Energy Conservation and Waste Heat Recovery
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Lecture - 61
Fuel Cells

Welcome back and we are going to continue the next lecture with the next lecture of our course on Energy Conservation and Waste Heat Recovery. In the last class we started with hydrogen economy and we initiated the concept of fuel cell. Where hydrogen is used as the fuel as the source of energy and the fuel cell directly converts it into other source of energy directly into electricity. So, it is a again an electro chemical process I would say like batteries, but however here the electricity will be produced as long as there is a supply of hydrogen as a fuel.

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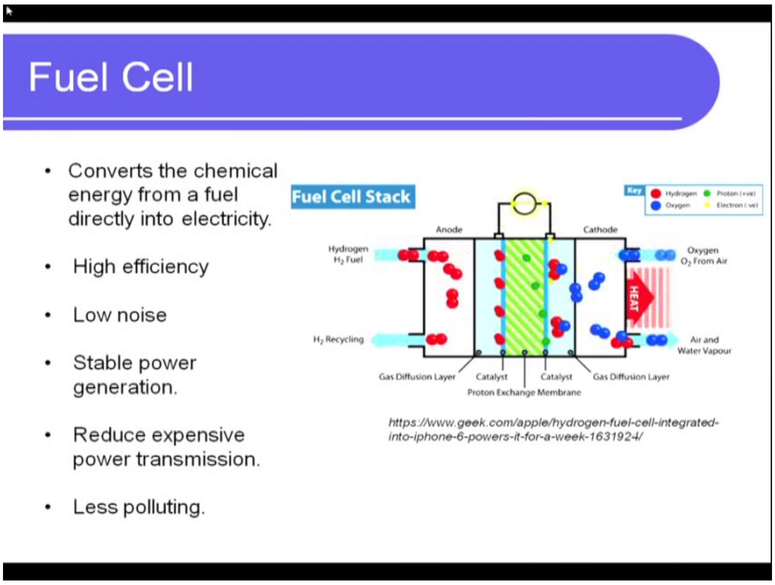

So, if you recall this is what we started with discussing as fuel cell. And this was the slide that we last saw. This is an animation and we are going to talk about this functioning in more details this time.

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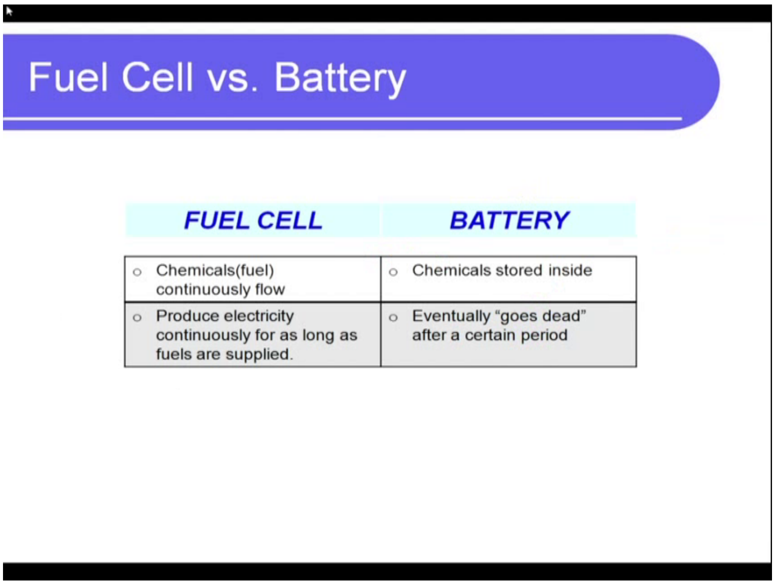

So fuel cell and batteries they are both, as I said electrochemical energy conversion. However, for a battery the chemicals are stored inside. As we know there is a discharging and charging cycle during charging the energy stored inside and then what happens is during the discharging cycle we will use up the stored energy and the battery will eventually go dead after a certain period. At which point depending on what you if it is a rechargeable battery we will charge it again, if it is an use and throw type we will throw it away and get a new battery.

Fuel cell on the other hand, it is a continuous flow device where the chemicals can continuously flow as long as we supply the chemicals which is a fuel here the electricity will be produced. So that is the primary difference between fuel cell and battery in a Layman term about for functioning; of course the way the two functions is completely different.

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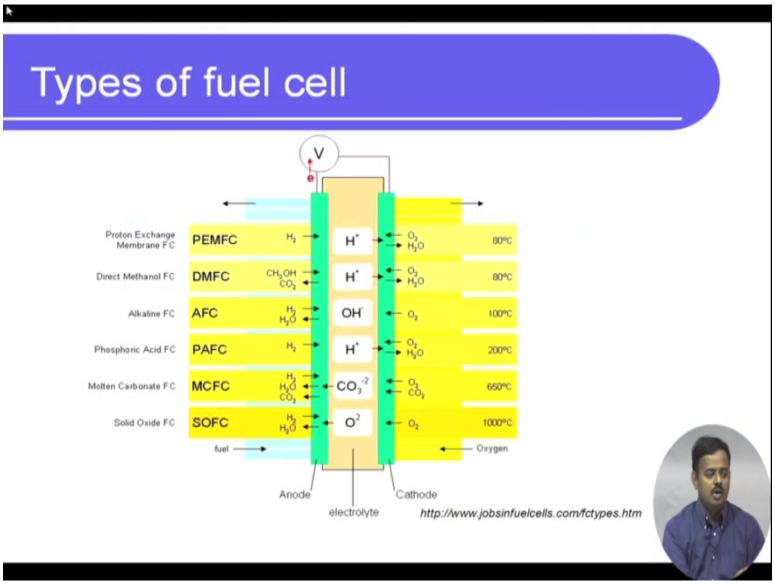

So, if we talk about fuel cells as we said, a typical fuel cell will have two electrodes and an electrolyte same as battery. So the fuel cell depending on what is there can be of several types which is shown pretty nicely in this schematic diagram. So, we have proton exchange membrane fuel cell which is PEMFC, PEM or PEM fuel cell is sometimes it is called and we are going to discuss this in details.

So what essentially differentiates between these several types of fuel cells is; what is the fuel that comes in; so for example, in PEM fuel cells is hydrogen in most of these cases it is hydrogen and in direct methanol fuel cell also it is hydrogen, but not in it is elementary form. And then what goes through the electrode; what goes through the electrolyte I am sorry that also is different. At least in three of these cases it is a proton, but in some of these cases it is like OH radical, OH ion rather, carbonate ion, and so on, alright.

And finally, what is the supply? In all these cases actually the supply on the other side is oxygen. In one case and then over here molten carbonate you have CO 2 also. The other thing that you see is, the temperature range of operation is different for each of these types or each of these fuel cells.

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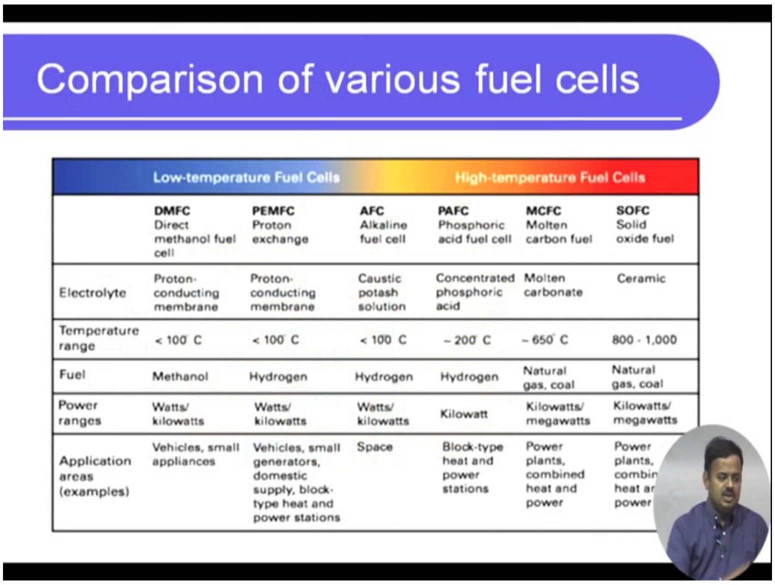

	Low-temperature Fuel Cells			High-temperature Fuel Cells		
	DMFC Direct methanol fuel cell	**PEMFC** Proton exchange	**AFC** Alkaline fuel cell	**PAFC** Phosphoric acid fuel cell	**MCFC** Molten carbon fuel	**SOFC** Solid oxide fuel
Electrolyte	Proton-conducting membrane	Proton-conducting membrane	Caustic potash solution	Concentrated phosphoric acid	Molten carbonate	Ceramic
Temperature range	< 100° C	< 100° C	< 100° C	~ 200° C	~ 650° C	800 - 1,000
Fuel	Methanol	Hydrogen	Hydrogen	Hydrogen	Natural gas, coal	Natural gas, coal
Power ranges	Watts/ kilowatts	Watts/ kilowatts	Watts/ kilowatts	Kilowatt	Kilowatts/ megawatts	Kilowatts/ megawatts
Application areas (examples)	Vehicles, small appliances	Vehicles, small generators, domestic supply, block-type heat and power stations	Space	Block-type heat and power stations	Power plants, combined heat and power	Power plants, combin heat ar power

So, the same thing over here is shown in this chart, pretty much what we saw before in a tabular form. So, these are low temperature fuel cells which are direct methanol, proton exchange, alkaline. And so as the temperature goes higher we go from left to right. Solid oxide fuel cell is of course operate at very high temperatures of 800 to 1000 degree centigrade, whereas a PEM direct methanol they can operate at slightly elevated room temperatures, alright.

So you can say a fuel in all these cases methanol hydrogen hydrogen hydrogen, then natural gas and coal natural gas and coal which all of these have hydrogen embedded in them. And you can also see application areas, and typically when we saw about vehicles we are talking about either direct methanol or PEM fuel cells.

However, space applications fuel cells are actually there today. Many people say that it has stopped at space. And then solid oxide fuel cell primarily is as well as molten carbon; these are being considered for power generation in a power plant. So because these can actually generate Kilowatts to megawatts power range so it is possible. So there are some of the leading companies of the world are looking at these options also. Let me stop at that.

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What I am going to show you now is with that introduction on fuel cells. Let us discuss a little bit more on proton exchange membrane fuel cell I will first play a small video and then we will talk about the details, alright.

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So, this is from a company called Ballard and it shows the functioning of proton exchange membrane fuel cells.

Fuel cells have the power to change our world.

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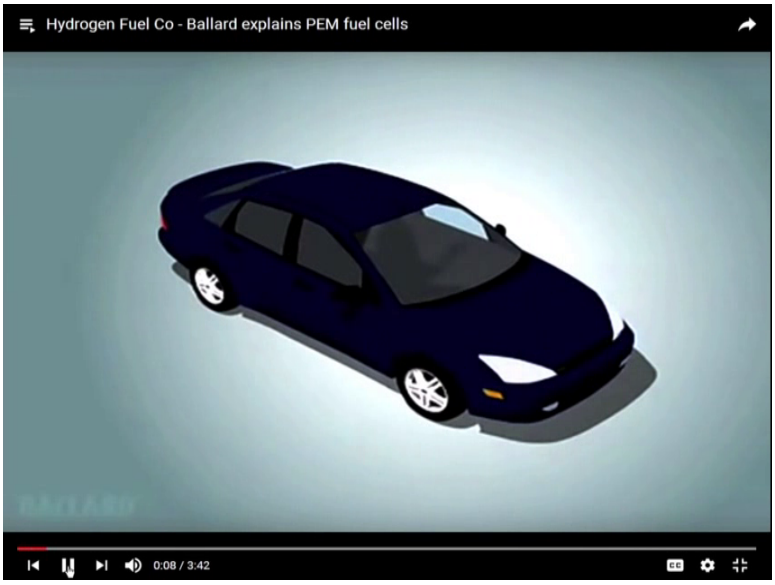

At Ballard, we are dedicated to making fuel cell technology or reality to replace the internal combustion engine in your car with a clean quiet pollution free fuel cell engine, fuel cell powered cars look just like other cars on the road today.

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But they are cleaner quieter more efficient and work very differently when you turn the key hydrogen and compressed air flow to the fuel cell module, which contains the fuel cell stack.

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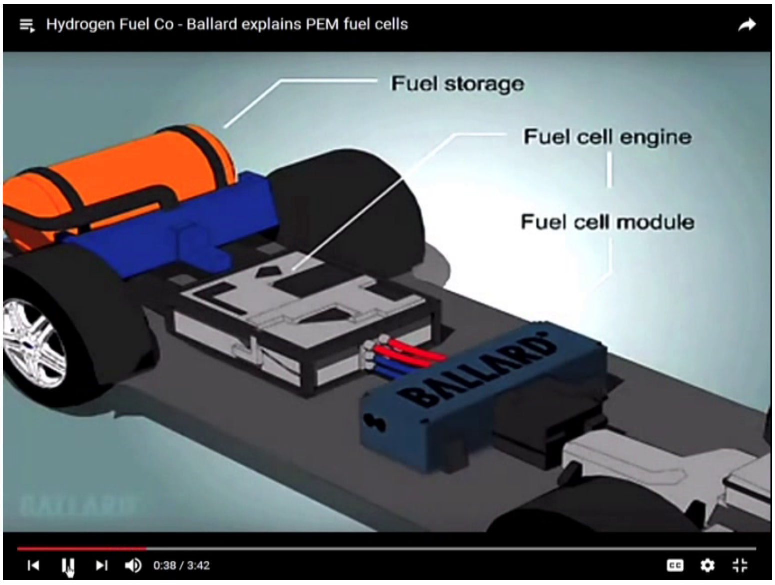

A fuel cell engine consists of the proton exchange membrane or PEM fuel cell module coupled with the systems required in a typical automotive engine.

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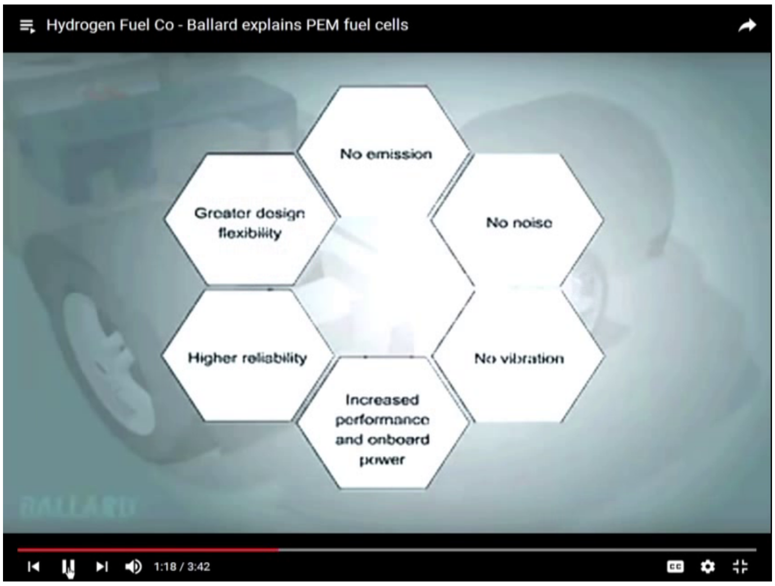

The electricity produced by the fuel cell is delivered to the electric drive system in the vehicle. The drive system converts electrical power into the mechanical energy that drives the wheels of the car the fuel cell generates electricity that can be used to power a car truck bus or other vehicle for as long as fuel is supplied. The fuel cell is 2 to 3 times more efficient than your gasoline engine and does not create pollution. Additional benefits include increased performance and onboard power higher reliability and greater flexibility in vehicle design and engine layout.

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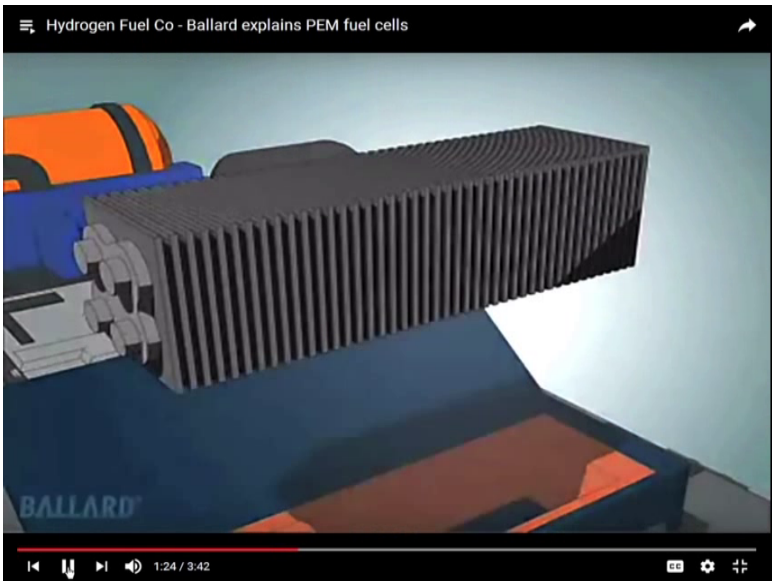

But how does the Fuel Cell work?

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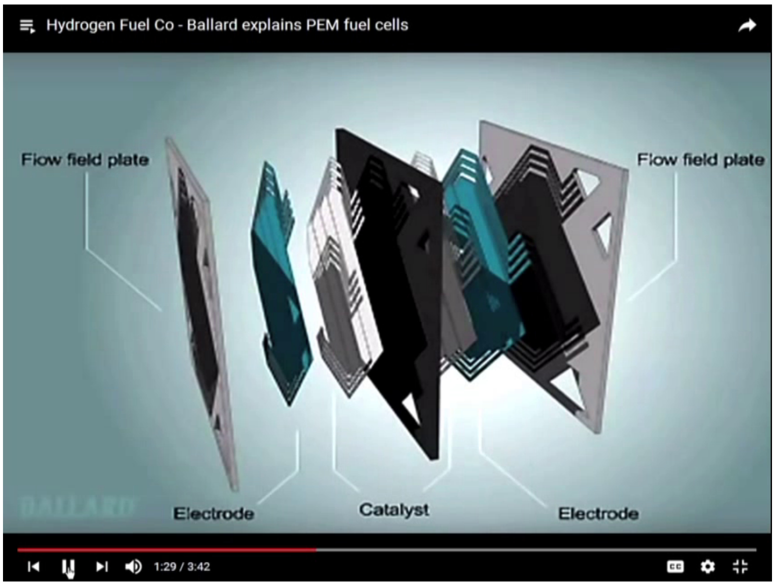

A single PEM fuel cell is made up of 2 plates, 2 electrodes and 2 thin layers of platinum based catalyst separated by a plastic membrane which when fed with the fuel reacts electrochemically to create electricity.

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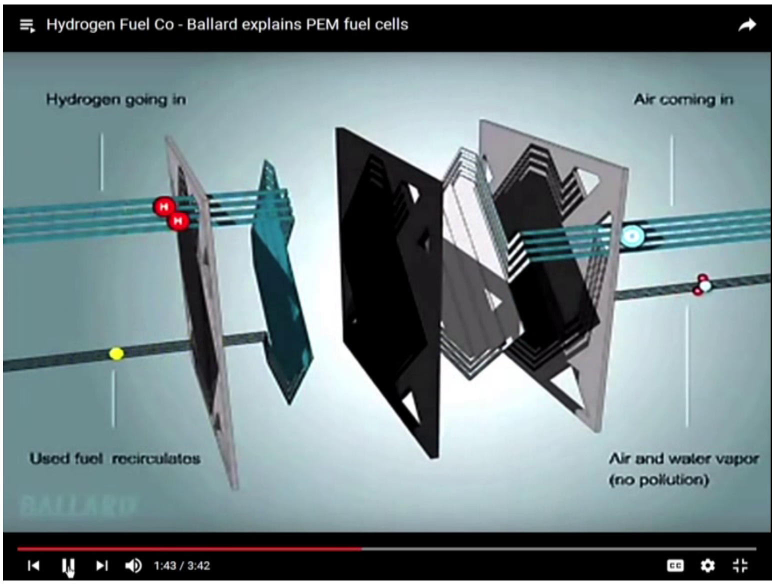

Hydrogen from an onboard storage tank and oxygen from air are fed through channels in the plates hydrogen flows on one side of the membrane air on the other.

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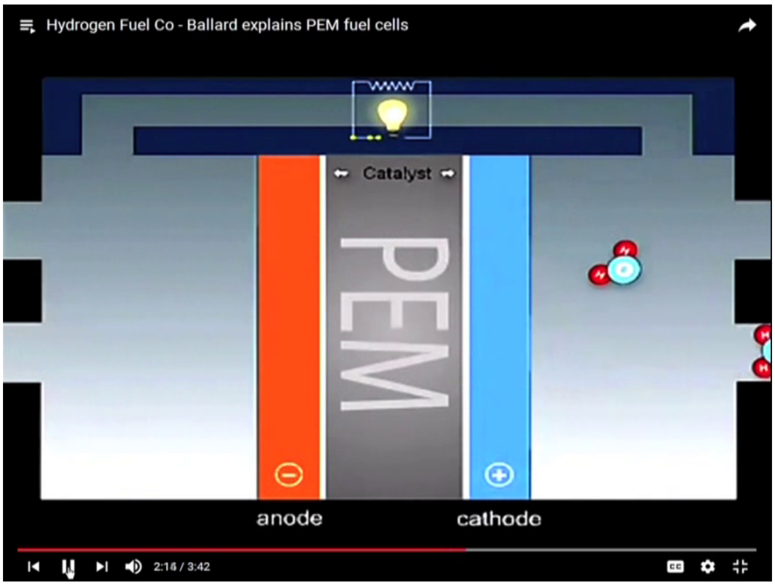

If the catalyst splits the hydrogen molecule into protons and electrons, if the protons can pass through the membrane the electrons cannot and have to pass through an external circuit creating useful electricity. On the oxygen side of the membrane the protons and the electrons react with oxygen from the air in the presence of a second catalyst layer generating water and heat.

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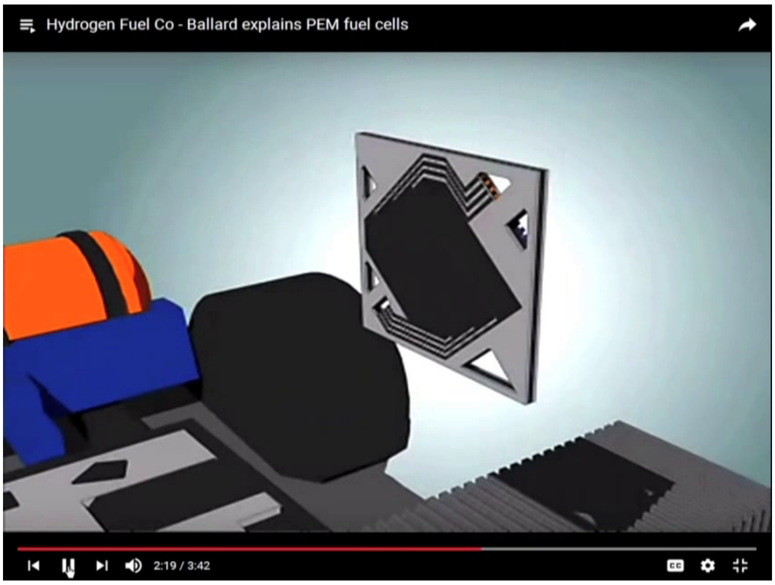

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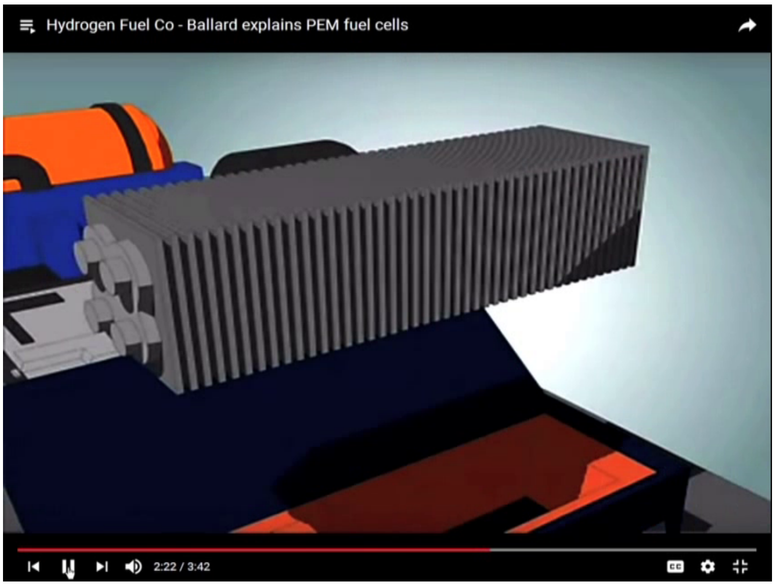

By stacking, together single cells like slices in a loaf of bread. You make a fuel cell stack to produce the required amount of power just like your car fuel cells need fuel to operate.

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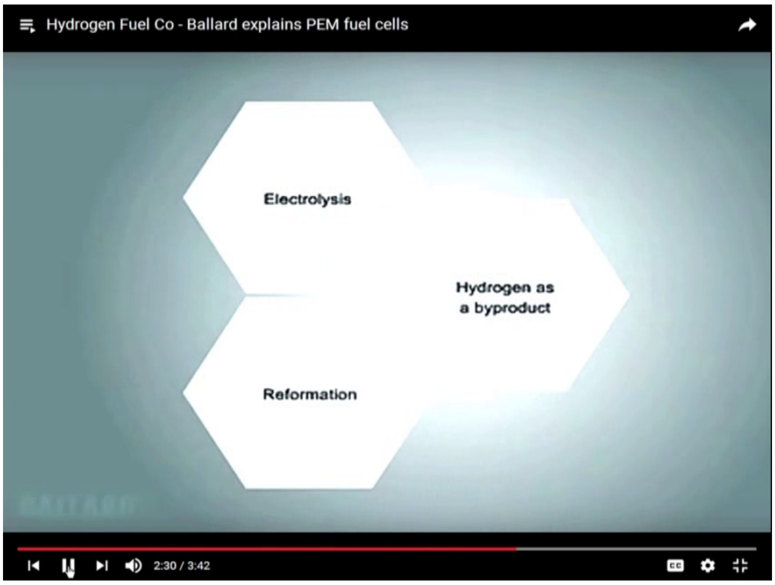

If the Ballard fuel cell uses hydrogen as a fuel which can be produced in many different ways and once produced can be stored as a compressed gas or liquid or in a chemical or metal compound.

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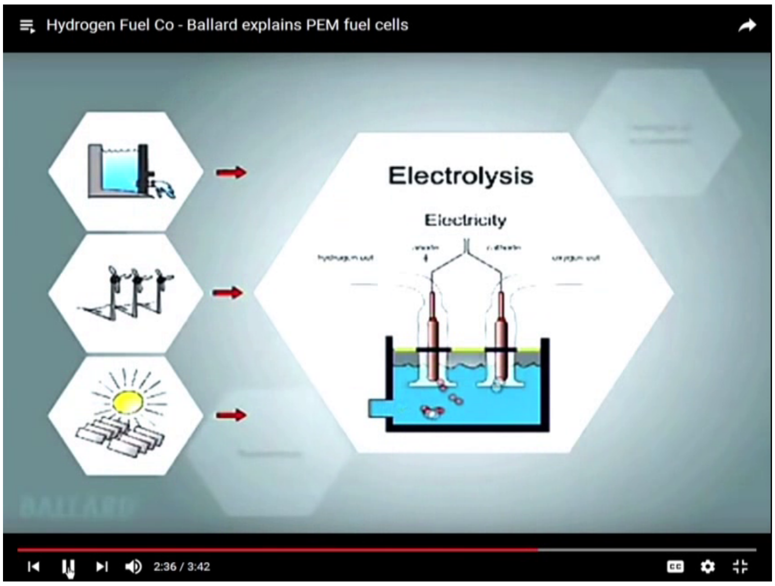

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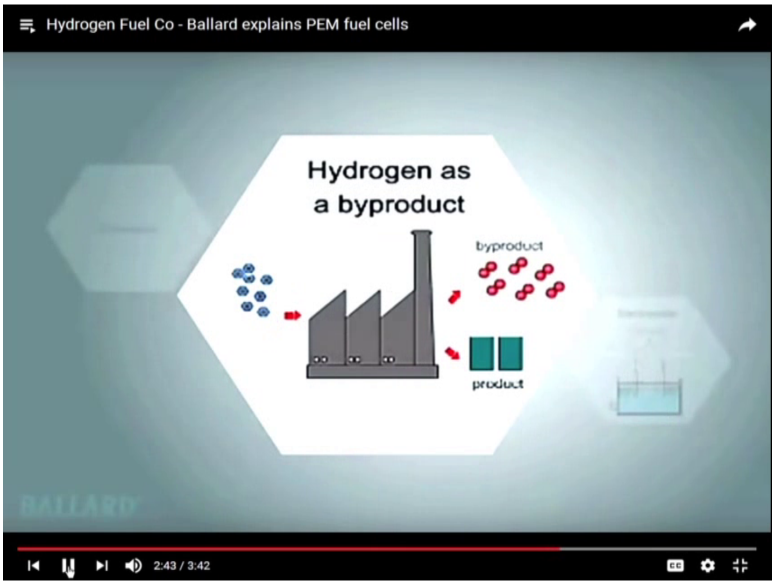

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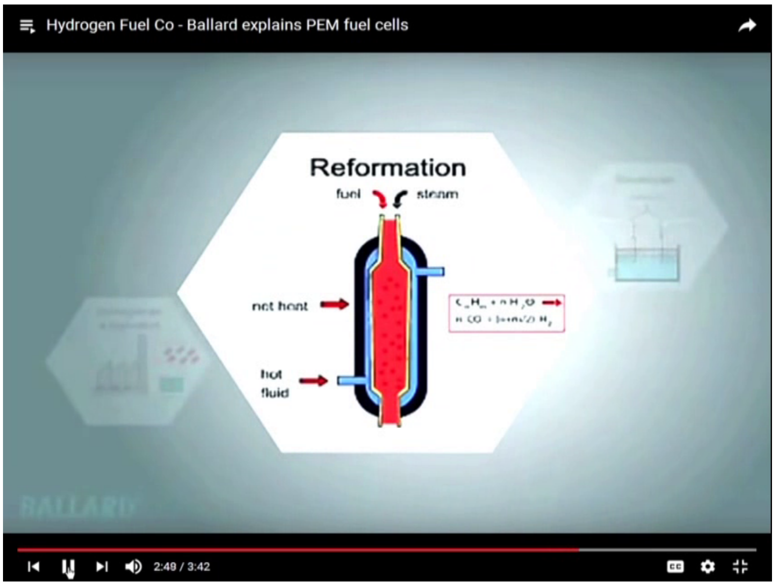

Different areas of the world will create hydrogen in different ways depending on economics and available resources.

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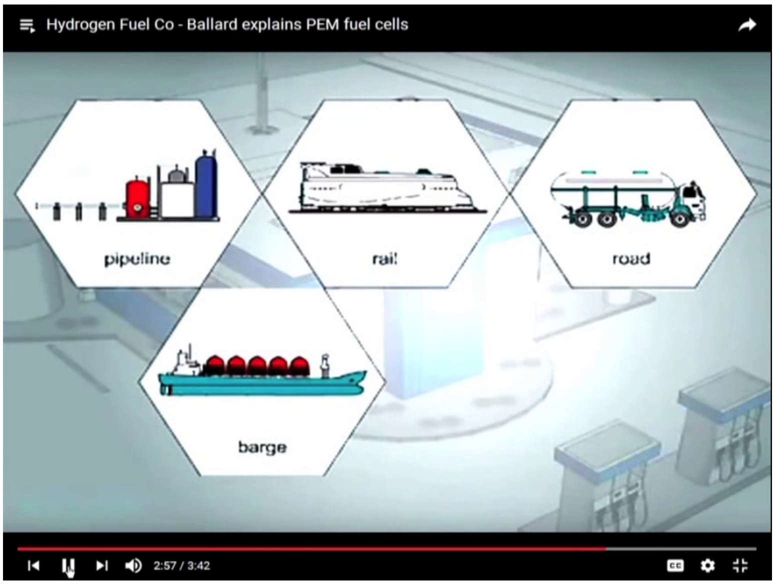

Hydrogen can be delivered to fueling stations by road barge rail or pipeline all can be made on site at gas stations.

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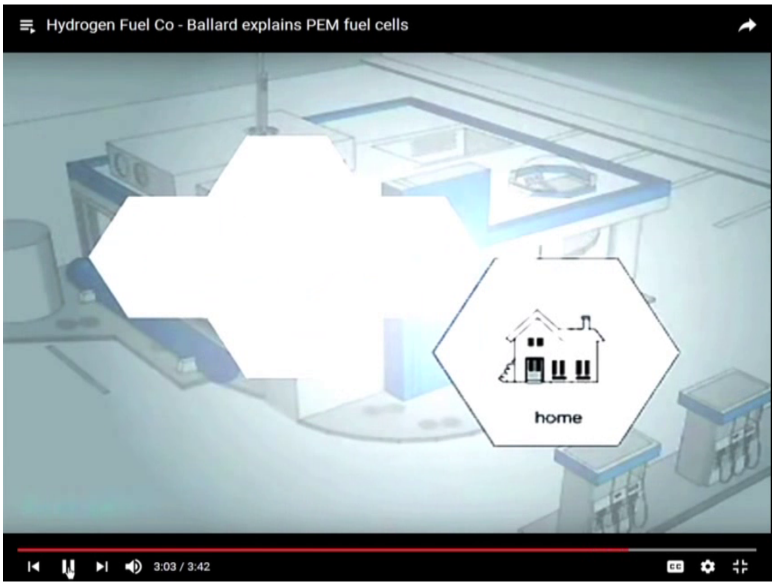

People may one day be able to produce their own hydrogen at home.

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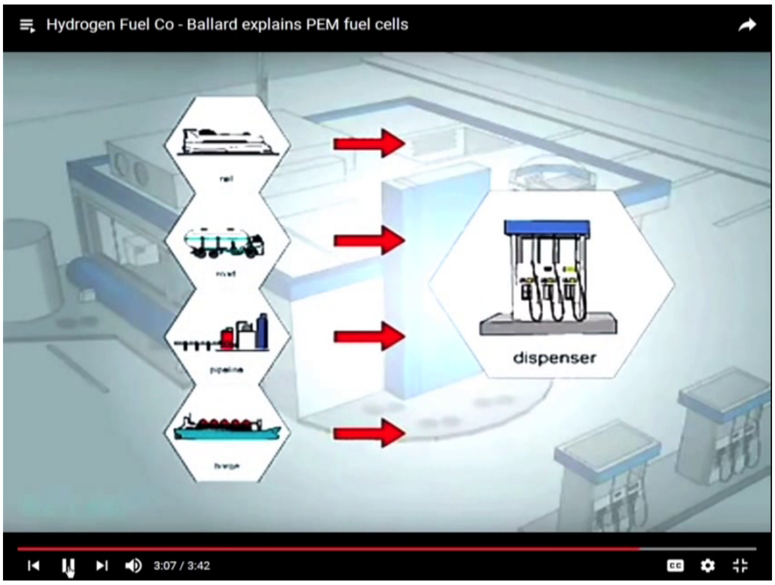

You can see there are many options available to enable the hydrogen infrastructure to grow.

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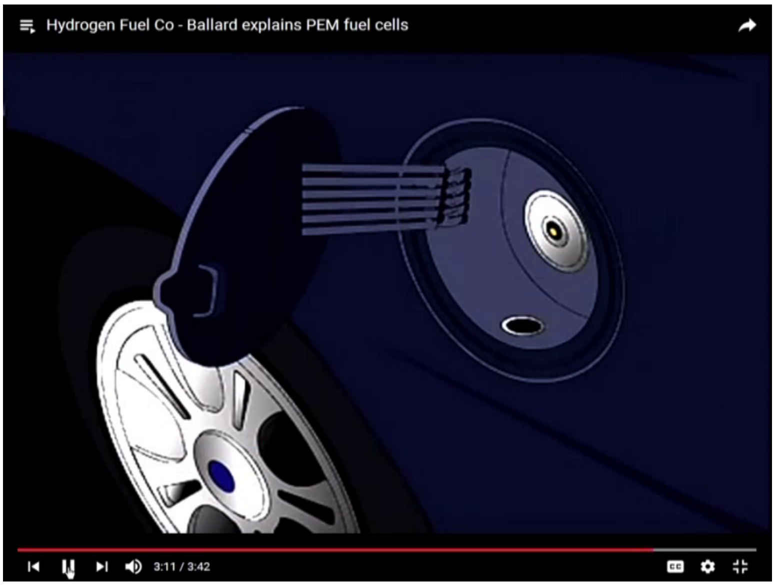

Fueling the vehicle is very similar to the way you refuel your vehicle today.

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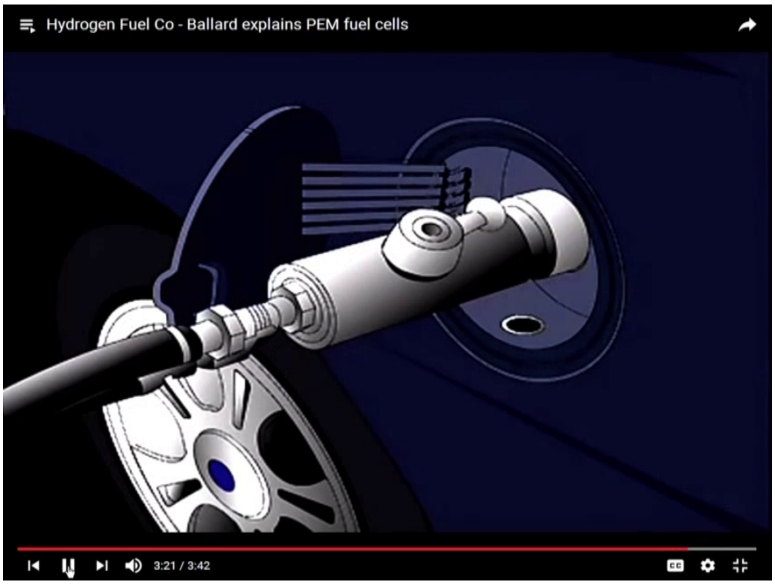

But requires a special sealed connection, before the hydrogen can be pumped into the vehicle storage tanks it only takes a few minutes to refuel a fuel cell car and when fueled by hydrogen a fuel cell emits water and heat and no pollution think with this means to the air around us. Now that you understand how the technology works in a fuel cell vehicle you can look for them on over roads and ask yourself whether the vehicle you see is powered by Ballard alright.

So, I think that was a very nice video from Ballard which shows the application of fuel cells for powering a vehicle we talked about how a proton exchange membrane fuel cell works it also talked about the infrastructure that is required I mean some of these are I mean whatever we saw artists renditions, but what it shows is what is possible you can generate hydrogen you can store it and you can transport it and just like we have gas stations today or petrol pumps today or diesel pumps. Today we can have such hydrogen stations where the vehicle can go we can put in pressurized hydrogen and then as the vehicle runs the hydrogen is released and it powers it generates electricity to run the motor which is connected to the termit to the transmission.

So, let us look at a brief history like we saw in hydrogen economy.

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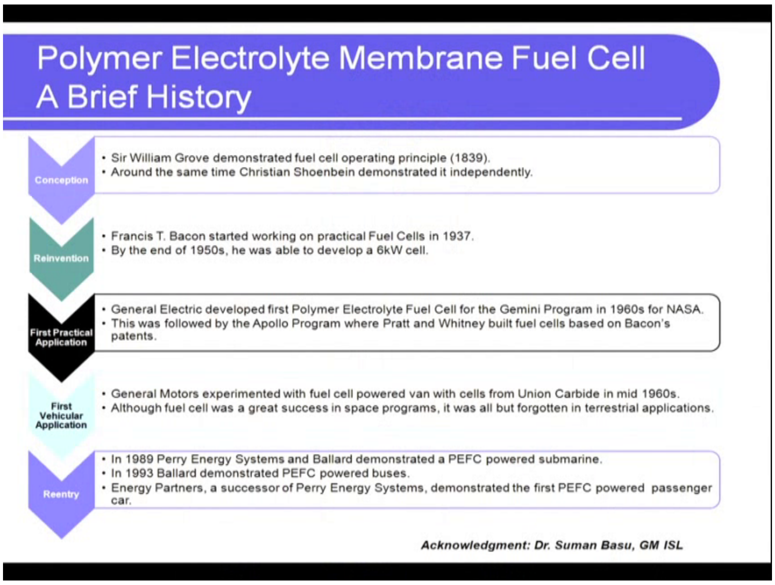

Let us look at a brief history of fuel cell here, I would like to acknowledge some of the information that I got from my friend Dr. Suman Basu he was a senior researcher at general Motors India Science Lab and while during his stint there he looked as a researcher he did a lot of study looking at PEM fuel cells for powering up of electric and hybrid vehicles.

So, look at there is a conception Sir William Grove as we saw in the in the case of when we were studying hydrogen economy and it is history William Grove and Christian Shawn Bin they were the first ones to show the or demonstrate the fuel cell operation. Then reinvention was though this was way back in the19th century first half of the 19th century and almost 100 years later, it was again reinvented by Francis Bacon and he was actually looking at practically working on that and almost after a decade of his effort or even more than because almost one and half decades he was able to finally, develop a 6 Kilowatt fuel cell commendable achievement given the constraints the lack of knowledge at that point what Francis Bacon did was commendable right.

Now the first application was by general electric, they are the ones who developed the first PEM fuel cell for one of their programs which was used in a space application they worked with NASA, they developed it for NASA and later on Pratt and Whitney also followed and they build some fuel cells based on Francis Bacon's patents and again this was also used in the NASA space mission, the Apollo program the very famous Apollo program alright. So these were the first step practical applications as I was saying that fuel cells have been in applied in space for even 50 years back, but then it kind of stayed there.

So, if you look at the first vehicular application this is where general Motors, it first showed that a fuel cell powered van is possible and that was also more than 50 years back in 1960s around the same time when GE was working with NASA, GM did it in the transportation sector. But unfortunately GM showed what is possible. But then they did not follow it up in terms of commercialization. Therefore, it kind of it is all, but forgotten for many many years for almost 30, 40 I mean 30, 35 years for terrestrial applications fuel cell was not considered till in the 90s again this the focus on fuel cells for other applications picked up alright.

So, that is what in 1993 the Ballard demonstrated the first PEFC powered buses the Ballard is the animation that we showed was from Ballard from the company Ballard so they in the 90s they showed the concept bus or basically they built a prototype where they showed that a bus could be driven powered by proton exchange fuel cells. Perry energy system and Ballard also demonstrated a proton exchange fuel cell power submarine so this is when again for terrestrial applications the focus picked up alright ok.

Last, but not least for the power remember GM showed it in a van way back in 60s, but after that energy partners which is a successor of Perry energy systems they demonstrated a PEFC powered passenger car. Of course, after that GM again looked at it I mean was it a lost did they did they lose the opportunity when they when they just showed and then did not follow up well I mean that is for the business analysts to judge, but GM also reentered and started looking at it so did Toyota, so did Ford and many and all the car giants alright.

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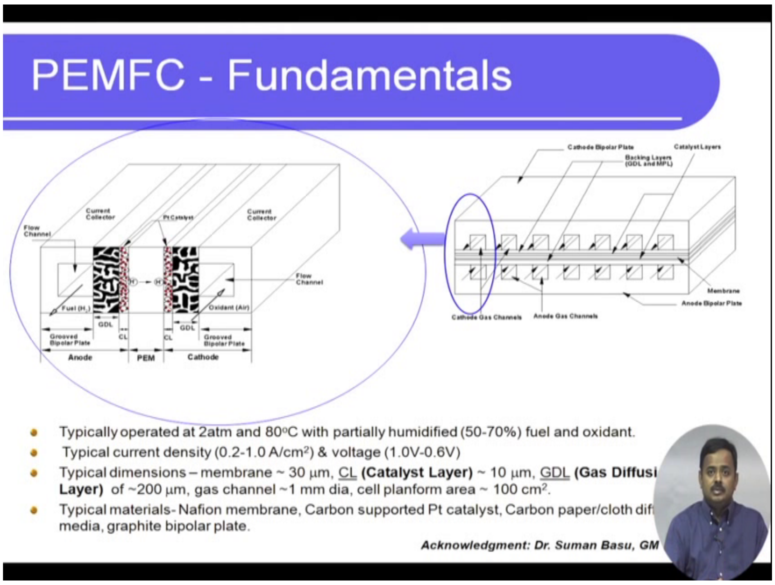

So Let us look at the fundamentals of proton exchange membrane fuel cells. What did we see there we saw the different components in that animation as well as in the first animation that we showed let us look at those in a little greater details. So, what you see in a fuel cell you have what is called the bipolar plates on the 2 ends shown here which has channels through which the gases flow on one side as you recall in one cell on one side you have the flow of hydrogen on the other side you have the flow of oxygen so that is how that is by these channels are built.

Actually in a bipolar plate what happens is on the other side as well you have channels that are built on both sides of the bipolar plate you have channels because remember these are stacked together so many of the sales cells individual cells are stacked together to form the large fuel cell which is used to generate powers of in the range of Kilowatts clear.

So, now let us take just one unit cell like this and look at the different parts so of course at the 2 ends you have the 2 bi polar plates, the cathode bipolar plate and the anode bipolar plate which have flow channels. So, through the one side you have oxidant which is air and on the other side you have the fuel which is hydrogen. The next layer is something called GDL or Gas Diffusion Layer alright and we are going to look at each the functions of each of them separately in the next few slides.

Then we have the catalyst layer and this is very important in the first catalyst layer the hydrogen actually breaks up into electron and proton and the proton then passes through the proton exchange membrane. So, this is what the reaction happens very very important and in the second catalyst layer what happens is the hydrogen the proton the electron and the oxygen that diffuses through the gas diffusion layer in the presence of the catalyst again react to form water vapour right alright so which is which comes out from the other end so this is very important.

These are the main you know the main components in a fuel cell so again to repeat you have bipolar plates on both sides then you have gas diffusion layer on one side is air and oxygen that flows through on the other side on the fuel side is hydrogen that flows through the diffuses through then you have the 2 catalysts and then the electrolyte is the proton exchange membrane right. So, typical dimensions etcetera are written here these are all in microns this is for a single cell and then you have many of these cells stacked one after the other so that the voltage that you get add up clear.

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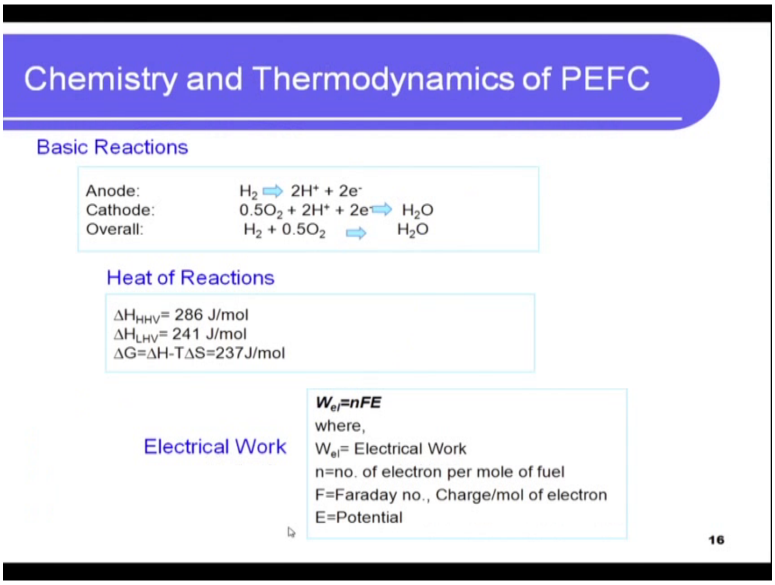

So what are the basic reactions that happen alright so at the anode the hydrogen breaks up into hydrogen atoms hydrogen ions positive ions and electrons and in the cathode the hydrogen the proton in this case the electrons and the oxygen combine to form water so overall this is what happens hydrogen oxygen actually react to form water.

If you look at the heat of reactions this is what it is and what is the electrical work that we get out of it this is given as n FE, where n is a number of electrons per mole of fuel F is a faraday number which is charge per mole of electron and E is the potential that we get.

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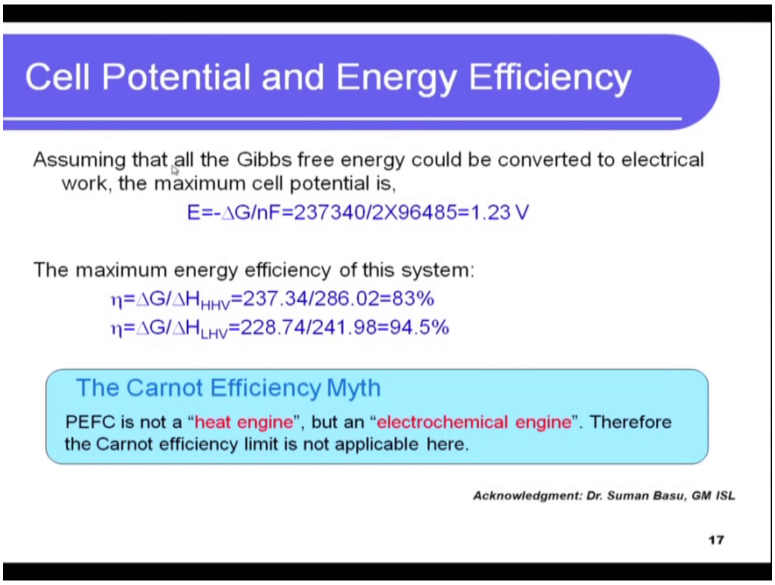

If you do some calculations, what we get is assume that all the Gibbs free energy could be converted to electrical work the maximum potential that we get is 1.23 Volts and the maximum energy efficiency is here whether you take the high higher heating value or the lower heating value or higher calorific value of the lower calorific value we get efficiencies that are very very high remember in the first slide when we are talking about fuel cells we said that these are very high efficiencies and when we are talking about high efficiencies we are talking about really high numbers ok.

So, many people say that this is a little conferee people say that come on I mean any of the other conversion devices that we talked of or that we have looked at that we have discussed I mean it was limited by Carnot Efficiency. But how come we are getting such high values over here you have to keep in mind that this is an electrochemical engine it is not a heat engine. So therefore, the Carnot efficiency limit is not applicable here so that is the reason there is no Carnot efficiency limit in case of fuel cells and that is the reason we can get such at least theoretically get such high values.

But if you think about it practically I would like to mention that the maximum efficiencies that people have seen in the various prototypes in the various experiments that people have done the efficiencies have not gone beyond 60s in the 60s I would say we have we are nowhere close to heating that 85, 90 percent type of efficiencies even though theoretically that is possible.

So there is a lot of work that is being done to see how we can improve this efficiency further. But here is something I would like to say and this is again based on my discussion with somebody who is a Bio Technologist.

Now, his point is or the point over here that I am trying to make and this is my personal opinion or our personal opinion and don not quote me this is just a discussion I am saying if you look at what is happening inside a fuel cell and compare it what happens inside our lungs it is very similar.

So, if you look at our and if we say that the God created or the nature creates or the creation of nature is most optimized, then it is very reasonable to assume that for a healthy individual the efficiency of the functioning of lungs is probably the best that we can achieve given that nature tries to optimize it is creations.

So, therefore if you look at you calculate the equivalent efficiency of the reactions that happen in our lungs during breathing process that efficiency is around 65, 67 percent. So the ultimate again not based on any theoretical calculations, but just based on what is available in nature or nature has been able to achieve it is an opinion that probably however, hard we try it may be difficult to surpass that limit of that nature has set for us.

So, again this is not based on any theoretical calculations like Carnot efficiency this is not a Carnot efficiency type of limit. But probably we will see if the researchers and scientists who are actively working on this can attain efficiencies that are really very high 70 percent or higher alright. So that was a little bit of what should be the philosophical discussion and efficiencies of fuel cell. But again the key message from this slide is fuel cell is an electrochemical engine. So the limit which is Carnot efficiency for a heat engine does not apply here.

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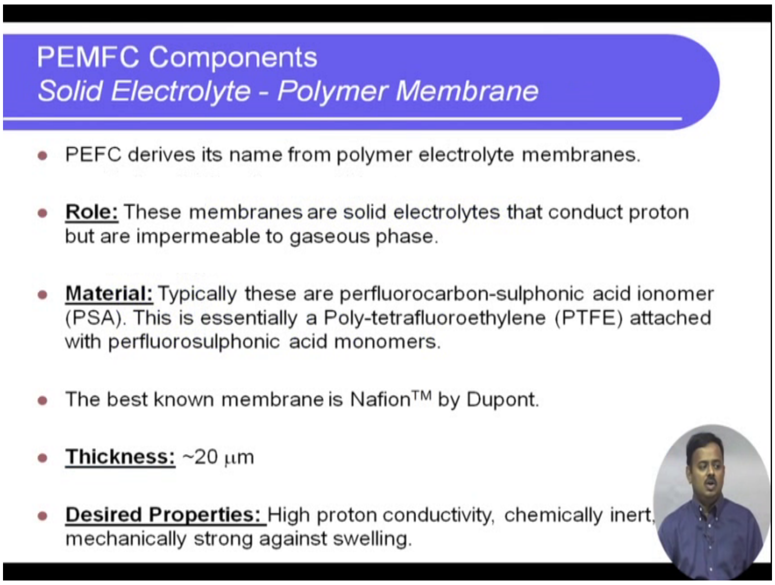

So, let us move on let us move on to some of the components that we saw in a PEM fuel cell. So what is the first one most important is the solid electrolyte which is a polymer membrane so polymer electrolyte membrane that is where the PEFC or PEMFC derives it is name from I again want to clarify something PEFC and PEMFC are used interchangeably proton exchange fuel cell is actually proton exchange membrane fuel cell.

So, what is the role these membranes are the solid electrolytes that conduct the proton what are impermeable to the gaseous phase alright ok. So, what is the kind of metal the best known material today is something that was developed by Dupont it is called Nafion. So it is if you look at fuel cell literature PEM fuel cell literature you will see Nafion being used very commonly as the proton exchange membrane.

The thickness typically comes in the order of like tens of microns 20 microns is a typical thickness and the desired properties should be that it should have high proton conductivity it should let the proton pass through it is thickness of 20 microns it should be chemically inert otherwise there should not be any reactions happening and it should be mechanically strong if there is swelling there is an expansion contraction due to temperature etcetera it should be mechanically strong to hold itself it is a membrane after all alright. So, that is the polymer membrane which is the solid electrolyte and one of the most important components of a PEM fuel cell alright. What next?

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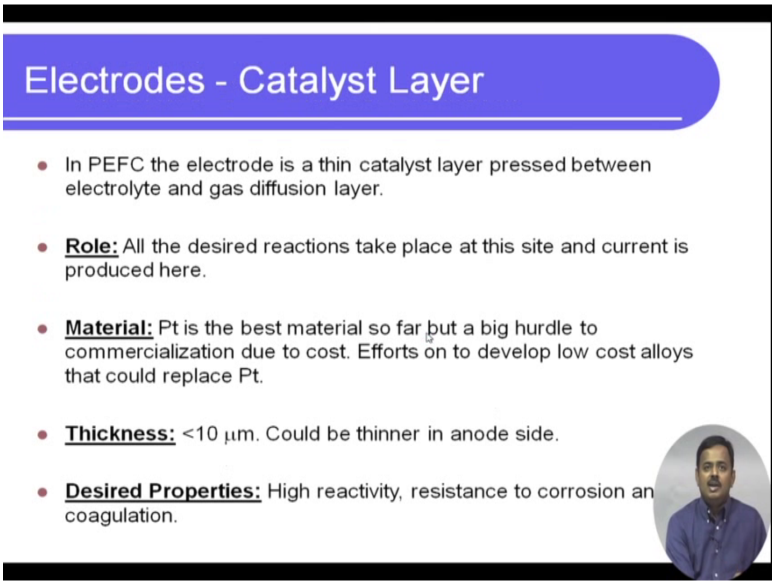

The second one are the electrodes which is the catalyst layer. So those are the electrodes the catalysts are the electrodes. So the electrode is a thin catalyst layer that is pressed between the electrolyte and the gas diffusion layer let us just go back to few slides this is the electrode that we are talking about press between the electrolyte and the GDL or the gas diffusion layer.

So, what is the best material for the electrolytes today platinum is the best material so far, but it is very costly as we know so that is a big hurdle to commercialization. But however, the research over the years as a result of research over the years scientists have been able to reduce the amount of platinum required in a PEM fuel cell to a large extent from what it is started in the 90s to what it is today only a fraction of the platinum is used today and there is also parallel efforts to develop low cost alloys that could replace platinum and still act as catalysts both in the node and the cathode ok.

The thickness is thin it is less than 10 microns and ideally at the anode side it could even be thinner the desired property should be it should have high reactivity resistance to corrosion and coagulation high reactivity because it is the mean that is why the chemical reactions are taking place that is why the hydrogen is breaking up that is why it is again recombining in the cathode side with oxygen to form water clear.

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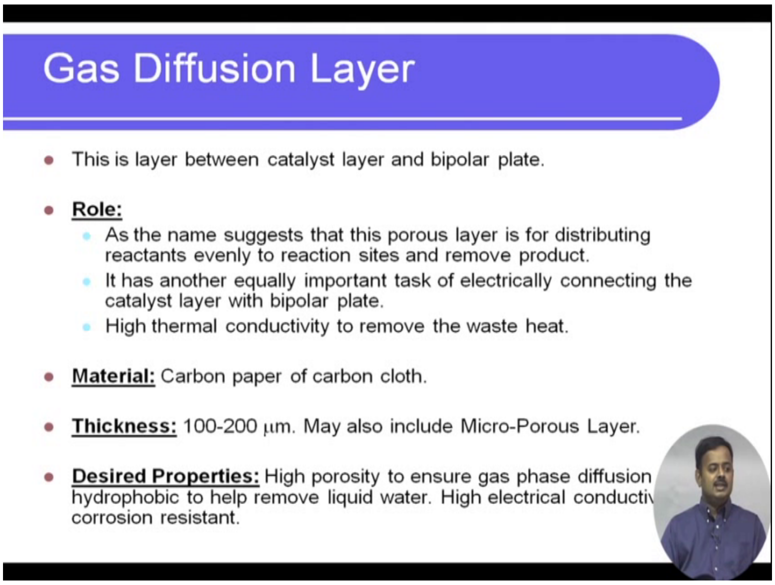

Gas diffusion layer as the name suggests, this is a porous layer and it is required for distributing the reactants evenly at the reaction sites and later remove the products also after the reactions happen at the catalysts. But however, it is also another equally important task of electrically connecting the catalyst layer with the bipolar plate clear, because this is what is actually sandwiched between the bipolar plate and the catalysts.

So, thermal conductivity ideally should be high because the heat that is generated should be at the cathode side electrode has to be removed otherwise the temperature inside should will go up. The material typically is carbon paper or carbon cloth thickness definitely much thicker than the electrodes or the electrolyte and desired properties should be it should be high porosity to ensure gas phase diffusion and it should be hydrophobic because it should not be you know the water that is formed at the cathode, I mean that should not clog the porous material because then the reactions will stop and several other and some other properties.

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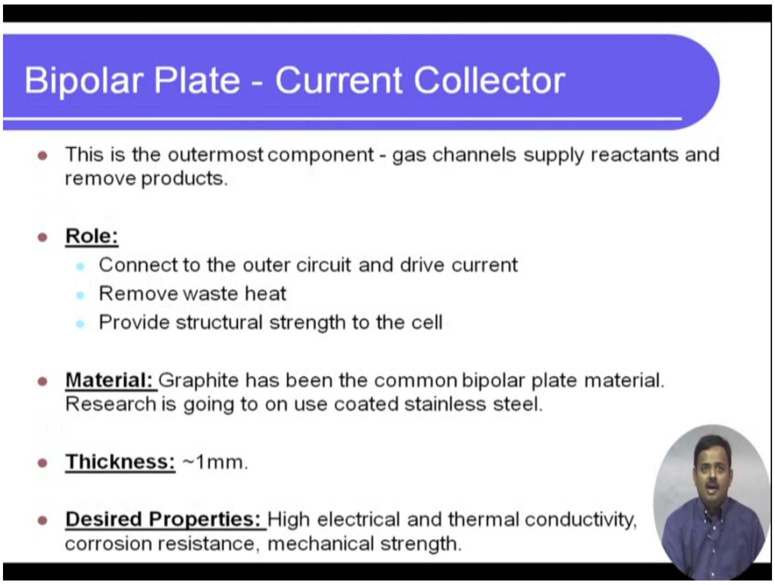

And the bipolar plate is the current collector that role is to connect outer circuits and drive the current it removes a waste heat and it provides structural strength to the cell so this is a thickest part which is 1 millimeter and as I said on both sides of the bipolar plate because we are sandwiching many of these cells one after the other. The bio polar plates are such that there are channels on both sides in that figure that I showed a few slides back it showed channels only on one side.

Because we were considering one cell with the same bipolar plate will form channels for oxygen on one side and hydrogen for the next set of this next cell. The desired property is high electrical and thermal conductivity corrosion resistance mechanical strength I mean those are it is functions ok.

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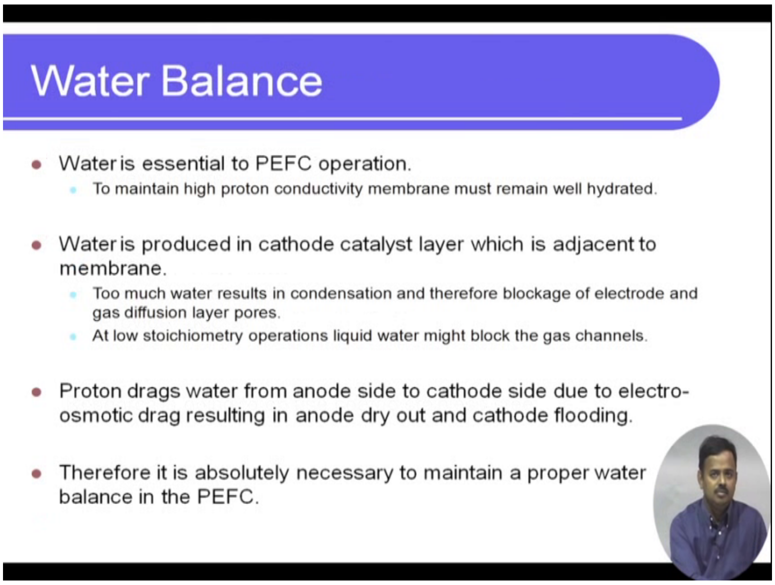

I would just end this by talking a little bit about water balance look water is essential for PEFC operation, the proton membrane has to be proton elect electrolyte membrane proton exchange membrane has to be well hydrated for the movement of the protons, but also the water is produced in the cathode catalyst which is adjacent to the membrane. But if there is too much of water what will happen is there will be blockage of the electrode and gas diffusion layer pores.

So, therefore, it is very very essential to maintain a proper water balance in PEFC and it is also seen I mean given that all the other draw all the other hurdles are crossed we have hydrogen as a source of fuel we have the fuel cell in place during it is functioning one of the big hurdles is this water problem there is water accumulation and if it is not removed properly then it can lead to you know all these other bad things blockage of the electrode the gas diffusion layers even the gas channels also can be blocked with time so these are not good. So, the water while it is necessary to keep the membrane hydrated excess water has to be removed so that the fuel cell functions smoothly alright.

So, with that concluding remark I would end this discussion on fuel cells so here we what we did as part of this discussion was we looked at how a fuel cell works we look at the different characteristics or whatever the different elements of a fuel cell and it is really and it is important functions and what function it achieves and all of these functions come together for a fuel cell to work efficiently and finally we said that even we have all these materials in place we have hydrogen as a fuel we have air as the oxidant during it is functioning one hurdle that comes into picture is accumulation of water so several research groups across the world are actually trying to solve this problem it is important to have some water, but not a whole lot not as much so that it clogs the pores it clogs the channels and prevents the reactions from happening alright.

So, fuel cell therefore I would say is a great invention great discovery using hydrogen it is a clean source that can be used for powering vehicles and at high temperatures and high when we talk about solid oxide fuel cells even people are developing power plants based on fuel cells.

So, definitely it is a great invention, but still for it is widespread implementation and commercialization several hurdles including size, including cost, including materials and very importantly source of steady source of hydrogen as a fuel has to be considered alright, so that kind of brings us to the end of our discussions on hydrogen economy and fuel cells.

I hope this you found this in discussion interesting and learnt a few things and what we will do is in the next lecture we will take up a completely new topic. Till then good bye have a great day.

Thank you very much.