Chapter 15

THERMODYNAMICS

PREVIEW

Thermodynamics is the study of heat transfer. Two of the laws that govern the flow of heat in or out of a system are called the *first and second laws of thermodynamics.* These laws relate to *conservation of energy*, the *direction* of heat flow from one system to another, and the amount of *entropy* (*disorder)* in a system. Often we analyze the energy transfer of a system using a *pressure-volume (PV) diagram.*

The content contained in sections 1 – 5, 7 – 13 of chapter 15 of the textbook is included on the AP Physics B exam.

QUICK REFERENCE

Important Terms

adiabatic
the expansion or compression of a gas without a gain or loss of heat.

Carnot principle
No irreversible engine operating between two reservoirs at constant temperatures can have a greater efficiency than a reversible engine operating between the same temperatures. Furthermore, all reversible engines operating between the same temperatures have the same efficiency.

entropy
the measure of the amount of disorder in a system

first law of thermodynamics
the heat lost by a system is equal to the heat gained by the system minus any work done by the system; conservation of energy

heat engine
device which changes internal energy into mechanical work

isobaric
any process in which the pressure of a gas remains constant

isochoric (or *isovolumetric*)
any process in which the volume of a gas remains constant

isothermal
any process in which the temperature of a gas remains constant

pressure-volume (PV) diagram
a graph of pressure vs. volume which gives an indication of the work done by or on a system, and the energy transferred during a process

reversible process
a process in which both the system and its environment can be returned to exactly the states they were in before the process occurred

second law of thermodynamics
heat flows naturally from a region of higher temperature to a lower temperature;all natural systems tend toward a state of higher disorder

thermodynamics
the study of heat transfer

Equations and Symbols

$$\Delta U = U_f - U_i = Q - W$$

$$W = P\Delta V = P(V_f - V_i)$$

$$e = \frac{W}{Q_H}$$

$$e = \frac{T_H - T_C}{T_H} = 1 - \frac{T_C}{T_H}$$

where

ΔU = change in internal energy
Q = heat
W = work
P = pressure
V = volume
T = Kelvin temperature
R = universal gas constant
= 8.31 J / (mol K)
e = efficiency
Q_H = input heat
T_H = temperature of the hot reservoir
T_C = temperature of the cold reservoir

Ten Homework Problems

Chapter 15 Problems 3, 5, 7, 8, 9, 12, 24, 27, 43, 58

DISCUSSION OF SELECTED SECTIONS

15.1 – 15.2 Thermodynamics

Thermodynamics is the study of heat flow and the work done on or by a system. There are four laws of thermodynamics, of which two appear on the AP Physics B exam by name (1st and 2nd). However, the concepts involved in the other two (0th and 3rd) are important to the understanding of thermodynamics as well. The *zeroth law of thermodynamics* states that if two systems are in equilibrium, that is, they have the same temperature, there is no net heat flow between them. Further, if systems A and B are each in thermal equilibrium with system C, they must be in equilibrium with each other.

The *third law of thermodynamics* states that it is impossible to reach a temperature of absolute zero.

15.3 The First Law of Thermodynamics

As we've discussed in previous chapters, energy can be transformed in many forms, but is conserved, that is, the total amount of energy must remain constant. This is true of a system only if it is isolated. Since energy can neither go in nor go out, it has to be conserved. A system can exchange energy with its surroundings in two general ways: as *heat* or as *work*. The *first law of thermodynamics* states that the **change in the internal energy ΔU of a system is equal to the heat Q added to the system plus the work W done ON the system:**

$$\Delta U = Q + W$$

On the AP Physics B exam, if work is done ON a system, the system gains energy and W is *positive*.
If work is done BY the system, the system loses energy and W is *negative*.

This convention is consistent with the energy transfers you studied in earlier chapters. If you do work on an object, you do positive work on that object. If the object does work on something else, we say the object has done negative work.

Note that in your textbook, W is defined as the work done ON, rather than BY the system, in which case the equation is written as $\Delta U = Q - W$, and the work done BY the system is considered positive. Regardless of which convention is used, if work is done ON a system, its energy would *increase*. If work is done BY the system, its energy would decrease. Work is generally associated with movement against some force. For ideal gas systems, for example, *expansion* against some external pressure means that work is done BY the system, while *compression* implies work being done ON the system.

For example, if a system has 60 J of heat added to it, resulting in 20 J of work being done BY the system, the change in internal energy of the system is $\Delta U = Q - W = 60\text{ J} - 20\text{ J} = 40\text{ J}$.

If 60 J of heat is added to a system AND work of 20 J is done ON the system, the internal energy of the system would increase all the more:

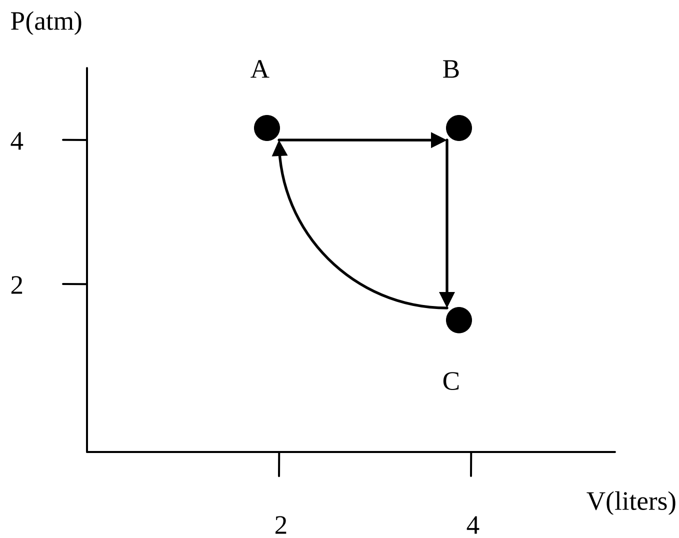
Change in internal energy ΔU = Heat Q added + work W done ON the system
= 60 J + 20 J = 80 J

If heat is added to a system and no work is done, then the heat lost by one element in the system is equal to the heat gained by another element. For example, if sample of metal is heated and then dropped into a beaker containing water, then the first law implies

Q lost by the metal = Q gained by the water

15.4 - 15.5 Thermal Processes, and Thermal Processes That Utilize an Ideal Gas

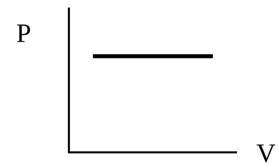
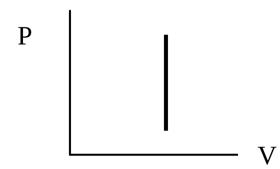
We can study the changes in pressure, volume, and temperature of a gas by plotting a graph of pressure vs. volume for a particular process. We call this graph a *PV diagram*. For example, let's say that a gas starts out at a pressure of 4 atm and a volume of 2 liters, as shown by the point *A* in the PV diagram below:



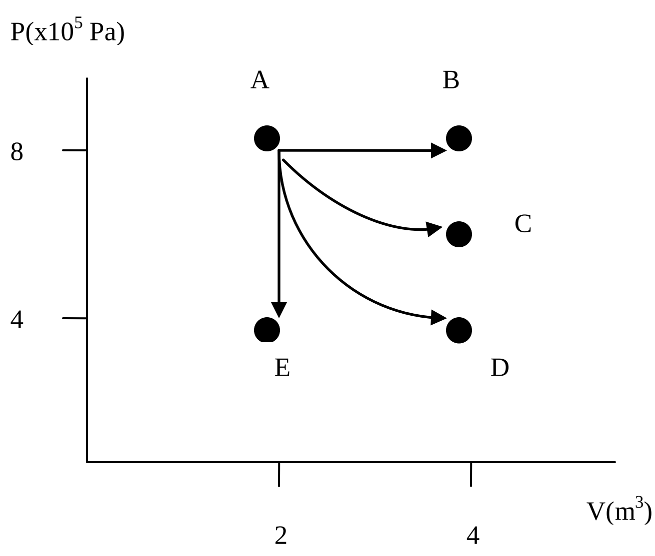
If the pressure of the gas remains constant but the volume changes to 4 liters, then we trace a line from point *A* to point *B*. Since the pressure remains constant from *A* to *B*, we say that the process is *isobaric*. The if we decrease the pressure to 2 atm but keep the volume constant, we trace a line from *B* to *C*. This constant-volume process is *isochoric*, or *isovolumetric*. If we want the gas to return to its original state without changing temperature, we must trace a curve from point *C* to *A* along an *isotherm*. Note that an isotherm on a PV diagram is not a straight line. The work done during the process ABCA is the area enclosed by the graph, since W = PΔV. In this case the work done on the system is positive.

Any process which is done without the transfer of heat is called an *adiabatic* process. Since there is no heat lost or gained in an adiabatic process, then the first law of thermodynamics states that the change in internal energy of a system is simply equal to the work done on or by the system, that is, $\Delta U = W$.

The processes discussed above are summarized in the table below:

Process	***Definition***	***PV diagram***
isobaric	constant pressure	
isochoric	constant volume	
isothermal	constant temperature	
adiabatic	no heat added or taken away ($\Delta U = W$)	

Example 1



Four separate processes (AB, AC, AD, and AE) are represented on the PV diagram above for an ideal gas.

(a) Determine the work done by the gas during process AB.

(b) Determine the work done on the gas during process AE.

(c) Is work done on the gas during any other process on the diagram? If so, identify which ones and explain how you know work is done.

(d) Identify the process which could be
 i. isothermal ________

 ii. adiabatic ________

(e) Calculate the heat lost during the process AE.

Solution

(a) $W_{AB} = P(\Delta V) = (8x10^5\ Pa)(4\,m^3 - 2\,m^3) = 1.6x10^5\ J$

(b) There is no work done during the process AE since there is no change in volume.

(c) There is work done during processes AB, AC, and AD, since there is a change in volume in each of these processes.

(d) i. Process AD is isothermal, since the pressure and change inversely proportionally, and the temperature remains constant.

 ii. Process AC could be adiabatic, since the pressure, volume, and temperature change, indicating that heat may not added or removed.

(e) The heat lost during process AE is equal to the change in energy of the system during the process.

$Q = (\Delta P)(V) = (4x10^5\ Pa - 8x10^5\ Pa)(2\,m^3) = -8x10^5\ J$

15.7 The Second Law of Thermodynamics

Entropy S is a measure of the disorder, or randomness, of a system. The greater the disorder of a system, the greater the entropy. If a system is highly ordered, like the particles in a solid, we say that the entropy is low. At any given temperature, a solid will have a lower entropy than a gas, because individual molecules in the gaseous state are moving randomly, while individual molecules in a solid are constrained in place. Entropy is important because it determines whether a process will occur spontaneously.

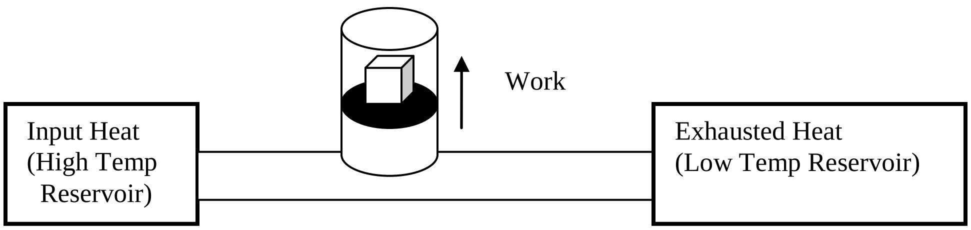
The second law of thermodynamics states that all spontaneous processes proceeding in an isolated system lead to an increase in entropy.

In other words, an isolated system will naturally pursue a state of higher disorder. If you watch a magician throw a deck of cards into the air, you would expect the cards to fall to the floor around him in a very disorderly manner, since the system of cards would naturally tend toward a state of higher disorder. If you watched a film of a magician, and his randomly placed cards jumped off the floor and landed neatly stacked in his hand, you would believe the film is running backward, since cards do not seek this state of order by themselves. Thus, the second law of thermodynamics gives us a direction for the passage of time.

15.8 Heat Engines

A *heat engine* is any device that uses heat to perform work. There are three essential features of a heat engine:

- Heat is supplied to the engine at a high temperature from a hot reservoir.
- Part of the input heat is used to perform work.
- The remainder of the input heat which did not do work is exhausted into a cold reservoir, which is at a lower temperature than the hot reservoir.



In the diagram above, heat is used to do work in lifting the block which is sitting on the piston in the gas-filled cylinder. Any heat left over after work is done is exhausted into the low temperature reservoir. This diagram is used in Example 2 below.

The *percent efficiency % e* of the heat engine is equal to the ratio of the work done to the amount of input heat:

$$\%e = \frac{Work}{Q_{Hot}} x100$$

Example 2

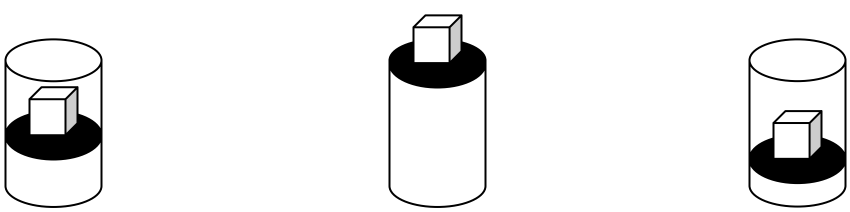


Fig. I Fig. II Fig III

In the figures above, heat is added to the cylinder in Fig. I where the gas occupies half the total volume of the cylinder, raising it to the top of the cylinder in Fig. II. Heat is then removed and the block is lowered so that the gas occupies ¼ of the total volume of the cylinder. The total volume of the cylinder is 2 x 10^{-3} m^3, and the area of the piston is 0.05 m^2. The mass of the block is 2.0 kg.

(a) If the block is at rest in Fig. I, determine the pressure of the gas in the cylinder.

(b) It is determined that the efficiency of this heat engine between Fig. I and Fig. II is 60%. How much heat was added to the cylinder in Fig. I to cause piston to rise to the level in Fig. II?

(c) Is the process between Fig. I and Fig. II isothermal, isobaric, or isochoric? Explain.

(d) If the temperature of the gas in Fig. I is 40º C, what is the temperature of the gas in Fig. II?

(e) i. Between Figs. II and III,is the system acting as a heat engine or a refrigerator? Explain.

ii. Determine the temperature of the gas in Fig. III

Solution

(a) The pressure the gas applies to the piston, block, and atmosphere is equal and opposite to the pressure the piston, block, and atmosphere apply to the gas. Neglecting the mass of the piston, we can write

$$P = \frac{F}{A} + 1atm = \frac{mg}{A} + 1atm = \frac{(2\,kg)(10\,m/s^2)}{0.05\,m^2} + (1x10^5\,Pa) = 1.004\,x10^5\,Pa$$

(b) The work done in lifting the block is

$$W = P\Delta V = (1.004\,x10^5\,Pa)\left[\frac{1}{2}(2x10^{-3}\,m^3)\right] = 1.004x10^2\,J$$

This work done represents 60% of the heat input to the gas. Thus,

$$Q_{input} = \frac{W}{\%e} = \frac{1.004\,x10^2\,J}{0.60} = 167.3J$$

and the heat exhausted is 167.3 J – 100.4 J = 66.9 J.

(c) The process between Figs. I and II is isobaric, since the pressure the block and atmosphere apply to the piston and gas does not change during the process.

(d) For constant pressure, volume and Kelvin temperature are proportional by the combined gas law.

T_I = 40º C +273 = 313 K

$$\frac{V_I}{T_I} = \frac{V_{II}}{T_{II}}$$

$$\frac{1x10^{-3}\,m^3}{313\,K} = \frac{2x10^{-3}\,m^3}{T_{II}}$$

$$T_{II} = 616\,K$$

For constant pressure, if the volume of a gas doubles, the temperature also doubles.

(e) i. The system is acting as a refrigerator, removing heat from the cylinder and reducing the volume of the gas.

ii. Since the pressure remains constant between Figs. II and III,

$$\frac{V_{II}}{T_{II}} = \frac{V_{III}}{T_{III}}$$

$$\frac{2x10^{-3}\,m^3}{616\,K} = \frac{0.5x10^{-3}\,m^3}{T_{III}}$$

$$T_{III} = 154\,K$$

15.9 Carnot's Principle and the Carnot Engine

The French engineer Sadi Carnot suggested that a heat engine has maximum efficiency when the processes within the engine are reversible, that is, both the system and its environment can be returned to exactly the states they were in before the process occurred. In other words, there can be no dissipative forces, like friction, involved in the *Carnot cycle* of an engine for it to operate at maximum efficiency. All spontaneous processes, such as heat flowing from a hot reservoir to a cold reservoir, are not reversible, since work would have to be done to force the heat back to the hot reservoir from the cold reservoir (a refrigerator), thus changing the environment by using some of its energy to do work. A reversible engine is called a *Carnot engine*.

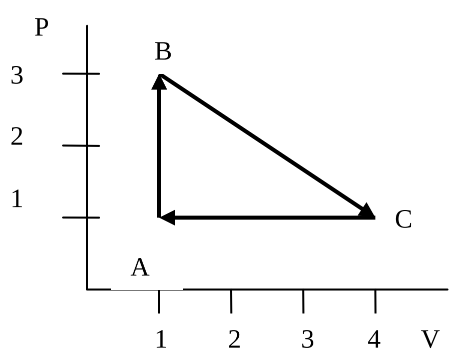
CHAPTER 15 REVIEW QUESTIONS

For each of the multiple choice questions below, choose the best answer.

1. The first law of thermodynamics is a form of
(A) the law of conservation of energy.
(B) the law of specific heat.
(C) the ideal gas law.
(D) the law of entropy.
(E) the law of conservation of temperature.

3. The law of entropy states that
(A) heat always flows spontaneously from a colder body to a hotter one.
(B) every natural system will tend toward lower entropy.
(C) heat lost by one object must be gained by another.
(D) the specific heat of a substance cannot exceed a certain value.
(E) every natural system will tend toward disorder.

Questions 4, 5, 6: Gas in a chamber passes through the cycle ABCA as shown below.



4. In which process is no work done on or by the gas?
(A) AB
(B) AC
(C) BC
(D) CB
(E) CA

2. A system has 60 J of heat added to it, resulting in 15 J of work being done by the system, and exhausting the remaining 45 J of heat. What is the efficiency of this process?
(A) 100%
(B) 60%
(C) 45%
(D) 25%
(E) 15%

5. At which point is the temperature of the gas the highest?
(A) A
(B) B
(C) C
(D) A and B
(E) the temperature is the same at points A, B, and C.

6. If 2 J of heat is added during process AB, and the total amount of work done in the cycle ABCA is 3 J, how much heat is added or removed during process BCA?
(A) 2 J of heat is added
(B) 2 J of heat is removed
(C) 1 J of heat is added
(D) 1 J of heat is removed
(E) 3 J of heat is added

7. Which of the following statements about a Carnot engine is true?
(A) Any Carnot engine has an efficiency of 100%.
(B) Irreversible engines have the greatest possible efficiency.
(C) Heat can spontaneously flow from a cold reservoir to a hoter reservoir.
(D) If a process is reversible, the

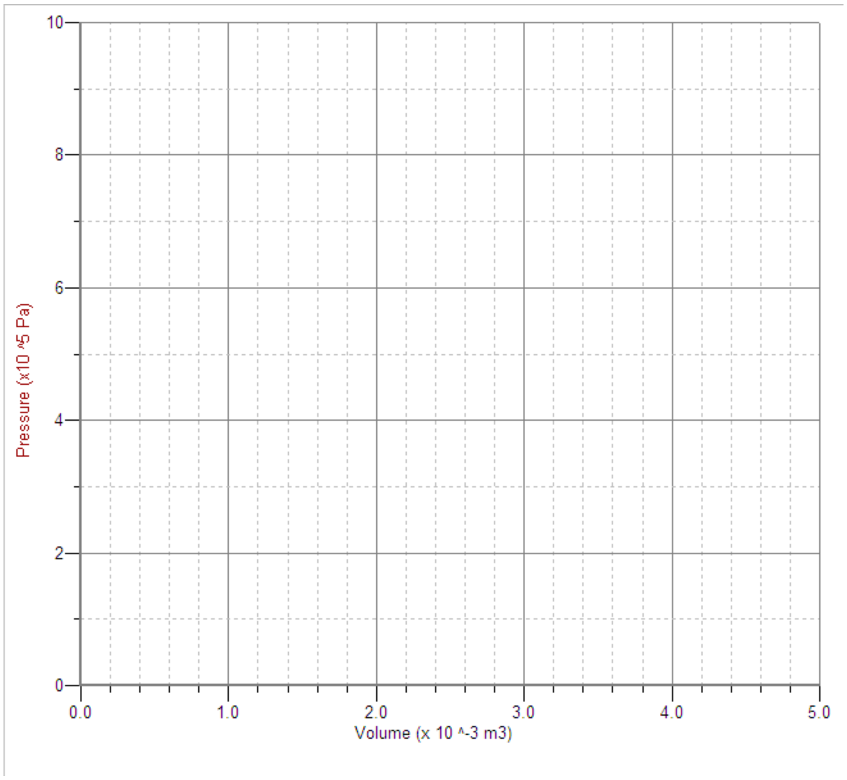
efficiency of an engine is maximum.
(E) All engines are reversible.

8. Which of the following best illustrates the second law of thermodynamics?
(A) a refrigerator cools warm food
(B) a piston in a cylinder is forced upward by expanding gas in the cylinder
(C) your bedroom gets cleaner as the week progresses
(D) a tadpole grows into a frog
(E) cards thrown from the top of a stairway land in a stack in numerical order.

1. (15 points)

A cylinder contains 3 moles of a monatomic gas that is initially at a state A with a pressure of 8 x 10^5 Pa and a volume of 2 x 10^{-3} m^3. The gas is then brought isochorically to state B, where the pressure is 2 x 10^5 Pa. The gas is then brought isobarically to state C where its volume is 4 x 10^{-3} m^3 and its temperature is 300 K. The gas is then brought back isothermally to state A.

(a) On the axes below, sketch a graph of the complete cycle, labeling points A, B, and C.



(b) Determine the work done by the gas during the process ABC.

(c) Determine the change in internal energy during the process ABC.

(d) Determine the temperature of the gas at state B.

(e) State whether this device is a heat engine or a refrigerator, and justify your answer.

ANSWERS AND EXPLANATIONS TO CHAPTER 15 REVIEW QUESTIONS

Multiple Choice

1. A
The 1^{st} law simply states that the energy of a thermodynamic system is constant.

2. D
$$\%e = \frac{W}{Q_H} = \frac{15J}{60J} = 25\%$$

3. E
The law of entropy states that any system will spontaneous ly go from a state of order to disorder.

4. A
No work is done on or by the gas in process AB since there is no change in volume.

5. B
The temperature is highest at point B, since all of the energy gained is a result of heat added to the gas without changing the volume.

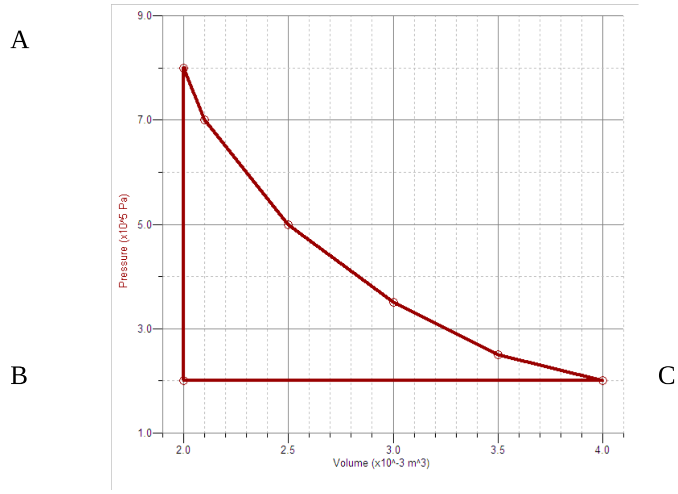
6. C
2 J of heat is added in the process AB, and since 3J of work is done in the cycle, 1 J of additional heat must have been added.

7. D
A reversible engine is always more efficient than an irreversible engine, since more energy is lost in an irreversible engine.

8. B
In all the other choices, each system is going from a state of disorder to order.

Free Response Question Solution

(a) 4 points



(b) 3 points
For the processes ABC, work is only done in the process BC:

$$W = P\Delta V = \left(2x10^5\,Pa\right)\left(2x10^{-3}\,m^3\right) = 4x10^2\,J$$

Since work is being done BY the gas, the work is considered negative on the AP Physics B exam, and thus we would write W = - 4 x 10^2 J.

(c) 3 points
Heat Q is removed in process AB and work is done BY the gas in process BC, both of which reduces the internal energy of the gas:

$$\Delta U = Q + W = (\Delta P)V + -(P)(\Delta V) = \left[\left(2x10^5\,Pa\right) - \left(8x10^5\,Pa\right)\right]\left(2x10^{-3}\,m^3\right) - 400\,J = -1600\,J$$

(d) 3 points
The combined gas law gives

$$\frac{P_A V_A}{T_A} = \frac{P_B V_B}{T_B}$$

Since the temperature at A is the same as at C, TA = 300 K. From the graph,

$$\frac{\left(8x10^5\,Pa\right)\left(2x10^{-3}\,m^3\right)}{300\,K} = \frac{\left(2x10^5\,Pa\right)\left(2x10^{-3}\,m^3\right)}{T_B}$$

$$T_B = 75\,K$$

(e) 2 points
This device is a refrigerator, since it removes heat from the system.