TABLE OF CONTENT

Introduction

To the Learner:

In chemistry there are many things that you must simply learn. Understanding comes after you have learnt the definitions, names, symbols and descriptions of the concepts.

In this study guide, things that should be learnt will be mentioned as the answer to a question is given.

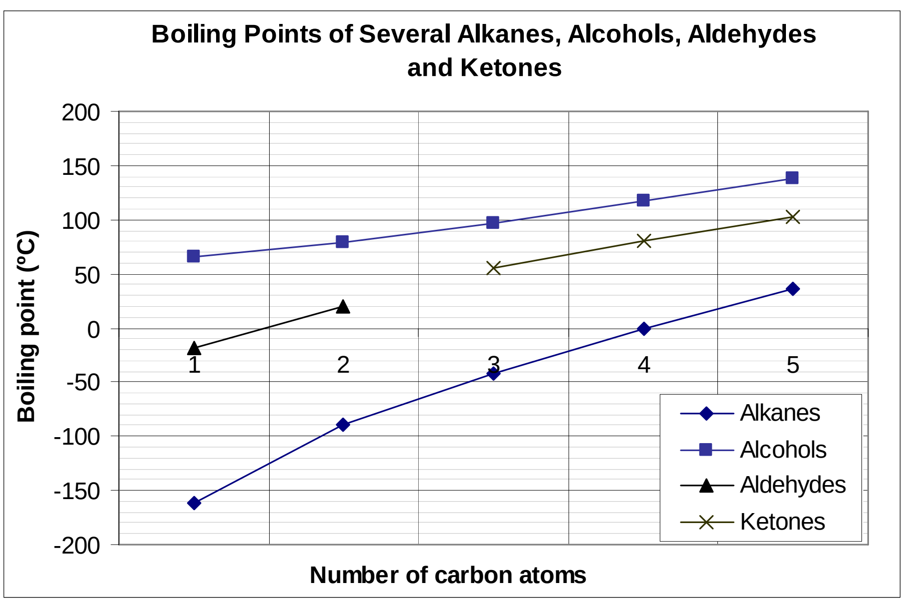
The space in the study guide is too short to cover everything in chemistry, (but perhaps by reading this study guide and working through the questions, you will learn how to approach problems in chemistry, and how to reason to reach a correct answer, so that when you are faced with an unfamiliar question, you will be able to apply the same methods of problem-solving to sections of chemistry not covered in this guide, and find enjoyment in answering the questions.)

The method that will be followed is to present some questions, and then to give you a model answer so that you can see how to solve the questions. When you have learnt how to think and reason in chemistry, you will be able to apply the techniques of reasoning to many different problems.

Organic Chemistry

Question 1

The graph shows the boiling points of some alkanes, alcohols, aldehydes and ketones.



Different questions could be asked, such as:

(a) Explain why the boiling point increases with an increase in the number of carbon atoms for (i) the alkanes (ii) for the aldehydes, and ketones and (iii) for the alcohols.

(b) Explain the difference in boiling points for the different homologous series. In your answer refer to the number of carbon atoms and the effect of the intermolecular forces.

<u>When you have to answer questions where a graph is shown, quickly but thoroughly, analyze the graph (that means make sure you understand what the graph is showing)</u>:

- <u>The *x* axis</u> shows the **number of carbon atoms**. The numbers one to five are found just above the -50 ºC line on the graph and not at the bottom of the graph on the *x* axis.
- <u>The *y* axis</u> shows the **boiling points**, for instance for one carbon atom on the alkane line (-♦-) the boiling point is approximately -160 ºC, and the boiling point for the ketone with three carbon atoms (-x-) is just more than 50 ºC.

Notice that all <u>the line-graphs show a positive slope</u>; which can be seen by the gentle rising of the line. The meaning of a positive slope is that the values on the *y* axis are increasing together with an increase in the values on the x-axis.

<u>Now analyze the question - that means make sure you understand what is actually being asked.</u>

Let us analyze the first question ((a)). (Make sure you know what is meant by all the words).

> Explain why the boiling point increases with an increase in the number of carbon atoms for the alkanes. (The question would be totally different yet the reasoning would be similar when "alkanes" is replaced by "aldehydes" or "ketones" or "alcohols").

You must know (because you learnt it before!) that the alkanes have the general formula of C_nH_{2n+2}. So you should be able to find the formula of the different alkanes.

(See Table 1 at the end of this answer).

An "*increase in the number of carbon atoms*" means that you have an alkane with one carbon atom (CH_4), then an alkane with two carbon atoms (CH_3CH_3 or C_2H_6), followed by an alkane with three carbon atoms ($CH_3CH_2CH_3$ or C_3H_8) and so on. (You should also have learnt how to name these compounds!).

An "*increase in boiling point*" means that the boiling point is getting higher, or that the boiling point of the first one is lower than the boiling point of the second one which is lower than the boiling point of the third one, and so on.

So what is actually being asked?

The question asks you to explain why the boiling point of the alkane with one carbon atom is less than the boiling point of the alkane with two carbon atoms, which is less than the alkane with three carbon atoms and so on.

The graph shows this:

- *The boiling points (on the y-axis) of the alkane series* (-♦-) *increase with increasing number of carbon atoms (on the x-axis). Similarly the boiling points of the aldehyde series (-■-), the ketone series (-x-) and the alcohol series (-●-) become higher as the number of carbon atoms increase.*

Let us analyze the second question ((b)). (Make sure you know what is meant by all the words).

Explain the difference in boiling points for the different homologous series. In your answer refer to the number of carbon atoms and the effect of the intermolecular forces.

Homologous series refers to the family, namely alkanes or alcohols or aldehydes or ketones (You should learn about this).

Intermolecular forces refer to the force between different molecules (Do not confuse intermolecular and intramolecular. For inter- think of the 'the internet' a 'world wide web' linking you all over the world in the same way intermolecular refer to the links (or bonds) between molecules. Intramolecular forces, on the other hand, refer to the forces inside a single molecule between the atoms of that molecule (think of 'intravenous' that refer to 'inside the body'.

So what is actually being asked is:

Why is the boiling point of the alcohol with one carbon atom different from the boiling point of the alkane with one carbon atom, and why are both boiling points different from the boiling point of the aldehyde with one carbon atom? (What is the reason for these differences?) Why is the boiling point of the alcohol with two carbon atoms different from the boiling point of the alkane with two carbon atoms, and both boiling points are different from the boiling point of the aldehyde with two carbon atoms? And so on.

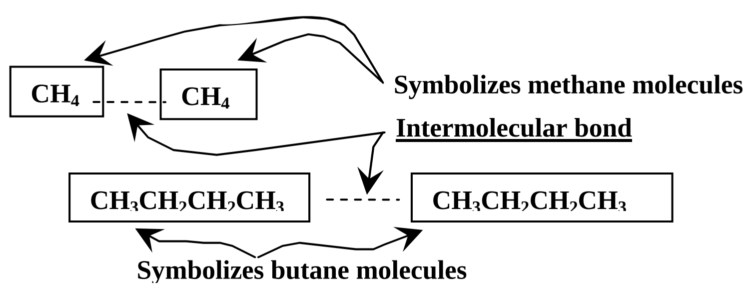
From the graph one notices that

- *The boiling points of the alkanes are lower than the boiling points for the aldehydes and ketones with a similar number of carbon atoms and the boiling points of the alcohols with a* *similar number of carbon atoms are higher than the boiling points of both the alkanes and the aldehyde / ketones. (You can see this because the lowest (or bottom) line on the graph is that of the alkanes and the top line is that of the alcohols).*

The graph is simply a way of showing this trend in the boiling points of the different homologous series. **The answer to these questions lies elsewhere, but where?**

In the second question you are provided with a 'tip' or a 'clue' to finding the answer, when the question refers to "*the effect of the intermolecular forces*". In your answer you will have to say something about the intermolecular forces of these substances. Start with that!
What do you know about the intermolecular forces of these molecules?

The alkanes are <u>non-polar</u>. Between two similar alkane molecules **induced dipole – induced dipole bonds** form. The force that holds these similar molecules together are **Van der Waals forces.**

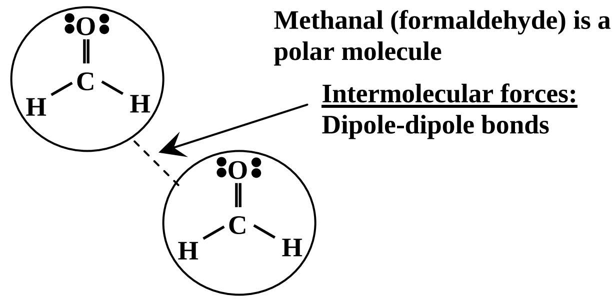


How can you tell what the strength of these forces are?
<u>The boiling point of a substance is an indication of how strong the intermolecular bonds are that hold the molecules of the species together</u>; that is, the easier it is to break the bonds, the lower the boiling point will be.
The more carbon atoms an alkane molecule has the more places are available for induced dipole – induced dipole "bonds" to form, so that more energy is needed to break the "bonds". "More energy" means that the substance must reach a higher boiling point before the molecules can separate into the gas phase or in ordinary language, before the substance 'boils'.

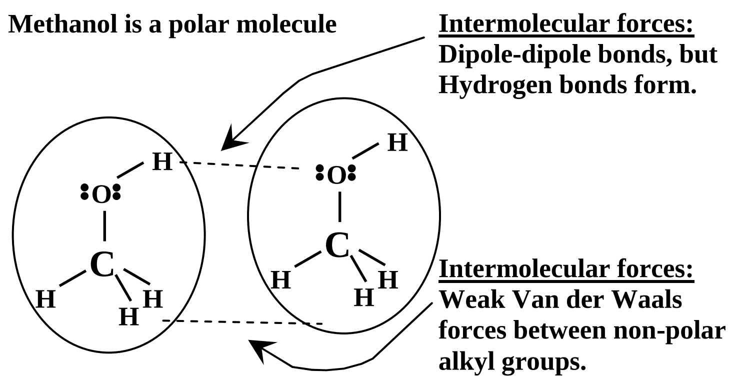
<u>Answer to Question 1 (a):</u>
Weak Van der Waals forces are responsible for the intermolecular bonds that form between alkane molecules.
The intermolecular bonds between alkane molecules with only one carbon atom are weaker than the bonds between alkane molecules with more carbon atoms; this is known because the boiling point of alkanes increases with an increase in the number of carbon atoms.

When answering Question 1 (ii) and (iii), for the situation where the "alkane" is replaced with "aldehyde" / "ketone" or "alcohol" one is also answering Question 1 (b).
In the answer one must look at the type of bond and the intermolecular forces that hold aldehydes (or ketones or alcohols) together.

<u>Answer to Question 1(ii):</u>
For aldehydes and ketones dipole-dipole bonds form in the carbonyl groups (C=O), they are stronger bonds and need more energy to break. Therefore the boiling points of aldehydes (with a similar number of carbon atoms as the alkanes) are higher.



<u>Answer when alkane is replaced by alcohol (Question 1(iii)):</u>
Similarly for alcohols we find that the intermolecular forces binding two alcohols together are strong hydrogen bonds which are generally stronger bonds than ordinary dipole-dipole bonds.



Therefore the boiling points of alcohols (with a similar number of carbon atoms as the alkanes or aldehydes) are higher.

<u>Answer to Question 1 (b):</u>
Induced dipole-induced dipole bonds (in alkanes) are weaker than dipole-dipole bonds (in aldehydes and ketones) which are usually weaker than hydrogen bonds (in alcohols) therefore the boiling points of alkanes are lower than the boiling points of aldehydes and ketones which are lower than the boiling points of alcohols with the same number of carbon atoms. The longer a chain becomes (more carbon atoms) the stronger the bonds become that bind similar molecules together. Therfore more energy is needed to break the bonds and the boiling point increases.

Point to consider:

In stating the question the graph could be replaced with a table such as Table 1.

Then you could have been asked to draw such a graph and answer the questions.

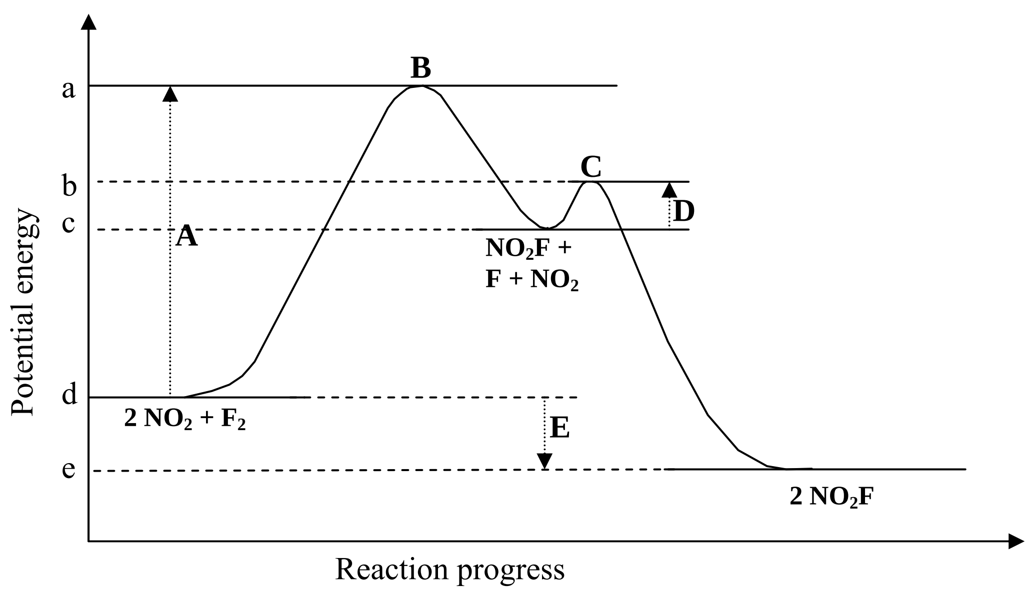
In whatever way the question is stated, the same things need to be known to answer the question and many of those things in Organic chemistry must simply be learnt!

Table 1.		Boiling points (°C) of some alkanes, alcohols, aldehydes and ketones							
		Alkanes		Alcohols		Aldehydes		Ketones	
Number of carbon atoms	1	CH_4	-162	CH_3OH	65	HCHO	-19		
	2	C_2H_6	-89	CH_3CH_2OH	79	CH_3CHO	20		
	3	C_3H_8	-42	$CH_3CH_2CH_2OH$	97			CH_3COCH_3	56
	4	C_4H_{10}	-0.5	$CH_3CH_2CH_2CH_2OH$	117			$CH_3CH_2COCH_3$	80
	5	C_5H_{12}	36	$CH_3CH_2CH_2CH_2CH_2OH$	138			$CH_3CH_2COCH_2CH_3$	102

Energy and Chemical Change

Question 2

For the given graph answer the following questions:



2.1 Give the meaning of A, B, C, D, and E.

2.2 Give the overall reaction.

2.3 How many steps does the reaction have?

2.4 What type of enthalpy change is experienced by the forward reaction? Explain.

You must first of all analyze and interpret the diagram:

- This diagram is a 'Reaction Energy Diagram', that means it shows what energy changes occur during a reaction.
- On the *y* axis the potential energy is shown.
- On the *x* axis the progress of the reaction is shown, but where is the reaction?
- The graph starts on energy 'd', and there you also find the 'Reactants', namely $2\ NO_2 + F_2$.
- The graph ends on energy 'e', and there you also find the 'Products', namely $2\ NO_2F$.
- So the overall (forward) reaction is $2\ NO_2 + F_2 \rightarrow 2\ NO_2F$
- The energy on which the reaction ends 'e' can also be expressed as $E_{Products}$, and is for this example lower in value than the energy on which the reaction started 'd' also expressed as $E_{Reactants}$.
- When $E_{Products} < E_{Reactantsl}$ then energy is given off during the reaction (energy flows out of the system to the surroundings), the arrow (E) indicating the energy flow points downward meaning energy flowed out.
- For the forward reaction, $\Delta H = E_{Products} - E_{Reactants}$ = (value at 'e') – (value at 'd') < 0 so that the enthalpy change $\Delta H < 0$ and we say an exothermic reaction occurred. Such a reaction can be expressed (written as):

$$\left.\begin{array}{lll} & 2\ NO_2 + F_2 \rightarrow 2\ NO_2F + \text{energy} & \\ \text{- Or} & 2\ NO_2 + F_2 \rightarrow 2\ NO_2F & \Delta H < 0 \\ \text{- Or} & 2\ NO_2 + F_2 \rightarrow 2\ NO_2F & \Delta H = - \end{array}\right\} \text{All indicate 'Exothermic reaction'}$$

- The graph has two peaks, one at B and one at C. This means that
  - there are two transition states
  - two intermediates were formed during the reaction
  - the reaction is a two step reaction. We find the proposed intermediates (or products for the first step) at energy 'c' and also (at energy 'c') the proposed reactants for he second step is shown, namely:

$NO_2 + F_2 \longrightarrow NO_2F + F$ (Proposed reaction for first step)

Reactants at the start at energy 'd' → Substances found at energy 'c' (after a 'reaction' has occurred).

$NO_2 + F \longrightarrow NO_2F$ (Proposed reaction for second step)

Reactants shown at energy 'c' → Products shown At energy 'e'

Notice that both proposed reactions are balanced.

When these two reactions are added together the F atoms on both sides cancel and we find: $NO_2 + NO_2 + F_2 \rightarrow NO_2F + NO_2F$ (Overall reaction) or add similar compounds together:

$2\ NO_2 + F_2 \rightarrow 2\ NO_2F$

- The energy values at ‘a’ and at ‘b’ indicate to what level (value) the energy had to rise to get the first step to take place (going from ‘d’ to ‘a’) and then to what level (value) the energy had to rise to get the second step to take place (going from ‘c’ to ‘b’).
- The energy to get the reaction going is shown by A and has the value of (‘a’ – ‘d’) and is called $E_{activation}$(step 1). The arrow indicating ‘A’ is pointing upward, because energy was needed (energy flowed from the surroundings into the system, meaning the energy of the system increased).
- The energy to get the second step going is shown by ‘D’ and has the value of (‘b’ – ‘c’) and is called $E_{activation}$(step 2). The arrow indicating ‘D’ points upward; because energy was needed (energy was added from the surroundings to the system).

Now you are ready to give the answers.

<u>Answers:</u>

2.1 Give the meaning of A, B, C, D, and E.

A – Activation energy for the first step and has value ‘a’ – ‘d’, (a positive value).
B – First reaction intermediate.
C – Second reaction intermediate.
D – Activation energy for the second step and has value ‘b’ – ‘c’, (a positive value).
E – Overall energy change or the change in enthalpy and has value ‘e’ –‘d’, (a negative value), therefore $\Delta H < 0$, indicating an exothermic reaction.

2.2 Give the overall reaction.

$2\ NO_2 + F_2 \rightarrow 2\ NO_2F \qquad \Delta H < 0$

2.3 How many steps does the reaction have?

The two peaks at B and C indicate that this is a two step reaction.

Step one is shown on the graph as starting at energy 'd' (and reactants: $2\ NO_2 + F_2$), by adding the activation energy (A) the intermediate at B is formed, and then the reaction proceeds to the point with energy 'c' showing the products for that step as: **$NO_2F + F$**

Step two is shown as starting at energy 'c' (showing the reactants as: **$F + NO_2$** where the F has just previously been shown as one of the products of step one), raising the energy by input D to the reaction intermediate at C and then the reaction proceeds to the products of step 2 (and the overall products of the reaction: $2\ NO_2F$) at energy with value 'e'.

2.4 What type of enthalpy change is experienced by the forward reaction? Explain.

$\Delta H = E_{Products} - E_{Reactants} =$ 'e' – 'd' < 0

The forward reaction is an exothermic reaction, because the final energy (at 'e') is lower than the energy at the start (at 'd'); energy flowed out of the system to the surroundings.

For interest: the enthalpy change experienced by the step one reaction is endothermic starting at energy 'd' and ending at energy 'c'.

In using the formula: $\Delta H_{step\ one} = (E_{Products} - E_{Reactants})_{step\ one} =$ 'd' – 'c' > 0.

The enthalpy change for the second step is exothermic, so that the overall energy change for the reaction is exothermic.

Question 3

In referring to Diagram 3.1, answer the following questions:

(a) What type of enthalpy change is experienced by the forward reaction? Explain.

(b) What type of enthalpy change is experienced by the reverse reaction? Explain.

(c) What is the meaning of the dotted line?

(d) By referring to the collision theory, discuss the effect that an increase in the temperature has on the reaction rate of the forward and reverse reaction.

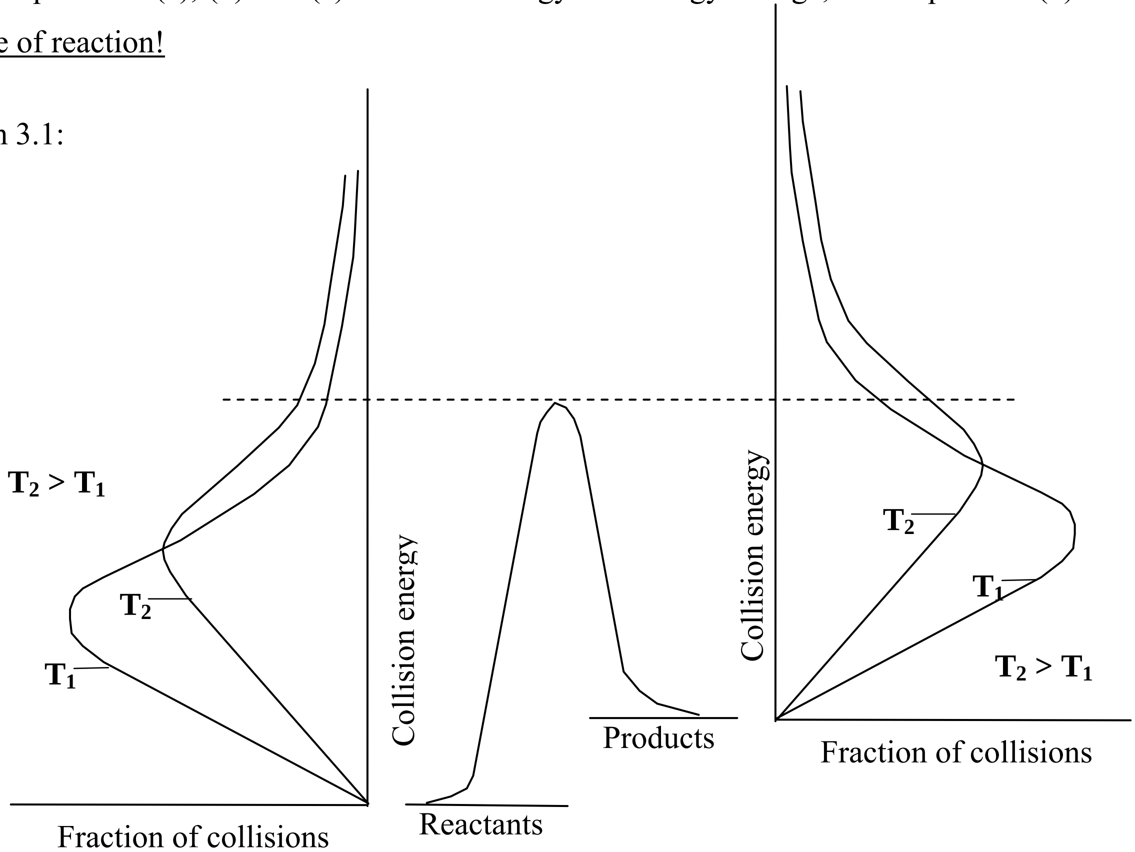
Note the "Explain" in questions (a) and (b) – remember to "explain" when giving your answer!

Note the "and" in question (d) – remember to give the answer for both the forward and reverse reaction!

Retention of the question (meaning: remembering what is asked) is part of the assessment!

Note that questions (a), (b) and (c) deal with energy and energy change, while question (d) deals with rate of reaction!

Diagram 3.1:

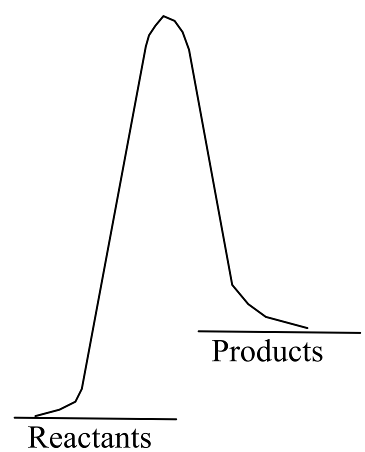


Notice that Diagram 3.1 is a combination of the **Reaction Energy Diagram (Diagram 3.2)** and the **Maxwell-Boltzmann distribution curve** for the same reaction.

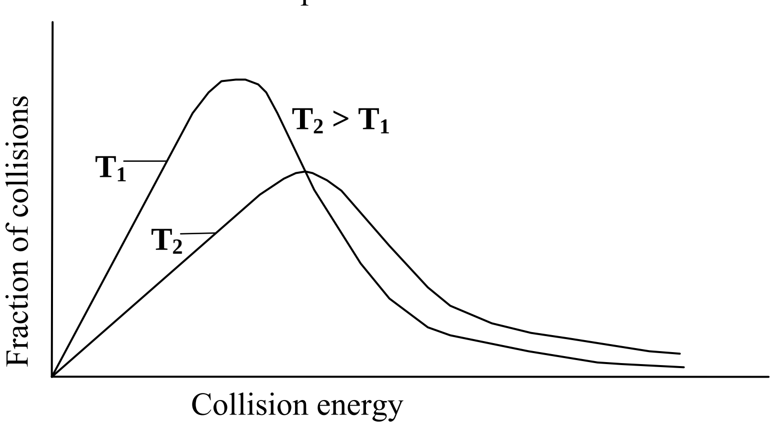
Diagram 3.2 is an energy level diagram for a reversible reaction:

Reactants → Products (forward reaction)
Products → Reactants (reversible reaction)

Diagram 3.2:



The **Maxwell-Boltzmann distribution curve** for the same reaction at different temperatures is shown below:

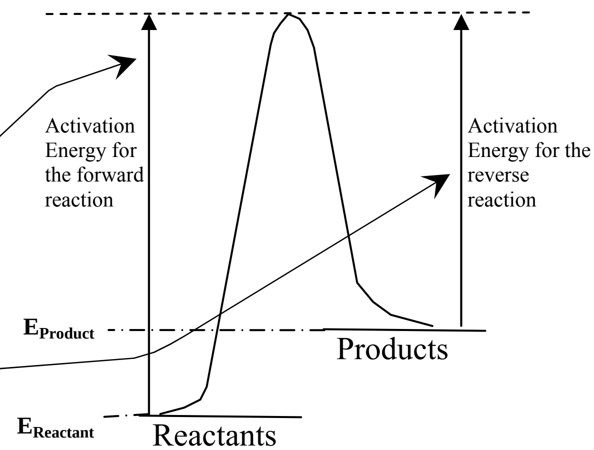


You must first of all analyze and interpret the different diagrams:

- Diagram 3.2 is a simple 'Reaction Energy Diagram', that means it shows what energy changes occur during a reaction. What are not shown are the axes, but you should know that for such a curve the *y* axis shows the potential energy and the *x* axis shows the progress of the forward reaction.
- For the forward reaction $E_{Reactants} < E_{Products}$, that means that $\Delta H = E_{Products} - E_{Reactants} > 0$.
- $\Delta H > 0$ or $\Delta H = +$ is an indication of an endothermic reaction. (The forward reaction is endothermic, but the reverse reaction (Products → Reactants) is an exothermic reaction.

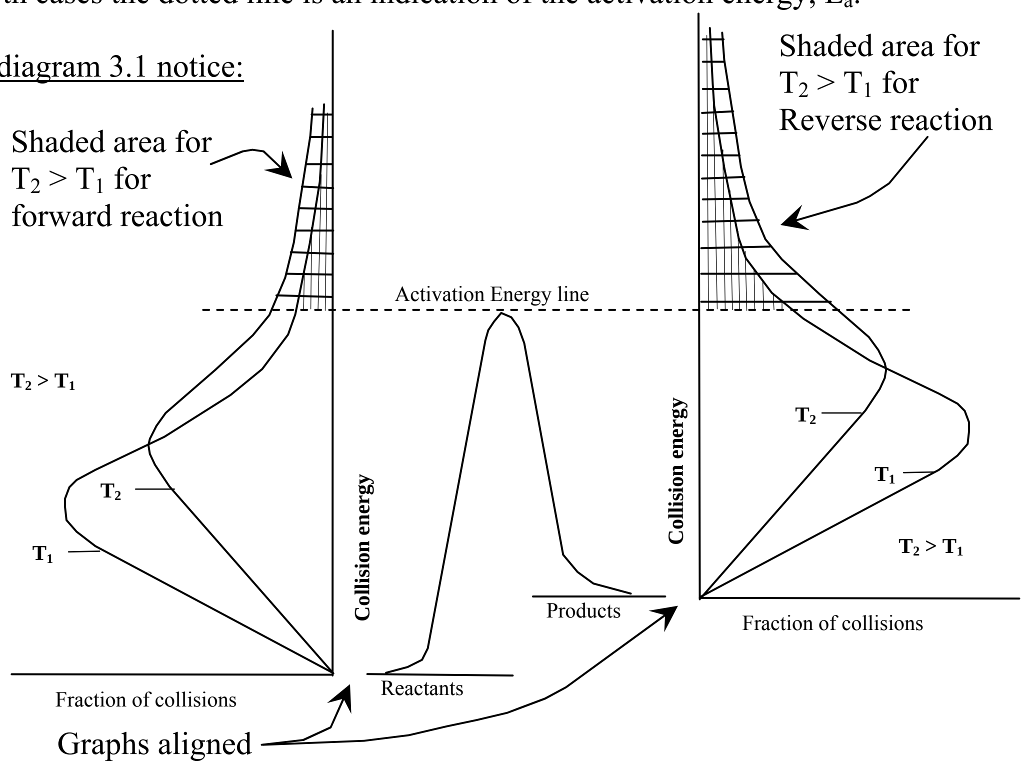
- The activation energy for the forward reaction is given by the energy needed to get from the reactants to the top of the curve (the dotted line).

- The activation energy for the reverse reaction is given by the energy needed to get from the products to the top of the curve (the dotted line).



So in both cases the dotted line is an indication of the activation energy, E_a.

For diagram 3.1 notice:



- Notice that there is a Maxwell-Boltzmann distribution curve that has been turned 90º in an anti-clockwise direction on the left of the 'Reaction Energy Diagram' (diagram 3.2) and on the right is a Maxwell-Boltzmann distribution curve that was rotated and flipped horizontally.
- Furthermore notice (for diagram 3.1) that the *y* axis of this Maxwell-Boltzmann diagram (or the starting point of the *x* axis) has been aligned with the Reactant Energy line of the 'Reaction Energy Diagram' – which is also the starting point of the forward reaction.

  Notice that the dotted line (activation energy line) dissects a part of the Maxwell-Boltzmann curve.
- Notice that on the right of the 'Reaction Energy Diagram' is a Maxwell-Boltzmann distribution curve that has been rotated and flipped horizontally. Furthermore notice that the *y* axis of this Maxwell-Boltzmann diagram (or the starting point of the *x* axis) has been aligned with the Product Energy line of the 'Reaction Energy Diagram' – which is also the starting point of the reverse reaction.

  Notice that the dotted line (activation energy line) dissects a part of this Maxwell-Boltzmann curve.
- A Maxwell-Boltzmann distribution curve is a special type of curve. Not only does it show the 'fraction of collisions' on the one axis and the 'collision energy' (or kinetic energy of the particles) on the other axis, but the total area under the curve represents the total number of particles taking part in the reaction. None of these particles were removed and no extra particles were added during the reaction. The given Maxwell-Boltzmann curve shows that the temperature was increased from T_1 to T_2. Notice what happened: the peak of the T_2 curve is flatter (on the *y* axis), but because the same number of particles remain under the curve, the curve is more spread out on the *x* axis and at the end, thicker (or fatter). The meaning of this is that there are more particles with higher collision energy (at the end of the curve). This is known, because the T_2 curve is above the T_1 curve toward the end of the curve.
- Very important is that the activation energy line (dotted line) remains the activation energy line even when it dissects the Maxwell-Boltzmann curve. The meaning is that only the top section of the Maxwell-Boltzmann curve (the section that lies to the top of the dotted line and has been shaded) has the correct collision orientation and enough energy to collide successfully and form products.
- Notice what has changed when the temperature was increased: There is a larger area of the T_2 – curve above the dotted line (for both Maxwell-Boltzmann curves) than for the T_1 curve. This is seen because the area shaded like ≡ is larger than the area shaded like ‖‖. The

importance of having a larger area above the dotted line is that there are more particles with the correct activation energy, so that more particles can take part in the reaction when the temperature increased to T_2 because at the higher temperature there are more successful or effective collisions.

<u>Now answer the questions:</u>

(a) What type of enthalpy change is experienced by the forward reaction? Explain.

The forward reaction is an endothermic reaction, because $\Delta H = E_{Products} - E_{Reactants} > 0$.

(b) What type of enthalpy change is experienced by the reverse reaction? Explain.

The reverse reaction is an exothermic reaction.
For the reverse reaction the products of the forward reaction becomes the reactants of the reverse reaction (the reaction is going back!) and the reactants of the forward reaction becomes the products of the reverse reaction.
So that the general formula: $\Delta H = E_{Products} - E_{Reactants}$ becomes

$$= E_{\text{Products now become Reactants}} - E_{\text{Reactants now become Products}}$$

< 0. (Indicating an exothermic reaction).

(c) What is the meaning of the dotted line?

The dotted line indicates the energy needed for the reaction to proceed (whether in the forward or the reverse direction). This energy is known as the ‘activation energy’

(d) By referring to the collision theory, discuss the effect increasing the temperature has on the reaction rate for the forward and reverse reaction. (<u>Notice</u> that this question actually deals with chemical kinetics and not so much with the energy of the reaction)

Only when effective collisions occur does a reaction take place. For an effective collision to occur the particles involved must have energy higher than the activation energy needed for that reaction. At a higher temperature the average kinetic energy of the particles involved in the reaction increases resulting in more particles with energy higher than the activation energy. (*The shaded area of the graphs gives an indication of particles with energy higher than the activation energy*). There are more particles with an energy higher than the activation energy at a higher temperature (*this is seen by the shaded area (≡) for both the T_2 graphs (for the forward and reverse reactions) being greater than the shaded area (‖ ‖) for the T_1 graphs)*. The rate of a reaction is determined by the number of effective collisions that occur. By increasing the number of effective collisions the rate of the reaction increases. When there are more particles with energy higher than the activation energy (curve T_2) the result is that more effective collisions occur consequently the rate of the reaction increases.

CHEMICAL KINETICS

Question 4

In the engine of a car a combustion reaction occurs when petrol (C_8H_{18}) reacts with the oxygen in air. However, at such high temperatures the nitrogen in the air also reacts with the oxygen in air and forms nitric oxide (NO). When the 'timing' of the engine is not right the temperature at which such a combustion reaction occurs is not high enough and the combustion is not complete and unburned hydrocarbons and carbon monoxide form. Most modern cars are equipped with a two-stage catalytic converter. An efficient catalytic converter serves two purposes: it oxidizes CO and the unburned hydrocarbons to CO_2 and H_2O, and it reduces NO and NO_2 to N_2 and O_2.

Answer the following questions:

(a) Give balanced chemical reaction equations for the combustion of petrol and air at a high temperature (complete combustion) and at a lower temperature (incomplete combustion).

(b) Give a balanced chemical equation for the reaction of oxygen and nitrogen to form nitrogen monoxide at high temperatures.

(c) What are hydrocarbons?

(d) What is so bad about the exhaust gases of a car that the exhaust of a car should be equipped with a catalytic converter?

(e) Give a short description of the way in which a two-stage catalytic converter works.

(f) Is the catalytic converter regarded as a homogeneous or a heterogeneous catalyst?

(g) Explain what is meant by

  (i) "it oxidizes CO and the unburned hydrocarbons to CO_2 and H_2O" and

(ii) “it reduces NO and NO_2 to N_2 and O_2”.

Note this question is a combination question: it has a little organic chemistry, rates of chemical reactions, and electro chemistry all thrown together. Do not let that disturb you. Continue to start by analyzing the question and then proceed to answer the question.

Analyze the question:

Combustion means “to burn” so a combustion reaction is when something is burned.

In the question three reactions are mentioned:

(1) the combustion reaction of petrol and air at high temperature (complete combustion),

(2) the combustion reaction of petrol and air at a lower temperature (incomplete combustion), and

(3) the reaction between the nitrogen (in air) and the oxygen (in air) at high temperatures.

In all three reactions the reactants are mentioned, but what about the products?

Tackle the equations one by one:

(1) When you studied organic chemistry you should actually have learned about the combustion of alkanes and oxygen! Is petrol an alkane? Remember the general formula for an alkane is C_nH_{2n+2}. So check: $C_8H_{2(8)+2} = C_8H_{18}$ showing that petrol is an alkane.

You should have learned that the complete combustion reaction of an alkane produces carbon dioxide and water as products, so the equation for the reaction is: $C_8H_{18} + O_2 \rightarrow CO_2 + H_2O$.

Now proceed to balance the equation. On the reactant side Petrol has 8 carbon atoms.

<table>
<tr><th></th><th>Reactants
(left hand side)</th><th>Products
(right hand side)</th><th></th></tr>
<tr><td>For carbon</td><td>8
From C_8H_{18}</td><td>1
From CO_2</td><td>therefore multiply CO_2 by 8, then there will also by 8 carbon atoms on the product side</td></tr>
<tr><td colspan="4">Now you have: $C_8H_{18} + O_2 \rightarrow \mathbf{8}\ CO_2 + H_2O$</td></tr>
<tr><td colspan="4">How do you know which element to balance next? Note that hydrogen is bonded to other elements on both the reactant and product side (to C on the reactants side and to O on the product side), whereas oxygen stands alone on the reactant side. Therefore it would be less complicated to balance the oxygen, so leave oxygen till last.</td></tr>
<tr><td>For hydrogen</td><td>18
From C_8H_{18}</td><td>2
From H_2O</td><td>Multiply H_2O by 9, then there will also by 18 hydrogen atoms on the product side</td></tr>
<tr><td colspan="4">Now you have: $C_8H_{18} + O_2 \rightarrow \mathbf{8}\ CO_2 + \mathbf{9}\ H_2O$</td></tr>
<tr><td>For oxygen</td><td>1 x 2 = 2
From O_2</td><td>(8 x 2) + (9) = 25
From
8 CO_2 + 9 H_2O</td><td>The 2 oxygen atoms on the reactant side are stuck together, you cannot separate them. For 25 oxygen atoms you will have</td></tr>
</table>

<table>
<tr><td></td><td></td><td></td><td>to multiply the oxygen by $\frac{25}{2}$, that is by 12½</td></tr>
<tr><td colspan="4">Now you have: C_8H_{18} + 12½ O_2 → 8 CO_2 + 9 H_2O</td></tr>
<tr><td colspan="4">May you have “½” a molecule? Yes, as long as you refer to the stoichiometric coefficient as moles, since you could have ½ a mole, but it would be better to get rid of the ½. You do that by multiplying every stoichiometric coefficient by 2.</td></tr>
<tr><td colspan="4">then you have: 2 C_8H_{18} + 25 O_2 → 16 CO_2 + 18 H_2O</td></tr>
<tr><td colspan="4">Now check the number of each element on both sides again! (Are you wasting time? – not if this will earn you marks!)
<table>
<tr><td></td><td>Left hand side (reactants)</td><td>Right hand side (products)</td></tr>
<tr><td>For carbon:</td><td>2 x 8 = 16</td><td>16 x 1 = 16</td></tr>
<tr><td>For hydrogen:</td><td>2 x 18 = 36</td><td>18 x 2 = 36</td></tr>
<tr><td>For oxygen:</td><td>25 x 2 = 50</td><td>(16 x 2) + (18 x 1) = 32 + 18 = 50</td></tr>
</table>
</td></tr>
</table>

So equation (1) *the combustion of petrol and air at a high temperature (complete combustion),* is

2 C_8H_{18} + **25** O_2 → **16** CO_2 + **18** H_2O

(2) The combustion reaction of petrol and air at a lower temperature (incomplete combustion): when you studied the alkane reactions you should also have learnt about this type of reaction! Incomplete combustion occurs when there is not enough oxygen available.
Consider the above reaction: **2** C_8H_{18} + **25** O_2 → **16** CO_2 + **18** H_2O, if there is not enough oxygen (on the reactant side) what would happen? You should have fewer oxygen atoms on the products side. How would that be possible? Well instead of CO_2 (where 2 oxygen atoms are present) CO form (where only one oxygen atom is present!). So the basic outline for reaction (2) is:

C_8H_{18} + O_2 → CO + H_2O

Balance this reaction (Follow the same procedure as above): First balance the carbon atoms, and then hydrogen and lastly oxygen and you should get as answer:

C_8H_{18} + **8½** O_2 → **8** CO + **9** H_2O

Again multiply all the stoichiometric coefficients by 2 and you find:

2 C_8H_{18} + **17** O_2 → **16** CO + **18** H_2O

Notice that you only used 17 moles of oxygen molecules (or 17 O_2 molecules) for this reaction (reaction (2)) compared to 25 moles (or 25 molecules) in reaction (1)!
(When you read the coefficients as moles you do so for the whole reaction or if you read the coefficients as molecules/atoms you do so for the whole reaction – don't mix the two!)

(3) The reaction between the nitrogen (in air) and the oxygen (in air) at high temperatures: Again you are given the reactants: nitrogen (in air) and oxygen (in air), N_2 and O_2. What about the products? Go read the question! …*at such high temperatures the nitrogen in the air also reacts with the oxygen in air and forms nitric oxide (NO)*.

$N_2 + O_2 \rightarrow NO$

The balancing should not be a problem: $N_2 + O_2 \rightarrow 2\ NO$

Next question:

(c) *What are hydrocarbons?* You should have learnt this in organic chemistry! What does the name tell you? "Hydro" is short for hydrogen and "carbons" means just that! So hydrocarbons are compounds of hydrogen and carbon. Do you know any such compounds? The alkanes and alkenes are such compounds!

Next question:

(d) *What is so bad about the exhaust gases of a car that the exhaust of a car should be equipped with a catalytic converter?*

(If you had not learned about this don't despair! Use your common sense!)

There are (according to the question) two exhaust chemicals that are formed, CO and NO. Say something about each chemical:

- Carbon monoxide combines with hemoglobin in the blood, thereby preventing the blood from transporting oxygen (with which the hemoglobin should have combined) around the body. Since carbon monoxide is an odorless, colourless and tasteless gas it is not easily detected.
- Nitrogen monoxide is a colourless reactive gas that is only slightly soluble in water. NO is a good reducing agent and reacts readily with quite a few other gases found in the atmosphere:
  - ∗ Nitrogen monoxide is slowly oxidized by oxygen to form nitrogen dioxide. The balanced reaction is: $2\ NO(g) + O_2(g) \rightarrow 2\ NO_2(g)$
    - NO_2 is a health hazard, primarily because it attacks the lungs, but usually the concentration is not high enough.
  - ∗ Nitrogen monoxide reduces ozone to oxygen and is oxidized to NO_2. The balanced reaction is: $NO(g) + O_3(g) \rightarrow O_2(g) + NO_2(g)$

- Ozone is an important chemical in the stratosphere (at altitudes (height above sea level) of 15 to 25 km). The reason why we need ozone is that an equilibrium situation is set up between two reactions:

  In one reaction the ozone absorbs dangerous ultraviolet radiation, with wavelengths between 240 and 310 nm (from the sun) and break up into oxygen atoms and oxygen molecules.

  O_3 + UV radiation $\rightarrow$ O + O_2

  In the other reaction, at lower altitudes, the oxygen atoms immediately react with the oxygen molecules to form ozone

  O + $O_2 \rightarrow O_3$

  Equilibrium is set up:

  O_3 + UV radiation $\leftrightarrows$ O + O_2

  The result of the equilibrium is that most of the ultraviolet radiation from the sun is absorbed before it reaches the earth's surface (where it could destroy living cells).

* Nitrogen monoxide also reacts with carbon dioxide to form carbon monoxide and nitrogen dioxide, increasing the concentrations of two dangerous gases in the atmosphere!

  $NO(g) + CO_2(g) \rightarrow CO(g) + NO_2(g)$

Do you have to give all of this as your answer? It (mainly) depends on the marks allocated to the question and on how much time you have to answer the question. Rather say too much than too little.

Next question:

(e) *Give a short description of the way in which a two-stage catalytic converter works.*

Never heard of a catalytic converter? You have no idea what one does not to mention a two stage one! Don't despair! Read the question again – the answer is given in the question!

> … Most modern cars are equipped with a two-stage catalytic converter. An efficient catalytic converter serves two purposes: it oxidizes CO and the unburned hydrocarbons to CO_2 and H_2O, and it reduces NO and NO_2 to N_2 and O_2.

You found that sentence? Now turn the sentence into the answer.

An efficient catalytic converter serves two purposes – **the two stages:**

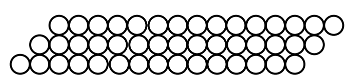
(1) *it oxidizes CO and the unburned hydrocarbons to CO_2 and H_2O* – first stage and

(2) *it reduces NO and NO_2 to N_2 and O_2* – second stage.

If you inspect the exhaust of a modern car you should see, starting from the exhaust outlet and looking back underneath the car, the exhaust pipe going into a rectangular shaped "box". On the other side of the "box" the exhaust pipe comes out just to go into a second, similarly shaped rectangular "box". Again the exhaust pipe comes out on the other side of the box and eventually the exhaust pipe connects up to the car engine. The rectangular shaped "boxes" contain the converters.

Usually the converter closest to the part of the engine (when the gases coming from the engine are still very hot), is the one converting the carbon monoxide, CO, and the unburned hydrocarbons (containing carbon and hydrogen compounds, C_xH_y) to CO_2 and to H_2O. By the time the gases reach the second converter (the second box closest to the end of the exhaust pipe, furthest from the engine) the gases have cooled down a bit. The second converter changes (or dissociates) the NO into N_2 and O_2 and usually operates at a much lower temperature (the gases being cooler) than the first converter.

Inside the converters ("boxes") you will find a sheet of tiny "beads" arranged in such a way that the hot gases have to pass over the "beads" as they move out through the exhaust pipe.



A representation of the transition metal "beads" inside the converter.

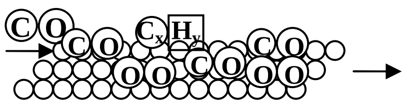
The beads contain platinum, or palladium, or some other transition metal or some other transition metal oxide (such as a combination of CuO and Cr_2O_3). Not all converters contain beads some might have a honeycomb structure made from alumina (Al_2O_3) which is saturated with the metal oxide. Usually the two converters in an exhaust system (the two "boxes") will have different transition metals or transition metal oxides (remember they do not operate at the same temperature).

Note that in the converters ("boxes") - the "beads" representing the catalyst (containing the transition metal or transition metal oxide), are solid and the gases passing over the converters are converted into other gases. Do you notice the different phases? The catalyst is a solid and the other chemical or compound is a gas. Therefore these catalysts are heterogeneous catalysts.

Notice the above is the answer to question (f):

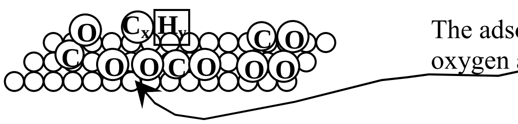
(f) *Is the catalytic converter regarded as a homogeneous or a heterogeneous catalyst?*

In heterogeneous catalysis, the surface of the solid catalyst is usually the site of the reaction, therefore such a catalyst usually has a huge surface area so that (in this case) the gas could make proper contact. The gas molecules get chemically adsorbed onto the surface of the catalysts. Adsorption means to adhere to (or to stick on) a surface. Adsorption and absorption are two different actions. (Absorption means to be taken into (the interior) of another substance, similar to how a spunge takes up water). In this case the gas molecules are adsorped onto the surface of the catalyst.



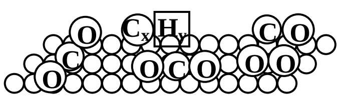
As the gas molecules (CO(g), O_2(g) and Hydrocarbons C_xH_y(g)) move over the surface of the "beads" they adsorp onto the surface until the whole surface could be full of gas molecules.

The hot gases from the engine are forced out through the exhaust pipe of the car. When these gases move through the first converter (the box-like thing closest to the engine) the carbon monoxide, oxygen and hydrocarbons get adsorped onto the metal surface.



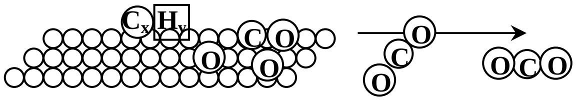
The adsorption weakens the O-O bond in O_2 and oxygen atoms become available.

The adsorption of the oxygen molecules weakens the O-O bonds and oxygen atoms form. They then combine with the adsorped CO molecules to form CO_2 molecules.



The oxygen atoms are now available to bond to the adsorbed carbon monoxide to form carbon dioxide.

The adsorption of the CO_2 molecules to the metal surface weakens and the CO_2(g) is released into the flow of the gases through the exhaust.



The adsorption of the molecules to the metal surface decreases and the carbon dioxide gas is released.

In a similar way the hydrocarbon (C_xH_y) molecules get adsorped onto the metal surface. The C-H bonds weaken and C atoms and H atoms form which bond to the oxygen atom to form carbon dioxide (CO_2) and water (H_2O) gas. These gases also get released into the flow of the gases through the exhaust pipe.

In the second converter (that functions at a lower temperature) the NO and NO_2 molecules get adsorped onto the metal- or metal oxide surface (the "beads"). The N-O bond weakens and N and

O atoms form which then combine to form N_2 and O_2 molecules. The adsorption of these molecules weakens and these gases are released.

Next question:

(g) *Explain what is meant by*

(i) *"it oxidizes CO and the unburned hydrocarbons to CO_2 and H_2O" and*

(ii) *"it reduces NO and NO_2 to N_2 and O_2".*

In Organic Chemistry the term oxidation is used to signify either the removal of the elements of hydrogen from a compound or the addition of oxygen to a compound. Often the symbol [O] is used to indicate an oxidation reaction without specifying the oxidation agent.
The chemical equation for the reaction could be written as:

$$2\,CO(g) + O_2(g) \rightarrow 2\,CO_2(g) \text{ and}$$

$$C_xH_y + m\,O_2 \rightarrow x\,CO_2 + \tfrac{y}{2}\,H_2O$$

(Note there is no visible addition of electrons. Nothing of the type: $A \rightarrow A^{2+} + 2e^-$, but if you calculate the oxidation number of the different atoms you find the following:

$$2\,\overset{+2}{C}\,\overset{-2}{O}(g) + \overset{0}{O_2}(g) \rightarrow 2\,\overset{+4}{C}\,\overset{-2}{O_2}(g) \qquad \text{and for} \qquad \overset{?}{C_x}\overset{+1}{H_y} + m\,\overset{0}{O_2} \rightarrow x\,\overset{+4}{C}\,\overset{-2}{O_2} + \tfrac{y}{2}\,\overset{+1}{H_2}\overset{-2}{O}$$

The oxidation number of the carbon atom has increased from +2 to +4, while the oxidation number of oxygen decreased from 0 to -2. Although it is not clear what the oxidation number of the carbon in the hydrocarbon is, the oxidation number of the carbon should have increased, since the oxidation number of the oxygen decreased. An increase in the oxidation number indicates that the substance was oxidized and a decrease indicates that that substance was reduced).

Conversely, if we add the elements of hydrogen to a compound or if we remove oxygen from a compound, we say that compound has been reduced or has undergone reduction. In Organic Chemistry the symbol [R] is often used to indicate a process of reduction reaction without specifying the reducing agent.
Similarly the oxidation numbers of the various atoms could be calculated:

$$2\,\overset{+2}{N}\,\overset{-2}{O}(g) \rightarrow \overset{0}{N_2}(g) + \overset{0}{O_2}(g)$$

The oxidation number of nitrogen decreased from +2 to 0, indicating that nitrogen was reduced. The nitrogen monoxide, NO, also lost an oxygen atom to become N_2, indicating reduction.