Non-conventional Energy Resources
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Lecture - 35
Fuel Cells Concept to Product

Hello, in today's class we are going to look at fuel cells from concept to product. So, I think that's an interesting journey for us to see as part of this course because we talk of so many technologies there is some work that happens in the lab maybe depending on where you are, you are working with one aspect of some technology, but there is a long journey from that you know work that happens in your lab to a product that you see that is being deployed.

So, there are many more steps then maybe are covered in this class, but it does give you my expectation is that it will give you an idea of what is involved when you know see when you read something in a textbook, when you try out an initial experiment in your lab. And then from there what are the kinds of steps and thought processes that are involved as you try and make a product out of it. So, this is our journey today which is fuel cells concept to product.

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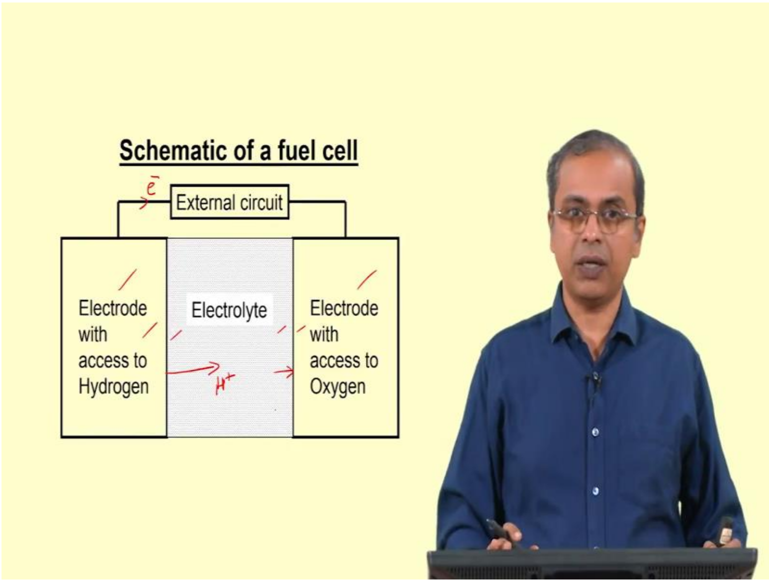

So, this is a schematic of a fuel cell. So, you can see here we have electrode with the access to hydrogen and so, that's something that is one of the; I mean basic requirements for a fuel cell and there is an electrode with access to oxygen. So, basically all you are doing is you are taking hydrogen and you are reacting it with oxygen. So, that's all the fuel cell does at least in one one of the versions of it the most common version that people tend to discuss. So, there's a hydrogen or some fuel and then it reacts with oxygen and generates energy and it also gets the fuel also gets oxidized. So, that's the general process that is involved.

So, the only, so in principle you can actually just burn hydrogen in air and use that heat to run some engine. So, so in fact, people do work with you know engines which are you know internal combustion engines where hydrogen is the fuel. So, instead of filling your petrol tank or gasoline tank with the gasoline or petrol or diesel, you would have a tank that is actually filled with hydrogen and this hydrogen is piped to the engine and in the engine it mixes with air and you know combusts generates water as the product and in the process of combustion it runs the engine.

In quite the same way similar to what you see your existing internal combustion engine in your automobile. It would still be a clean way of doing things because your product is water it's not carbon dioxide or carbon monoxide for that matter and therefore, is a clean way of you know generating energy in a manner that is portable and it is also good for the environment. However, we still look at the technologies such as fuel cells because that combustion that I just discussed with you which happens inside an internal combustion engine is basically direct combustion or oxidation in the in the form of a combustion process. Whereas in when you use a fuel cell you are actually doing the oxidation through an electrochemical process as opposed to a chemical process.

So, in the engine you are doing what is referred to as a chemical oxidation which means physically hydrogen mixes with oxygen combust and generates water and energy. In a fuel cell we are doing the same combustion process same reaction between hydrogen and oxygen except that we do not do it in a manner that is described as chemical instead we do it in a manner that is described as electrochemical. So, that may seem like not much of a difference, but actually it is a distinct difference both in terms of how the setup of the fuel setup of this process changes and also most importantly it changes the efficiency of the process.

So, here for example, as I said there is an electrode with access to hydrogen and an electrode with access to oxygen. So, importantly hydrogen and oxygen do not directly mix in a fuel cell as opposed to become a direct mixture of these two inside an engine in an internal combustion engine. Instead we are now, splitting this reaction into two parts there is a part that where hydrogen reacts independently with an electrode and then you have protons moving through this electrolyte H plus that moves through this electrolyte. And arrives at the other electrode which is the oxygen electrode and in that process it react, now reacts with oxygen with some electrons appearing in the external circuit and that is how you operate the system.

So, this transfer of charge between an electrode phase and an electrolyte phase that is between this electrode phase and this electrolyte phase this chance for transfer of charge similarly transfer of charge between this electrolyte location here, and the electrode location here. This transfer of charge is what is ending up in resulting in this reaction being referred to as an electrochemical reaction. And the big difference between this and the other combustion process that we previously discussed is that the normal combustion process of an IC engine is limited by the efficiency of a Carnot cycle which basically means that you know you are roughly leveling off at about twenty percent efficiency of energy that you can get out of the reaction which you can usefully use somewhere else.

Whereas here when you do it electrochemically just the electrical efficiency itself would put you at 40 percent plus or maybe even more than that, and then when you take the heat and other things included into the process you are looking at efficiencies which may even hit close to 80 percent. So, you have much higher efficiencies possible with the same amount of fuel. So, you could go twice the distance for even 3 times the distance etcetera with the same amount of you simply because it’s a more efficient process. So, this is the schematic of a fuel cell, this is the kind of diagram that you would see in a textbook and significant amount of explanation on what is happening in the fuel cell.

So, we will start from here and we will take this as a starting point and see how we can move till we get a product at the end of it.

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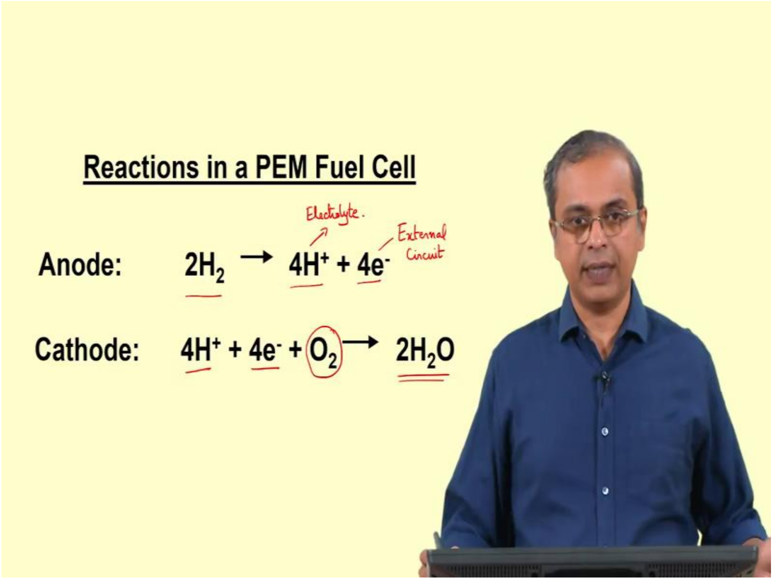

So, as I mentioned at the anode there, there is a reaction you have two hydrogen molecules they give you 4 protons H plus is a proton because once you remove the electron you only have a proton and electron in a in a hydrogen atom. So, once you remove the electron you are left with only a proton. So, the 4 H plus are just basically 4 protons and 4 electrons.

These 4 electrons are traveling through the external circuit, whereas this H plus is traveling through the electrolyte. So, once this journey completes the H plus that arrives through the electrolyte and the 4e minus which arrives through the external circuit react with oxygen and you generate water. So, this is the reaction that happens in a fuel cell and in that process energy is released for us for useful activity.

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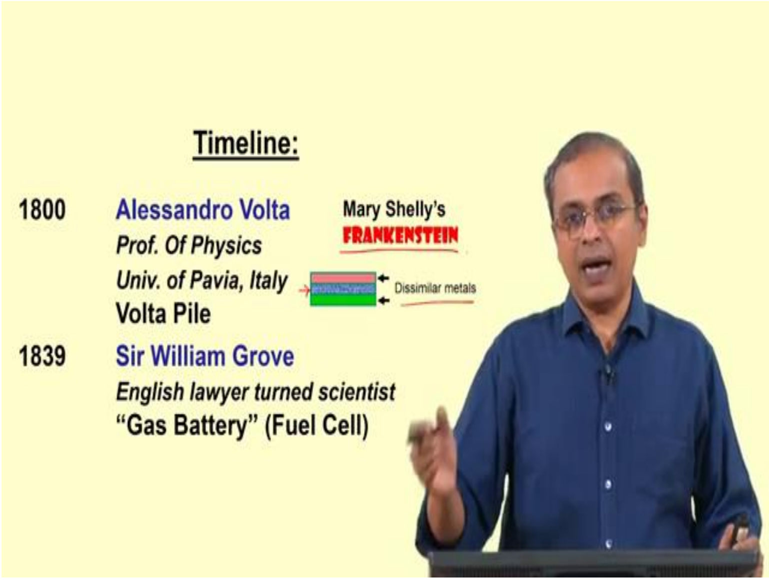

So, let's look briefly at the timeline of this kind of a technology and how it has evolved. So, if you look at the timeline it traces itself back to the 1800s where initial experiments were made which result in resulted in what we are now, referring to as the battery the original batteries that appeared.

So, the credit for this goes to Alexandro Volta. So, he is the one who created this battery that we you know at his the first version of the battery that we currently use. It's a very interesting history in the sense that at that point in time there was a lot of discussion going on between Galvani the other famous personality in this topic and Volta. And it was it it was it was centered around this experiment that Galvani had a chanced upon where he found that the limbs, limbs of dead animals such as frogs could get to twitch when they were touched by the different metals there was no clear understanding as to why it was twitching due to the you know presence of these other metals. But the conclusion that Galvani drew was that there was some life force inside this the leg which was in the form of electricity and that was what was getting the legs to twitch.

Volta had another view he said that the electricity was not coming from inside, but it was coming from outside and it had to do with the kinds of metals that were used to contact that dead frogs leg. So, he created this Volta pi where he basically had two dissimilar metals one on top and one in the bottom, and he had a a material in the middle which was basically something like a cloth which was soaked in brine solution basically salt kind of solution.

And in this process he had several of them stacked up and the stack has. Now, become famously referred to as the Volta pile this is the first you know demonstration of a battery in action. And he was very successful in doing it and therefore, he is credited with this invention. The interesting you know aside of this whole story and activity is that this discussion between Volta and Galvani about what was this life force and you know this idea that a dead animals leg could get to twitch because of electrical signals, resulted in this famous story book which I am sure at least you have heard of even if you have not read it called Frankenstein written by Mary Shelly. It was written around that time and her inspiration for that book was this discussion between Volta and Galvin.

So, in any case that is in the 1800s and that’s the story behind the battery and an interesting story associated with that story. After that and around the year 1839s, William Grove, Sir William Grove who was an English lawyer turned scientist maybe perhaps these days there are maybe scientists who turn into lawyers, but in those days there were people with wide range of different backgrounds who also had keen interest in science and therefore, dabbled along with different experiments.

So, he was a lawyer who dabbled along with certain experiments and he created a version of this battery which he referred to as the gas battery and that had to do with the fact that the reactants were gases and he could still generate electricity out of it. And this gets gas battery that he created is the original version of the fuel cell that we are talking about and today what we have is essentially traces itself back to this first demonstration of this gas battery.

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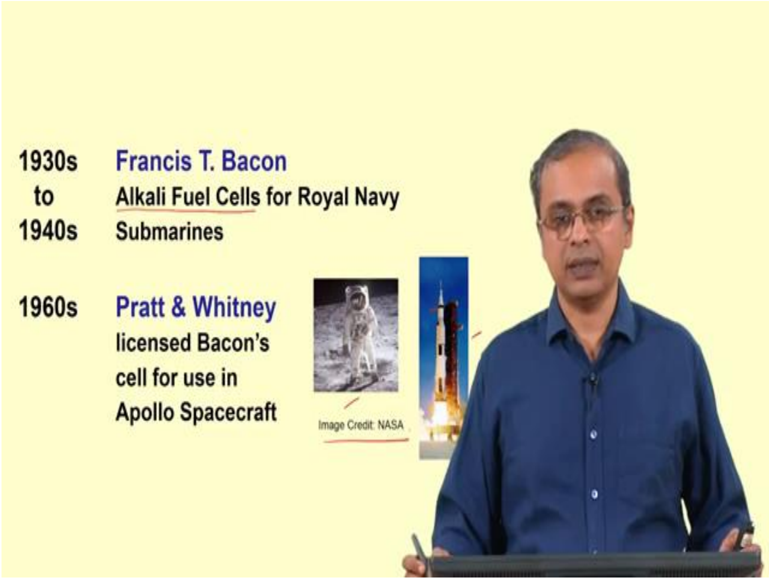

If you look it took about 100 years you know of lot of things going on in the background well about a 100 years went by before this fuel cell technology began to get used in any sense in any grand scale so to speak.

So, in the 1930s and 1940s these fuel cells or one version of the fuel cell referred to as the alkali fuel cell began to get used for the royal navy for their submarines. So, I mean one of the nice things about the fuel cell is that it's a very quiet power source, it does not create any noise and therefore, is particularly useful in military you know utilities where they want complete silence where they don't want to be you know detected. So, it was used extensively for the royal navy submarines and was the first you know one version of it which is credited to bacon was then used for these submarines.

And in the 1960s very famously it was the same fuel cell which was used by the royal navy the same kind of fuel cell which is credited to bacon, the Pratt and Whitney licensed this, but took the license for this bacon cell and used it for the space program. So, the people who walked on the surface of the moon the only people who walked on the surface of the moon used spacecraft where one aspect of the power of that spacecraft which was the Apollo 11 spacecraft the satellites associated with those spacecrafts which was which were the modules in which these astronauts traveled one aspect of the power for those satellites was provided by fuel cells. Those fuel cells where these alkali fuel cells the product of the fuel cell was water and so that was actually clean water. So, it could actually even be used for drinking purposes.

So, this was the combination that was used. This you can see here is an image of the Saturn rocket launch system and that's the image of people on the moon, of course, credit for the both these images goes to NASA. So, this is this is something which if you go and look up a history of space flight you will find fuel cells a manned space flight you will find fuel cells have played a very critical role in this.

Also as an aside if you watch the movie Apollo 13 the one of the critical issues that happens in that movie or that if you read up about Apollo 13 you will find that the issue that occurred during that flight was also associated with the one of the supply sources for a fuel cell so that's just an interesting aside if you are interested please look it up and you will get some interesting information on how it was handled and how the fuel cell played a role there.

So, in any case, this was the progression of the development of your cell still till about 1960s.

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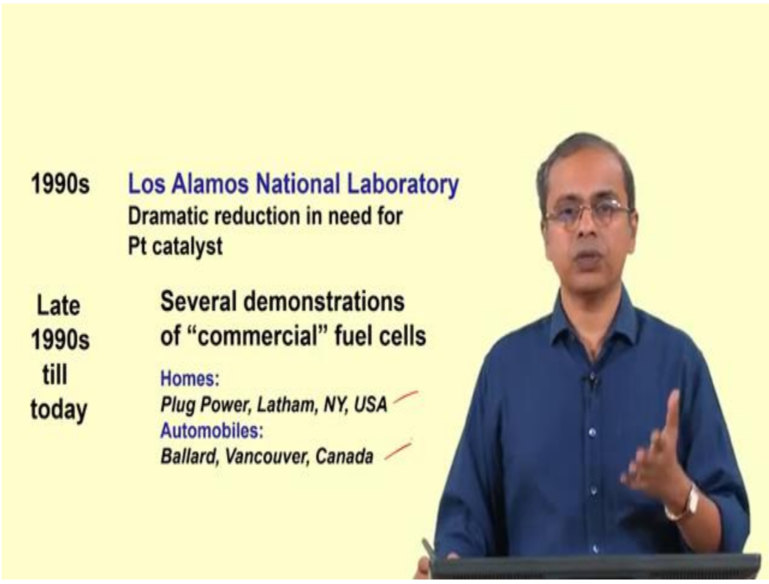

If you take it forward one of the critical aspects of the development of the fuel cell or the limitation in the development of the fuel cell lay with the fact that the electrodes being used for the fuel cells had catalysts in them. Generally speaking the catalyst being used were you know noble metals or precious metals typically platinum was the catalyst that was being used, and platinum is inherently very expensive.

So, so it was always felt that you know you could use this only for specialized purposes you may never be able to use it for mass market purposes because so much platinum was necessary. And so so people were you know just doing research because they felt maybe there was a possibility that something could be done, but this was one you know one roadblock so to speak that they had to overcome.

So, in the 1990s it turned out that scientists working at the Los Alamos National Lab figured out a way in which you could get the same kind of a performance from a fuel cell with a lot less platinum. You know more than an order of magnitude less platinum in fact, 40 times less amount of platinum they could use and still get the same kind of current densities that fuel cells previously had been demonstrating. That breakthrough really made a difference because that suddenly made it possible to look at fuel cells from a mass market perspective that at least you know there was at least a hope that it could be used for mass market perspectives.

Even now, the I mean the cost issues associated with the fuel cell have not been completely overcome there are still issues that have to be worked on and dealt with, but still this has this was one promising step in the right direction. So, since late 1990s still today till date there have been several companies which have tried to make commercially available fuel cells. In other words fuel cells that have in some ways the possibility of standing on their own in a commercial sense where in you know the cost of the product is recovered during the usage of the product and some profit is made in the process as well.

So, many companies have been around I have just listed a couple of them which were notable in the sense that they were the early companies that started working on it. One is based in New York it’s called plug power, it has tended to focus on residential type of applications or stationary applications in a more general sense. So, a fuel cell that could be used for a house or you know office or you know or you know let’s say a hospital or something like that and that’s the kind of application that they have looked at and at least in the earlier days of their operation and the other company is based of Canada called Ballard they are still significant players in this arena. And they have tended to focus on the automotive sector of the fuel cell I mean nothing prevents either of them from looking at other sectors. But this is generally how they have tended to be in the artists in the early stages of their development.

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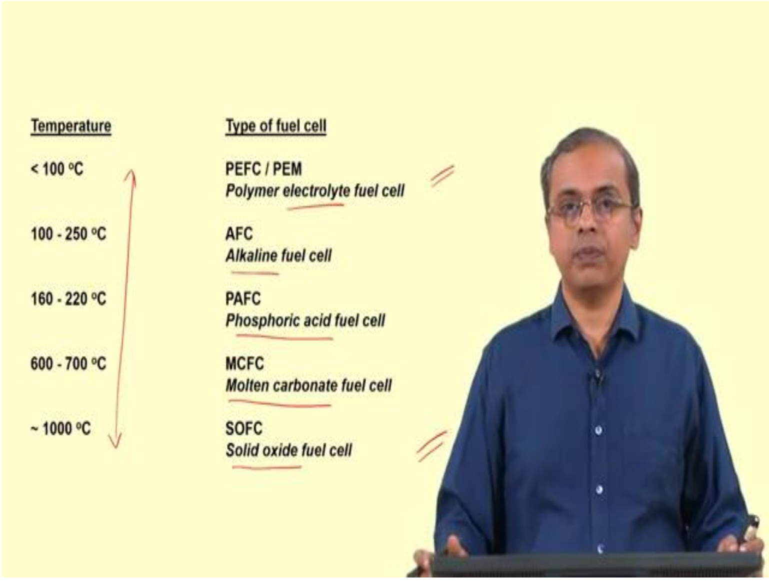

So, there are various types of fuel cells and in another class I discussed them in great detail. But just to give you an idea this is just a table that shows you a wide range of fuel cells. Conceptually they are all the same there is an electrolyte and there are two electrodes and both of them have access to gas and then you generate electricity.

The real difference between these fuel cells that you see here is the choice of electrolyte. So, the electrolyte is different in each case and that's the real difference between these fuel cells. That may not seem like much because the electrolyte actually does not generate any electricity it simply completes the circuit for one of the components of that fuel cell which is the ion that is moving along.

But the choice of the electrolyte decides the temperature of operation that you see here, this entire scheme of temperature of operation that you see here this temperature of operation is primarily decided by the choice of the electrolyte because it is you need to get to these temperatures for that electrolyte to conduct that ion at a reasonable rate ok. So, whatever ion it is conducting as an electrolyte has to be conducted at a reasonable rate only then the circuit will complete and you can generate current at a reasonable rate.

Otherwise you simply have buildup of charge and then it's just not you know transferring the current in a you know reasonable rate. So, you will never be able to use it. So, the rate at which the ion is transferred is dependent on the temperature and typically the higher the temperature the faster the transfer of the ion or faster the conductivity of the ion in that electrolyte. And based on the electrolyte material the temperature you have to reach for it to be reasonably good conductivity to maintain you know sustain good current in the external circuit happens to be what you see on your left hand side of your of the slide that you are seeing right now.

So, I will discuss this in greater detail in another in another class, but you can see that there is a wide range of temperatures here starting from less than 100 degree C to over 1000 degree C. Each of these fuel cells differs from the other in terms of what are some strong points of them what are some weak points, what are some challenges associated with developing those fuel cells and maybe the kind of application where they are better suited to you know be applied.

So, these kinds of challenges are there and in fact so if you decide to work on the in the field of fuel cell based on which fuel cell you select to work on chances are you will have a certain range of challenges that you have to work on. Mostly the first and the last that you see here are the ones that are being worked on extensively in many fuel cell companies and research groups and in fact, maybe perhaps much more the first one because you can envision even room temperature usage with it. The solid oxide fuel cell gets looked at more from the perspective of a very large scale power generation which is at a stationary location, but they all have some issues which they have to be which have to be overcome for this technology to really succeed in a large scale ok.

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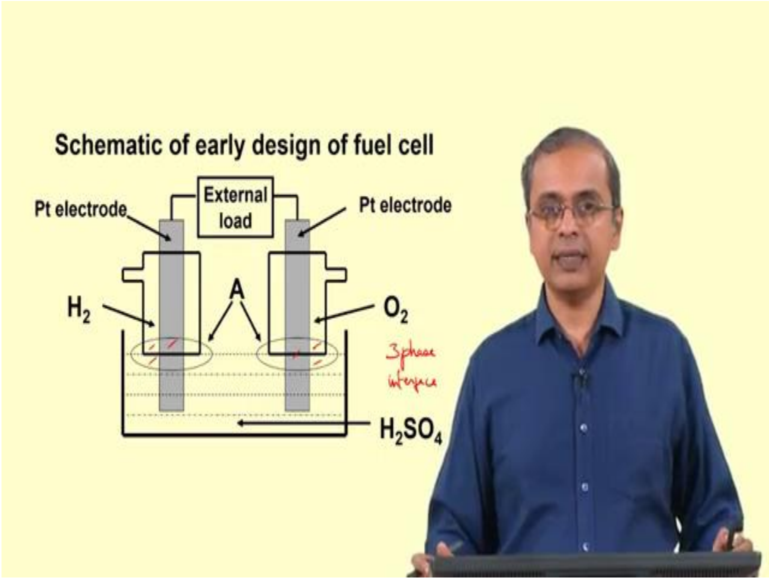

So, now, let’s look at this movement from the concept to product that I kept referring to with this background that I have just given you on how the fuel cell you know historically evolved and where it is now, and also the fact that you have all these types of fuel cells.

I told you at the beginning that William Grove created this gas battery. So, what you see here is a schematic of you know roughly what was being tried at that point in time. So, you have an electrode here which is the platinum electrode on both sides you have a platinum electrode. The electrolyte is basically sulfuric acid which is know, this container containing sulfuric acid. So, you have two platinum electrodes dipped into this sulfuric acid as you can see here. So, you have this electrode here and this electrode here and around 1 electrode you have some kind of a container of this nature here that you see here into which you can flow this hydrogen gas and it fills up that container. And similarly you can flow oxygen gas into this container it fills up this container.

And when you do that you find that you are able to sustain some electricity in the external circuit. So, this is what is happening in the fuel cell in an early attempt to create a fuel cell. So and when you do this when you arrive at this stage you know you have hit upon something because you have now, got a situation where you have two gases which are getting into some region in some controlled manner and you are able to generate some electricity out of it is showing up in your external circuit you are able to sense the electricity in the external circuit.

So, then your next challenge is to see how you can increase the amount of electricity, maybe you are getting some miniscule amount of electricity. So, as a concept you have shown something, but that’s not good enough you want to raise that to a value that is acceptable and you have to define what is acceptable to you what is the amount of current that should come given that you have made this massive setup out there are you satisfied with just getting you know pico amps or nano amps, micro amps would you rather prefer milliamps or amps or even more. So, that’s something that you have to look at.

So, the early researchers tried to see taking this setup in as the background as the basis what should be improved, what should be modified. So, that the current can go, so as it played around with various things say the size of the platinum electrode, the amount of electrolyte that was present maybe you add more electrolyte you add less electrolyte you change the shape of this containers which hold the gas etcetera a lot of things they tried. And then they realized that the current was actually being controlled by this region that you see here that I have marked as A, that region A here and the region A here.

So, the size of this region was what was deciding the current was having the most impact on the current. In other words if they increase this region A, they got more current if they decrease the region A they got less current. So, then they tried to understand what is it that we have got at that region ok. If you look carefully at this region, for example, if I just clear this up if you see at this region you have the gas that is available here. So, that gas is available here you have electrolyte available here and you have electrode available here.

So, you have electrode, electrolyte and the reactant gas all being present here similarly here as well, you have the electrode the gas and the electrolyte all 3 are present. So, the presence of all 3 at one location led to this location being referred to as the 3 phase interface. So, 3 phases are present the gas, the electrode and the electrolyte, so the 3 phase interface. So, 3 phase interface is present there and all the 3 phases are in a position to participate in the reaction.

So, they understood that if you increase the region of 3 phase interface in your cell then you are able to produce more electricity. So, they took this idea and they tried to modify it. So, that you would have a cell where you still have gas coming in you have two gases coming in and you have an electrolyte, but the region where the gas the electrolyte and the electrode are present that region the total area associated with that region was increased significantly.

So, the next version of the fuel cell as they tried to make a product out of it began to look something like this.

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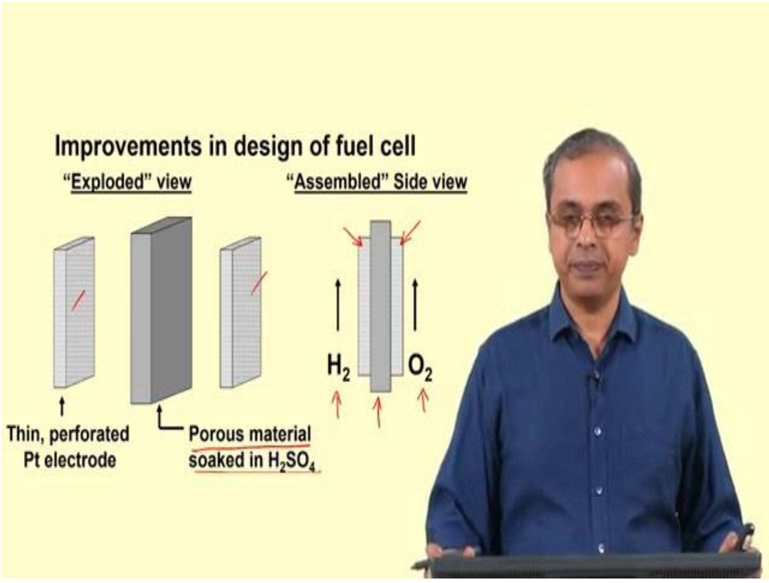

So, whereas, previously you had a beaker containing sulfuric acid, instead they now, came up with a porous material which was soaked in sulfuric acid. So, you suddenly came up with the porous material soaked with sulfuric acid. And on either side instead of having you know a rod of platinum dipped in sulfuric acid there was actually a perforated thin perforated platinum electrode the thin perforated platinum electrode something like a mesh and that mesh was now, you know you know it was a porous mesh.

So, gas could penetrate into it and when the mesh was pressed against the the electrolyte material the porous electrolyte material then it increased the amount of area over which the electrode electrolyte and the gas were present simultaneously was greatly increased. So, in this manner by simply going from you know the previous design that we had to this design suddenly the amount of 3 phase interface was increased dramatically. So, here in the on the left side which I am calling the exploded view I am showing you the 2 electrodes separately and the electrolyte separately and then on the right side I am simply assembling them together as they would stay assembled in a fuel cell. So, this is how it actually would be you would have hydrogen flowing one side you have oxygen flowing the other side, this is the electrolyte that is present and this is the porous platinum on one side and porous platinum on the other side.

So, this is how these parts come together and they become the assembled fuel cell. So, they have realized that you have already you know improved the fuel cell quite a bit. So, then they studied in this somehow they said ok, look this is the right direction in which we are going let's see if you can improve it even further.

So now, instead of simply having a perforated platinum electrode which was already increasing the area significantly they tried to see if we can increase it even further.

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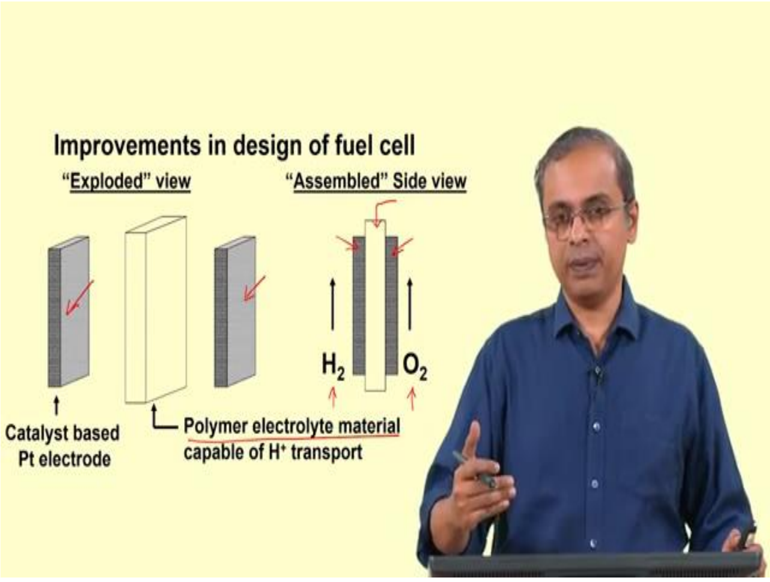

So, to do that what they had what they have done is instead of simply having perforated platinum they had finely powdered platinum. So, this means now, it's the same amount of platinum, but has significantly massively more amount of area associated with it finely powdered platinum which was mixed with the electrolyte and then applied as a paste onto the electrolyte.

And even the electrolyte whereas, previously it was a porous material soaked in sulfuric acid they did have issues with that because the sulfuric acid would evaporate or you know it would eventually leave the it would leak out of that separator etcetera. So, instead of that they now, came up with a polymer electrolyte which was capable of proton transfer, so capable of transporting protons. So, and there are electrolytes like that you can create you can synthesize the polymers which have groups in them which will permit the proton to keep moving from location to location. So, it take such a material that would then be your electrolyte.

And on either side of it you put a structure like this which basically has a mix of that electrolyte as well as this finely divided platinum. And then you also make it such that this structure that you see here is a very porous structure it is not a very you know solid structure it's a very porous structure. So, when you have such a porous structure with finely divided platinum in it and also a fair amount of you know the polymer electrolyte in it. You have dramatically increased the amount of 3 phase interface because gas is able to go into the pores when it goes into the pores it sees a mix of the finely divided platinum as well as the mixed polymer electrolyte which is present inside the electrode itself and therefore, you have a very dramatically increased the 3 phase interface.

So, again a very similar you know assembled side view that you see here except that now, you have here an electrolyte which is polymer it is not something soaked in sulfuric acid and you have 2 electrodes here which are both a mix of finely divided platinum and some polymer the same polymer that has been used in the electrode electrolyte as far as it's a porous structure. So, this is how it is now, in a steadily progressed from two solid electrodes I dipped in sulfuric acid to now, material to a construction where you have a polymer electrolyte with you know extremely porous electrodes on either side.

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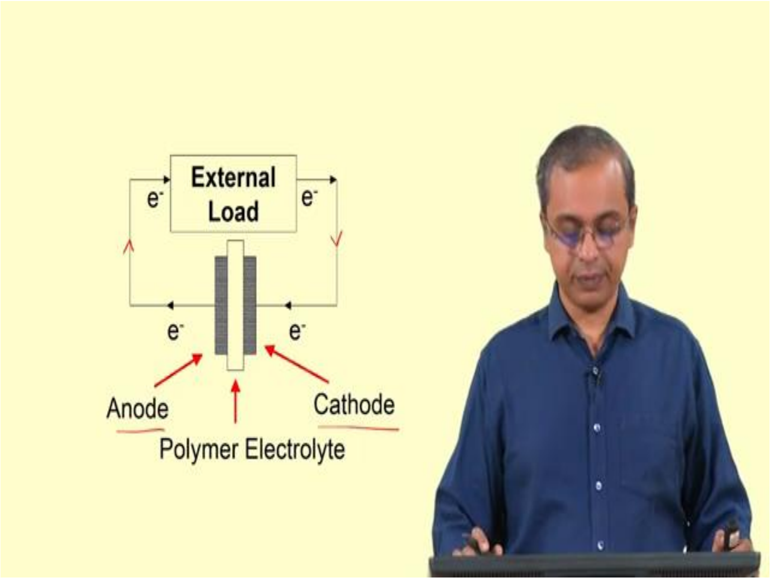

So, this is the version the current versions of the fuel cell that are there in the market that people are you know sort of investigating or working on scientifically in the lab basically has this construction.

So, today's fuel cell has this construction may maybe if you are interested in research in this area you can think if there are ways to further improve it. But the current you know structure that is used for a fuel cell is basically this structure that I just described you consisting of a polymer electrolyte an anode and a cathode which are both again mix of polymer electrolyte plus finely divided catalyst and made in a porous structure.

When this operates you have electrons being released into the external circuit from the anode and these electrons then travel through the external circuit then they carry out some work for you maybe power your fan, or power a ceiling light or whatever it is and then find their way back to the cathode. At the cathode they complete the reaction and therefore, your electrical chemical reaction is complete. So, this is the you know scheme in which the fuel cell operates these days.

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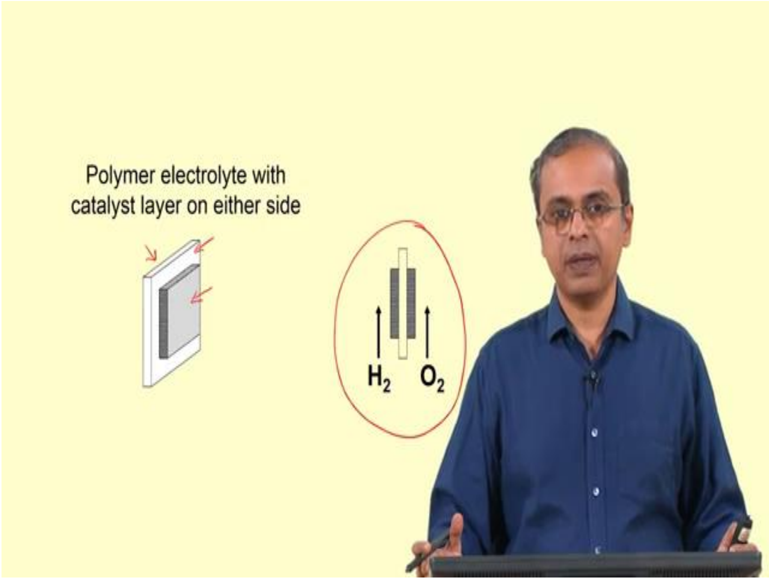

Now, this is again you know the same structure that I just showed you, you have a polymer electrolyte and your I am just showing you one electrode this side there's another electrode on the other side which is not visible in this image and that is visible in this side view that you assemble side view that you see here.

Now, although I can show you or described to you a setup like this where I say you know this is the polymer electrolyte with catalyst on either side and you simply have to flow gases on either side that is not how you can actually run this as a technology. So, I cannot simply hold this polymer electrolyte in my hand, I cannot just hold it in my hand and then have a hose have one person hold a hose which sends oxygen on one side another person who holds the hose and send you know hydrogen from the other side and then loosely holds onto wires and then generate electricity.

So, that is not how it happens you need to have some set up where you can you know do this for this entire process in a very controlled manner and then generate your electricity. So, your gas flow has to be controlled you cannot just have two gases mixing in air right there in front of you and you cannot be holding this. So, although all that I have described to you so far is what is typically tested or considered as a concept in the lab you need many more steps than this and many more parts than this before it can become a product and the next several minutes we will look at those steps.

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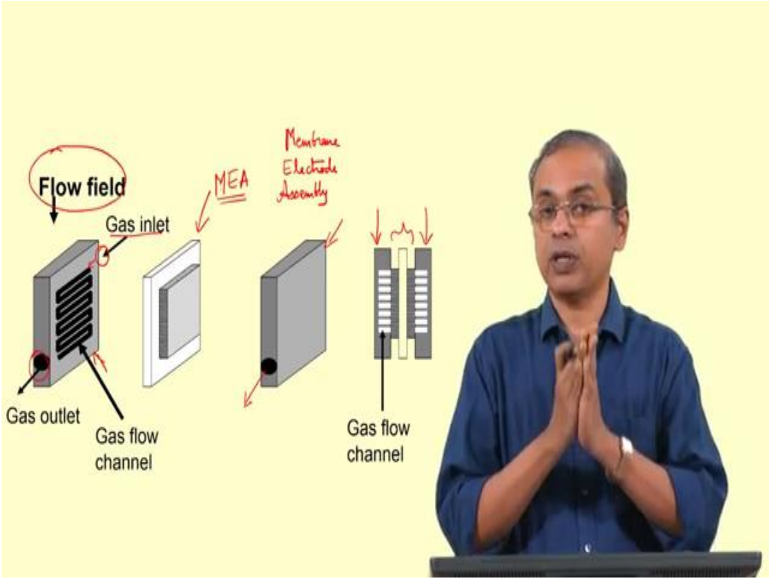

So, the first thing is as I said you need to know how to control the flow of gas on either side of the central unit which is this assembly we need to know how to control the gas. And that is associated with the central unit which is this assembly here that I refer to as the proton exchange polymer electrolyte membrane or proton exchange membrane based fuel cell and this assembly is referred to as the MEA it stands for membrane electrode assembly MEA; or membrane electrode assembly and on either side of it you have to now, put this unit referred to as the flow field.

The flow field typically is you know something like a graphite block which is what you see here some kind of a graphite block into which a channel has been you know engraved. So, you engrave a channel into it and there is an opening on this side here as well as an opening here that you see here through which the gas can come in and flow through that flow channel and come out the exit ok. So, this can you can treat this here as the gas inlet gas enters this flow channel it flows through the channel and it comes out of the exit. So, that's what you would do.

So, so now, you certainly have controlled flow of gas you have a situation where you know the gas is not all over the place you can take a hose or a tube and connect it to this inlet and from the bottle you will have gas going through this flow channel and it will come out the exit. Similarly on the other side you can have say oxygen coming out this way oxygen going in this way, and so if you have hydrogen on your left hand side you can have oxygen on the right hand side and you suddenly have a much controlled setup over way through which the gas flows in the system.

So, if you look here on your right hand side you have the same thing as I said you know I am following the same scheme of showing you the assembled a fuel cell on on this side. So, now, in addition to the membrane electrode assembly which is sitting here I now, have the two flow fields and you can see the channels through which the gas would flow ok. So, suddenly you have a much better structure something that looks as a as a product that you can start beginning to look at and handoff. But still we still have some steps to go which is what we will see. You can I am now, going to enlarge one region of this cell, I am going to highlight one region of the cell which is what you see here and I am going to enlarge it.

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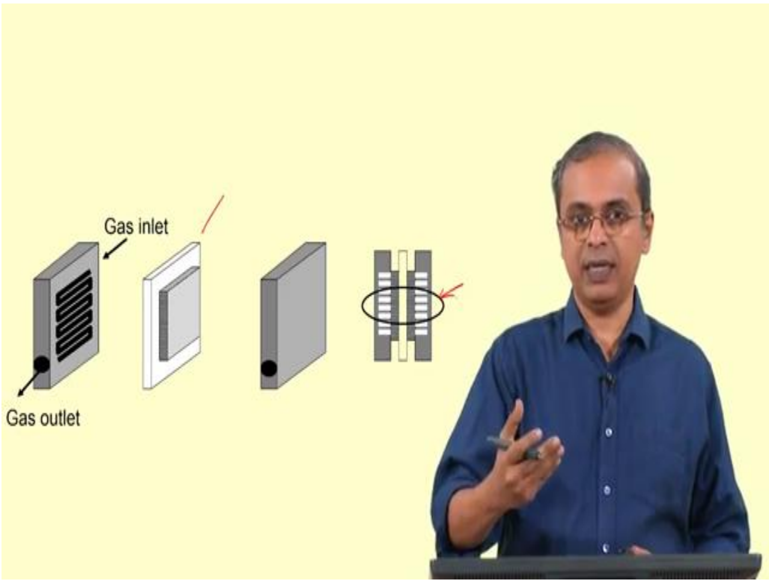

And specifically enlarge it because that will help you understand one issue associated with that region which is what helps us to you know understand what else we need to put into the structure, so that its starts working as well as we feel it should work.

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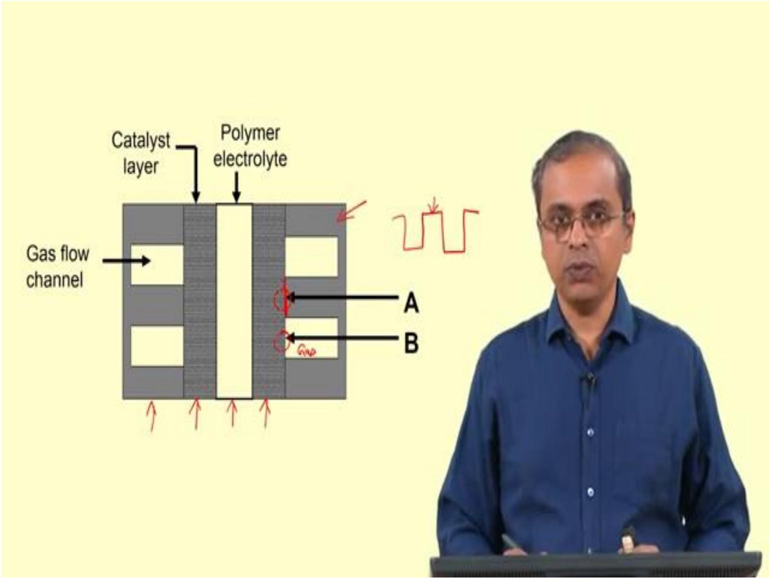

So, if I magnify this you will see here this is the flow field, this is the electrode, another electrode another flow field and this is the membrane, so this is what you have here. Now, if you look at it this flow field contacts the electrode at two locations A and B. Now, at B the difference between these two locations is that at B there is a lot of gas acess. So, gas is available here. So, there’s plenty of gas axis to B, the catalyst particles at B. So, they are able to generate a lot of electricity.

However, the catalyst particles at a have no access to gas because this what we refer to as the land area, land area of the flow channel. So if you have a flow channel that looks like this top part would be referred to as the land area which is what you which is, now, in the vertical disposition is sitting here this land area has no access to gas because there is no flow path for the gas. So, therefore, the location A has almost no access to gas location B has plenty of access to gas.

However, if you look at the other part of this requirement which is that once the electricity is generated the electrons have to find a path to the external circuit you find that the region A has a situation where the catalyst is an excellent contact with the gas flow field. And therefore, the electrons can very easily travel in and out of this region whereas, the region B has a situation where it doesn’t have good contact with the external flow field.

So, electrons generated in the region B will have a difficult time to get to the external circuit. So, you will still have some current coming off of this kind of a setup, but it is still not as good as you would like it to be. So, therefore, we look at ways to improve the situation. So, you want better conductivity at region B without lack of without loss of gas access you want better a gas access in contact in location A without loss of conductivity.

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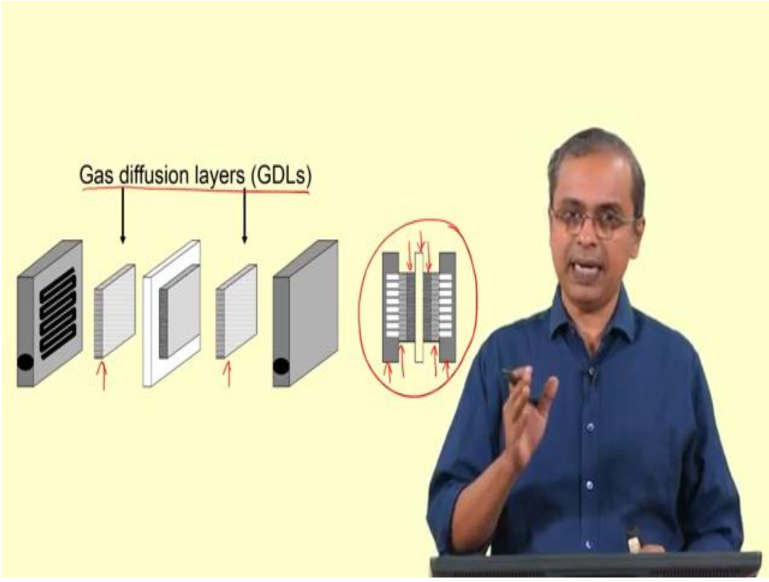

So, the best way you can do it is to introduce one more layer referred to as the gas diffusion layer on either side of the cell, ok. So, we introduced something called the gas diffusion layer and these are simply porous materials could be made out of you know carbon fibers which have good conductivity and also good porosity. So, if you now, look at this assembled view it looks something like what you see here.

So, you suddenly have now, more parts here you have flow channels on either side then you have the gas diffusion layers on either side then the two electron electrodes and right in the middle you have the electrolyte. So, we have now, added more parts to create this assembled fuel cell which helps us deal with a wide range of requirements ok. So, so that is what we have done here.

So, I will again magnify the same region just to show you what we have accomplished by adding these gas diffusion layers.

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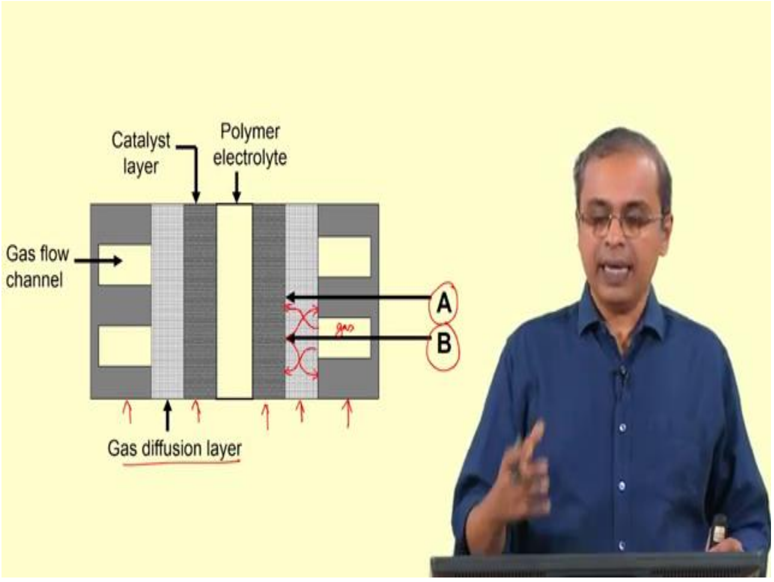

So, if you now, go back to the same region I have whereas, previously this electrode was directly in contact with this gas flow channel we now, have in the middle a gas diffusion layer. The same is true on this side you have the catalyst layer you have the gas diffusion layer that is marked here and then you have the flow channel ok. So, so this is what we have accomplished.

So, now, look at the same two regions A and B. So, although you have gas here this gas is in a position to diffuse to all regions, right. So, the gas is now, able to diffuse to all regions along the surface of the electrode and therefore, not just B, but also locations adjacent to A get sufficient access to gas. So, gas access is not an issue we then look at for example, the region B if you have electricity generated in region B it is able to find its way back to this flow channel through this mesh which is a conducting mesh ok. So, you have an electronically conducting mesh which is able to transfer electrons from the electrode to the gas flow channel and the same mesh because it is porous is able to transfer gas from the flow channel to the electrode.

So, since it is able to serve both these purposes suddenly both region A as well as region B are able to comfortably participate in the process of generation of electricity. Therefore this structure is now, much better suited for generating electricity as a standalone unit. Indeed today's a fuel cell technology the extent of fuel cell technology is broadly based on this structure, at least the main the version of the fuel cell which is used for low temperature applications which is the proton exchange membrane fuel cell PEM fuel cell version of the fuel cell essentially uses this structure. And it is this structure that is you know takes into account all the issues that this kind of a fuel cell design requires.

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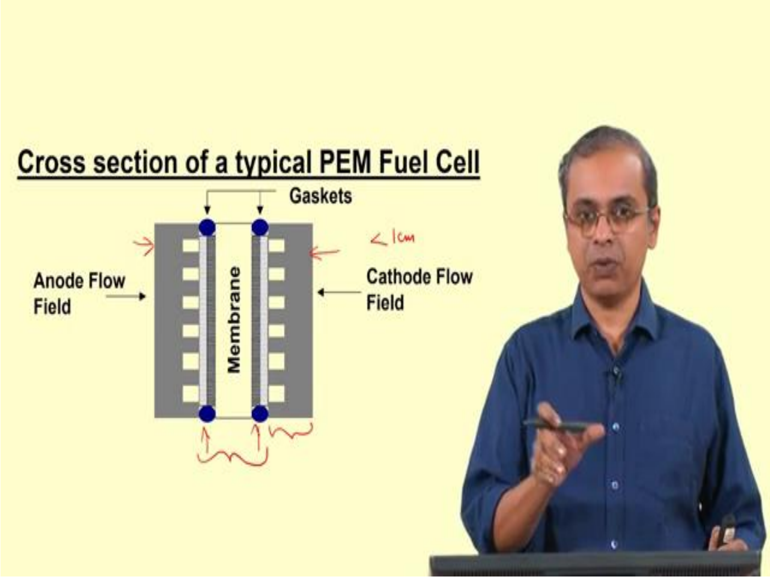

So, now we are now, closer to a technology. So, we are just a few steps away from you know having the complete cell put together so to speak, and you can see here the only other point that was missing there was the gasket. So, you do need a gasket and I am just showing you the gaskets here. These are gaskets that ensure that there is sealing and there is no you know leak of gas on either the fuel side of it or the oxygen side of the fuel cell. So, that is something that you will have.

I also want to you know draw your attention to something that maybe this figure does not completely convey to you, and that is the dimension associated with this system I have drawn these as large components. So, that they are visually easy for you to look at, but actually in a real fuel cell you are looking at this membrane electrode combination from here to here which has the 2 GDLs, 2 electrodes and membrane that entire unit is likely to be just about you know 2 or 3 millimeters thick if at all maybe even less than that you know. So, just a couple of millimeters thick is what you are looking at this entire setup. So, it will look very thin it is some it's like a membrane that you can hold in your hand and it will flutter in the air. So, to speak it's a very thin membrane on either side of which you put this catalyst the catalyst layers as well as the GDS.

The flow channels themselves are typically only about you know say 4 or 5 millimeters thick. So, you are looking at an entire or even less maybe. So, you are looking at an entire set up here where this whole structure that you see here from here till here is less than about a centimeter, maybe less than a centimeter 1 centimeter, less than 1 centimeter thick. So, even if you put in 100 such cells together that would just be 1 meter long ok. So, so that's the point that I wanted to highlight which is perhaps not immediately evident to you from this image because I have drawn things in a very large scale ok.

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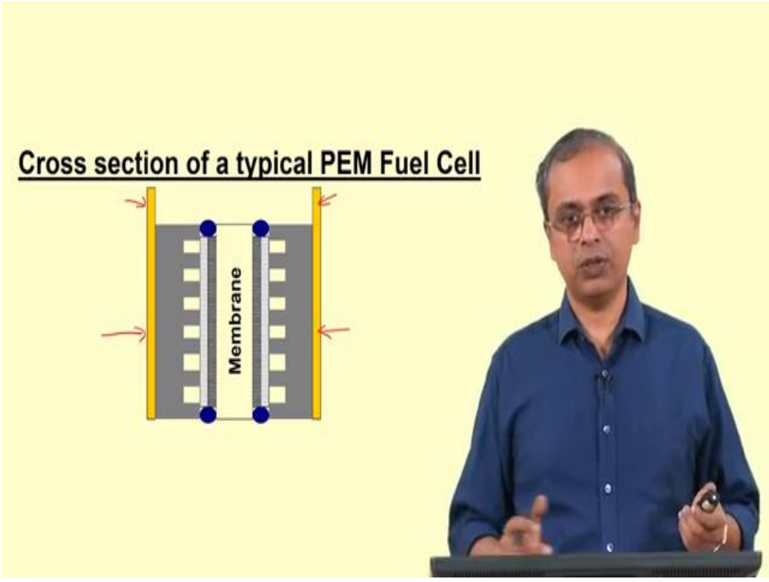

So, I just want to show how you know this single cell in in in many ways the fuel cell has this basic idea which is similar to what you would see in you know batteries which is that you know you use a single you know double A battery or a triple A battery which would then be referred to as a single cell for certain applications. But if you want to run a larger you know activity with it you would put several such cells in series or parallel right.

So, that's a similar concept like that exists with respect to fuel cells you would need to put several of these in series or parallel for you to actually handle a much larger you know output to generate a much larger output for some application which requires a larger output ok. So, although the only thing I have added in this figure which was not there in the previous figure are these two things on either side which is the current collector which is the which will be are the two ends of the cell, simply to create a you know to connect a which would be a connection to the external circuit. And so that's all that these two units are doing here you just you know connect attach leads to those two points and then you would reach the external circuit.

Now, if you take several of these units and put them in series so that you know you can now, generate you know each of them let's say how generates half a volt and you put know 100 of these together you can get 50 volts right. So, if you want to do something like a your arrangement would look something as you see in your screen here.

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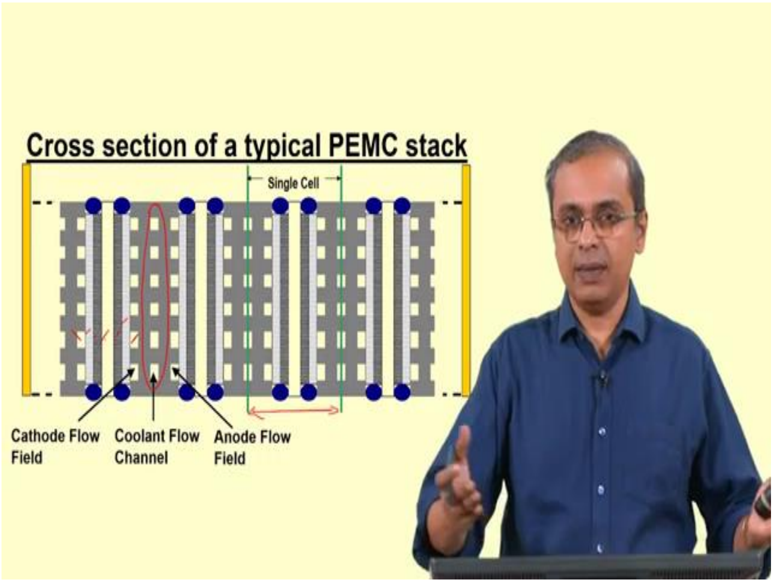

You will have right only are the very extremes of this setup you would actually have the two current collectors in between you will have a whole bunch of these fuel cells stacked one against the other.

And hence this is referred to as a PEM fuel cell stack proton exchange membrane fuel cell stack okay. So, PEMC fuel cell stack is what you will have here. And while it may not be very evident immediately you basically have for every cell there are several cells here each is a cell here, this is a cell, this is a cell, this is a cell and this is a cell. So, there are 4 cells that you see on your screen and they are all touching each other.

So, some aspects of the common you know region between the cells has been marginally modified, but just to compare against something that you previously saw if you see here what you see between these 2 green lines is what you were previously looking at as a single cell ok. So, you actually have the anode let's say this is the anode, so this is the anode of flow of flow field list. So, this is the if you look at this image here this is the cathode flow field this side you have the anode flow field this side and you have the membrane in the middle and the two electrodes and the 2 GDLs.

What you have in the central region here, is a coolant channel which helps you control the temperature of the stack because as the stack runs it can generate a lot of heat and you need to have some control on it and you can even use that heat for some purpose. And so, you have a coolant running through the channel usually it is water, but they may also try other coolants for various applications. So, this is a fuel cell stack. And this is how the complete system builds from you know the demonstration that I first showed you in the laboratory.

So, we are now, very close to a product and in fact, this is the primary unit that sits in your product as a fuel cell stack.

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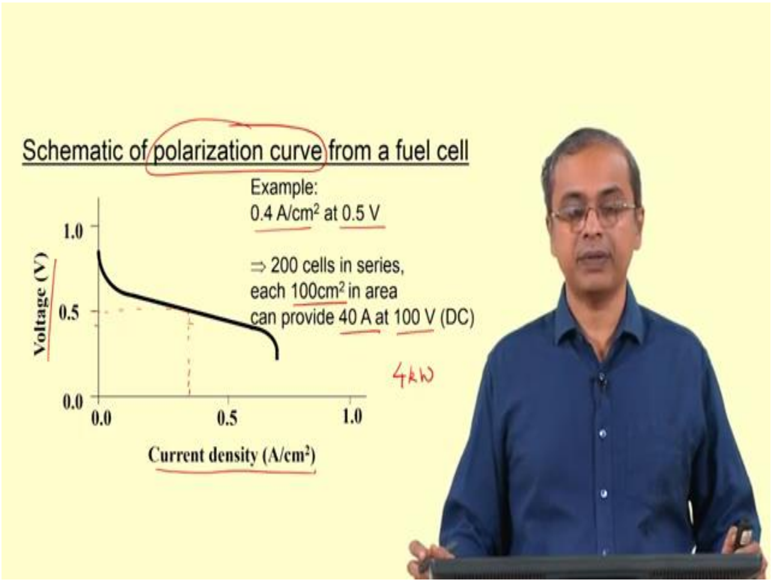

So, for example, if you have some current density from the cell let's say it is 0.4 amps per centimeter square and it's a it has an operating Voltage of 0.5 volt, this is something that is referred to as a polarization curve from the fuel cell and we will discuss polarization curves in greater detail. But for the moment you please see that this is the performance characteristic of the fuel cell it shows you what kind of Voltages the fuel cell will demonstrate when you draw different amounts of current from it or different amounts of current density from it because it normalizes for the area.

So, for example, at 0.5 volts I am saying that approximately it's generating about 0.4 at or at 0.5 volts here is generating roughly about 0.4 amps per square centimeter. Let's just say that that is the operating point for the fuel cell. So, charge is clear that here. So, that's the 0.5 volts and the 0.4 amps per square centimeter.

So, supposing you have 200 of these cells in series and each of the cell has a 100 centimeter square area, because you have 0.4 amps per square centimeter that will generate 40 amps for you, each cell will generate 40 amperes and then since they are 100, 200 of those cells in series that comes to about 100 volts. So, this will generate 4 kilowatts ok. So, 4 kilowatts of power is going to be generated by this cell by the stack and that is more than adequate to power a household. So, that is the kind of a power density that you are looking at, power that you are looking at.

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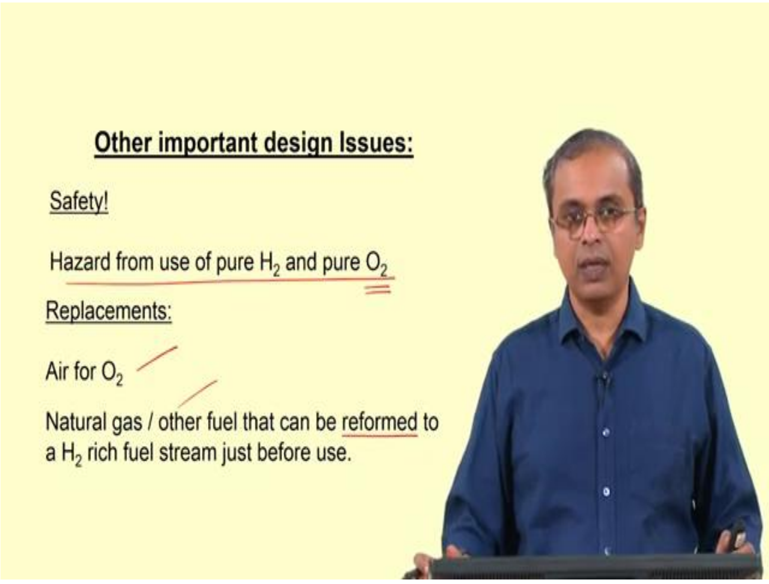

So, a few important design issues associated with this technology. The first is the hazard from the use of pure hydrogen and oxygen. I think a lot of people recognize the hazard associated with the hydrogen. But in in in reality what is true is that any fuel has hazard with it whether it's petroleum, it's gasoline, it's diesel, it's hydrogen, compressed natural gas, all of them have hazard with them because fundamentally they can burn, fundamentally they can oxidized and you can get oxidized and fundamentally there is a lot of energy that they can release. So, you have to handle them carefully.

Also if you take pure oxygen that also has some hazards associated with it because much of what we use is stable at atmospheric condition. And under atmospheric condition, under 1 atmosphere of whatever it is that we breathe that is only 21 percent oxygen it is not 100 percent oxygen. So, when you shift from 21 percent oxygen to 100 percent oxygen and still keep the pressure at say 1 atmosphere you have increased the you know partial pressure of oxygen by a factor of 5. And that can cause certain things which were stable at you know one atmosphere of you know atmospheric air to suddenly be little bit more reactive because they are seeing one atmosphere of pure oxygen. So, you have to be a little bit careful for it.

And therefore, we look at things like a replacement for oxygen, air is often used as a replacement for oxygen and then natural gas or other fuels can often be used as a replacements for hydrogen and in some cases they would need to be reformed before they are used. So, this reforming process and you know fuel processing is is a topic that we discussed in another class, but this is how the you know the the technology comes together.

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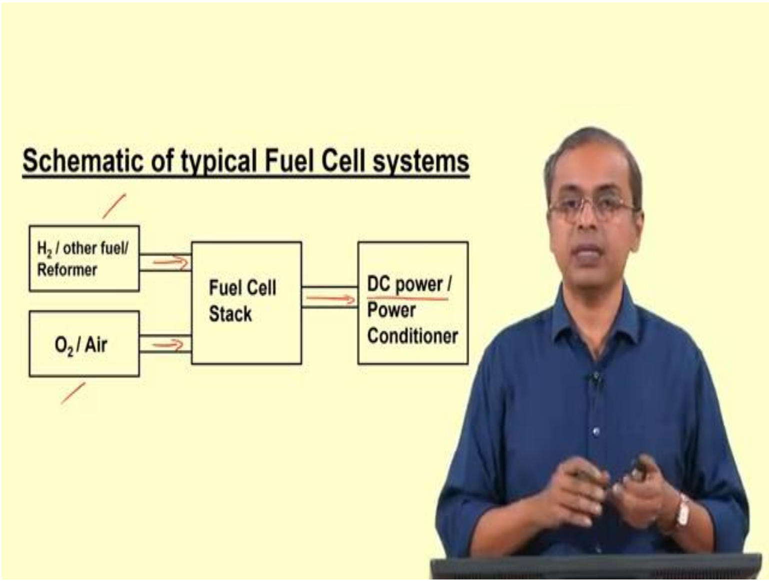

So, this is the overall schematic of the fuel cell and you can see here you can have either hydrogen or other fuel or something that goes through a reformer gets converted to a hydrogen rich stream. And then on the other side you have oxygen or air and both of these are piped into a fuel cell, and the output from the fuel cell is dc power which is what you see here, but in many cases DC power is not what we use in most of our homes are set up to run on AC, so alternating current. So, therefore, we also need an electrical unit which does the conversion from DC to AC.

If that is what is necessary if you have some other set of applications where DC power can directly be used you can directly use the output from the fuel cell with some minor modifications for the Voltage for example. But if you wanted it to be used for any alternating current application you have to do this process of power conditioning which would then get you your AC power.

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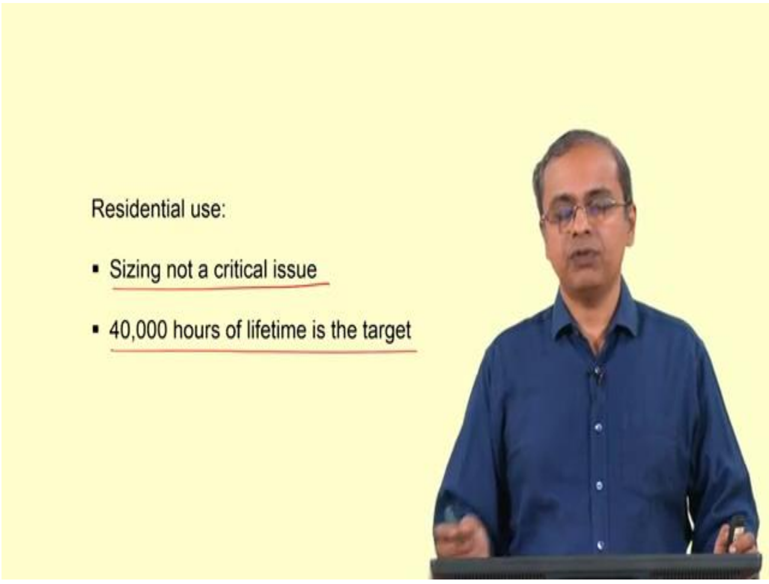

So, I will close with just a couple of comments one on the idea of how this can be used for residential application and another on how this can be used for automotive application.

Now, what we have seen so far is the sequence of you know steps that are involved in moving from concept to product for a fuel cell, and I am hoping that in this in this class you have learnt what is that concept that is there in a fuel cell and what are those steps that have led us from the concept to a product that can actually be deployed.

So, in the case of residential use the couple other points that you have to keep in mind are that generally speaking sizing is not a very critical issue from a residential application. So, many of the companies that look at you know creating this for a residential application are really essentially okay with a unit that is say the size of a refrigerator, the size of a refrigerator or the size of a washing machine these are units that are already there in many of our homes and the assumption is that such a sizing of the product will be completely acceptable to most most of the users.

The target lifetime that people are looking for is about 4,0000 hours of lifetime and if you generally look at you know the number of hours present in a year which is a little over 8000 hours, this is roughly 5 years of operation. So, people would like a fuel cell system to be set up with the sizing of say a refrigerator or a washing machine or some combination thereof that can last for 5 years and generate current for a household for 5 years. So, that's the kind of target and you know ideas that are present when people look at developing fuel cells for residential application.

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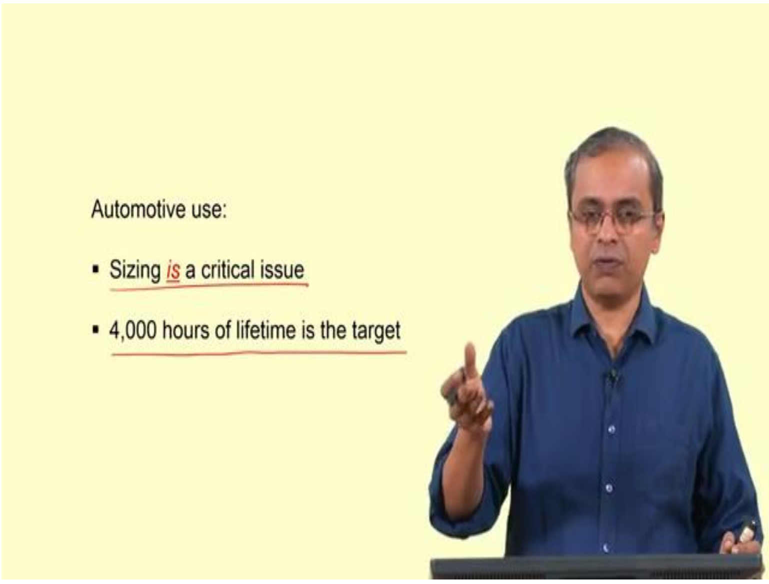

If you look at automotive application, size is a critical issue, it's a very very critical issue because you have a very compact automobile that people are already used to. You cannot put a refrigerator and a washing machine inside an automobile, you don't have that freedom, we don't have that flexibility, you have you know basically the hood of the vehicle and maybe some space in the trunk. You have to leave some space in the trunk for the occupants to also use for other purposes, but between the hood, the trunk and some region under the car that's really all the space that you have.

So, your entire fuel system your gas supply you are a storage tank, your gas supply the fuel cell stack any reforming that you are doing any electrical you know modifications that you are doing everything has to sit compactly within this region and still generate enough power for that vehicle to operate very comparable to a modern automobile. So, sizing is a critical issue for automotive applications, and in this case of automotive applications the lifetime target is about 4,000 hours as opposed to the 4,0000 hours.

If you see 4,000 hours you may think that it's distinctly less than that of a residential application, but that's not the critical issue. If you take a normal automobile let's say it is traveling at on average only let's say between 40 and 50 kilometers per hour, then in 4,000 hours it has you know covered a distance of 160,000 kilometers to 200,000 kilometers which is roughly what we expect as a lifetime for most automobiles.

There are of course, automobiles which done you know million kilometers and so on, but generally you know the mass market automobiles that you are looking at are typically doing between 150,000 to 200, 250,000 kilometers in their life time, during which the engine is actually on essentially for about 4,000 hours. And therefore, if you can show a fuel cell system that can operate for 4,000 hours in a comfortable manner meeting all it's you know operational parameters then you have a fuel cell system that is applicable for automotive applications.

So, in summary in this class we have looked at the journey of fuel cells from concept to product. We have looked at all these steps involved, how the ideas have come together, how they have been incorporated into this fuel cell design such that in the end you have something that can actually deliver power to a specific application. And we have also finished the class by looking at what those kinds of constraints would be from the perspective of a you know residential or stationary application versus that for a automotive or you know mobile application.

So, with this we will conclude this class and look at other topics in another class.

Thank you.

KEYWORDS:

Combustion; Chemical Oxidation; Electrochemical Process; Efficiency of Fuel cell; Internal Combustion Engine; Carnot Cycle; Fuel Cell Time Line; Volta Pile; Gas Battery; Three Phase Interface; Electrode ; Electrolyte; Membrane Electrode Assembly (MEA); Flow Field; Land; Channel; Gas Diffusion Layer; Gasket; Proton Exchange Membrane Fuel Cell (PEMFC); PEMFC stack; Coolant Channel; Polarization Curve; PEMFC Design issues

LECTURE:

The idea of fuel cell s and it’s evolution is discussed with the help of a historical time line. The principle on which it works is illustrated and the stages involved in converting this principle to a product has been elaborated by adding components into the FC assembly. A Fuel cell design that can actually deliver power to a specific application is discussed and the constraints from the perspective of residential or stationary application versus that for a automotive or mobile application is looked into.