Hydrogen Energy: Production, Storage, Transportation and Safety
Prof. Pratibha Sharma
Department of Energy Science and Engineering
Indian Institute of Technology, Bombay

Lecture - 62
Use of Hydrogen in Fuel Cells

Fuel cell like internal combustion engine is an energy conversion device. In this class we will see very briefly the working of fuel cell what are the different types of fuel cell; however, when we studied the hydrogen production at that time we have considered a similar device which is electrolyzer in much more detail at that time we studied the thermodynamics of electrolysis process, the different components of electrolyzer and the different types of electrolyzer.

The difference between an electrolyzer and fuel is that the electrolyzers takes electricity and water as input and produces hydrogen and oxygen while fuel cell that is opposite, it takes the oxygen and hydrogen as the input and produces water and electricity as the output.

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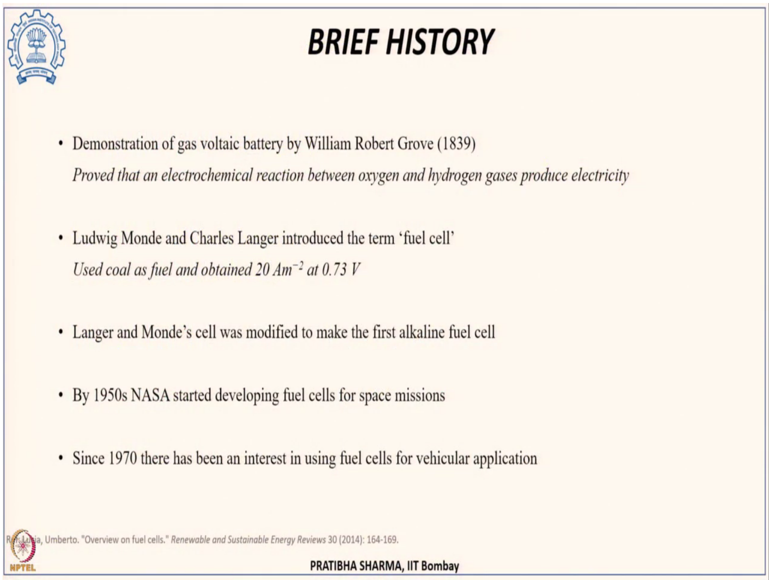

Just to give a brief background the demonstration of a first gas voltage battery was done by William Grove in 1839 when he proved that an electrochemical reaction between hydrogen and oxygen can produce electricity. So, that was the very first demonstration of a working of a fuel cell it was later by Langer and Monde they introduced the term fuel cell and at that time they used coal as a fuel and obtained 20 amperes per meter square at a voltage of 0.73 volt.

This cell they modified for the first time to make it into alkaline fuel cell. It was in 1950 when NASA first started developing fuel cell and then they used it for the space missions. After then say 1970s there was a lot of interest in fuel cell and especially for the vehicular application.

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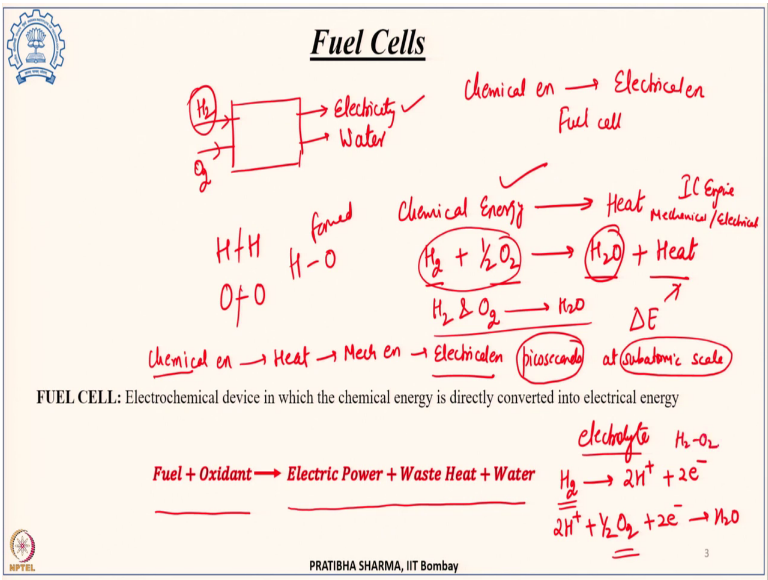

Now when it comes to fuel cell, if we consider it to be a black box such that it takes hydrogen and oxygen as inputs and gives electricity and water as output. Now as long as we provide the fuel and oxidant, hydrogen and oxygen to it will keep on supplying electricity ideally.

In that sense it works like a internal combustion engine; however, fuel cells they are electrochemical devices which convert the chemical energy of fuel into electrical energy as such they have a similarity with the batteries both are electrochemical devices. But the major difference between fuel cell and battery is, in fuel cell if we supply fuel we will get electricity ideally continuously as long as we supply fuel and it is not being consumed, but in battery that energy chemical energy is stored inside and then it gets used up. So, that is the basic difference between fuel cell and battery, but both are electrochemical devices which convert the chemical energy into electrical energy. Now there is again a similarity with the IC engine in IC engine it converts the chemical energy of the fuel into heat via reaction let us say hydrogen and oxygen they combine to give water and heat this is what occurs in the IC engine.

So, there is again similarity between fuel cell and IC engine that it can be converted later on into mechanical energy and then into electrical energy this heat being produced. Now what happens in case of an IC engine is hydrogen oxygen reacting to reduce water and heat. On a molecular scale there occurs collision between hydrogen and oxygen and that forms water that is what how it reacts.

But on an atomic scale what occurs in this particular reaction is the hydrogen-hydrogen bond breaks, oxygen-oxygen bonds these breaks and the hydrogen-oxygen bond is formed. So, the hydrogen-hydrogen bond, oxygen-oxygen bond break and hydrogen oxygen bond is formed. Now this bond reconfiguration this occurs by means of an electron transfer.

The bond configuration energy of the product is higher than the bond configuration energy of the reactants and that difference in energy it comes out as heat in the process. Now that means, during the bonding reconfiguration electron transfer takes place from one bonding state to another bonding state and that electron transfer in this reaction which occurs in the internal combustion engine occurs in a matter of picoseconds and at sub atomic scale.

As such this energy difference between the bonding configuration that comes out only in the form of heat in case of an internal combustion engine. Now in this process if this chemical energy in the case of internal combustion engine if that has to be converted into heat from there it has to be converted into mechanical energy and then finally, electrical energy; that means, the number of steps involved to convert chemical energy into electrical energy in case of an internal combustion engine is higher and as such the process gets complex and inefficient because there will be losses involved at every step. Now this electron transfer that occurs at time scale of picoseconds at sub atomic scale that cannot be harnessed or are difficult to harness.

However, if that electron transfer which occurs during bonding reconfiguration could be harnessed then we can directly convert this chemical energy into electrical energy and that is what happens in a fuel cell. Now how such a time less time scale that reaction is occurring at the time scale of picoseconds and on a sub atomic scale how these electrons can be harnessed.

Now, this can be done by partially separating hydrogen and oxygen. So, if these reactants hydrogen and oxygen these are partially separated, then the electron transfer will occur over a partially extended length and in that process when it is being transferred from one reactant to another we can harness those electrons and this partial separation is done by using electrolyte. So, this electrolyte partially separates the 2 reactions which occurs in the fuel cell hydrogen forms H+ ions and 2 electrons are liberated.

And these 2 H+ ions combine with oxygen and 2 electrons to give H_2O. So, these the reactants are separated partially by means of an electrolyte and these 2 half cell reactions occurs at electrodes surface. So, overall if we see a fuel cell is an electrochemical device which directly converts the chemical energy into electrical energy and the reaction is that the fuel with oxidant, it converts into electricity certain amount of waste heat will be liberated and water as the output.

Now this reaction that I have written here is for a hydrogen oxygen fuel cell, but then there can be other fuels also that can be used in a fuel cell that we will see later. Now if we compare fuel cell, battery or IC engine we see that there are certain similarities like in case of internal combustion engine and fuel cell as long as you supply the fuel ideally it should give the output that way it is similar to IC engines.

It is an electrochemical device and as such it converts chemical energy into electrical energy it has a similarity with the batteries, but then there are certain advantages of both batteries and internal combustion engines which are there in the fuel cell.

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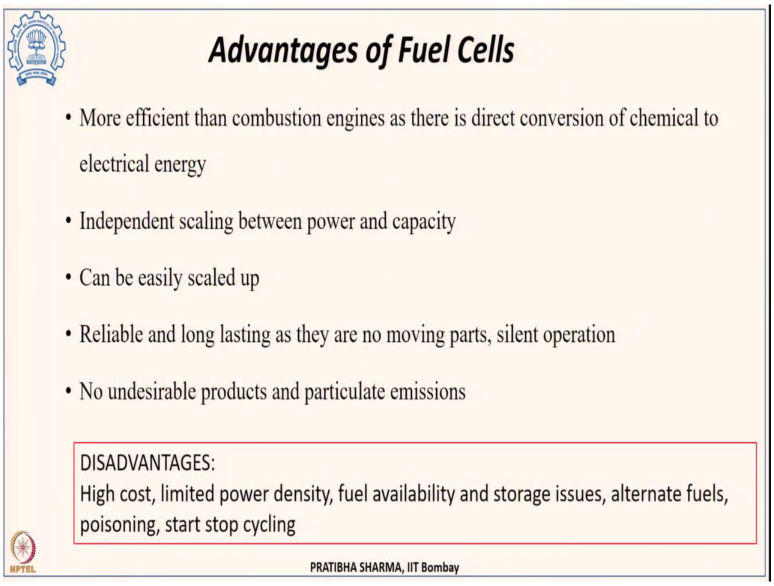

So, if we compare then fuel cell since they are directly converting chemical energy into electrical energy they are more efficient than the combustion engines because the number of steps involved are less compared to that in the combustion engines. At the same time the biggest advantage of fuel cell as against the battery is, there is an independent scaling up that can be done for power and capacity. So, we can have a higher fuel cell size or we can have a higher fuel reservoir so, as to increase the power and energy.

So, independently we can scale them up and it is easier to scale up compared to the batteries. At the same time these electrochemical devices fuel cell they are more reliable, long lasting since they do not have any moving part as such the operation is silent. At the same time since the product is water and electricity we are getting as output. So, there is no undesirable product which we are getting like NOx or SOx or any particulate matter.

So, these are basically the advantages of fuel cell, but then there are certain disadvantages also associated with fuel cell they have higher cost and we will see that the cost is higher because of the electrolyte or the precious metals at times which are used as electro catalyst. There is a limitation so, in fact, battery and IC engines they outperform in terms of volumetric power density.

So, power density is limited for fuel cell at the same time fuel availability and storage issues are there these are the major challenges and if we are using alternate fuels other than hydrogen pure hydrogen in that case we have to those fuels have to undergo reforming there will be auxiliary equipment and the overall the performance of fuel cell will come down.

We use different catalyst at times impurities present in the gaseous fuel that also can cause poisoning of the catalyst and then the dynamic conditions are start stop cycling that also need to be considered here and there could be degradation associated with the start stop cycling.

Now if we look at the basic principle of operation of a fuel cell in general, in fuel cell the current which is being produced that directly depends upon the reaction surface area or the interfacial area. Now this is the area where electrode, electrolyte and reactants they meet. Now; that means, if we want to scale it up if you want to increase the current being produced from a fuel cell we have to increase that reaction area interfacial area and that can that is done in a fuel cell by making it thin and plainer in structure.

And at the same time we can have porous electrodes not only to increase the surface area, surface to volume ratio, but also it makes the gas access easier in the fuel cell. Now if we see the basic operation of a fuel cell then there are primarily 4 steps involved in its operation.

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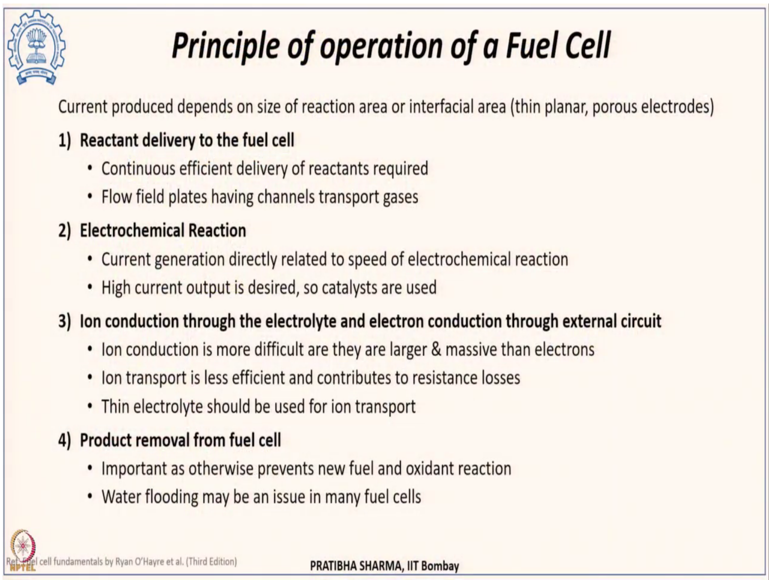

First the reactants they have to be supplied to the fuel cell reactants are hydrogen and oxygen or hydrogen and air or the fuel and oxidant in general because that will depend upon which type of fuel cell we are talking about. So, there is a requirement of continuous supply of the reactants so, as to get a continuous supply of the electrical output and when it operates under higher current conditions at a higher rating in that case that supply needs to be even higher.

Now in order to have a continuous supply of fuel across or fuel an oxidant or the gases on the 2 sides of the fuel cell the flow field plates and even porous electrodes they help in transport of the gases. Now these flow field plates which are component of a fuel cell they have channels or grooves such that it transport gases throughout the surface of the fuel cell. Now important is the size, the shape, the design of these patterns these grooves these channels and these flow field plates that determines the performance of the fuel cell.

Now, second step involved is the electrochemical reaction the 2 electrochemical half-cell reactions. Now the current generated we know that it is directly proportional to the rate of these electrochemical reactions that will occur on the anode and cathode side. And if we want higher current output so, as such that rate of reaction or electrochemical reaction should be faster and as such there is a requirement of catalyst to accelerate the reaction.

Now, appropriate choice of catalyst is essential together with the design of the fuel cell, design of the reaction surface area is essential for getting a better performance of the fuel cell. Now the third step involved is conduction of ion through the electrolyte and electron conduction through the external circuit.

Now as mentioned electrolyte it partially separates the 2 electrochemical half cell reactions or the 2 electrodes and it separates the 2 reactants in such a manner that ions which are formed on one side these are transported through the electrolyte and consumed on the other side of the fuel cell or other electrode of the fuel cell. And similarly the electrons they are produced from electrode they have to move through the external circuit to the other electrode and there they are consumed.

So, the electrolyte which is selected as we have seen earlier also in electrolyzer. The electrolyte used is such that it allows the conduction of ions, but not of electrons. So, ion conduction should take place through electrolyte and electron conduction should occur through the external circuit. Now this ion conduction is; however, more difficult compared to the electron conduction because these ions are more massive and larger in size compared to that of electron.

And as such its transport is comparatively less efficient than electronic conduction and thus this also gives rise to different losses. So, it contributes towards the resistance losses. To address this, issue the electrolyte is made thin and that reduces the path for ion flow ion transport across the electrolyte. The last step involved is removal of the product as they are formed from the fuel cell.

Now this is an important step, the requirements are similar to what that was for the reactant delivery and the products form needed to be removed else the new fuel and oxidant will not be able to reach the reaction surface. And this is done in a similar manner as the reactant delivery is being done, water flooding could be an issue in the fuel cell that needs to be considered.

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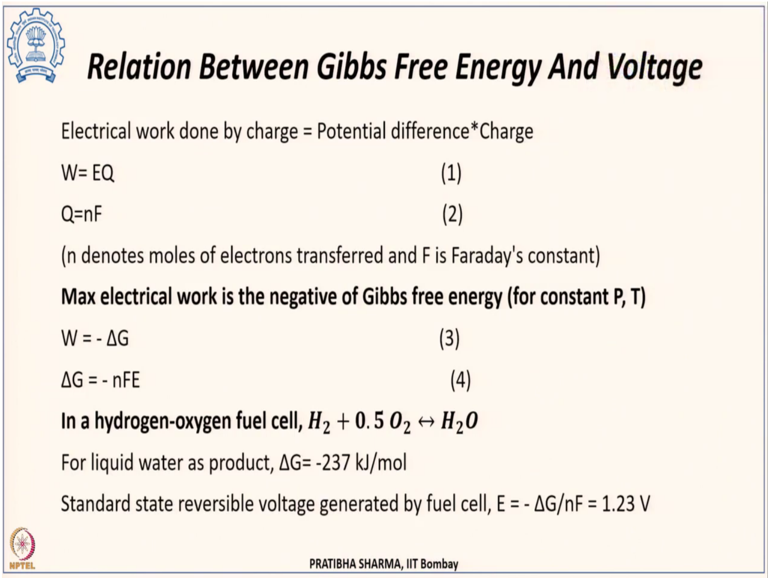

Just to revise some of the thermodynamic equations we have also seen that in the electrolyzer we know that the electrical work done by the charge is given by potential difference times the charge. So, the work done is potential difference time charge W = EQ, where Q is the charge, that is n times the number of electrons transfer times the Faraday's constant. Now the maximum electrical work it is -ΔG that is the negative of the Gibbs free energy at a constant temperature and pressure.

And this change in the Gibbs free energy is given by if we substitute then it is -nEF. Now if we consider a hydrogen oxygen fuel cell under standard conditions value of ΔG is -237 kilo joule per mole. So, the standard state reversible cell voltage we can obtain from here ΔG/nF and that is given by 1.23 volt. So, this is the reversible cell voltage under standard state conditions atmospheric pressure, room temperature and considering unit activities of the different species.

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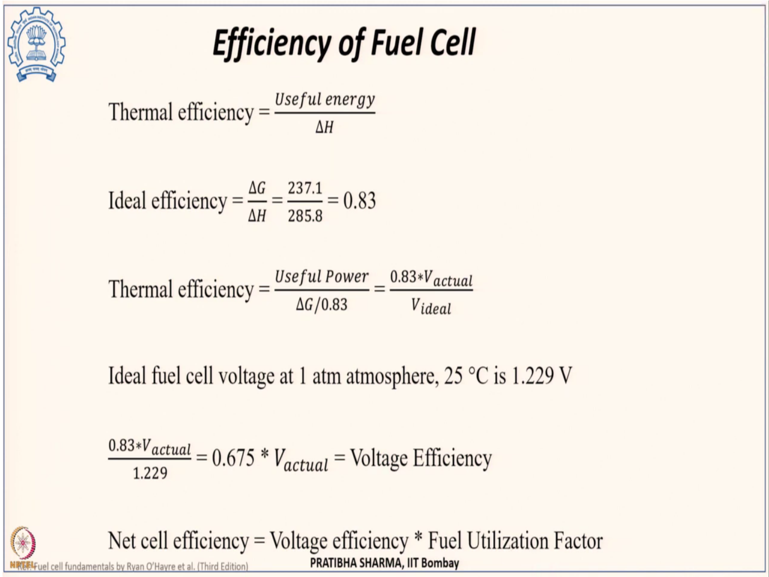

Now in order to find the efficiency of a fuel cell there is a thermal efficiency which is given by the useful energy divided by the ΔH enthalpy change of the reaction and the ideal efficiency is ΔG/ΔH. Substituting the values under standard state conditions 237.1 for ΔG, 285.8 for ΔH we get the ideal efficiency to be 0.83 or 83 percent. And thermal efficiency can be obtained by useful power divided by ΔH which is ΔG divided by 0.83 and that is 0.83 times the actual cell voltage divided by the ideal cell voltage.

And ideal cell voltage we have just now seen it is 1.23 or exactly 1.229 volt which can give us the voltage efficiency to be 0.83 times the actual cell voltage divided by the ideal cell voltage 1.229 that is 0.675 times the actual cell voltage which will give us the voltage efficiency of the fuel cell or the net cell efficiency could be obtained as voltage efficiency times the fuel utilization factor.

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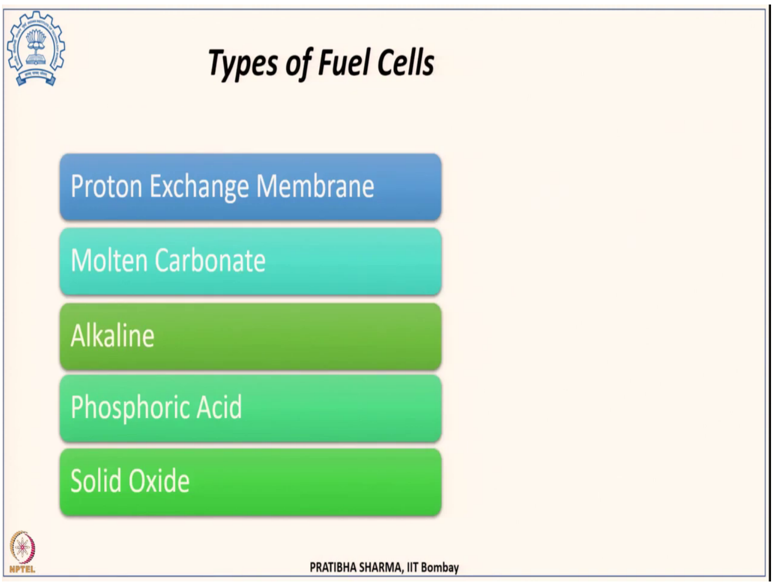

So, this is very briefly we have talked about some of the relations used in the fuel cell. Now there are different types of fuel cell depending upon what electrolyte it is being used the fuel cells can be as we have seen in electrolyzers also fuel cells also can be categorized into different types like the proton exchange membrane fuel cell, molten carbonate fuel cell, alkaline fuel cell, phosphoric acid fuel cell and solid oxide fuel cells.

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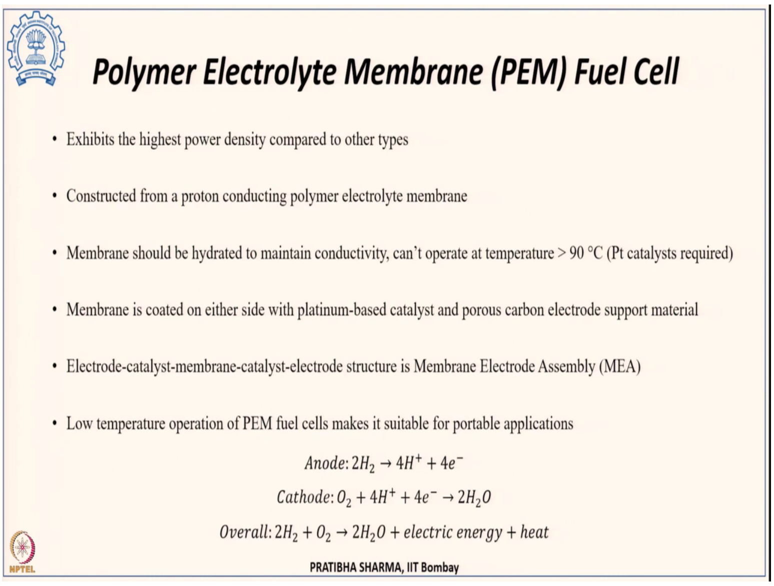

Now, let us consider first the polymer electrolyte membrane fuel cell, this is the fuel cell which has highest power density as compared to the other types of fuel cells that we are going to consider and the name itself suggests it is polymer electrolyte membrane or proton conducting membrane which is used as an electrolyte. The most commonly used membrane is nafion and that membrane it has to be operated at temperatures because we are using a membrane that has to be hydrated to maintain the conductivity, it cannot operate beyond 90 degree centigrade.

The electro catalyst used are platinum and these are coated on either side with platinum based catalyst and porous carbon electrode support material. The combination of electrode, catalyst, then membrane and the other side catalyst electrode structure this combined structure is known as membrane electrode assembly.

So, since they operate at less than 90 degrees centigrade. So, the low temperature operation of polymer electrolyte membrane fuel cells because of that they can be used for various portable applications. In general, the reaction that occurs on the anode side is, the hydrogen forms proton and 4 electrons here $2H_2$ giving $4H^+$ plus 4 electrons these electrons flow through the external circuit, protons are conducted through the electrolyte the polymer membrane.

It goes on to the cathode side where it reacts with the oxygen, oxygen plus $4H^+$ plus 4 electrons giving $2H_2O$. So, the overall reaction is $2H_2$ plus O_2 giving $2H_2O$ plus electrical energy and heat.

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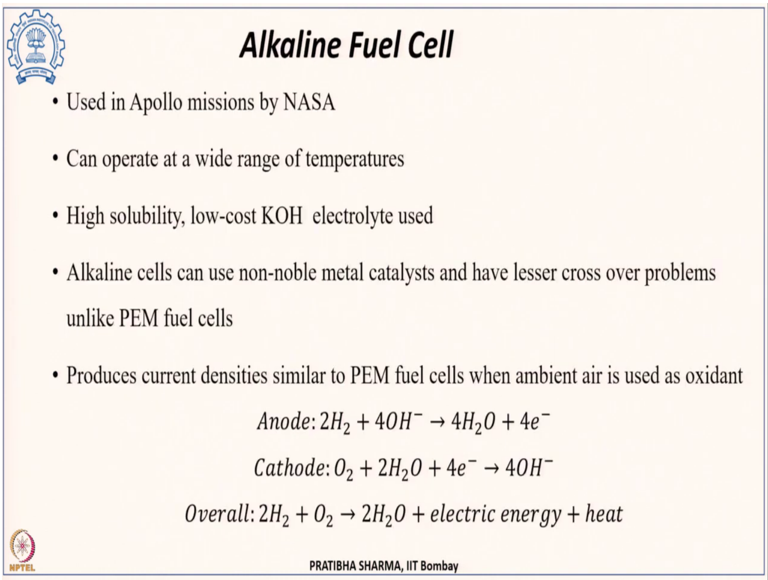

Another category of fuel cell is alkaline fuel cell this was for the first time used in Apollo mission by NASA and this can be operated with a wide temperature range. As the name itself suggests it has an alkaline electrolyte low cost KOH is used as electrolyte in such fuel cells and the biggest advantage of alkaline fuel cell is, they can use non noble metal catalyst which reduces the cost and they have a lesser crossover problems compared to the polymer electrolyte membrane fuel cell.

They can produce current density which are similar to PEM fuel cell and the reaction that takes place is 2H2 plus $4OH^-$. So, the electrolyte is an OH^- conducting electrolyte. So, $2H_2$ plus $4OH^-$ giving $4H_2$ plus 4 electrons this flow through the external circuit. This $4OH^-$ moves from the or is migrated through the electrolyte to the cathode side reacting with oxygen O_2 plus $2H_2O$ plus 4 electron giving $4OH^-$.

The overall reaction is $2H_2$ plus O_2 giving $2H_2O$ plus electrical energy plus heat.

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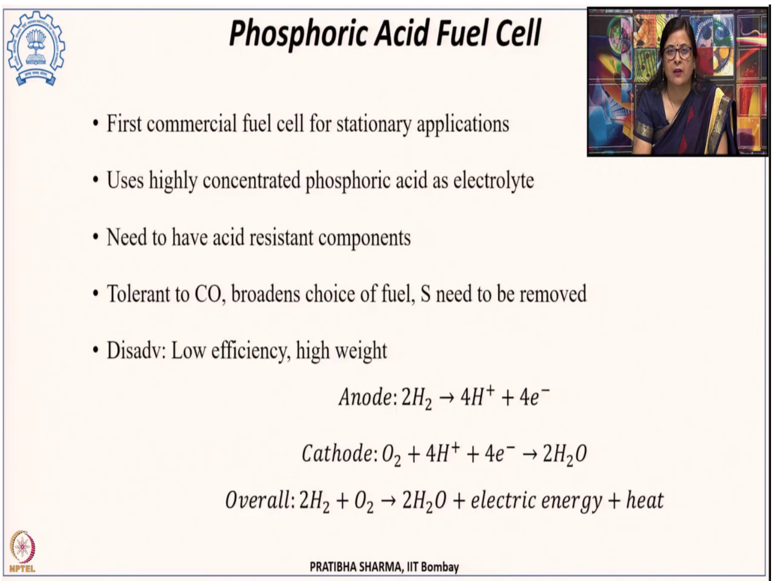

The next class of fuel cell is phosphoric acid fuel cell. Now in this H_3PO_4 is used as the electrolyte and either a dilute or highly concentrated phosphoric acid is used as an electrolyte. This was the first commercial fuel cell which was used for stationary applications and the components which are used because we are using an acidic electrolyte. So, it is essential that the components which are used needs to be acid resistant.

It is tolerant to carbon monoxide, it can be 1.5 percent that is tolerated and as such that provides the flexibility towards the choice of fuel. Sulfur here needs to be removed the major disadvantage associated with phosphoric acid fuel cells they have a low efficiency and high weight. So, the reaction that occurs on the anode side is $2H_2$ giving $4H^+$ plus 4 electron.

These $4H^+$ they migrate onto the cathode side and electrons to the external circuit on the cathode side the reaction that occurs is O_2 plus $4H^+$ plus 4 electron giving $2H_2O$. So, the overall reaction H_2 plus O_2 giving water plus electrical energy and heat.

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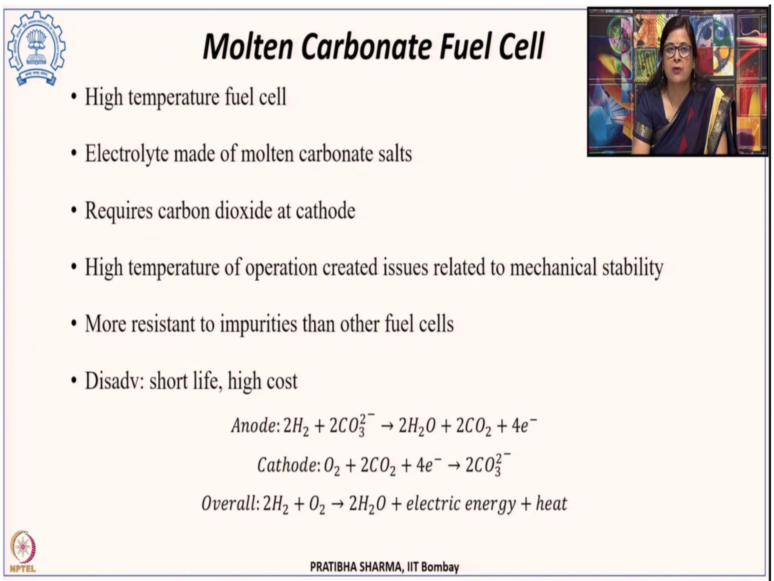

Molten carbonate fuel cell the name itself suggests they are high temperature fuel cell, the electrolyte is made up of molten carbonate salts and they require carbon dioxide at cathode. So, it is produced and consumed within the fuel cell and since this is a high temperature fuel cell there are issues associated with the stability of the material. They are more resistance to impurities compared to the other types of fuel cell, but the major challenge is they are short life and high cost.

At the anode side 2H2 it combines with the carbonate ion, plus $2CO3^{2-}$ giving H_2O plus CO_2 plus 4 electrons. And the overall reaction is $2H_2$ plus O_2 giving $2H_2O$ plus electrical energy and heat.

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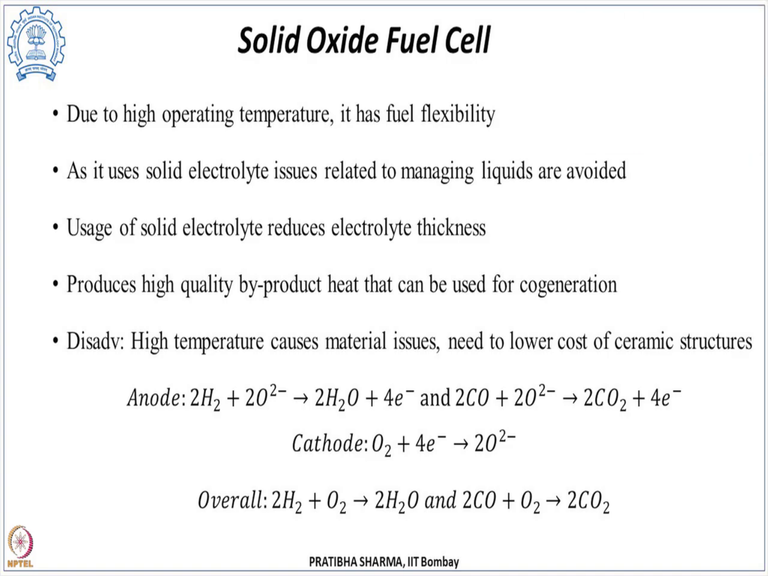

Solid oxide fuel cell they are again high operating temperature fuel cell and it has a fuel flexibility. We can use a wide variety of fuels for the solid oxide fuel cell and name itself suggests that a solid electrolyte is being used and here the issues related to managing the liquids as against the other fuel cells is not there.

Now, the solid electrolyte it reduces the electrolyte thickness and it produces high quality byproduct heat that can also be used for cogeneration. But the major disadvantage that remains with solid oxide fuel cells they are high temperature fuel cells as such the material degradation at high temperatures is the major challenge and need to have a lower cost of ceramic materials which are stable under these conditions is the basic requirement.

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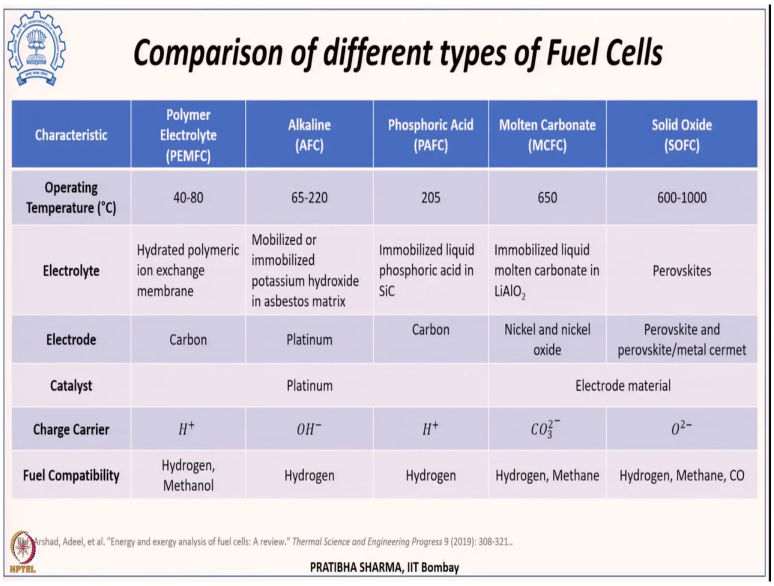

Comparison of different types of Fuel Cells

Characteristic	Polymer Electrolyte (PEMFC)	Alkaline (AFC)	Phosphoric Acid (PAFC)	Molten Carbonate (MCFC)	Solid Oxide (SOFC)
Operating Temperature (°C)	40-80	65-220	205	650	600-1000
Electrolyte	Hydrated polymeric ion exchange membrane	Mobilized or immobilized potassium hydroxide in asbestos matrix	Immobilized liquid phosphoric acid in SiC	Immobilized liquid molten carbonate in $LiAlO_2$	Perovskites
Electrode	Carbon	Platinum	Carbon	Nickel and nickel oxide	Perovskite and perovskite/metal cermet
Catalyst	Platinum			Electrode material	
Charge Carrier	H^+	OH^-	H^+	CO_3^{2-}	O^{2-}
Fuel Compatibility	Hydrogen, Methanol	Hydrogen	Hydrogen	Hydrogen, Methane	Hydrogen, Methane, CO

Arshad, Adeel, et al. "Energy and exergy analysis of fuel cells: A review." Thermal Science and Engineering Progress 9 (2019): 308-321.

PRATIBHA SHARMA, IIT Bombay

If we compare the different types of fuel cell then the operating temperature range it varies between 40 to 80 for PEM fuel cell, for alkaline it is 65 to 220 degree centigrade, for phosphoric acid 205 degrees centigrade, for molten carbonate 650, for solid oxide it is 600 to 1000-degree centigrade.

Electrolyte in case of PEM is a polymeric ion exchange membrane usually nafion, for alkaline it is mobilized or immobilized potassium hydroxide in asbestos matrix, for phosphoric acid it is phosphoric acid in silicon carbide matrix, for molten carbonate it is liquid molten carbonate in LiAlO2. While for solid oxide these electrolytes are perovskites based materials.

Electrode is carbon based in polymer electrolyte membrane fuel cell, in alkaline it is platinum, in phosphoric acid it is carbon, in molten carbonate it is nickel and nickel oxide based and here it is perovskite based in SOFCs. The catalyst which is used is generally platinum except for molten carbonate and solid oxide fuel cells.

Depending upon the charge carrier or the ions which are transported polymer electrolyte membrane they have H^+ ion conducting membrane, alkaline fuel cell OH^-, phosphoric acid H^+, molten carbonate - carbonate ion and oxide ion in case of solid oxide.

Polymer electrolyte membrane usually for hydrogen as a fuel but it is also can be used with methanol then reforming will be required, alkaline with hydrogen, phosphoric acid for hydrogen and molten carbonate again can use hydrogen, methane and there is a wide fuel flexibility for solid oxide fuel cells.

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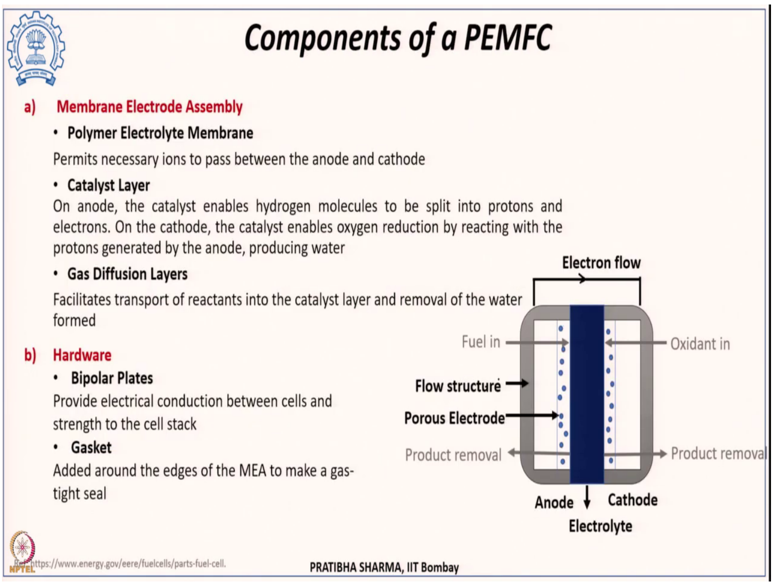

Now the major component if you look at the polymer electrolyte membrane fuel cell, then the major component in a polymer electrolyte membrane fuel cell is the membrane electrode assembly which consists of electrolyte membrane that is a polymer which allows ion conduction. Then there is a catalyst layer on the anode side the catalyst it allows hydrogen molecules to split into protons and electrons and on the cathode side it reacts these ions they react with the oxygen and then forming water.

Then there is gas diffusion layer we have seen their roles already, there are bipolar plates which provide electrical connection between cell and also provide strength to the cell stack and gasket provides the air tightness.

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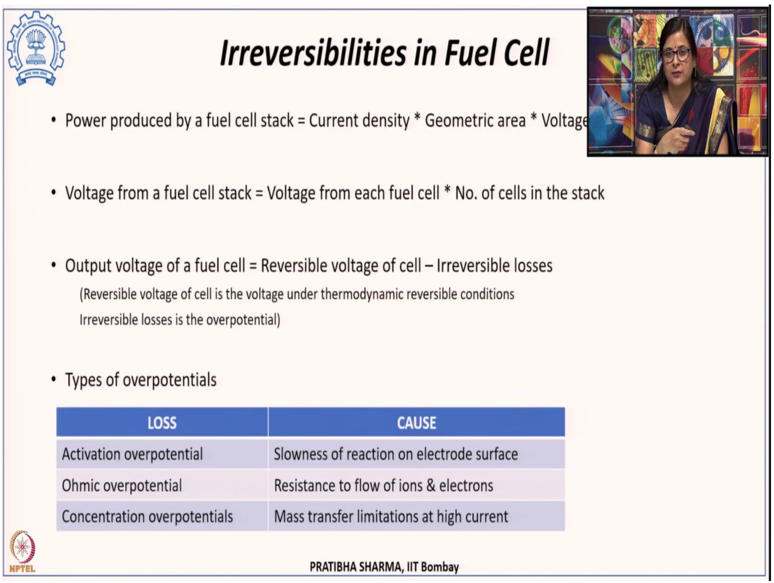

In a typical fuel cell, the standard reversible voltage we have seen is 1.23 volts, but then there are irreversibilities involved in the fuel cell. Now if we see the power which is being produced by a fuel cell stack it is given by current density times the geometric area times the voltage. Now this voltage from the fuel cell stack is given by the number of cells operating in the stack times the voltage from each of the stack and the output voltage of a fuel cell is given by the difference of the reversible cell voltage minus the irreversible losses.

Now, these irreversible losses these can arise because of several regions, one is because of the electrochemical reaction their rate of the reaction which gives rise to activation over voltage, because there is a resistance to the flow of ions and electrons that gives rise to Ohmic overvoltage and then there are mass transfer limitations which gives rise to the concentration over voltage.

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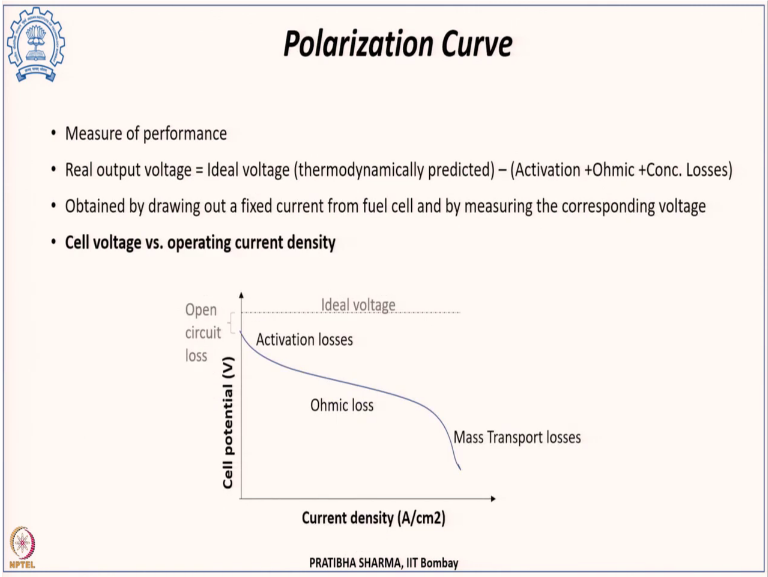

So, if we consider the performance of a PEM fuel cell we can plot cell voltage with the current density. So, the actual output voltage is given by the ideal voltage minus the sum of the different over voltages. So, if we see in the lower current density regime activation losses predominant, in the real operational region Ohmic losses these predominant, in the medium current densities and in the higher current density regime mass transport losses are the predominant losses involved.

There are different parameter which affect the performance of a fuel cell like the current density we have seen that the losses they are directly proportional to the current density and Ohmic losses they are usually dominant in the normal operation region of the fuel cell.

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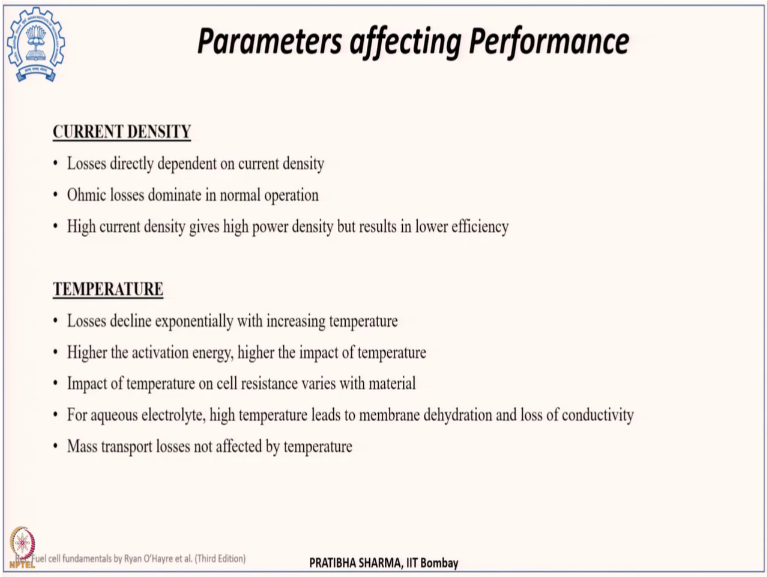

If we want high current density or high power density that will also result into a lower efficiency. It also depends upon temperature. So, the losses they decline exponentially with the increase in temperature impact of temperature on cell resistance it varies with the material. For aqueous electrolyte the high temperature leads to membrane dehydration and it also leads to loss of conductivity. Mass transport losses however, they are not affected by the temperature.

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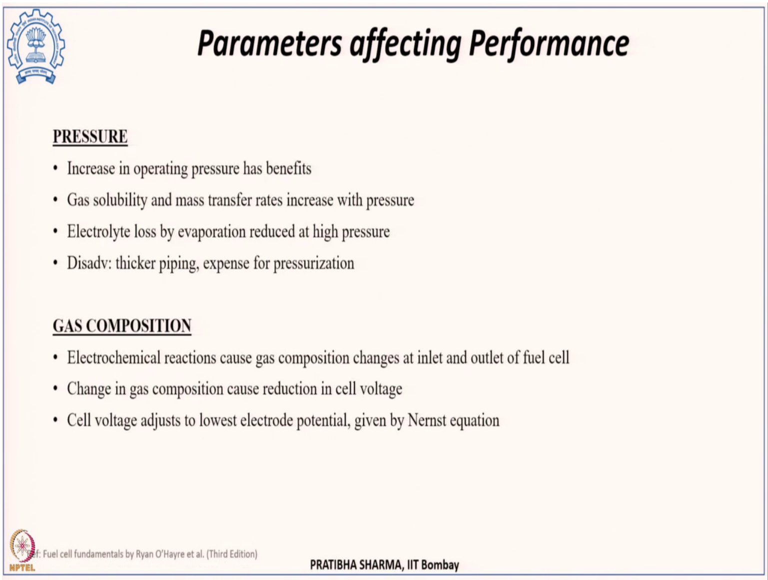

Another important parameter which affects the performance of a fuel cell is pressure. If there is an increase in the operating pressure it has several benefits the gas solubility mass transfer rates they increase with pressure, the electrolyte loss by evaporation also reduces. But the disadvantages if we increase the pressure then the piping thickness will increase we have to pressurize it and that will add up to the cost.

And gas composition also affects the performance, the change in the gas composition it cause reduction in the cell voltage. So, that could be the relationship we can get by the Nernst equation.

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There have been several developments recently fuel cell has been considered to be a major component which could be helpful towards green energy transition. There are certain companies which are in the key player in the fuel cell development like the Ballard, fuel cell energy, Mitsubishi plug power and Cummins.

Fuel cells they are widely being explored for their use for distributed power as well as vehicular application and they have a wide scope of application in automobiles that could provide the longer driving range and lesser fueling time. Asia-Pacific has emerged as a major market for fuel cell because of the government policies like in countries like China, Japan, South Korea where the interest in fuel cell has increased and major applications being considered is heavy duty transport and energy storage.

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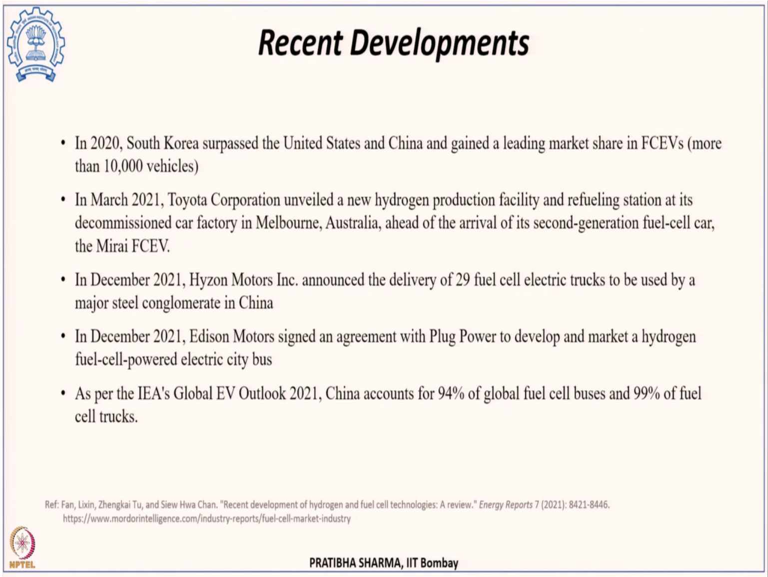

In 2020, South Korea surpassed the United States and China and gained a leading market in fuel cell electric vehicles about more than 10,000 vehicles in South Korea. In 2021, Toyota they unveiled a new hydrogen production facility and gas refueling station at its factory in Melbourne Australia and in December 2021 Hyzon Motors they announced the delivery of 29 fuel cell electric trucks that will be used in China in a major steam conglomerate.

In 2021 Edison Motors they signed an agreement with Plug Power for providing to develop and market a hydrogen fuel powered electric bus and as per IEA's global EV Outlook China accounts for 94 percent of the fuel cell buses and 99 percent of the fuel cell trucks.

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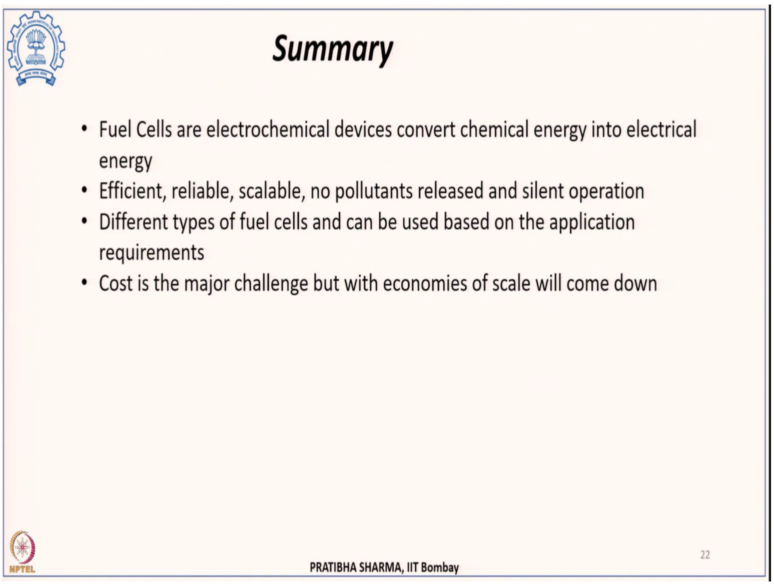

To summarize we have seen the electrochemical device fuel cell which converts chemical energy into electrical energy, it is a very efficient, reliable, scalable device which does not produce any pollutant. There are different types of fuel cell we have seen very briefly and when it comes to the economies of scale, economies of scale will be the major contributing factor which will bring down the cost of fuel cell.

Thank you.