Carnot showed that for an ideal reversible engine, the heats Q_H and Q_L are proportional to the operating temperatures T_H and T_L (in kelvins), so the efficiency can be written as

Carnot (ideal) efficiency

$$e_{ideal} = \frac{T_H - T_L}{T_H} = 1 - \frac{T_L}{T_H}. \qquad \begin{bmatrix}\text{Carnot (ideal)}\\ \text{efficiency}\end{bmatrix} \quad \textbf{(15–5)}$$

Equation 15–5 expresses the fundamental upper limit to the efficiency. Real engines always have an efficiency lower than this because of losses due to friction and the like. Real engines that are well designed reach 60 to 80% of the Carnot efficiency.

EXAMPLE 15–10 **Steam engine efficiency.** A steam engine operates between 500°C and 270°C. What is the maximum possible efficiency of this engine?

APPROACH The maximum possible efficiency is the idealized Carnot efficiency, Eq. 15–5. We must use kelvin temperatures.

SOLUTION We first change the temperature to kelvins by adding 273 to the given Celsius temperatures: $T_H = 773\text{ K}$ and $T_L = 543\text{ K}$. Then

$$e_{ideal} = 1 - \frac{543}{773} = 0.30.$$

To get the efficiency in percent, we multiply by 100. Thus, the maximum (or Carnot) efficiency is 30%. Realistically, an engine might attain 0.70 of this value, or 21%.

NOTE In this Example the exhaust temperature is still rather high, 270°C. Steam engines are often arranged in series so that the exhaust of one engine is used as intake by a second or third engine.

EXAMPLE 15–11 **A phony claim?** An engine manufacturer makes the following claims: An engine's heat input per second is 9.0 kJ at 435 K. The heat output per second is 4.0 kJ at 285 K. Do you believe these claims?

APPROACH The engine's efficiency can be calculated from the definition, Eq. 15–4. It must be less than the maximum possible, Eq. 15–5.

SOLUTION The claimed efficiency of the engine is

$$e = \frac{Q_H - Q_L}{Q_H} = \frac{9.0\text{ kJ} - 4.0\text{ kJ}}{9.0\text{ kJ}} = 0.56.$$

However, the maximum possible efficiency is given by the Carnot efficiency, Eq. 15–5:

$$e_{ideal} = \frac{T_H - T_L}{T_H} = \frac{435\text{ K} - 285\text{ K}}{435\text{ K}} = 0.34.$$

The manufacturer's claims violate the second law of thermodynamics and cannot be believed.

It is quite clear from Eq. 15–5 that at normal temperatures, a 100% efficient engine is not possible. Only if the exhaust temperature, T_L, were at absolute zero could 100% efficiency be obtained. But reaching absolute zero is a practical (as well as theoretical) impossibility.†

†Careful experimentation suggests that absolute zero is unattainable. This result is known as the **third law of thermodynamics**.