# The Heart of the NASCAR Car-
# The Thermodynamics of Heat Engines

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What has made NASCAR racing one of the fasting growing sports in America today? It popularity is base partially in the fact the cars are based on four door American made "stock" cars. While the cars today are not truly stock, the rules state that car designs are based on three cars: the Chevrolet Impala, Ford Fusion, and Toyota Camry. The wheelbase is exactly 110 inches, the car weighs 3,400 pounds, and the car engine is a 358 cubic inch V8 engine producing about 750 horsepower. For comparison a stock Chevy Corvette with a V8 produces "only" 400 horsepower.[1]

The roaring engine is like the heart of the car providing the conversion of the chemical energy in the fuel to torque in the crankshaft to the rotation in the wheels. So how does this work? That is the question I will answer in this curriculum unit. I will address the conversion of chemical energy in the fuel to thermal energy and how that thermal energy in the working gas is converted to mechanical energy by the piston. The driving force of the piston creates the torque transferred to the tires that propel the car forward.

## Classroom and School Environment

I teach at an urban, partial magnet high school with a total population of roughly 1800 students, with approximately 750 students who are part of the International Baccalaureate (IB) magnet. The school is comprised of approximately 52% Africans American, 25% white, 16% Hispanics and 6% Asian. More than 60% of the student population is on free and reduced lunch. I will be using the curriculum unit in my AP and IB Physics classes; in both classes most of the students are taking their second year of Physics.

## Background information

Combustion is the chemical reaction of a hydrocarbon compound with oxygen from air to form carbon dioxide, water and thermal energy from the exothermal reaction. In car engines the fuel chemistry is often calculated using octane which when reacted with oxygen produces approximately 46KJ /kg. The chemical reaction is:

If this reaction occurs in a closed container like a piston in a cylinder, the energy from the heated and expanding $CO_2$ and $H_2O$ gases will push a piston down creating useful work. The amount of work created is equal to the product of the pressure and the change in

volume. The piston is connected to a rotating axle (crankshaft) so that when the piston is pushed down, it drives the crankshaft around.[2]

Physics and the Heat Engine

The first Law of Thermodynamics is a restatement of the law of conservation of energy, stating that energy is neither created nor destroyed. As related to thermodynamics it is stated that the net change in the internal energy of the gas is equal to the sum of heat add or removed from a confined gas and the work done by or on the confined gas. In a formula it look like this

Where
$\Delta U$ represents the net change in the internal energy of the gas
Q represents the net heat added (+) or removed (-) for a confined gas
W is work done by the confined gas (-) or on the confined gas (+)

For a gas, the change in its internal energy, $\Delta U$ is directly proportion to the change in it temperature measured in Kelvin and is equal to

$\Delta U = (3/2)\, nR\Delta T$ for a monatomic gas
$\Delta U = (5/2)\, nR\Delta T$ for a diatomic gas such as $O_2$

Where n is the number of moles of gas, R is the ideal gas constant and $\Delta T$ is the change in temperature.

This means that the change in the internal energy of a gas only reflect a change in the kinetic energy of the gas molecules. Potential energy change can only occur when there is a change in phase.

This statement of the conservation of energy places emphasis on the internal energy of the gas. The law states that the internal energy of a gas can be increased in two ways: by adding heat or doing work on the system by an external agent. Exerting a force on the piston causing the volume of the piston to decrease does work done on the system by an external agent. The work is considered to be positive. Conversely, if the gas expands the piston, work is negative since the internal energy of the gas is decreasing as the temperature is decreasing. [3]

The Second Law of Thermodynamics

There are many ways to state the Second Law of Thermodynamics; the best statement for a heat engine is as follows:

If an isolated system is permitted to undergo spontaneous change, it changes in such a way that its disorder increases, or at best remains the same. A measure of the disorder is called entropy, S, and is measured in units of joules per Kelvin.

An alternative statement of the second law is heat only flows spontaneously from hot to cold and never in the opposite direction. The concept of entropy becomes particularly important when we consider the total change in entropy of a system and it's surrounding during a process. It is found that, although the entropy of an individual system can decrease, this total entropy never decreases. For a reversible processes the change in the total entropy is zero, and for all other processes the total entropy increases. Reversibility is an idealization and the belief that all processes are irreversible, but in reality the total entropy of the universe is always increasing. The statement that the entropy of the universe increases is yet another way to state the second law of thermodynamics. In fact the second law of thermodynamics is commonly called "the law of increase of entropy"[4]

One can gain some insight into the physical meaning of entropy by thinking of it as a measure of the amount of disorder in the universe. When processes occur, the Universe always comes away more disordered than it was before. An example is the natural flow of heat from a hot reservoir to a cold reservoir. In the cold reservoir the molecules are moving more slowly and scattering off of each other at a slower rate. If the system is cold enough they may even lump together and form a solid. When heat from the hot reservoir comes in, that heat increases the speed of the molecules causing them to move about more randomly increasing the disorder and the entropy of the system. Of course, the disorder and entropy of they hot reservoir will decrease, but the increase in entropy of the cold reservoir is always greater in magnitude than the decrease in the entropy of the hot reservoir. The total disorder always increases.[5]

Galileo has a wonderful quote about entropy and reversibility which states; "We can take wood and see it go up in fire and light, but we do not see it recombine to form wood; we see fruits and flowers and a thousand other solid bodies dissolve largely into odors, but we do not observe these fragrant atoms coming together to form fragrant solids.[6]"

Heat Cycles

To apply the first and second laws of Thermodynamics to a heat engine or cycle I want to begin by defining the properties of the four fundamental gas processes: isothermal, isobaric, isovolumetric (or isochoric) and adiabatic and use a P-V diagram to portray each process. When examining a PV diagram the state variable are the ones that always maintain a constant value at a given position on a PV diagram. These variables are: Pressure, P, Volume, V, Temperature, T, internal energy, $\Delta U$ and entropy, S. The

ideal gas law that states, PV = nRT. If n, the amount of gas, does not change, then $\Delta PV = \Delta T$.

An isothermal process means that the temperature of the gas does not change during the expansion or compression. It is a constant temperature process. In an isothermal process the internal energy, $\Delta U$, does not change because the temperature is constant. The PV diagram of an isothermal process is show below:

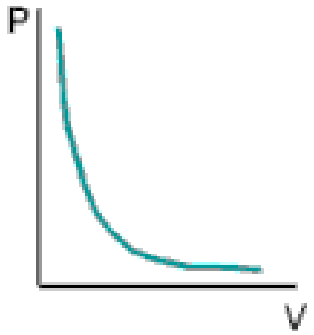



Figure 1 Isothermal line on PV diagram[7]

An isobaric process means that the pressure of the gas does not change. The work into or out of the system is the area under the PV diagram and most work is found when an isobaric process is used. The PV diagram for an isobaric process is as follows:

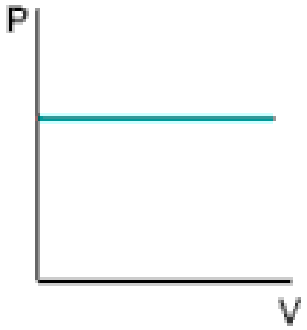



Figure 2. Isobaric line on PV diagram[8]

An adiabatic process is one in which no heat is added or removed from the system. An adiabatic processes can occur in thermally isolated system or spontaneously, when there is a rapid expansion or compression of a gas. Examples of adiabatic processes are compressed gas when sprayed out of an aerosol can or in the rapid compression of air in a bicycle pump. The PV diagram for an adiabatic process is shown below:

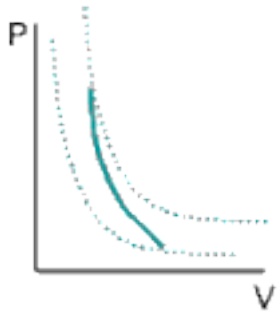



**Figure 3 Adiabatic line on PV diagram**[9]

In an isovolumetric or isochoric process the volume is held constant and the work is equal to zero because there is no change in the volume of the piston so no movement of the piston no work enters or leaves the system. The PV diagram for an isovolumetric process is shown below:

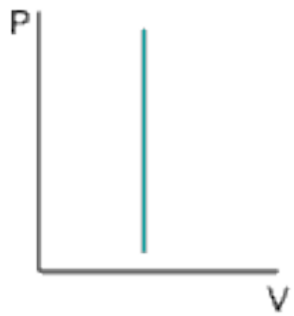
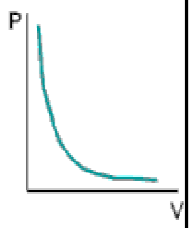
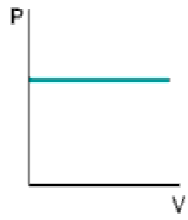
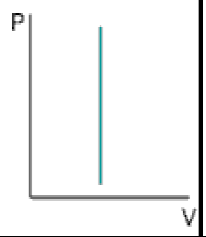
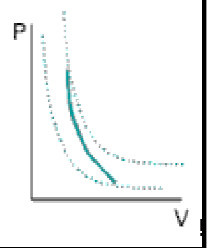



**Figure 4 Isovolumetric line on PV diagram**[10]

The following table highlights the six important properties of each of the four processes. The constant pressure heat capacity, Cp and constant volume heat capacity, Cv are represented as the molar specific heats of a gas. They are equal the amount of heat, in joules, needed to raise one mole of gas one degree. My students will be given the following table as a guide to understanding the thermodynamics of heat cycles. [11]

**Table 1. Pressure Volume diagrams**

| ! | Isothermal! | Isobaric! | Isovolumetric! | Adiabatic! |
|---|---|---|---|---|
| Held!constant! | **Temperature!** | **Pressure!** | **Volume!** | **Heat!** |
| Combined!gas! law! | **$P_1V_1$!=!$P_2V_2$!** | **$V_1/T_1=V_2/T_2$!** | **$P_1/T_1=P_2/T_2$!** | **$P_1V_1/T_1=P_2V_2/T_2$!** |
| ! ! ! P@V!diagram! |   |   |   |   |
| !W!=!@∫P!dV!@ expanding! +compression! | **W!=!@RT! [ln(V2÷V1)]!** | **! W!=!@V!** | **! 0!** | **! W!=!ΔU!** |
| Q! | **Q!=!@W!** | **Q!=!nCp!ΔT!** | **Q!=nC!ΔT!** | 0! |
| ΔU! | 0! | **ΔU!=!nCv!Δt!** | **ΔU!=!nCv!ΔT!** | **ΔU!=!nCv!ΔT!** |
| ! ! ! First!Law! | **! ΔU!=!Q!+!W!!!!!!!!! ΔU!=!0!!!!Q!=!@W!!!!! as!the!gas!expands,! heat!must!be!added!** | **! ΔU!=!Q!+!W!!!!!!!!! nCvΔT!=!nCp!ΔT!@ PΔ!V!!!!! since!P!ΔV!=nRΔT!!! so!Cp!=!Cv!+!nRΔT!** | **ΔU!=!Q!+!W!!!!!!!!! ΔU!=!Q!!!!!!!!!!!!! since!no!work!is! done,!the!internal! energy!of!the!gas! increases!with! addition!of!heat!** | **ΔU!=!Q!+!W!!!!!!!!! ΔU!=!W!!!!!!!!!!!!! since!no!heat!can!be! added!or!removed,! any!work!done!is!at! the!expense!of!the! internal!energy!of! the!gas!** |

The ideal gas law that states that PV = nRT. If n, the amount of gas, does not change, then $\Delta PV \propto \Delta T$ ($\propto$ = "proportional to"). The ideal gas law can now be used to determine the temperature at different position on a PV diagram. For example on the PV diagram show below.[12] The temperature at point A is lower than the temperature at point B by comparing the product of the pressure, P, and the volume, V. Since the volume at point A is smaller than the volume at point B, and the pressure is the same, the PV product would be less than at B. The same calculation would tell us the temperature at point C is lower that that at point B. Using the value proportional value of P and V the relative values of Temperature can be determined.

At point A: $T \propto P_oV_o$

At point B: $T \propto 4P_oV_o$

At point C $T \propto 2P_oV_o$

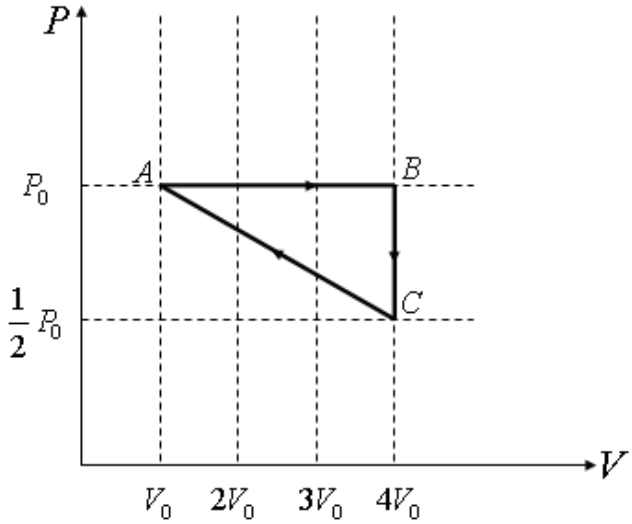



**Figure 5 PV path for fluid in a Heat Engine**[13]

Since the internal energy of a gas is directly proportional to its temperature, we can conclude that the internal energy of the gas at point B is greater than at either point A or C. When the gas expands isobaricly along path AB, the internal energy of the gas should increase and work is leaving the system. Since the temperature at point B is higher, we know that heat must have been added to the system. During the isovolumetric process BC, no work was done on the gas since its volume remained the same. However, we know that heat must have been released from the system since the temperature at point C is less then at point B. The final compression along path AC returns the gas to its starting position that is, to its original state values of pressure, volume, temperature, internal energy and entropy. As a general rule the entropies at two positions can be compared knowing whether heat has been added (increased entropy) or heat has been removed (decreased entropy). In the above example, entropy increased along path AB and decreased along path BC. I want to reinforce to students that heat (Q) and work (W) are not state variables. That is, heat is the energy transferred between states-from a warm body to a cooler body as a result of their temperature differences and work is done whenever the energy content of the system changes.

For the closed path, ABCA, the first law reduces to Q = -W since $\Delta U = 0$. The changes in all state variables are zero whenever there is a complete cycle on a PV diagram.

Heat Engines and the First Law

A heat engine is a device that converts thermal energy into useable, mechanical work. Engines can be classified according to one or more of their characteristics, for example, the motion of its parts such as, reciprocating or rotary. Engines can be classified by where the fuel is burned such as an internal combustion engine compared or external combustion. Engines can be classified by the PV cycle through which the operating gas is

run for example; the Otto cycle or Diesel cycle.[14] The heat engine completes a cycle in which it receives heat from a high-temperature, "hot reservoir," and then converts part of the internal energy into useable work, and exhausts the remainder to a lower-temperature "cold reservoir." Using the First Law of Thermodynamics, this process can be written mathematically as

$$Q_{in} = W_{done} + Q_{out}$$
$$Q_{hot} = W_{done} + Q_{cold}$$

In the internal combustion engine:

$Q_{in}$ is the chemical energy in the gasoline
$W_{done}$ is the kinetic energy of the car as it moves
$Q_{out}$ is the wasted heat and unused gasoline that escape from the car

The efficiency, $\eta$, of a heat engine is the ratio of the work done to the amount of energy put into the system to make it work. Mathematically it is:

$$\eta = W_{done}/Q_{in}$$

Since $Q_{in} = W_{done} + Q_{out}$

$$\eta = (Q_{in} - Q_{out})/Q_{in}$$
$$\eta = 1- (Q_{out}/Q_{in})$$[15]

Carnot Cycle and Ideal Efficiencies

In the pressure-volume diagram for a heat engine the effective work done by the engine is the interior area of the cycle. The larger the area the larger the temperature difference between the hot and cold sinks, the greater the efficiency of the engine. It can be said that without a difference in temperature no net-work could be accomplished during a heat cycle.

In 1824, Sadi Carnot proposed an ideal, reversible heat engine cycle comprised of an isothermal expansion followed by an adiabatic expansion for the power phase followed by and isothermal compression followed by an adiabatic compression. The diagram below shows a Carnot cycle[16]:

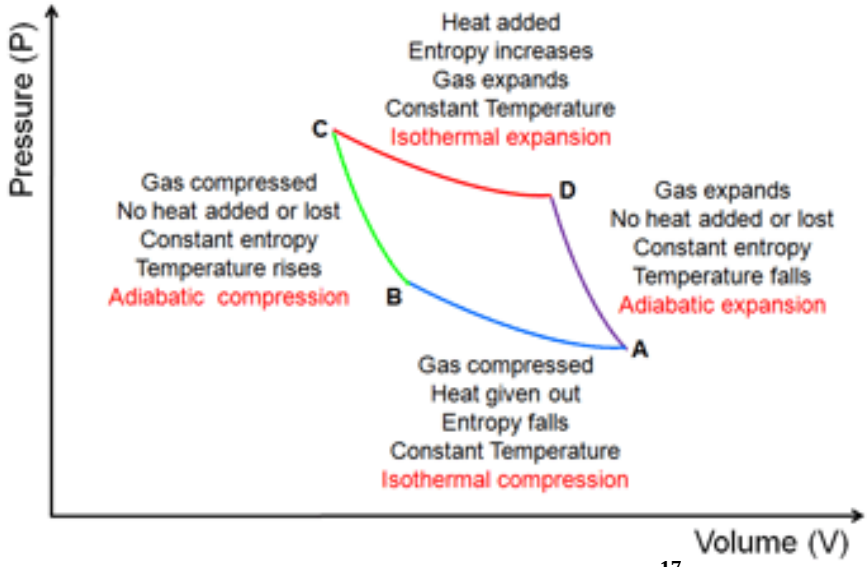



**Figure 6 Carnot (Ideal) Heat Cycle P-V Diagram**[17]

Carnot's analysis showed that this ideal heat engine's efficiency depended solely on the temperature differential between the hot and cold reservoirs.

$$\eta = 1- (Q_{out}/Q_{in})$$

$Q_{in}$ only occurs during points CD (at $T_{hot}$) and $Q_{out}$ only during points AB (at $T_{cold}$)

$$\eta = 1- (T_{cold}/ T_{hot})$$

The results of Carnot calculations show that a one hundred percent efficient engine can only be obtained if the temperature of the cold reservoir was zero kelvin or absolute zero.[18]

Stirling Engines

Robert Stirling (1790-1878) invented the Stirling engine or "air engine" because he was concerned about the danger of the popular (and high pressure) steam engine of the time period. Stirling was a minister of the Church of Scotland and was concerned when many of his parishioners were killed and maimed with steam engines of the day exploding because of poor material strength. Stirling's "hot air engine" could not explode because the pressures in the cylinder are small.[19]

The Stirling engine used air as the working gas over and over again inside the engine. The air inside is never used up nor dumped into the environment as dirty exhaust which means Stirling engines are "regenerative." In a Stirling engine, one side of the engine is continuously heated while the other side is continuously cooled. Initially, the air is moved to the hot side, where it is heated and expands, pushing up on a piston. Then the

air is moved through the regenerator (where it stores some heat for the next cycle) to the cold side, where it cools off and contracts pulling down on the piston. The temperature change inside the engine produces the pressure change needed to push on the piston and produces the work to run the engine.

The four basic phases of the Stirling engine are as follows. First an isochoric or constant volume heating, the high temperature source provides thermal energy and the pressure and the air temperature increase. Secondly, an isothermal expansion, the volume increases and the pressure drops this is the work-out phase. The third and fourth phase return the engine to the starting point first with an isochoric cooling in which the cold source recovers the thermal energy so the temperature and pressure decrease while the volume is held constant. The final stage is an isothermal compression the pressure of the gas is increased as the volume decreases and work must be provided to the gas. On a PV diagram the cycle looks like the following diagram. The net-work from the cycle is the area inside the curved path. Below is the Pressure-Volume diagram for a Sterling engine.[20]

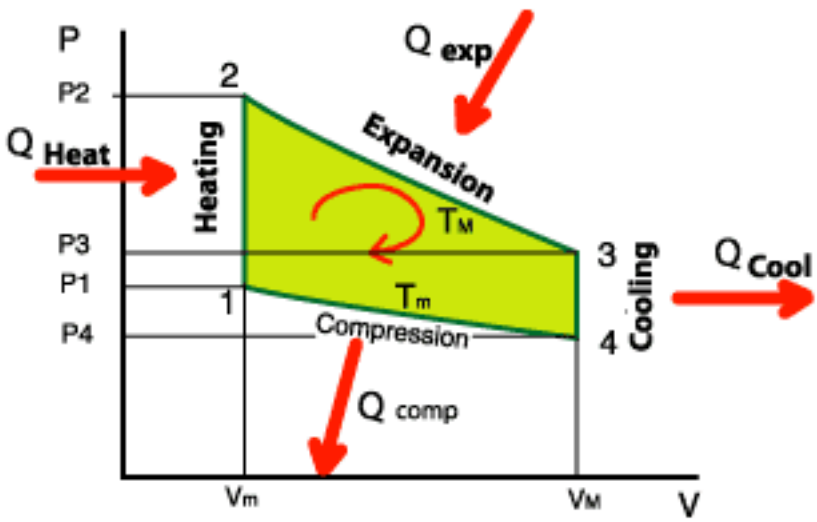



**Figure 7 The Stirling Cycle[21]**

The efficiency of the Stirling engine is equal to the ratio between the recovered mechanical energy, $W_{net}$, and the heat, $Q_{total}$ which is required.
The net work provide by the cycle is:

$$W_{net} = W_{expansion} + W_{compression} \text{ where, } W_{compression} \text{ will be negative.}$$

Work is the integral of PdV and P = nRT/V for an ideal working gas

So,

$$W_{net} = W_{expansion} + W_{compression}$$

$W_{net}$ = (for $P_{expansion}$) + (for $P_{compression}$)

$W_{net}$ = +

$W_{net} = nR(T_{max} - T_{min})\ln(V_{max}/V_{min})$

The total heat:

$Q_{total} = Q_{heat} + Q_{expansion}$

Since during the isothermal expansion, U = 0 so $Q_{expansion} = W_{expansion}$. The heat provided to the gas is equal to the work produced during this same phase.

$Q_{expansion} = nRT_{max} \ln(V_{max}/V_{min})$

During the isochoric heating the heat provided to the system is

$Q_{heat} = nC_v (T_{max} - T_{min})$

Where $C_v$ is the constant-volume molar heat capacity of the gas.

The total heat provided is

$Q_{total} = nC_v (T_{max}-T_{min}) + nRT_{max}\ln (V_{max}/V_{min})$

The Stirling cycle efficiency is the ratio of the net work out to the total heat added or

Efficiency = $W_{net}/Q_{total}$ or

Efficiency = $(R (T_{max}-T_{min}) \ln (V_{max}/V_{min}))/(C_v (T_{max}-T_{min}) + RT_{max}\ln (V_{max}/V_{min}))$

This efficiency is not equal to the Carnot cycle efficiency but if the energy used for isochoric heating is entirely recovered during the isochoric cooling by using a regenerator then the

$C_v (T_{max}-T_{min})$ is equal to zero and the above Stirling efficiency reduces to

Efficiency = $\eta = (T_{max}-T_{min})/T_{max}$ or the Carnot efficiency.

What the regenerator does is it collects the heat exhausted; $Q_{cool}$ and uses it at the time of the constant volume heating then $Q_{heat}$ could be saved. The regenerator is a heat exchanger situated between the hot source and the cold source. The diagram below shows a rhombic drive Sterling engine with a regenerator and the pressure-volume diagram with regeneration.[22]

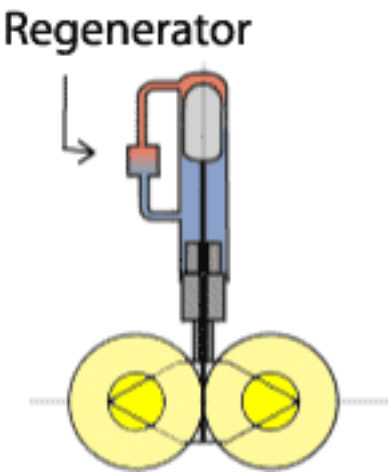



**Figure 8 Rhombic drive Sterling engine**[23]

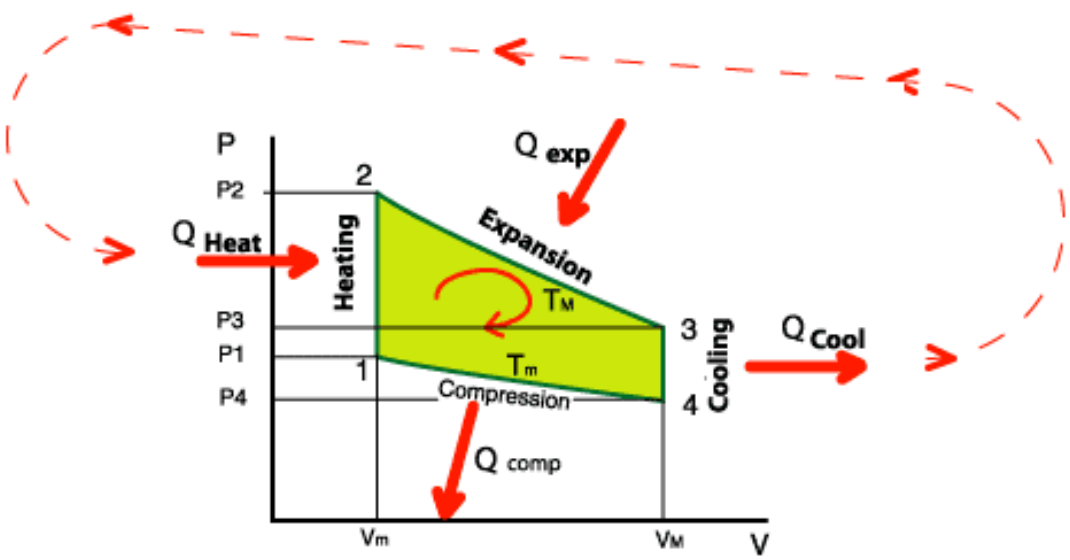



**Figure 9 PV diagram of a Sterling cycle showing heat and work.**[24]

The advantages of the Stirling engine are the high efficiency when using the regenerator. The efficiency is the same as the Carnot engine, which is the most efficient heat engine and is only a function of the temperatures of the hot and cold sources. The greater the difference between the temperatures of the hot and cold sources the greater the efficiency. The source of energy can have a multitude of possibilities from waste heat to combustion of gases, wood, sawdust, and solar or geothermic energy. The Stirling engine is reliable

and easy to maintain and since it is technologically simple it is reliable and has a long lifetime. The major draw back for using a Sterling engine is the difficulty of sealing the gas in the pistons and the best "ideal" gas to use in the engine would be hydrogen and because of its lightweight it is the most difficult gas to seal especially at high pressures. The second major disadvantage of the Sterling engine is fast and effective changes in power are difficult to obtain and it makes a Sterling engine problematic to use as an automobile engine.[25]

**Classroom Activities**

In my class, the above information is taught to the students just as it is described using power point for the diagrams. My students will be given a copy of Table one as reference and a full-page copy of the handouts in appendix 2. Also available in Appendix 2 are to vocabulary and ranking exercises which will be used as a class activity. An example problem set is also available in Appendix 2. I have a low differential temperature Sterling engine to use as demonstration and to measure its Carnot efficiency. As a class, students will go the Animated Engines website, http://www.animatedengines.com, and select one engine to present to the class describing the thermodynamic of its cycle.

**Appendix 1 Objectives**

**IB and AP Objectives**

**Thermodynamics**

1. State the equation of state for an ideal gas
2. Describe the difference between an ideal gas and a real gas
3. Describe the concept of the absolute zero of temperature and the Kelvin scale of temperature
4. Solve problems using the equation of state of an ideal gas.

**Processes**

**The First Law of Thermodynamics**

1. Deduce an expression for the work involved in a volume change of a gas at constant pressure
2. State the first law of thermodynamics
3. Identify the first law of thermodynamics as a statement of the principle of energy conservation
4. Describe the isochoric, isobaric, isothermal and adiabatic changes of state of an ideal gas
5. Draw and annotate thermodynamic processes and cycles on P-V diagrams

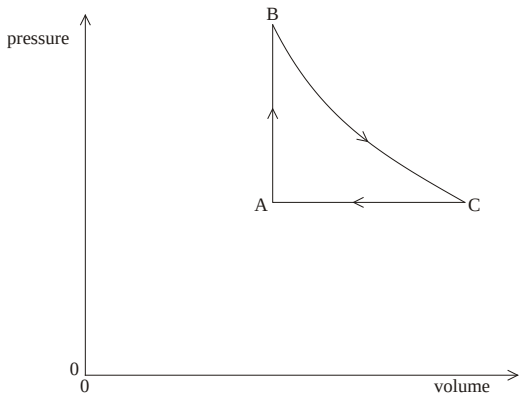
6. Calculate from a P-V diagram the work done in a thermodynamic cycle
7. Solve problems involving state changes of a gas.

**Second law of thermodynamics and entropy**

1. State that the second law of thermodynamics implies that thermal energy cannot spontaneously transfer from a region of low temperature to a region of high temperature
2. State that entropy is a system property that expresses the degree of disorder in the system

**Appendix 2 Student Handouts and Problems:**

1. The diagram below shows the variation with volume of the pressure of a fixed mass of an ideal gas.




The change from B to C is an isothermal change at 546 K. At point A, the pressure of the gas is 1.01 $\times 10^5$ Pa, the volume of the gas is 22.0 $m^3$ and the temperature of the gas is 273 K.

a. For the change from B to C, 31.5 $\times 10^5$ J of thermal energy is transferred to the gas.

b. Determine the temperature and volume of the gas at point C.
c. Determine the work done during the change from A to B and C to A.
d. Determine the work done by the gas during one cycle ABCA.
e. Using the first law and your calculation explain whether the work from A to B is done **by** the gas or **on** the gas and the work from C to A is done by the gas or on the gas.

2. One mole of an ideal, monatomic gas runs through a four step cycle. All processes are either isobaric or isochoric. The pressure and volume of the gas at the extreme points in

the cycle are given in the first two data rows of the table below.

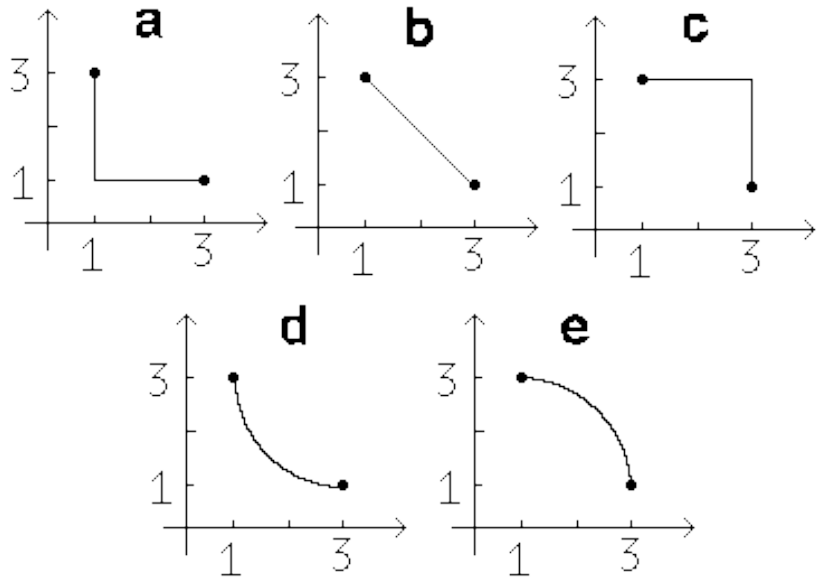
a. Sketch the PV graph of this cycle.
b. Determine the temperature at state A, B, C, and D.
c. Calculate *W*, *Q*, and $\Delta U$ on the path A→B, B→C, C→D, D→A and for one complete cycle. (Include the algebraic sign with each value.)

Does this cycle behave more like an engine or a refrigerator?

| State | A | B | C | D | |
|---|---|---|---|---|---|
| P(Pa) | 100,000 | 200,000 | 200,000 | 100,000 | |
| V($m^{3)}$ | 0.020 | 0.020 | 0.060 | 0.060 | |
| T(K) | | | | | |
| path | A→B | B→C | C→D | D→A | ABCD |

3. The figure below shows five different processes (labeled a-e) that each lead from an Initial state (P = 3 atm., V = 1 $m^3$) to a final state (P = 1 atm., V = 3 $m^3$).
Please answer each of the following questions.
For which process is W the largest? The smallest?
The smalle**st?**

For which process is



## Pressure, Temperature, and Molecules—Internal Energy [114]

Rank the total internal energies of the ideal gases below that contain a different number ($N$) of molecules at various temperatures ($T$) and pressures ($P$). Note: The volumes are not given; they may or may not be the same.

| A | B | C | D |
|---|---|---|---|
| $P$= 2 atm<br>$T$= 200 K<br>$N$= 10,000 | $P$= 2 atm<br>$T$= 200 K<br>$N$= 5,000 | $P$= 2 atm<br>$T$= 200 K<br>$N$= 20,000 | $P$= 2 atm<br>$T$= 300 K<br>$N$= 10,000 |

| E | F | G | H |
|---|---|---|---|
| $P$= 2 atm<br>$T$= 150 K<br>$N$= 10,000 | $P$= 1 atm<br>$T$= 150 K<br>$N$= 10,000 | $P$= 1 atm<br>$T$= 300 K<br>$N$= 10,000 | $P$= 3 atm<br>$T$= 200 K<br>$N$= 20,000 |

Greatest 1____ 2____ 3____ 4____ 5____ 6____ 7____ 8____ Least

Or, all these gases have the same internal energy. _____

Or, it is not possible to rank the internal energies for these gases. _____

Please carefully explain your reasoning.

How sure were you of your ranking? (circle one)

| Basically guessed | | | | Sure | | | | | Very Sure |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

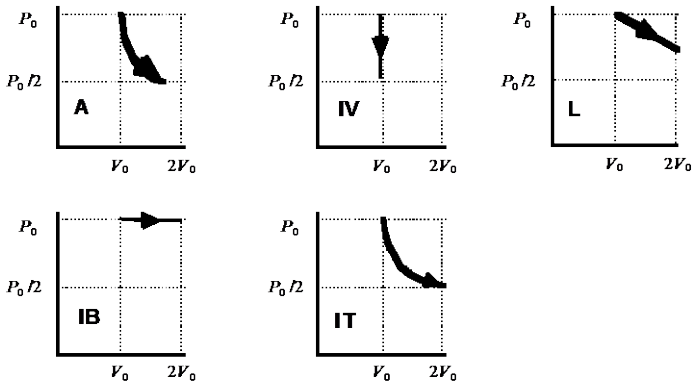
[114] C. Hieggelke

## Various Thermodynamic Processes—Work Done by Gas [110]

Five thermodynamic processes are illustrated below. All five processes are for the same ideal gas starting at the same initial pressure and temperature ($P_0$ and $T_0$). Each of the five distinctly different processes results in different final equilibrium states. The labels on each of the diagrams are to be interpreted as follows:

A = adiabatic  L = linear  IT = isothermal
IV = isovolumetric  IB = isobaric

Rank these processes from greatest to least on the basis of the amount of work that is done by the gas. Positive work should be ranked higher than negative work.




Greatest Work  1_____  2_____  3_____  4_____  5_____  Least Work

Or, all of the diagrammed processes require the same amount of work done by the gas. ____

Or, there is no work done by the gas in any of these processes. ____

Please carefully explain your reasoning.

How sure were you of your ranking? (circle one)

| Basically Guessed | | | | Sure | | | | Very Sure | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

[110] J. Popp

**Key Terms and Phrases:**

**State function**: a quantity that only depends on the thermodynamic state of a system (determined by P, V, and T).

**Reversible process**: a process that allows a system to return precisely to a previous state.

**Irreversible process**: a process that is not reversible.

**Isothermal process:** a process that takes place at constant temperature.

**Adiabatic process**: a process during which no heat is transferred.

**Molar specific heat**: the heat needed to change the temperature of one mole of a substance by one Celsius degree.

**Heat engine**: a device that converts heat into work.

**Carnot's theorem**: the theorem that states the conditions that give the maximum efficiency of a heat engine.

**Refrigerator**: a device that uses work to cause heat to flow from a cooler region to a warmer region.

**Entropy**: the ratio of the heat that flows at a fixed temperature for a reversible process. It measures the amount of disorder in a system.

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[1] (Pelecky 2009), 45.
[2] ibid
[3] (Walker 2010)
[4] (Walker 2010)
[5] ibid
[6] (Elert 1998)
[7] (Colwell 1997)
[8] ibid
[9] ibid
[10] ibid
[11] (Colwell 1997)
[12] (Colwell 1997)
[13] (Walker 2010)
[14] (Elert 1998)

[15] (Walker 2010)
[16] (Walker 2010)
[17] (Elert 1998)
[18] (Walker 2010)
[19] (Gras n.d.)
[20] ibid
[21] ibid
[22] ibid
[23] (Gras n.d.)
[24] (Gras n.d.)
[25] ibid

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