis of the second law is therefore experimental evidence.
2. Both statements are equivalent. Two statements are equivalent if the truth of either statement implies the truth of the other or if the violation of either statement implies the violation of the other.
3. Both statements state the impossibility of Perpetual Motion Machine of 2nd Kind (PMM2).

Perpetual Motion Machines

1. A perpetual-motion machine of the first kind (PMM1) would create work from nothing or create mass or energy, thus violating the first law.
2. A perpetual-motion machine of the second kind (PMM2) would extract heat from a source and then convert this heat completely into other forms of energy, thus violating the second law.

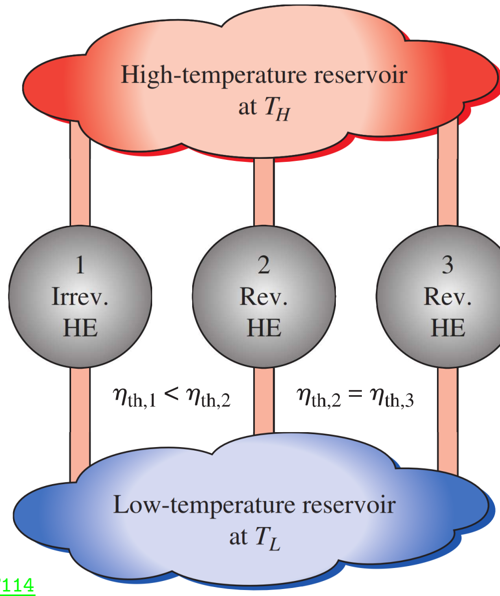


T140

A perpetual-motion machine of the second kind.

Carnot's Principles

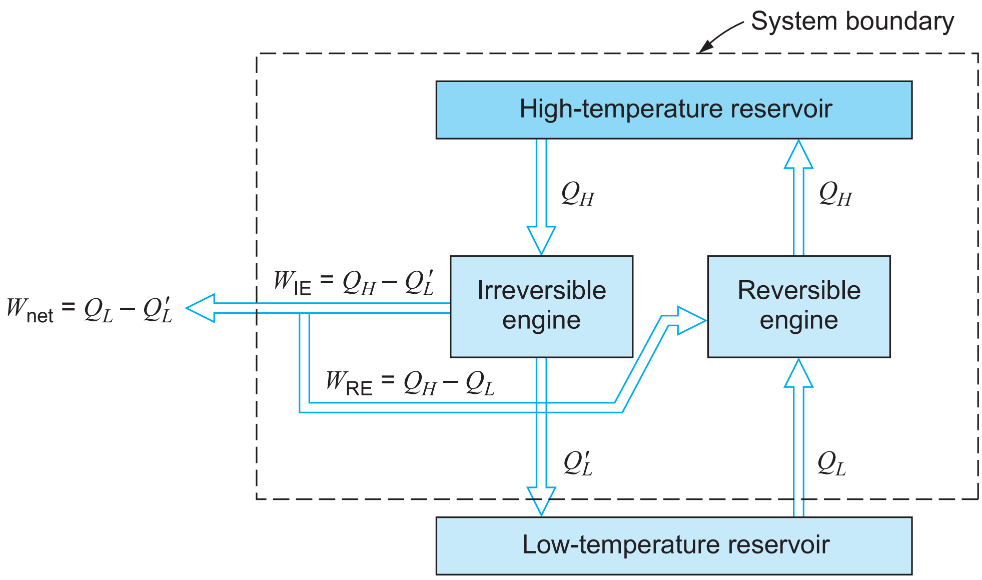
- It is impossible to construct an engine that operates between two given reservoirs and is more efficient than a reversible engine operating between the same two reservoirs.
- All engines that operate on the Carnot cycle between two given constant-temperature reservoirs have the same efficiency.



T114

- An absolute temperature scale may be defined which is independent of the measuring substances.

Proof: $\eta_{rev} > \eta_{irr}$



T032

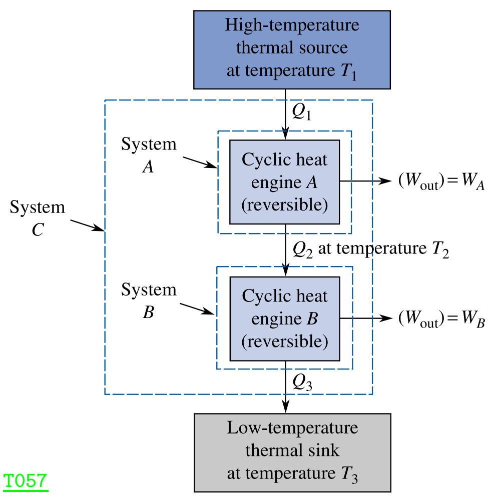
If $\eta_{irr} > \eta_{rev} \Rightarrow W_{IE} > W_{RE}$ for same Q_H. Hence, composite system produces net work output while exchanging heat with a single reservoir $\Rightarrow$ violation of K-P statement.

Proof: η_{rev} = same for same T_H & T_L

The proof of this proposition is similar to the proof just outlined, which assumes that there is one Carnot cycle that is more efficient than another Carnot cycle operating between the same temperature reservoirs. Let the Carnot cycle with the higher efficiency replace the irreversible cycle of the previous argument, and let the Carnot cycle with the lower efficiency operate as the refrigerator.

Thermodynamic Temperature Scale

Thermal efficiency of a reversible heat engine at a given set of reservoirs is independent of construction, design and working fluid of the engine.



T057

- $\eta_{th} = 1 - \frac{Q_L}{Q_H} = 1 - \psi(T_L, T_H)$
- $\frac{Q_1}{Q_2} = \psi(T_1, T_2)$, $\frac{Q_2}{Q_3} = \psi(T_2, T_3)$
- $\frac{Q_1}{Q_3} = \psi(T_1, T_3) = \frac{Q_1}{Q_2} \cdot \frac{Q_2}{Q_3}$
- $\psi(T_1, T_3) = \underbrace{\psi(T_1, T_2).\psi(T_2, T_3)}_{\textit{Not a function of } T_2}$

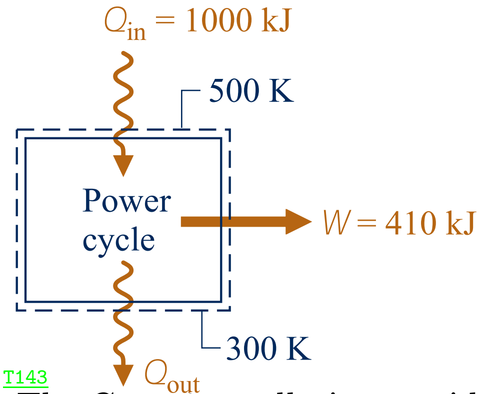
$$\Rightarrow \psi(T_1, T_2) = \frac{f(T_1)}{f(T_2)}, \psi(T_2, T_3) = \frac{f(T_2)}{f(T_3)}$$

$$\Rightarrow \psi(T_1, T_3) = \frac{f(T_1)}{f(T_3)} = \frac{f(T_1)}{f(T_2)} \cdot \frac{f(T_2)}{f(T_3)}$$

$$\Longrightarrow \boxed{\frac{Q_L}{Q_H} = \psi(T_L, T_H) = \frac{f(T_L)}{f(T_H)}}$$

Kelvin proposed that, $f(T) = T \rightsquigarrow \boxed{\frac{Q_L}{Q_H} = \frac{T_L}{T_H}} \Rightarrow \boxed{\eta_{rev.engine} = 1 - \frac{T_L}{T_H}}$

Moran Ex. 5.1: ▷ An inventor claims to have developed a power cycle capable of delivering a net work output of 410 kJ for an energy input by heat transfer of 1000 kJ. The system undergoing the cycle receives the heat transfer from hot gases at a temperature of 500 K and discharges energy by heat transfer to the atmosphere at 300 K. Evaluate this claim.



T143

- Claimed efficiency:

$\Rightarrow \eta = \frac{W}{Q_{in}} = \frac{410}{1000} = 0.41 = 41\%.$

- Maximum possible thermal efficiency:

$\Rightarrow \eta_{max} = 1 - \frac{T_L}{T_H} = 1 - \frac{300}{500} = 0.40 = 40\%.$

The Carnot corollaries provide a basis for evaluating the claim: Since the thermal efficiency of the actual cycle exceeds the maximum theoretical value, the claim cannot be valid.