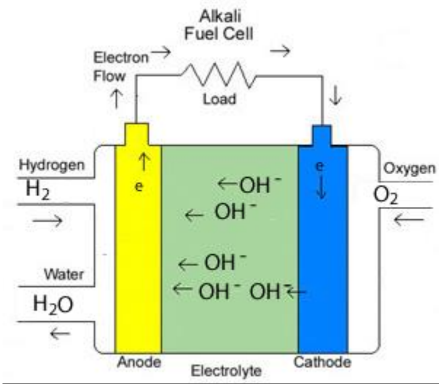
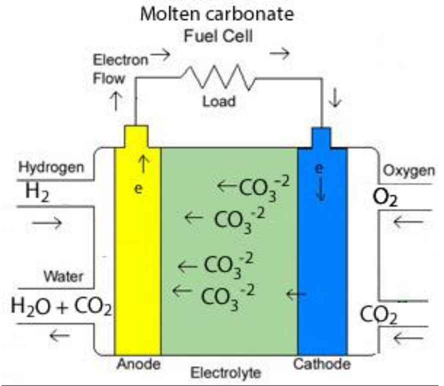
Alkaline fuel cell. The most common electrolyte is a solution of KOH. Efficiency is about 70 percent, and operating temperatures are about 150 to 200 °C. The most common fuel is hydrogen gas, as shown on the right. Advantages of these type of cells are the relatively low operating temperatures hence low cost of operation and quick start-up times. A major disadvantage is that due to low operating temperatures expensive catalysts have to be used to increase the rate of reactions taking place at the cathode and anode.



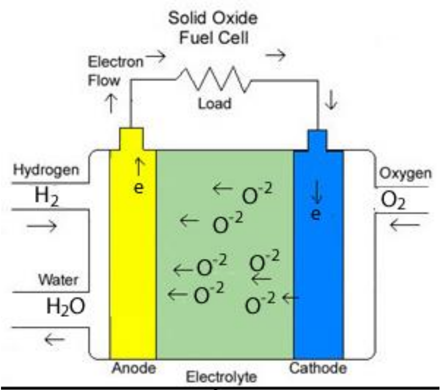
$2OH^- + H_2 \rightarrow 2H_2O + 2e$ | $4e + 2H_2O + O_2 \rightarrow 4OH^-$

Molten Carbonate fuel cells (MCFC) use high-temperature compounds of salt (like sodium or magnesium) carbonates as the electrolyte. Efficiency ranges from 60 to 80 percent, and operating temperature is about 650 °C. The main disadvantage of this fuel cell is its short life-span(5 years) due to the high temperatures at which it operates. The cost of operating at such high temperatures can also be a negative factor. Advantage, however, of high operating temperatures of the MCFC is that expensive precious metals do not have to be used as catalyst to drive chemical reactions at the cathode and anode.



$H_2 + CO_3^{-2} \rightarrow H_2O + CO_2 + 2e$ | $O_2 + 4e + 2CO_2 \rightarrow 2CO_3^{-2}$

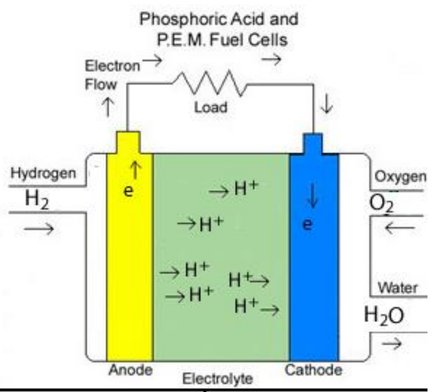
Solid Oxide fuel cells (SOFC) use a hard, ceramic compound of metal (like calcium or zirconium) oxides as an electrolyte. Efficiency is about 60 percent, and operating temperatures are about 1,000 °C . Much like the MCFC this type of cell is very efficient in generating electrical power, but unlike the MCFC is very stable long term. A significant disadvantage, however, is its high operating temperature which can be very expensive to maintain and it's long start-up time. An advantage, however, of high operating temperatures of the SOFC is that expensive precious metals do not have to be used as catalyst to drive chemical reactions at the cathode and anode.



$2H_2 + 2O^{-2} \rightarrow 2H_2O + 4e$ | $4e + O_2 \rightarrow 2O^{-2}$

Phosphoric Acid fuel cells (PAFC) use phosphoric acid as the electrolyte. Efficiency ranges from 40 to 80% , and operating temperature is between 150 to 200 °C.

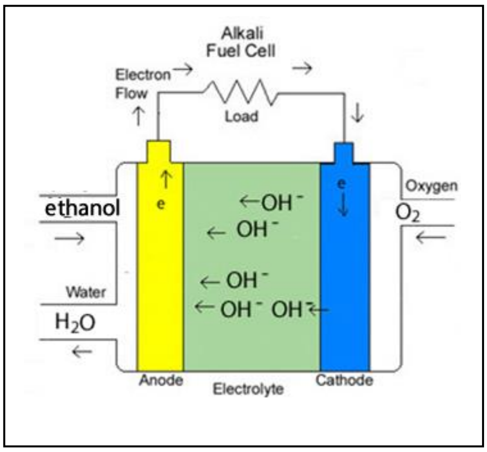
Proton Exchange Membrane (PEM) fuel cells work similar to the PAFC but with a polymer electrolyte in the form of a thin, permeable sheet. This permeable membrane allows for H^+ ions only to move from the anode to the cathode. Efficiency is about 40 to 50%, and operating temperature is about 80 °C . Advantages of these type of cells are the relatively low operating temperatures hence low cost of operation and quick start-up times. One disadvantage, however, is the use of expensive catalysts to increase the rate of reactions at the cathode and anode.



$H_2 \rightarrow 2H^+ + 2e$ | $O_2 + 4e + 4H^+ \rightarrow 2H_2O$

Writing half reactions for fuel cells. Writing half reactions for an alkaline or acidic fuel cell is identical to writing half equations for an alkaline or acidic galvanic cell. Keep in mind that the fuel always goes at the anode (-) of a fuel cell.

Write the half equations for an alkaline fuel cell that burns ethanol in oxygen gas to generate electrical energy.



Anode

=> $C_2H_6O \rightarrow CO_2$
=> $C_2H_6O \rightarrow 2CO_2$(balance for carbons)
=> $3H_2O + C_2H_6O \rightarrow 2CO_2$(balance for oxygens)
=> $3H_2O + C_2H_6O \rightarrow 2CO_2 + 12H^+$(balance for hydrogens)
=> $3H_2O + C_2H_6O \rightarrow 2CO_2 + 12H^+ + 12e^-$ (balance for charge)

(Replace H^+ with OH^-)
=> $12OH^- + 3H_2O + C_2H_6O \rightarrow 2CO_2 + 12H^+ + 12OH^- + 12e^-$
=> $12OH^- + 3H_2O + C_2H_6O \rightarrow 2CO_2 + 12H_2O + 12e^-$
(cancel water)
=> $12OH^- + C_2H_6O \rightarrow 2CO_2 + 9H_2O + 12e^-$

Cathode
=> $O_2 \rightarrow H_2O$
=> $O_2 \rightarrow 2H_2O$ (balance for oxygens)
=> $4H^+ + O_2 \rightarrow 2H_2O$ (balance for hydrogens)
=> $4e^- + 4H^+ + O_2 \rightarrow 2H_2O$ (balance for charge)
(Replace H^+ with OH^-)
=> $4e^- + 4H^+ + 4OH^- + O_2 \rightarrow 2H_2O + 4OH^-$
=> $4e^- + 4H_2O + O_2 \rightarrow 2H_2O + 4OH^-$
(cancel water)
=> $4e^- + 2H_2O + O_2 \rightarrow 4OH^-$

Overall equation
$12OH^- + C_2H_6O \rightarrow 2CO_2 + 9H_2O + 12e^-$
+
3 X ($4e^- + 2H_2O + O_2 \rightarrow 4OH^-$)

=> $C_2H_6O + 3O_2 \rightarrow 2CO_2 + 3H_2O$

Try these
Give the anode and cathode half reactions when the following fuels undergo complete combustion with atmospheric oxygen in an alkaline fuel cell. The unbalanced chemical equation is given below.

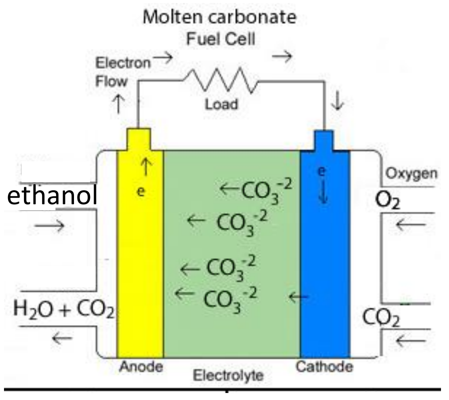
$CH_3CH_2CH_2OH + O_2 \rightarrow H_2O + CO_2$

$NH_3 + O_2 \rightarrow N_2 + H_2O$

$C_3H_8 + O_2 \rightarrow CO_2 + H_2O$

Write the half equations for a molten carbonate fuel cell that burns ethanol in oxygen gas to generate electrical energy.

Now the electrolyte is slightly different. Here liquid CO_3^{2-} ions migrate from the cathode to the anode. The O^{2-} ion is carried to the anode via CO_3^{2-} ions.



Cathode

Carbonate ions are formed at the cathode via the following reduction reaction. This reaction is the same for all molten carbonate fuel cells using atmospheric oxygen.

=> $O_2 + 2CO_2 + 4e^- \rightarrow 2CO_3^{2-}$

Anode

At the anode the fuel reacts with the carbonate ions to form water and carbon dioxide as shown in the schematic. Always refer to the diagram for information on the products formed.

=> $C_2H_6O \rightarrow CO_2 + H_2O$
=> $C_2H_6O \rightarrow 2CO_2 + H_2O$ (balance for carbons)
=> $C_2H_6O \rightarrow 2CO_2 + 3H_2O$ (balance for hydrogens)
Balance for oxygen atoms in a two-step process.
=> $C_2H_6O + 6CO_3^{2-} \rightarrow 2CO_2 + 3H_2O$ (balance for oxygens by firstly adding CO_3^{2-} to the left side for every oxygen needed)
=> $C_2H_6O + 6CO_3^{2-} \rightarrow 8CO_2 + 3H_2O$ (balance for oxygens by finally adding the same number of CO_2 molecules to the right as CO_3^{2-} ions added to the left side. In this case 6 CO_3^{2-} ions were added on the left so 6 CO_2 molecules were added to the right.)
=> $C_2H_6O + 6CO_3^{2-} \rightarrow 8CO_2 + 3H_2O + 12e^-$ (balance for charge)

Overall equation

$C_2H_6O + 6CO_3^{2-} \rightarrow 8CO_2 + 3H_2O + 12e^-$
+
3 X ($O_2 + 2CO_2 + 4e^- \rightarrow 2CO_3^{2-}$)

=> $C_2H_6O + 3O_2 \rightarrow 2CO_2 + 3H_2O$

Try these

Give the anode and cathode half reactions when the following fuels undergo complete combustion with atmospheric oxygen in a molten carbonate fuel cell. The unbalanced chemical equation is given below.

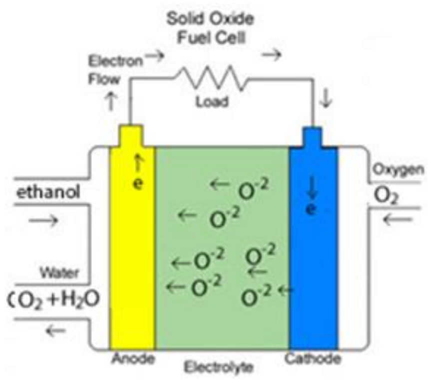
$CH_3CH_2CH_2OH + O_2 \rightarrow H_2O + CO_2$ Solution

$NH_3 + O_2 \rightarrow N_2 + H_2O$ Solution

$C_3H_8 + O_2 \rightarrow CO_2 + H_2O$ Solution

Write the half equations for a solid oxide fuel cell that burns ethanol in oxygen gas to generate electrical energy.

Once again, the electrolyte is different. Here a solid ceramic electrolyte allows for the movement of O^{2-} from the cathode to the anode.



Cathode

Oxide ions (O^{2-}) are formed at the cathode. This reaction is the same for all solid oxide fuel cells using atmospheric oxygen.

=> $O_2 + 4e^- \rightarrow 2O^{-2}$

Anode

At the anode the fuel reacts with the oxide ions to form water and carbon dioxide as shown in the schematic. Always refer to the diagram for information on the products formed.

=> $C_2H_6O \rightarrow CO_2 + H_2O$

=> $C_2H_6O \rightarrow 2CO_2 + H_2O$ (balance for carbons)

=> $C_2H_6O \rightarrow 2CO_2 + 3H_2O$ (balance for hydrogens)

=> $C_2H_6O + 6O^{2-} \rightarrow 2CO_2 + 3H_2O$ (balance for oxygens by adding O^{2-} to the left side)

=> $C_2H_6O + 6O^{2-} \rightarrow 2CO_2 + 3H_2O + 12e^-$ (balance for charge)

Overall equation

$C_2H_6O + 6O^{2-} \rightarrow 2CO_2 + 3H_2O + 12e^-$

+

3 X ($O_2 + 4e^- \rightarrow 2O^{2-}$)

=> $C_2H_6O + 3O_2 \rightarrow 2CO_2 + 3H_2O$

Try these

Give the anode and cathode half reactions when the following fuels undergo complete combustion with atmospheric oxygen in a solid oxide fuel cell. The unbalanced chemical equation is given below.

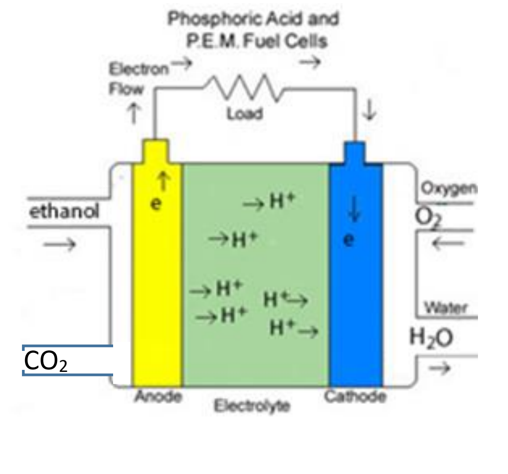
$CH_3CH_2CH_2OH + O_2 \rightarrow H_2O + CO_2$ Solution

$NH_3 + O_2 \rightarrow N_2 + H_2O$ Solution

$C_3H_8 + O_2 \rightarrow CO_2 + H_2O$ Solution

Write the half equations for an acidic electrolyte fuel cell or proton exchange membrane cell that burns ethanol in oxygen gas to generate electrical energy.

Once again, the electrolyte is different. Here an acidic electrolyte or proton exchange membrane allows for the movement of H^+ ions from the cathode to the anode.



Cathode

From the schematic on the right we can write the following reaction.

=> $O_2 \rightarrow H_2O$

=> $O_2 \rightarrow 2H_2O$ (balance for oxygens)

=> $4H^+ + O_2 \rightarrow 2H_2O$ (balance for hydrogens)

=> $4e^- + 4H^+ + O_2 \rightarrow 2H_2O$ (balance for charge)

Anode

At the anode the fuel reacts with the oxide ions to form water and carbon dioxide as shown in the schematic. Always refer to the diagram for information on the products formed.

=> $C_2H_6O \rightarrow CO_2$

=> $C_2H_6O \rightarrow 2CO_2$ (balance for carbons)

=> $C_2H_6O + 3H_2O \rightarrow 2CO_2$ (balance for oxygens)

=> $C_2H_6O + 3H_2O \rightarrow 2CO_2 + 12H^+$ (balance for hydrogen)

=> $C_2H_6O + 3H_2O \rightarrow 2CO_2 + 6H^+ + 6e^-$(balance for charge)

Overall equation

$C_2H_6O + 3H_2O \rightarrow 2CO_2 + 12H^+ + 12e^-$

+

$(4e^- + 4H^+ + O_2 \rightarrow 2H_2O)$ X 3

=> $C_2H_6O + 3O_2 \rightarrow 2CO_2 + 3H_2O$

Try these

Give the anode and cathode half reactions when the following fuels undergo complete combustion with atmospheric oxygen in an alkaline fuel cell. The unbalanced chemical equation is given below.

$CH_3CH_2CH_2OH + O_2 \rightarrow H_2O + CO_2$

$NH_3 + O_2 \rightarrow N_2 + H_2O$

$C_3H_8 + O_2 \rightarrow CO_2 + H_2O$

Below is a table to summarise how to treat fuel cells.

Fuel cell	Balance for oxygens by
PAFC and PEMFC	adding H_2O to the side with least amount of oxygen atoms
Alkaline	adding H_2O to the side with least amount of oxygen atoms. Similar to acidic fuel cell, however, the difference is that you now need to remove H^+ by adding OH^-
SOFC	Adding O^{2-} ions to the side with least amount of oxygen atoms.
MCFC	Adding CO_3^{2-} ions to the side with least amount of oxygens and add same number of CO_2 molecules to the other side.

How do I know if a cell is:

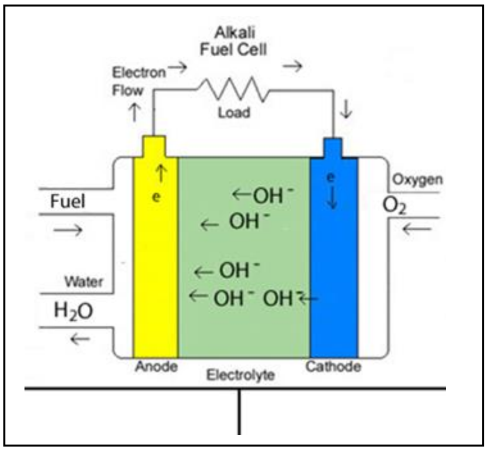
acidic
- The question will state "***in an acidic electrolyte"***
- *H^+ will be present in the half equations.*
- *the question will state the type of fuel cell as PEMFC or PAFC*

alkaline
- The questions will state *" **alkaline**"*
- *OH^- will appear in one or more of the half equations*

- *A solid ionic hydroxide compound may exist in the overall equation or half reaction eg $Cd(OH)_2(s)$*

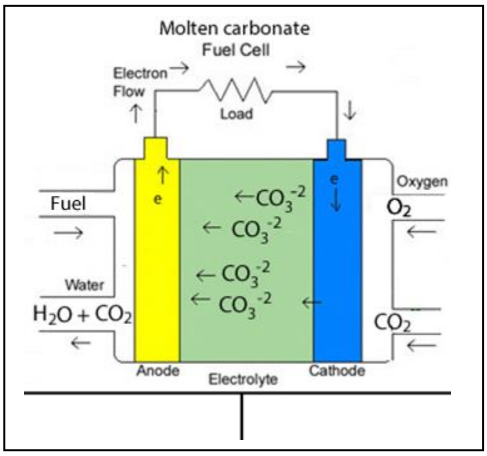
Alkaline fuel cells operate on compressed hydrogen and oxygen gases. The most common electrolyte is a solution of KOH. Efficiency is about 70 percent, and operating temperatures are about 150 to 200 °C For each fuel cell below write the half reactions occurring at the anode and cathode when the fuel used is:

- CH_4
    - anode
    - cathode
- C_4H_{10}
    - anode
    - cathode



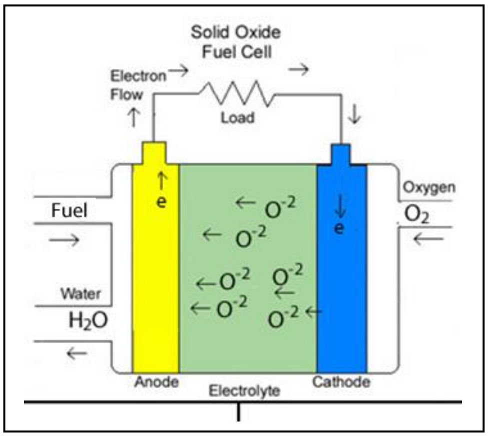
Molten Carbonate fuel cells (MCFC) use high-temperature compounds of salt (like sodium or magnesium) carbonates as the electrolyte. Efficiency ranges from 60 to 80 percent, and operating temperature is about 650 degrees °C

- CH_4
    - anode
    - cathode
- C_4H_{10}
    - anode
    - cathode



Solid Oxide fuel cells (SOFC) use a hard, ceramic compound of metal (like calcium or zirconium) oxides as an electrolyte. Efficiency is about 60 percent, and operating temperatures are about 1,000 °C

- CH_4
    - anode
    - cathode
- C_4H_{10}
    - anode
    - cathode



Phosphoric Acid fuel cells (PAFC) use phosphoric acid as the electrolyte. Efficiency ranges from 40 to 80% , and operating temperature is between 150 to 200 °C.

Proton Exchange Membrane (PEM) fuel cells work similar to the a PAFC but with a polymer electrolyte in the form of a thin, permeable sheet. This permeable membrane allows for H^+ ions only to move from the anode to the cathode. Efficiency is about 40 to 50%, and operating temperature is about 80 °C .

- CH_4
    - anode
    - cathode
- C_4H_{10}
    - anode
    - cathode