## KEY EQUATIONS

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ W_{\text{cycle}} \leq 0 ]</td>
<td>Internal irreversibilities present. ( \leq 0 ): Internal irreversibilities present. ( = 0 ): No internal irreversibilities. ( \text{single reservoir} )</td>
<td>(5.3) p. 254</td>
</tr>
<tr>
<td>[ \eta_{\text{max}} = 1 - \frac{T_C}{T_H} ]</td>
<td>Analytical form of the Kelvin–Planck statement.</td>
<td>(5.9) p. 265</td>
</tr>
<tr>
<td>[ \beta_{\text{max}} = \frac{T_C}{T_H - T_C} ]</td>
<td>Maximum thermal efficiency: power cycle operating between two reservoirs.</td>
<td>(5.10) p. 267</td>
</tr>
<tr>
<td>[ \gamma_{\text{max}} = \frac{T_H}{T_H - T_C} ]</td>
<td>Maximum coefficient of performance: refrigeration cycle operating between two reservoirs.</td>
<td>(5.11) p. 267</td>
</tr>
<tr>
<td>[ \int \left( \frac{\delta Q}{T} \right)<em>b = -\sigma</em>{\text{cycle}} ]</td>
<td>Maximum coefficient of performance: heat pump cycle operating between two reservoirs.</td>
<td>(5.13) p. 273</td>
</tr>
<tr>
<td>[ \sigma_{\text{cycle}} ]</td>
<td>Clausius inequality.</td>
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</tr>
</tbody>
</table>

## EXERCISES: THINGS ENGINEERS THINK ABOUT

1. What is an example of a process that would satisfy the conservation of energy principle but not actually be observed in nature?
2. Are health risks associated with consuming tomatoes induced to ripen by an ethylene spray? Explain.
3. What is the cost, per lb, of the refrigerant used in the air conditioner of the car you drive?
4. Are irreversibilities found in living things? Explain.
5. Is the power generated by fuel cells limited by the Carnot efficiency? Explain.
6. Does the second law impose performance limits on elite athletes seeking world records in events such as track and field and swimming? Explain.
7. Which method of heating is better in terms of operating cost: electric-resistance baseboard heating or a heat pump? Explain.
8. What is delaying the appearance in new car showrooms of automobiles powered by hydrogen fuel cells?
9. What options exist for effectively using energy discharged by heat transfer from electricity-generating power plants?
10. How significant is the roughness at a pipe’s inner surface in determining the friction factor? Explain.
11. One automobile engine requires SW20 motor oil while another engine requires SW30 oil. What do these designations mean and why might they differ for the two engines?
12. What factors influence the actual coefficient of performance achieved by refrigerators in family residences?
13. What is the SEER rating labeled on refrigerators seen in appliance showrooms?
14. How does the thermal glider (Sec. 5.4) sustain underwater motion for missions lasting weeks?

## CHECKING UNDERSTANDING

1. A reversible heat pump cycle operates between cold and hot thermal reservoirs at 300 °C and 500 °C, respectively. The coefficient of performance is closely (a) 1.5, (b) 3.87, (c) 2.87, (d) 2.5.
2. Referring to the list of Sec. 5.3.1, irreversibilities present during operation of an internal combustion automobile engine include (a) friction, (b) heat transfer, (c) chemical reaction, (d) all of the above.
3. Referring to the list of Sec. 5.3.1, irreversibilities present during operation of a forced-air, natural gas-fueled furnace include all of the following except (a) chemical reaction, (b) fluid friction, (c) polarization, (d) heat transfer.

4. Uses of the second law of thermodynamics include (a) defining the Kelvin scale, (b) predicting the direction of processes, (c) developing means for evaluating internal energy in terms of more readily measured properties, (d) all of the above.

5. For heating a home, does electrical-resistance baseboard heating or a heat pump use less electricity? Explain.

6. A power cycle operates between hot and cold thermal reservoirs at 2000 °F and 1000 °F, respectively. If the thermal efficiency of the power cycle were 45%, its mode of operation (a) is reversible, (b) is irreversible, (c) is impossible, (d) cannot be determined with the data provided.

7. When placed outside and exposed to the atmosphere, an ice cube melts, forming a thin film of liquid on the ground. Overnight, the liquid freezes, returning to the initial temperature of the ice cube. The water making up the cube undergoes (a) a thermodynamic cycle, (b) a reversible process, (c) an irreversible process, (d) none of the above.

8. Extending the discussion of Fig. 5.1a, how might work be developed when $T_f$ is less than $T_h$?

9. Extending the discussion of Fig. 5.1b, how might work be developed when $p_f$ is less than $p_h$?

10. An ideal gas in a piston-cylinder assembly expands isothermally, doing work and receiving an equivalent amount of energy by heat transfer from the surrounding atmosphere. Is this process of the gas in violation of the Kelvin-Planck statement of the second law? Explain.

11. The maximum coefficient of performance of any heat pump cycle operating between cold and hot reservoirs at 40°F and 80°F, respectively, is __________.

12. A throttling process is (a) reversible, (b) internally reversible, (c) irreversible, (d) isobaric.

13. Absolute temperature scales include the (a) Rankine scale, (b) Centigrade scale, (c) Fahrenheit scale, (d) Kelvin scale.

14. The energy of an isolated system remains constant, but change in entropy must satisfy (a) $\Delta S < 0$, (b) $\Delta S > 0$, (c) $\Delta S = 0$, (d) $\Delta S = 0$.

15. The maximum thermal efficiency of any power cycle operating between hot and cold reservoirs at 1000°C and 500°C, respectively, is __________.

16. A power cycle operating between hot and cold reservoirs at 500 K and 300 K, respectively, receives 1000 kJ by heat transfer from the hot reservoir. The magnitude of the energy discharged by heat transfer to the cold reservoir must satisfy (a) $Q_c > 600$ kJ, (b) $Q_c \leq 600$ kJ, (c) $Q_c = 600$ kJ, (d) $Q_c = 600$ kJ.

17. Referring to Fig. 5.13, if the gas obeys the ideal gas model, and $p_1 = 3$ atm, $v_1 = 4.2$ ft³/lb, $p_4 = 1$ atm, the specific volume at state 4 is ______ ft³/lb.

18. Referring to Fig. 5.15, if the boiler and condenser pressures are 50 bar and 0.5 bar, respectively, the thermal efficiency of the power cycle is __________.

19. An internal irreversibility within a gearbox is (a) chemical reaction, (b) unrestrained expansion of a gas, (c) mixing, (d) friction.

20. The coefficient of performance of a reversible refrigeration cycle is always (a) greater than, (b) less than, (c) equal to the coefficient of performance of an irreversible refrigeration cycle when each operates between the same two thermal reservoirs.

21. When hot and cold gas streams pass in counterflow through a heat exchanger, each at constant pressure, the principal internal irreversibility for the heat exchanger is __________.

22. A cell phone initially has a fully charged battery. After a period of cell phone use, the battery is recharged to its initial state. The quantity of electricity to recharge the battery is (a) less than, (b) equal to, (c) greater than the quantity required to operate the phone, Explain.

23. Referring to Fig. 5.12, if the temperature corresponding to point b is 1225°C, the Carnot efficiency is __________%.

24. The thermal efficiency of a system that undergoes a power cycle while receiving 1000 kJ of energy by heat transfer from a hot reservoir at 1000 K and discharging 500 kJ of energy by heat transfer to a cold reservoir at 400 K is __________%.

25. The coefficient of performance of an irreversible heat pump cycle is always (a) equal to, (b) greater than, (c) less than the coefficient of performance of a reversible heat pump cycle when each operates between the same two thermal reservoirs.

26. For a closed system, entropy (a) may be produced within the system, (b) may be transferred across its boundary, (c) may remain constant throughout the system, (d) all of the above.

27. Referring to the list of Sec. 5.3.1, significant irreversibilities present during operation of a household refrigerator include (a) inelastic deformation, (b) chemical reaction, (c) heat transfer through a finite temperature difference, (d) none of the above.

28. As shown in Fig. 5.28C, energy transfer between hot and cold reservoirs takes place through a rod insulated on its outer surface and at steady state. The principal source of irreversibility is __________.
29. As shown in Fig. P5.29C, a rigid, insulated tank is divided into halves by a partition that has gas on one side and an evacuated space on the other side. When the valve is opened, the gas expands to fill the entire volume. The principal source of irreversibility is

![Fig. P5.29C](image)

30. As shown in Fig. P5.30C, when the steam in the piston-cylinder assembly expands, the transmission converts the piston motion to rotary motion of a paddlewheel that stirs a viscous liquid. Later the steam is returned to its initial state. Does the steam undergo a reversible process? Explain.

![Fig. P5.30C](image)

**Indicate whether the following statements are true or false. Explain.**

31. The change in entropy of a closed system is the same for every process between two specified end states.

32. The maximum thermal efficiency of any power cycle operating between the same hot and cold thermal reservoirs at 1000°C and 500°C, respectively, is 50%.

33. A process of a closed system that violates the second law of thermodynamics necessarily violates the first law of thermodynamics.

34. One statement of the second law of thermodynamics recognizes that the extensive property entropy is produced within systems whenever internal irreversibilities are present.

35. In principle, the Clausius inequality applies to any cycle.

36. The Kelvin scale is the only absolute temperature scale.

37. Friction associated with flow of fluids through pipes and around objects is one type of irreversibility.

38. There are no irreversibilities within a system undergoing an internally reversible process.

39. The second Carnot corollary states that all power cycles operating between the same two thermal reservoirs have the same thermal efficiency.

40. When left alone, systems tend to undergo spontaneous changes until equilibrium is attained, both internally and with their surroundings.

41. Internally reversible processes do not actually occur but serve as hypothetical limiting cases as internal irreversibilities are reduced further and further.

42. For reversible refrigeration and heat pump cycles operating between the same hot and cold reservoirs, the relation between their coefficients of performance is \( \gamma_{\text{max}} = \beta_{\text{max}} + 1 \).

43. The maximum coefficient of performance of any refrigeration cycle operating between cold and hot reservoirs at 40°F and 80°F, respectively, is closely 12.5.

44. Mass, energy, entropy, and temperature are examples of extensive properties.

45. Every process consistent with the conservation of energy and conservation of mass principles can actually occur in nature.

46. The Clausius statement of the second law denies the possibility of transferring energy by heat from a cooler to a hotter body.

47. When an isolated system undergoes a process, the values of its energy and entropy can only increase or remain the same.

48. The Kelvin–Planck and Clausius statements of the second law of thermodynamics are equivalent because a violation of one statement implies the violation of the other.

49. The Carnot efficiency also limits the efficiency of wind turbines generating electricity.

50. When \( \alpha_{\text{cycle}} = 0 \) in Eq. 5.13, the corresponding cycle is one that you will never encounter on the job.

**PROBLEMS: DEVELOPING ENGINEERING SKILLS**

**Exploring the Second Law**

5.1 Complete the demonstration of the equivalence of the Clausius and Kelvin–Planck statements of the second law given in Sec. 5.2.2 by showing that a violation of the Kelvin–Planck statement implies a violation of the Clausius statement.

5.2 Shown in Fig. P5.2 is a proposed system that undergoes a cycle while operating between cold and hot reservoirs. The system receives 500 kJ from the cold reservoir and discharges 400 kJ to the hot reservoir while delivering net work to its surroundings in the amount of 100 kJ. There are no other energy transfers between the system and its surroundings. Evaluate the performance of the system using
5.3 Classify the following processes of a closed system as possible, impossible, or indeterminate.

<table>
<thead>
<tr>
<th>Energy Change</th>
<th>Entropy Transfer</th>
<th>Entropy Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) &gt; 0</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>(b) &lt; 0</td>
<td>&lt; 0</td>
<td>&lt; 0</td>
</tr>
<tr>
<td>(c) 0</td>
<td>&gt; 0</td>
<td>0</td>
</tr>
<tr>
<td>(d) &gt; 0</td>
<td>&lt; 0</td>
<td>&lt; 0</td>
</tr>
<tr>
<td>(e) 0</td>
<td>0</td>
<td>&lt; 0</td>
</tr>
<tr>
<td>(f) &lt; 0</td>
<td>0</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>(g) &lt; 0</td>
<td>&lt; 0</td>
<td>&gt; 0</td>
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</table>

5.4 Complete the discussion of the Kelvin-Planck statement of the second law in the box of Sec. 5.4 by showing that if a system undergoes a thermodynamic cycle reversibly while communicating thermally with a single reservoir, the equality in Eq. 5.3 applies.

5.5 As shown in Fig. 5.5, a reversible power cycle R and an irreversible power cycle I operate between the same hot and cold thermal reservoirs. Cycle I has a thermal efficiency equal to one-third of the thermal efficiency of cycle R.

(a) If each cycle receives the same amount of energy by heat transfer from the hot reservoir, determine which cycle (i) develops greater net work, (ii) discharges greater energy by heat transfer to the cold reservoir.

(b) If each cycle develops the same net work, determine which cycle (i) receives greater energy by heat transfer from the hot reservoir, (ii) discharges greater energy by heat transfer to the cold reservoir.

5.6 A power cycle I and a reversible power cycle R operate between the same two reservoirs, as shown in Fig. 5.6. Cycle I has a thermal efficiency equal to two-thirds of that for cycle R. Using the Kelvin-Planck statement of the second law, prove that cycle I must be irreversible.

5.7 Provide the details left to the reader in the demonstration of the second Carnot corollary given in the box of Sec. 5.6.2.

5.8 Using the Kelvin-Planck statement of the second law of thermodynamics, demonstrate the following corollaries:

(a) The coefficient of performance of an irreversible refrigeration cycle is always less than the coefficient of performance of a reversible refrigeration cycle when both exchange energy by heat transfer with the same two reservoirs.

(b) All reversible refrigeration cycles operating between the same two reservoirs have the same coefficient of performance.

(c) The coefficient of performance of an irreversible heat pump cycle is always less than the coefficient of performance of a reversible heat pump cycle when both exchange energy by heat transfer with the same two reservoirs.

(d) All reversible heat pump cycles operating between the same two reservoirs have the same coefficient of performance.

5.9 Use the Kelvin-Planck statement of the second law to show that the specified process is irreversible.

(a) As shown in Fig. 5.9a, a hot thermal reservoir is separated from a cold thermal reservoir by a cylindrical rod insulated on its lateral surface. Energy transfer by conduction between the two reservoirs takes place through the rod, which remains at steady state.

(b) As shown in Fig. 5.9b, a rigid insulated tank is divided into halves by a partition. On one side of the partition is a
5.10 Figure P5.10 shows two power cycles, denoted 1 and 2, operating in series, together with three thermal reservoirs. The energy transfer by heat into cycle 2 is equal in magnitude to the energy transfer by heat from cycle 1. All energy transfers are positive in the directions of the arrows.

(a) Determine an expression for the thermal efficiency of an overall cycle consisting of cycles 1 and 2 expressed in terms of their individual thermal efficiencies.

(b) If cycles 1 and 2 are each reversible, use the result of part (a) to obtain an expression for the thermal efficiency of the overall cycle in terms of the temperatures of the three reservoirs, \( T_H, T, \) and \( T_C \), as required. Comment.

(c) If cycles 1 and 2 are each reversible and have the same thermal efficiency, obtain an expression for the intermediate temperature \( T \) in terms of \( T_H \) and \( T_C \).

**Fig. P5.10**

5.11 Two reversible refrigeration cycles are arranged in series. The first cycle receives energy by heat transfer from a cold reservoir at temperature \( T_C \) and rejects energy by heat transfer to a reservoir at an intermediate temperature \( T \) greater than \( T_C \). The second cycle receives energy by heat transfer from the reservoir at temperature \( T \) and rejects energy by heat transfer to a higher-temperature reservoir at \( T_H \). Obtain an expression for the coefficient of performance of a single reversible refrigeration cycle operating directly between cold and hot reservoirs at \( T_C \) and \( T_H \), respectively, in terms of the coefficients of performance of the two cycles.

5.12 Repeat Problem 5.11 for the case of two reversible heat pump cycles.

5.13 Two reversible cycles operate between hot and cold reservoirs at temperature \( T_H \) and \( T_C \), respectively.

(a) If one is a power cycle and the other is a heat pump cycle, what is the relation between the coefficient of performance of the heat pump cycle and the thermal efficiency of the power cycle?

(b) If one is a refrigeration cycle and the other is a heat pump cycle, what is the relation between their coefficients of performance?

5.14 Figure P5.14 shows a system consisting of a reversible power cycle driving a reversible heat pump. The power cycle receives \( Q_1 \) by heat transfer at \( T_H \) from a high-temperature source and delivers \( Q_1 \) to a dwelling at \( T_0 \). The heat pump receives \( Q_0 \) from the outdoors at \( T_0 \) and delivers \( Q_0 \) to the dwelling. Obtain an expression for the ratio of the total heating provided to the dwelling to the heat transfer supplied from the high-temperature source: \( (Q_1 + Q_2)/Q_1 \) in terms of the temperatures \( T_0, T_0, \) and \( T_0 \).

**Fig. P5.14**

5.15 To increase the thermal efficiency of a reversible power cycle operating between reservoirs at \( T_H \) and \( T_C \), would you increase \( T_H \) while keeping \( T_C \) constant, or decrease \( T_C \) while keeping \( T_H \) constant? Are there any natural limits on the increase in thermal efficiency that might be achieved by such means?

5.16 Before introducing the temperature scale now known as the Kelvin scale, Kelvin suggested a logarithmic scale in which the function \( \psi \) of Sec. 5.8.1 takes the form

\[
\psi = \exp \theta_C / \exp \theta_H
\]

where \( \theta_H \) and \( \theta_C \) denote, respectively, the temperatures of the hot and cold reservoirs on this scale.

(a) Show that the relation between the Kelvin temperature \( T \) and the temperature \( \theta \) on the logarithmic scale is

\[
\theta = \ln (T + C)
\]

where \( C \) is a constant.

(b) On the Kelvin scale, temperatures vary from 0 to \( +\infty \). Determine the range of temperature values on the logarithmic scale.

(c) Obtain an expression for the thermal efficiency of any system undergoing a reversible power cycle while operating between reservoirs at temperatures \( \theta_H \) and \( \theta_C \) on the logarithmic scale.

**Power Cycle Applications**

5.17 The data listed below are claimed for a power cycle operating between hot and cold reservoirs at 1500 K and 450 K, respectively. For each case, determine whether the cycle operates reversibly, operates irreversibly, or is impossible.
5.18 A power cycle receives energy \( Q_H \) by heat transfer from a hot reservoir at \( T_H = 1200^\circ R \) and rejects energy \( Q_C \) by heat transfer to a cold reservoir at \( T_C = 400^\circ R \). For each of the following cases, determine whether the cycle operates reversibly, operates irreversibly, or is impossible.

(a) \( Q_H = 900 \text{ Btu} \), \( W_{\text{cycle}} = 450 \text{ Btu} \)
(b) \( Q_H = 900 \text{ Btu} \), \( Q_C = 300 \text{ Btu} \)
(c) \( W_{\text{cycle}} = 600 \text{ Btu} \), \( Q_C = 400 \text{ Btu} \)
(d) \( \eta = 70\% \)

5.19 A power cycle operating at steady state receives energy by heat transfer at a rate \( Q_H \) at \( T_H = 1800 \text{ K} \) and rejects energy by heat transfer to a cold reservoir at a rate \( Q_C \) at \( T_C = 600 \text{ K} \). For each of the following cases, determine whether the cycle operates reversibly, operates irreversibly, or is impossible.

(a) \( Q_H = 500 \text{ kW} \), \( Q_C = 100 \text{ kW} \)
(b) \( Q_H = 500 \text{ kW} \), \( W_{\text{cycle}} = 250 \text{ kW} \), \( Q_C = 200 \text{ kW} \)
(c) \( W_{\text{cycle}} = 350 \text{ kW} \), \( Q_C = 150 \text{ kW} \)
(d) \( Q_H = 500 \text{ kW} \), \( Q_C = 300 \text{ kW} \)

5.20 As shown in Fig. 5.20, a reversible power cycle receives energy \( Q_H \) by heat transfer from a hot reservoir at \( T_H \) and rejects energy \( Q_C \) by heat transfer to a cold reservoir at \( T_C \).

(a) If \( T_H = 1600 \text{ K} \) and \( T_C = 400 \text{ K} \), what is the thermal efficiency?
(b) If \( T_H = 500^\circ C \), \( T_C = 20^\circ C \), and \( W_{\text{cycle}} = 1000 \text{ kW} \), what are \( Q_H \) and \( Q_C \), each in kW?
(c) If \( \eta = 60\% \) and \( T_C = 40^\circ F \), what is \( T_H \), in °F?
(d) If \( \eta = 40\% \) and \( T_H = 727^\circ C \), what is \( T_C \), in °C?

![Fig. P5.20](image)

5.21 A reversible power cycle whose thermal efficiency is 40% receives 50 kJ by heat transfer from a hot reservoir at 600 K and rejects energy by heat transfer to a cold reservoir at temperature \( T_C \). Determine the energy rejected, in kJ, and \( T_C \), in K.

5.22 At a particular location, magma exists several kilometers below Earth’s surface at a temperature of 1100°C, while the average temperature of the atmosphere at the surface is 15°C. Determine the maximum thermal efficiency for any power cycle operating between hot and cold reservoirs at these temperatures.

5.23 Power can be generated in principle by utilizing the naturally occurring decrease with depth of the temperature of ocean water. At one location the ocean surface temperature is 60°F, while at a depth of 1800 ft the temperature is 35°F. Determine the maximum thermal efficiency for any power cycle operating between hot and cold reservoirs at these temperatures.

5.24 During January, at a location in Alaska winds at \(-30^\circ C\) can be observed. However, several meters below ground the temperature remains at \(13^\circ C\). An inventor claims to have devised a power cycle working between these temperatures having a thermal efficiency of 5%. Investigate this claim.

5.25 A reversible power cycle operating as in Fig. 5.5 receives energy \( Q_H \) by heat transfer from a hot reservoir at \( T_H \) and rejects energy \( Q_C \) by heat transfer to a cold reservoir at \( 40^\circ F \). If \( W_{\text{cycle}} = 3 \times Q_C \), determine (a) the thermal efficiency and (b) \( T_H \), in °F.

5.26 As shown in Fig. 5.26, two reversible cycles arranged in series each produce the same net work, \( W_{\text{cycle}} \). The first cycle receives energy \( Q_H \) by heat transfer from a hot reservoir at \( 1000\text{°R} \) and rejects energy \( Q \) by heat transfer to a reservoir at an intermediate temperature, \( T \). The second cycle receives energy \( Q \) by heat transfer from the reservoir at temperature \( T \) and rejects energy \( Q_C \) by heat transfer to a reservoir at \( 400\text{°R} \). All energy transfers are positive in the directions of the arrows. Determine

(a) the intermediate temperature \( T \), in °R, and the thermal efficiency for each of the two power cycles.
(b) the thermal efficiency of a single reversible power cycle operating between hot and cold reservoirs at \( 1000\text{°R} \) and \( 400\text{°R} \), respectively. Also, determine the net work developed by the single cycle, expressed in terms of the net work developed by each of the two cycles, \( W_{\text{cycle}} \).

![Fig. P5.26](image)

5.27 Two reversible power cycles are arranged in series. The first cycle receives energy by heat transfer from a hot reservoir at \( 1000\text{°R} \) and rejects energy by heat transfer to a reservoir at temperature \( T \) (\(<1000\text{°R}\)). The second cycle
receives energy by heat transfer from the reservoir at
temperature \( T \) and rejects energy by heat transfer to a cold
reservoir at 500°F (\(< T\)). The thermal efficiency of the first
cycle is 50% greater than that of the second cycle. Determine
(a) the intermediate temperature \( T \), in °F, and the thermal
efficiency for each of the two power cycles,
(b) the thermal efficiency of a single reversible power cycle
operating between hot and cold reservoirs at 1000°F and
500°F, respectively.

5.28 The data listed below are claimed for power cycles
operating between hot and cold reservoirs at 1000 K and
400 K, respectively. For each case determine whether such a
cycle is in keeping with the first and second laws of
thermodynamics.

(a) \( Q_H = 300 \text{ kJ}, W_{\text{cycle}} = 160 \text{ kJ}, Q_C = 140 \text{ kJ} \)
(b) \( Q_H = 300 \text{ kJ}, W_{\text{cycle}} = 180 \text{ kJ}, Q_C = 120 \text{ kJ} \)
(c) \( Q_H = 300 \text{ kJ}, W_{\text{cycle}} = 170 \text{ kJ}, Q_C = 140 \text{ kJ} \)
(d) \( Q_H = 300 \text{ kJ}, W_{\text{cycle}} = 200 \text{ kJ}, Q_C = 100 \text{ kJ} \)

5.29 A power cycle operates between a lake's surface water at
a temperature of 300 K and water at a depth whose
temperature is 285 K. At steady state the cycle develops a
power output of 10 kW, while rejecting energy by heat transfer
to the lower-temperature water at the rate 14,400 kW/min.
Determine (a) the thermal efficiency of the power cycle and
(b) the maximum thermal efficiency for any such power cycle.

5.30 An inventor claims to have developed a power cycle
having a thermal efficiency of 40%, while operating between
hot and cold reservoirs at temperature \( T_H \) and \( T_C = 300 \text{ K} \),
respectively, where \( T_H \) is (a) 900 K, (b) 500 K, (c) 375 K.
Evaluate the claim for each case.

5.31 A power cycle receives 1000 Btu by heat transfer from a
reservoir at 1000°F and discharges energy by heat transfer
to a reservoir at 300°F. The thermal efficiency of the cycle is
75% of that for a reversible power cycle operating between
the same reservoirs. (a) For the actual cycle, determine the
thermal efficiency and the energy discharged to the cold
reservoir, in Btu; (b) Repeat for the reversible power cycle.

5.32 Referring to the cycle of Fig. 5.13, if \( p_1 = 2 \text{ bar}, v_1 = 0.31
\text{ m}^3/\text{kg}, T_H = 475 \text{ K}, Q_H = 150 \text{ kJ} \), and the gas is air obeying
the ideal gas model, determine \( T_C \), in K, the net work of the
cycle, in kJ, and the thermal efficiency.

5.33 At steady state, a new power cycle is claimed by its
inventor to develop net power at a rate of (a) 4 hp, (b) 5 hp
for a heat addition rate of 300 Btu/min, while operating
between hot and cold reservoirs at 1500°F and 500°F,
respectively. Evaluate each claim.

5.34 A power cycle operates between hot and cold reservoirs
at 500 K and 310 K, respectively. At steady state the cycle
develops a power output of 0.1 MW. Determine the minimum
theoretical rate at which energy is rejected by heat transfer
to the cold reservoir, in MW.

5.35 At steady state, a new power cycle is claimed by its
inventor to develop power at a rate of (a) 90 hp, (b) 100 hp,
(c) 110 hp for a heat addition rate of \( 5.1 \times 10^5 \text{ Btu/h} \), while
operating between hot and cold reservoirs at 1000 and 500 K,
respectively. Evaluate each claim.

5.36 An inventor claims to have developed a power cycle
operating between hot and cold reservoirs at 1175 K and
295 K, respectively, that provides a steady-state power output
of (a) 28 kW, (b) 31.2 kW, while receiving energy by heat
transfer from the hot reservoir at the rate 150,000 kW/h.
Evaluate each claim.

5.37 At steady state, a power cycle develops a power output
of 10 kW while receiving energy by heat transfer at the rate
of 10 kW per cycle of operation from a source at temperature
\( T \). The cycle rejects energy by heat transfer to
cooling water at a lower temperature of 300 K. If there
are 100 cycles per minute, what is the minimum theoretical
value for \( T \), in K?

5.38 A power cycle operates between hot and cold reservoirs
at 600 K and 300 K, respectively. At steady state the cycle
develops a power output of 0.45 MW while receiving energy
by heat transfer from the hot reservoir at the rate of 1 MW.
(a) Determine the thermal efficiency and the rate at which
energy is rejected by heat transfer to the cold reservoir, in
MW.
(b) Compare the results of part (a) with those of a reversible
power cycle operating between these reservoirs and receiving
the same rate of heat transfer from the hot reservoir.

5.39 As shown in Fig. 5.39, a system undergoing a power cycle
develops a net power output of 1 MW while receiving energy
by heat transfer from steam condensing from saturated vapor
to saturated liquid at a pressure of 100 kPa. Energy is
discharged from the cycle by heat transfer to a nearby lake
at 17°C. These are the only significant heat transfers. Kinetic
and potential energy effects can be ignored. For operation at
steady state, determine the minimum theoretical steam mass
flow rate, in kg/s, required by any such cycle.

![Fig.P5.39](image-url)
5.40 A power cycle operating at steady state receives energy by heat transfer from the combustion of fuel at an average temperature of 1000 K. Owing to environmental considerations, the cycle discharges energy by heat transfer to the atmosphere at 300 K at a rate no greater than 60 MW. Based on the cost of fuel, the cost to supply the heat transfer is $4.50 per GJ. The power developed by the cycle is valued at $0.10 per kW·h. For 8000 hours of operation annually, determine for any such cycle: (a) the maximum value of the power generated and (b) the corresponding fuel cost.

5.41 At steady state, a 750-MW power plant receives energy by heat transfer from the combustion of fuel at an average temperature of 317°C. As shown in Fig. P5.41, the plant discharges energy by heat transfer to a river whose mass flow rate is $1.65 \times 10^5$ kg/s. Upstream of the power plant the river is at 17°C. Plot the increase in the temperature of the river, $\Delta T$, traceable to such heat transfer, in K, versus the thermal efficiency of the plant, ranging upward from 20%.

Refrigeration and Heat Pump Cycle Applications

5.43 A refrigeration cycle operating between two reservoirs receives energy $Q_c$ from a cold reservoir at $T_c = 275$ K and rejects energy $Q_h$ to a hot reservoir at $T_h = 315$ K. For each of the following cases, determine whether the cycle operates reversibly, operates irreversibly, or is impossible:

(a) $Q_c = 1000$ kJ, $W_{cycle} = 80$ kJ.
(b) $Q_c = 1200$ kJ, $Q_h = 2000$ kJ.
(c) $Q_h = 1575$ kJ, $W_{cycle} = 200$ kJ.
(d) $\beta = 6$.

5.44 A reversible refrigeration cycle operates between cold and hot reservoirs at temperatures $T_C$ and $T_H$, respectively.

(a) If the coefficient of performance is 3.5 and $T_C = -40$°F, determine $T_H$, in °F.
(b) If $T_C = -30$°C and $T_H = 30$°C, determine the coefficient of performance.
(c) If $Q_C = 500$ Btu, $Q_H = 800$ Btu, and $T_C = 20$°F, determine $T_H$, in °F.
(d) If $T_C = 30$°F and $T_H = 100$°F, determine the coefficient of performance.
(e) If the coefficient of performance is 8.9 and $T_C = -5$°C, find $T_H$, in °C.

5.45 At steady state, a reversible heat pump cycle discharges energy at the rate $Q_H$ to a hot reservoir at temperature $T_H$ while receiving energy at the rate $Q_C$ from a cold reservoir at temperature $T_C$.

(a) If $T_H = 13$°C and $T_C = 2$°C, determine the coefficient of performance.
(b) If $Q_H = 10.5$ kW, $Q_C = 8.75$ kW, and $T_C = 0$°C, determine $T_H$, in °C.
(c) If the coefficient of performance is 10 and $T_H = 27$°C, determine $T_C$, in °C.

5.46 A heating system must maintain the interior of a building at 20°C during a period when the outside air temperature is 5°C and the heat transfer from the building through its roof and walls is $3 \times 10^6$ kJ. For this duty heat pumps are under consideration that would operate between the dwelling and

(a) the ground at 15°C.
(b) a pond at 10°C.
(c) the outside air at 5°C.

For each case, evaluate the minimum theoretical net work input required by any such heat pump, in kW.

5.47 A refrigeration cycle rejects $Q_h = 500$ Btu per cycle to a hot reservoir at $T_H = 540°R$, while receiving $Q_c = 375$ Btu per cycle from a cold reservoir at temperature $T_C$. For 10 cycles of operation, determine (a) the net work input, in Btu, and (b) the minimum theoretical temperature $T_C$, in °R.

5.48 The thermal efficiency of a reversible power cycle operating between hot and cold reservoirs is 20%. Evaluate the coefficient of performance of

(a) a reversible refrigeration cycle operating between the same two reservoirs.
(b) a reversible heat pump cycle operating between the same two reservoirs.
5.49 Shown in Fig. P5.49 is a system consisting of a power cycle and a heat pump cycle, each operating between hot and cold reservoirs whose temperature are 500 K and 300 K, respectively. All energy transfers are positive in the directions of the arrows. The accompanying table provides two sets of steady-state data, in kW. For each set of data, determine if the system is operating in accord with the first and second laws of thermodynamics.

<table>
<thead>
<tr>
<th>Power cycle</th>
<th>Heat pump cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{Q}_H$</td>
<td>$\dot{Q}_C$</td>
</tr>
<tr>
<td>(a)</td>
<td>60</td>
</tr>
<tr>
<td>(b)</td>
<td>120</td>
</tr>
</tbody>
</table>

![Fig.P5.49](image)

5.50 An inventor has developed a refrigerator capable of maintaining its freezer compartment at 20°F while operating in a kitchen at 70°F, and claims the device has a coefficient of performance of (a) 10, (b) 9.6, (c) 4. Evaluate the claim in each of the three cases.

5.51 An inventor claims to have developed a food freezer that at steady state requires a power input of 0.6 kW to extract energy by heat transfer at a rate of 3000 J/s from freezer contents at 270 K. Evaluate this claim for an ambient temperature of 293 K.

5.52 An inventor claims to have developed a refrigerator that at steady state requires a net power input of 0.7 horsepower to remove 12,000 Btu/h of energy by heat transfer from the freezer compartment at 0°F and discharge energy by heat transfer to a kitchen at 70°F. Evaluate this claim.

5.53 An inventor claims to have devised a refrigeration cycle operating between hot and cold reservoirs at 300 K and 250 K, respectively, that removes an amount of energy $Q_c$ by heat transfer from the cold reservoir that is a multiple of the net work input—that is, $Q_c = NW_{cycle}$, where all quantities are positive. Determine the maximum theoretical value of the number $N$ for any such cycle.

5.54 Data are provided for two reversible refrigeration cycles. One cycle operates between hot and cold reservoirs at 27°C and $-8°C$, respectively. The other cycle operates between the same hot reservoir at 27°C and a cold reservoir at $-28°C$. If each refrigeration removes the same amount of energy by heat transfer from its cold reservoir, determine the ratio of the net work input values of the two cycles.

5.55 By removing energy by heat transfer from its freezer compartment at a rate of 1.25 kW, a refrigerator maintains the freezer at $-26°C$ on a day when the temperature of the surroundings is $22°C$. Determine the minimum theoretical power, in kW, required by the refrigerator at steady state.

5.56 At steady state, a refrigeration cycle maintains a clean room at 55°F by removing energy entering the room by heat transfer from adjacent spaces at the rate of 0.12 Btu/s. The cycle rejects energy by heat transfer to the outdoors where the temperature is 80°F.

(a) If the rate at which the cycle rejects energy by heat transfer to the outdoors is 0.16 Btu/s, determine the power required, in Btu/s.

(b) Determine the power required to maintain the clean room’s temperature by a reversible refrigeration cycle operating between cold and hot reservoirs at 55°F and 80°F, respectively, and the corresponding rate at which energy is rejected by heat transfer to the outdoors, each in Btu/s.

5.57 For each kW of power input to an ice maker at steady state, determine the maximum rate that ice can be produced, in lb/h, from liquid water at 32°F. Assume that 14 Btu/lb of energy must be removed by heat transfer to freeze water at 32°F and that the surroundings are at 78°F.

5.58 At steady state, a refrigeration cycle operating between hot and cold reservoirs at 300 K and 275 K, respectively, removes energy by heat transfer from the cold reservoir at a rate of 600 kW.

(a) If the cycle’s coefficient of performance is 4, determine the power input required, in kW.

(b) Determine the minimum theoretical power required, in kW, for any such cycle.

5.59 An air conditioner operating at steady state maintains a dwelling at 20°C on a day when the outside temperature is 35°C. Energy is removed by heat transfer from the dwelling at a rate of 2800 J/s while the air conditioner’s power input is 0.8 kW. Determine (a) the coefficient of performance of the air conditioner and (b) the power input required by a reversible refrigeration cycle providing the same cooling effect while operating between hot and cold reservoirs at 35°C and 20°C, respectively.

5.60 A heat pump is under consideration for heating a research station located on an Antarctic ice shelf. The interior of the station is to be kept at 15°C. Determine the maximum theoretical rate of heating provided by a heat pump, in kW per kW of power input, in each of two cases: The role of the cold reservoir is played by (a) the atmosphere at $-20°C$, (b) ocean water at 5°C.

5.61 A refrigeration cycle has a coefficient of performance equal to 75% of the value for a reversible refrigeration cycle operating between cold and hot reservoirs at $-5°C$ and 40°C, respectively. For operation at steady state, determine the net power input, in kW per kW of cooling, required by (a) the actual refrigeration cycle and (b) the reversible refrigeration cycle. Compare values.

5.62 By removing energy by heat transfer from a room, a window air conditioner maintains the room at 22°C on a day when the outside temperature is 32°C.

(a) Determine, in kW per kW of cooling, the minimum theoretical power required by the air conditioner.
(b) To achieve required rates of heat transfer with practical-sized units, air conditioners typically receive energy by heat transfer at a temperature below that of the room being cooled and discharge energy by heat transfer at a temperature above that of the surroundings. Consider the effect of this by determining the minimum theoretical power, in kW per kW of cooling, required when \( T_C = 18^\circ \text{C} \) and \( T_H = 36^\circ \text{C} \), and compare with the value found in part (a).

5.63 A heat pump cycle is used to maintain the interior of a building at 21\(^\circ\)C. At steady state, the heat pump receives energy by heat transfer from well water at 9\(^\circ\)C and discharges energy by heat transfer to the building at a rate of 120,000 kW h. Over a period of 14 days, an air meter records that 1490 kW h of electricity is provided to the heat pump. Determine
(a) the amount of energy that the heat pump receives over the 14-day period from the well water by heat transfer, in kW.
(b) the heat pump's coefficient of performance.
(c) the coefficient of performance of a reversible heat pump cycle operating between hot and cold reservoirs at 21\(^\circ\)C and 9\(^\circ\)C.

5.64 As shown in Fig. P5.64, an air conditioner operating at steady state maintains a dwelling at 70\(^\circ\)F on a day when the outside temperature is 90\(^\circ\)F. If the rate of heat transfer into the dwelling through the walls and roof is 30,000 Btu/h, might a net power input to the air conditioner compressor of 3 hp be sufficient? If yes, determine the coefficient of performance. If no, determine the minimum theoretical power input, in hp.

5.65 At steady state, a refrigeration cycle driven by an electric motor maintains the interior of a building at 20\(^\circ\)C when the outside temperature is 35\(^\circ\)C. The rate of heat transfer into the building through its walls and roof is given by \( R(T_H - T_C) \), where \( R \) is a constant, in kW K. The coefficient of performance of the cycle is 20% of a reversible refrigeration cycle operating between cold and hot reservoirs at \( T_C \) and \( T_H \) respectively.
(a) If the power input to the motor is 3 kW, evaluate \( R \).
(b) If \( R \) is reduced by 5%, determine the power input required, in kW, assuming all other data remain the same.

5.66 A refrigeration cycle driven by an electric motor must maintain a computer laboratory at 18\(^\circ\)C when the outside temperature is 30\(^\circ\)C. The thermal load consists of heat transfers entering through the walls and roof of the laboratory at a rate of 75,000 kW h and from the computers, lighting, and occupants at a rate of 15,000 kW h.
(a) Determine the minimum theoretical power required by the electric motor, in kW, and the corresponding coefficient of performance.
(b) If the actual power required by the motor for this duty is 8.3 kW, determine the coefficient of performance.
(c) If the given temperature and thermal load data are observed for a total of 100 hours and electricity costs 13 cents per kW h, determine the cost, in $, over that period for each of cases (a) and (b).

5.67 At steady state, a heat pump driven by an electric motor maintains the interior of a building at \( T_H = 293 \text{ K} \). The rate of heat transfer, in kW h, from the building through its walls and roof is given by \( 8000(T_H - T_C) \), where \( T_C \) is the outdoor temperature. Plot the minimum theoretical electric power, in kW, required to drive the heat pump versus \( T_C \) ranging from 273 K to 293 K.

5.68 The refrigerator shown in Fig. P5.68 operates at steady state with a coefficient of performance of 5.0 within a kitchen at 23\(^\circ\)C. The refrigerator rejects 4.8 kW by heat.
transfer to its surroundings from metal coils located on its exterior. Determine
(a) the power input, in kW.
(b) the lowest theoretical temperature inside the refrigerator, in K.

5.69 At steady state, a heat pump provides energy by heat transfer at the rate of 25,000 Btu/h to maintain a dwelling at 70°F on a day when the outside temperature is 30°F. The power input to the heat pump is 4.5 hp. Determine
(a) the coefficient of performance of the heat pump.
(b) the coefficient of performance of a reversible heat pump operating between hot and cold reservoirs at 70°F and 30°F, respectively, and the corresponding rate at which energy would be provided by heat transfer to the dwelling for a power input of 4.5 hp.

5.70 By supplying energy at an average rate of 24,000 kJ/h, a heat pump maintains the temperature of a dwelling at 20°C. If electricity costs 8.5 cents per kW - h, determine the minimum theoretical operating cost for each day of operation if the heat pump receives energy by heat transfer from
(a) the outdoor air at −7°C.
(b) the ground at 5°C.

5.71 A heat pump with a coefficient of performance of 3.5 provides energy at an average rate of 70,000 kJ/h to maintain a building at 20°C on a day when the outside temperature is −5°C. If electricity costs 8.5 cents per kW - h,
(a) determine the actual operating cost and the minimum theoretical operating cost, each in $/day.
(b) compare the results of part (a) with the cost of electrical-resistance heating.

5.72 As shown in Fig. P5.72, a heat pump provides energy by heat transfer to water vaporizing from saturated liquid to saturated vapor at a pressure of 2 bar and a mass flow rate of 0.05 kg/s. The heat pump receives energy by heat transfer from a pond at 16°C. These are the only significant heat transfers. Kinetic and potential energy effects can be ignored. A faded, hand-to-read data sheet indicates the power required by the heat pump at steady state is 35 kW. Can this value be correct? Explain.

5.73 As shown in Fig. P 5.73, a heat pump receives energy by heat transfer from below Earth's surface where the temperature is 50°F and delivers energy by heat transfer to ammonia vaporizing from saturated liquid to saturated vapor at 75°F. These are the only significant heat transfer. At steady state, the power input to the heat pump is 3 hp. Determine the maximum theoretical ammonia mass flow rate, in lb/min, for any such heat pump. For the ammonia ignore kinetic and potential energy effects.

5.74 To maintain a dwelling steadily at 68°F on a day when the outside temperature is 32°F, heating must be provided at an average rate of 700 Btu/min. Compare the electrical power required, in kW, to deliver the heating using
(a) electrical-resistance heating, (b) a heat pump whose coefficient of performance is 3.5, (c) a reversible heat pump operating between hot and cold reservoirs at 68°F and 32°F, respectively.

5.75 A heating system must maintain the interior of a building at 70°F when the outside temperature is 32°F. If the rate of heat transfer from the building through its walls and roof is 16.4 kW, determine the electrical power required, in kW, to heat the building using
(a) electrical-resistance heating, (b) a heat pump whose coefficient of performance is 3.0, (c) a reversible heat pump operating between hot and cold reservoirs at 20°C and 2°C, respectively.

Carnot Cycle Applications

5.76 A gas within a piston-cylinder assembly executes a Carnot power cycle during which the isothermal expansion occurs at $T_H = 600$ K and the isothermal compression occurs at $T_C = 300$ K. Determine
(a) the thermal efficiency.
(b) the percent change in thermal efficiency if $T_H$ increases by 15% while $T_C$ remains the same.
(c) the percent change in thermal efficiency if $T_C$ decreases by 15% while $T_H$ remains the same.
(d) the percent change in thermal efficiency if $T_H$ increases by 15% and $T_C$ decreases by 15%.

5.77 Referring to the heat pump cycle of Fig. 5.16, if $p_1 = 14.7$ psia and $p_2 = 18.7$ psia, each in lb/in.², $v_1 = 12.6$ ft³/lbf and $v_2 = 10.6$, each in ft³/lbf, and the gas is air obeying the ideal gas model, determine $T_H$ and $T_C$, each in °R, and the coefficient of performance.

5.78 An ideal gas within a piston-cylinder assembly executes a Carnot power cycle, as shown in Fig. 5.13. The isothermal compression occurs at 300 K from 90 kPa to 120 kPa. If the
5.79 An ideal gas within a piston-cylinder assembly undergoes a Carnot refrigeration cycle, as shown in Fig. 5.16. The isothermal compression occurs at 325 K from 2 bar to 4 bar. The isothermal expansion occurs at 250 K. Determine (a) the coefficient of performance, (b) the heat transfer to the gas during the isothermal expansion, in kJ per kmol of gas, (c) the magnitude of the net work input, in kJ per kmol of gas.

5.80 Air within a piston-cylinder assembly executes a Carnot heat pump cycle as shown in Fig. 5.16. For the cycle, $T_H = 600$ K and $T_C = 300$ K. The energy rejected by heat transfer at 600 K has a magnitude of 250 kJ per kg of air. The pressure at the start of the isothermal expansion is 325 kPa. Assuming the ideal gas model for the air, determine (a) the magnitude of the net work input, in kJ per kg of air, and (b) the pressure at the end of the isothermal expansion, in kPa.

5.81 A quantity of water within a piston-cylinder assembly executes a Carnot power cycle. During isothermal expansion, the water is heated from saturated liquid at 50 bar until it is a saturated vapor. The vapor then expands adiabatically to a pressure of 5 bar while doing 364.31 kJ/kg of work.

(a) Sketch the cycle on $p-v$ coordinates.
(b) Evaluate the heat transfer per unit mass and work per unit mass for each process, in kJ/kg.
(c) Evaluate the thermal efficiency.

5.82 One and one-half pounds of water within a piston-cylinder assembly execute a Carnot power cycle. During isothermal expansion, the water is heated at 500°F from saturated liquid to saturated vapor. The vapor then expands adiabatically to a temperature of 100°F and a quality of 70.38%.

(a) Sketch the cycle on $p-v$ coordinates.
(b) Evaluate the heat transfer and work for each process, in Btu.
(c) Evaluate the thermal efficiency.

5.83 Two kilograms of air within a piston-cylinder assembly execute a Carnot power cycle with maximum and minimum temperatures of 750 K and 300 K, respectively. The heat transfer to the air during the isothermal expansion is 60 kJ. At the end of the isothermal expansion the volume is 0.4 m$^3$. Assuming the ideal gas model for the air, determine

(a) the thermal efficiency,
(b) the pressure and volume at the beginning of the isothermal expansion, in kPa and m$^3$, respectively,
(c) the work and heat transfer for each of the four processes, in kJ.
(d) Sketch the cycle on $p-V$ coordinates.

Clausius Inequality Applications

5.84 A system executes a power cycle while receiving 1000 kJ by heat transfer at a temperature of 500 K and discharging energy by heat transfer at a temperature of 300 K. There are no other heat transfers. Applying Eq. 5.13, determine $\sigma_{net}$ if the thermal efficiency is (a) 100%, (b) 40%, (c) 25%. Identify cases (if any) that are internally reversible or impossible.

5.85 A system executes a power cycle while receiving 1050 kJ by heat transfer at a temperature of 525 K and discharging 700 kJ by heat transfer at 350 K. There are no other heat transfers.

(a) Using Eq. 5.13, determine whether the cycle is internally reversible, irreversible, or impossible.
(b) Determine the thermal efficiency using Eq. 5.4 and the given heat transfer data. Compare this value with the Carnot efficiency calculated using Eq. 5.9 and comment.

5.86 For the refrigerator of Example 5.2, apply Eq. 5.13 on a time-rate basis to determine whether the cycle operates reversibly, operates irreversibly, or is impossible. Repeat for the case where there is no power input.

5.87 For each data set of Prob. 5.49, apply Eq. 5.13 on a time-rate basis to determine whether the system operates reversibly, operates irreversibly, or is impossible.

5.88 The steady-state data listed below are claimed for a power cycle operating between hot and cold reservoirs at 1200 K and 400 K, respectively. For each case, evaluate the net power developed by the cycle, in kW, and the thermal efficiency. Also in each case apply Eq. 5.13 on a time-rate basis to determine whether the cycle operates reversibly, operates irreversibly, or is impossible.

(a) $Q_H = 600$ kW, $Q_C = 400$ kW
(b) $Q_H = 600$ kW, $Q_C = 0$ kW
(c) $Q_H = 600$ kW, $Q_C = 200$ kW

5.89 At steady state, a thermodynamic cycle operating between hot and cold reservoirs at 1000 K and 500 K, respectively, receives energy by heat transfer from the hot reservoir at a rate of 1500 kW, discharges energy by heat transfer to the cold reservoir, and develops power at a rate of (a) 1000 kW, (b) 750 kW, (c) 0 kW. For each case, apply Eq. 5.13 on a time-rate basis to determine whether the cycle operates reversibly, operates irreversibly, or is impossible.

5.90 Figure P5.90 gives the schematic of a vapor power plant in which water steadily circulates through the four components shown. The water flows through the boiler and condenser at constant pressure and through the turbine and pump adiabatically. Kinetic and potential energy effects can be ignored. Process data follow:

Process 4-1: constant pressure at 1 MPa from saturated liquid to saturated vapor

Process 2-3: constant pressure at 20 kPa from $x_2 = 88\%$ to $x_3 = 18\%$

(a) Using Eq. 5.13 expressed on a time-rate basis, determine if the cycle is internally reversible, irreversible, or impossible.
(b) Determine the thermal efficiency using Eq. 5.4 expressed on a time-rate basis and steam table data.
(c) Compare the result of part (b) with the Carnot efficiency calculated using Eq. 5.9 with the boiler and condenser temperatures and comment.

5.91 Repeat Problem 5.90 for the following case:

Process 4-1: constant pressure at 8 MPa from saturated liquid to saturated vapor

Process 2-3: constant pressure at 8 kPa from $x_2 = 67.5\%$ to $x_3 = 34.2\%$
5.92 Repeat Problem 5.90 for the following case:

Process 4–1: constant pressure at 0.15 MPa from saturated liquid to saturated vapor
Process 2–3: constant pressure at 20 kPa from \( x_2 = 90\% \) to \( x_3 = 10\% \)

5.93 As shown in Fig. P5.93, a system executes a power cycle while receiving 750 kJ by heat transfer at a temperature of 1500 K and discharging 100 kJ by heat transfer at a temperature of 500 K. Another heat transfer from the system occurs at a temperature of 1000 K. Using Eq. 5.13, plot the thermal efficiency of the cycle versus \( \phi_{cycle} \) in kJ/K.

5.94 Shown in Fig. P5.94 is a system that executes a power cycle while receiving 600 Btu by heat transfer at a temperature of 1000°F and discharging 400 Btu by heat transfer at a temperature of 800°F. A third heat transfer occurs at a temperature of 600°F. These are the only heat transfers experienced by the system.

(a) Applying an energy balance together with Eq. 5.13, determine the direction and allowed range of values, in Btu, for the heat transfer at 600°F.
(b) For the power cycle, evaluate the maximum theoretical thermal efficiency.

 DESIGN & OPEN-ENDED PROBLEMS: EXPLORING ENGINEERING PRACTICE

5.1D The second law of thermodynamics is sometimes cited in publications of disciplines far removed from engineering and science, including but not limited to philosophy, economics, and sociology. Investigate use of the second law in peer-reviewed nontechnical publications. For three such publications, each in different disciplines, write a three-page critique. For each publication, identify and comment on the key objectives and conclusions. Clearly explain how the second law is used to inform the reader and propel the presentation. Score each publication on a 10-point scale, with 10 denoting a highly effective use of the second law and 0 denoting an ineffective use. Provide a rationale for each score.

5.2D Investigate adverse health conditions that might be exacerbated for persons living in urban heat islands. Write a report including at least three references.

5.3D For each of three comparably sized spaces in your locale, a preschool, an office suite with cubicles, and an assisted-living facility, investigate the suitability of a heat pump/air-conditioning system employing a natural refrigerant. Consider factors including, but not limited to, health and safety requirements, applicable codes, performance in meeting occupant comfort needs, annual electricity cost, and environmental impact, each in comparison to systems using conventional refrigerants for the same duty. Summarize your findings in a report, including at least three references.

5.4D For a refrigerator in your home, dormitory, or workplace, use a plug-in appliance load tester (Fig. P5.4D) to determine
the appliance's power requirements, in kW. Estimate annual electrical usage for the refrigerator, in kW·h. Compare your estimate of annual electricity use with that for the same or a similar refrigerator posted on the ENERGY STAR® website. Rationalize any significant discrepancy between these values. Prepare a poster presentation detailing your methodologies and findings.

**5.5D** The objective of this project is to identify a commercially available heat pump system that will meet annual heating and cooling needs of an existing dwelling in a locale of your choice. Consider each of two types of heat pump: air source and ground source. Estimate installation costs, operating costs, and other pertinent costs for each type of heat pump. Assuming a 10-year life, specify the more economical heat pump system. What if electricity were to cost twice its current cost? Prepare a poster presentation of your findings.

**5.6D** Insulin and several other pharmaceuticals required daily by those suffering from diabetes and other medical conditions have relatively low thermal stability. Those living and traveling in hot climates are especially at risk by heat-induced loss of potency of their pharmaceuticals. Design a wearable, lightweight, and reliable cooler for transporting temperature-sensitive pharmaceuticals. The cooler also must be solely powered by human motion. While the long-term goal is a moderately priced consumer product, the final project report need only provide the costing of a single prototype.

**5.7D** Over the years, claimed perpetual motion machines have been rejected because they violate physical laws, primarily the first or second laws of thermodynamics, or both. Yet, while skepticism is deeply ingrained about perpetual motion, the ATMOS clock is said to enjoy a nearly unlimited operational service life, and advertisements characterize it as a perpetual motion clock. Investigate how the ATMOS operates. Provide a complete explanation of its operation, including sketches and references to the first and second laws, as appropriate. Clearly establish whether the ATMOS can justifiably be called a perpetual motion machine, closely approximates one, or only appears to be one. Prepare a memorandum summarizing your findings.

**5.8D** Four hundred feet below a city in southern Illinois sits an abandoned lead mine filled with an estimated 70 billion gallons of water that remains at a constant temperature of about 58°F. The city engineer has proposed using the impounded water as a resource for heating and cooling the city’s central administration building, a two-story, brick building constructed in 1975 having 8500 ft² of office space.

You have been asked to develop a preliminary proposal, including a cost estimate. The proposal will specify commercially available systems that utilize the impounded water to meet heating and cooling needs. The cost estimate will include project development, hardware, and annual operating cost. Report your findings in the form of a PowerPoint presentation suitable for the city council.

**5.9D** Figure P5.9D shows one of those bobbing toy birds that seemingly takes an endless series of sips from a cup filled with water. Prepare a 30-min presentation suitable for a middle school science class explaining the operating principles of this device and whether or not its behavior is at odds with the second law.

**5.10D** As shown in Fig. P5.10D, a pump delivers water to a 500-foot-long pipe at a pressure of 55 lbf/in.² and a temperature of 60°F. The pipe supplies water at a volumetric flow rate of 200 ft³/min to a storage tank whose pressure cannot be less than 20 lbf/in.². For an ANSI Schedule 40 steel pipe, determine the smallest standard pipe diameter, in inches, that meets these requirements. Assume steady state with negligible change in pipe elevation from inlet to exit, and the Moody friction factor diagram applies.