Non-conventional Energy Resources
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Lecture - 33
Types of Fuel Cells

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Hello, in this class we will look at types of fuel cells.

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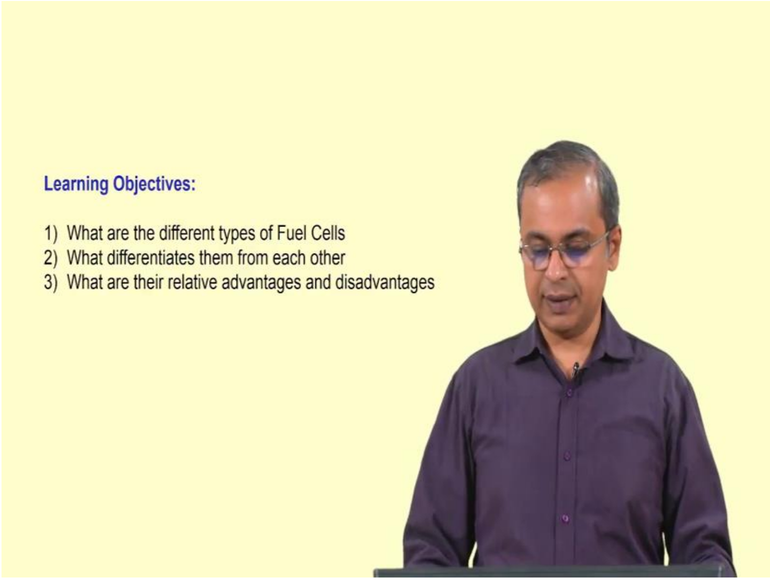

The learning objectives for this class are threefold first we look at what are the different types of fuel cells then we will also see what differentiates them from each other. Because as a technology it seems like it’s the same thing, but there are specific aspects by which one fuel cell or a type of fuel cell differs from the other and so we will try to look at that in some level of detail. And we will close by also looking at what are their you know relative advantages and disadvantages.

Of course, as we go through the material in this class we will see a lot more detail about each type of fuel cell. But this is the broad set of objectives that I would like to you know accomplish as we go through this class.

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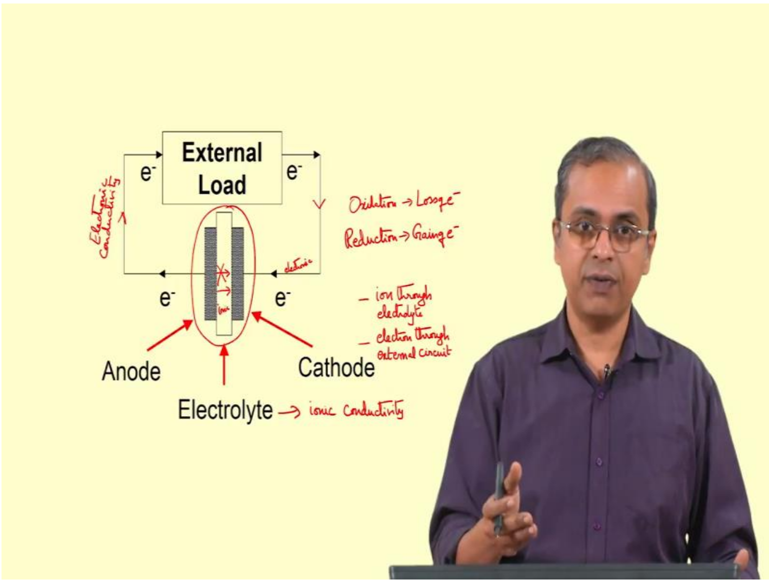

So, on the screen you see a sketch of a fuel cell or a schematic of a fuel cell and so as you broadly know there is you know at the end of the day there is an external load that you are trying to drive. So, that could be anything that could be a fan or a light or you know powering a house or it could be powering an automobile. So, all of that you know whatever is your end use is all clubbed into this you know terminology that we call here as the external load and so that is something that we will is something that we are already using.

The unit that you see here is the simplified actually this entire unit that you see here, is the simplified you know a schematic of the fuel cell. So, that is the primary piece in this entire you know circuit that you see here which is what we are discussing. So, you see that the fuel cell basically consists of 3 parts here, one is the anode that you see here, then there is a cathode which is the this unit here which is marked here, and then in the centre you have the electrolyte.

So, if you look at the 3 major parts of a fuel cell which is the anode, cathode and electrolyte in principle is the same as a battery. So, therefore, I you know in in terms of technology, in terms of science at least the fuel cell is fundamentally the same as that of as that of a battery the science that you know governs the behaviour of a fuel cell many of the you know parameters that are of interest in a fuel cell are essentially the same as what you will see in a battery.

Really the main difference is in the fact that the reactants that are being used here or either gases or liquids whereas, in a typical battery they are solids. So, that's something and we will see that in, so that's something that is the distinction between these two and can also be looked at in greater detail. But that's not the focus of our current discussion, but that is something that we should be aware of.

So, in any case an anode, an electrolyte and a cathode and a typical use of a fuel cell would involve actually having a several of these fuel cells connected in series or parallel and so that would be considered as a stack. So, that's no different from what you do with the battery. So, if you take the remote of your you know television or you know let's say a calculator or any such you know or even a toy electronic toy you see multiple cells which are present inside that toy. If you actually watch it carefully if you follow the circuit carefully you will find that in some cases those cells are connected in series in some cases they are connected in parallel and you can have a combination of these.

So, that combination simply decides what is the current you can have in the circuit and also what is the voltage you can have in the circuit. So, that combination is then decided by how you have arranged these cells in series and parallel and therefore, that also decides the power that is available in the circuit. And the power is usually a critical parameter that decides whether or not your external load is going to be able to function given that you have attached this power supply to it ok. So, that's the basic idea and typically a anode is where the oxidation reaction takes place.

So, some species is getting oxidized, typically that means, in the most fundamental way in which you define the oxidation process is that an electron is released from the species ok. So, an electron is released that electron is what you see here which is headed off into this external circuit, right. So, that’s what you see here that the electron has been released by some species at the anode, at this region somewhere in the anode, throughout this anode. I am just giving you a location there so that you know it lines up with the wire. So, that you just see the relationship general relationship, but it could be anywhere on that anode these species is getting oxidized it releases an electron.

And that electron is actually as we will see in just in a moment it is put under circumstances where it can only go through the external circuit. And this you know this wire that you see this wire that you see here which is headed out is called is referred to as the external circuit because it leads to this external load bank here. So, it leads to this external load bank here and then comes off the external load not load bank the external load and comes off the external load and returns back to this fuel cell unit at some region with at the cathode. So, this is the general you know process that is happening.

Now, at the cathode you have a reduction reaction going on. So, reduction reaction is typically again an electron. So, oxidation is loss of electrons and reduction would be a gain of electrons ok. So, reduction occurs at the. So, this is for some species that is present in the circuit. So, that species happens to be at the cathode and that incident that picks up the electrons and is getting reduced. So, this is the general process that is happening in this circuit so to speak.

And, one key parameter here in all this discussion that I just went through I spoke about the anode. So, I spoke about this region, I spoke about the circuit, I spoke about the external load, I spoke about this part of the circuit and I spoke about the cathode. So, in all this discussion there is one, one important part of this circuit that I did not talk about at all for the most part and that is the electrolyte. And it is very interesting to note that actually in many of these technologies the electrolyte is a very deciding factor, it’s a very crucial factor is very critical factor although it’s not the part that is generating the current.

So, if you see all the description I just gave you some reaction happens at the anode electrons are appearing in the external circuit and through that electron some work is being done and that is what you are trying to accomplish you know to run some machine or run something at your house. So, all that is happening in the external circuit and then finally, the electron comes back to the cathode and then another reaction happens. So, in all this process it appears that the electrode is doing nothing I am I am sorry it appears if the electrolyte is doing nothing. But actually it’s a very critical part of the circuit because it decides in which direction the electrons will flow and in which direction and how the reaction actually occurs and how the reaction is completed ok,, because you have a reaction where some electron is released, another reaction where a electron is gained and a pathway for the electron.

Now, if you didn’t have the electrolyte you will have this oxidation and reduction happening in an uncontrolled manner and no energy will come to the external circuit. So, no energy will arrive at this you know external load that you have and therefore, nothing will happen. So, it is just like you know burning fuel in a useless manner ok. So, you want to utilize that fuel to do something and to enable you to utilize that fuel to do something you need this electrolyte because this electrolyte then splits the reaction in to two parts. One part is this electron going into the external circuit and getting some job done for you and another part is this some species goes through the electrolyte, arrives at the cathode and regains this electron in some some manner and then gets you know reduced and some species gets reduced and the reaction is completed.

So, in the as we progress through this class, we will look at different types of fuel cells in particular you will find that one important manner in which these fuel cells differ is in the choice of the electrolyte ok. So, this part this electrolyte part is very crucial in differentiating between different types of fuel cells. And it also then creates some other aspects of the fuel cells are that of the fuel cell are then controlled by this choice of the electrolyte and so that is something that we will also look at.

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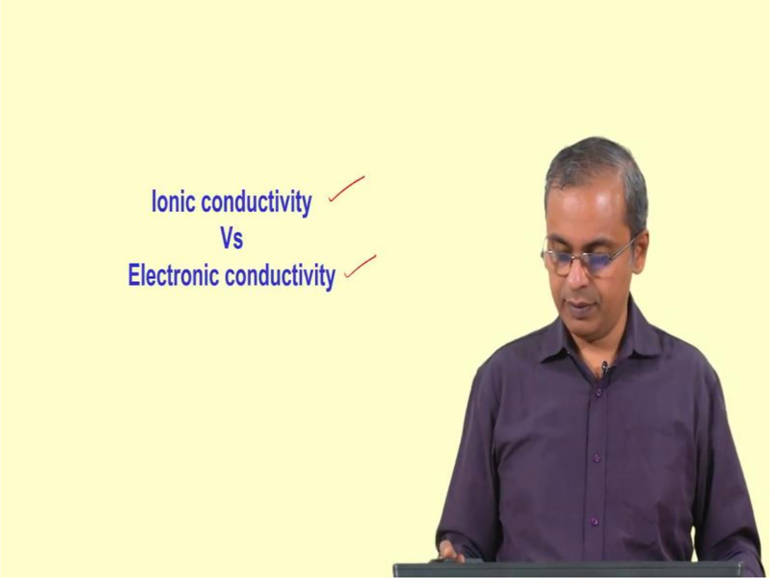

So, in this context I want to talk about a little bit about ionic conductivity versus electronic conductivity. So, for example, in our last in our in our previous slide which we will go back to I spoke about the I will just clear this a little bit. So, we spoke about the flow of electrons.

So, now, in the external circuit you have a flow of electrons. So, in this path you have a flow of electrons and in this path also you have a flow of electrons. So, in other words in this entire circuit which is other than anything other than this central part which is the fuel cell, anything other than the central path which is the fuel cell is getting referred to as the external circuit and in the external circuit the electron is travelling. So, in other words there is a path for electronic conductivity in the external circuit

Now, clearly the way I have drawn this and the way I am explaining this to you it also means that the electron cannot go across like this. So, this pathway is not permitted for the electron, all right. So, the electron simply goes through the external circuit and arrives at the cathode, but cannot go through the go from the anode to the cathode, through the electrolyte, right.

So, if you simply have electrons continuously going from anode to cathode you will have a continuous build up of negative charge and the cathode and continuous build up of positive charge at the anode. So, that actually it doesn’t happen. If it continues to happen and then it will simply build up enough of a reverse potential on the circuit that it will stop the flow of electrons ok.

So, it will so basically or it is like piling up things in the in one direction and once you have piled it up to some point you are unable to push things up they will they will start sliding down faster as fast as you push it up. So, then you will halt. So, that is basically what will happen, if you don't complete the reaction and make it neutral again. If you complete the reaction and make it neutral again you can keep continuing to push electrons in one direction.

So, to complete the reaction from in two in the process the reaction process to complete the reaction process you have to have some species that goes across and completes this reaction the species that goes across through the electrolyte is typically an ion, ok. So, the ion goes through the electrolyte electron goes to the external circuit.

So, the electrolyte has ionic conductivity whereas, the wires which are there in the external circuit have electronic conductivity ok. So, you have electronic connectivity in the external circuit, but you have ionic conductivity in the electrolyte. It is very important to know that you know when you when you measure conductivity there are various instruments which are used to measure conductivity, sometimes you will get a value of a conductivity which is actually the mix of both these conductivities okay because conductivity fundamentally means there has been a transfer of charge ok. So, you conducted some charge. So, that is what it basically means.

It is just at in common parlance, in common usage we assume that it is electrons. So, we say something has some high conductivity metals have high conductivity is a common statement that we have. Typically we mean metals have high electronic conductivity. So, a typical metal for example, will not conduct any ion by ion, I mean anything you know like H plus or an O_2 minus ion oh. So, typical ion like that it is not going to be conducted by a metal, but when we keep saying it has high conductivity, but it is going to conduct electrons.

So, when we talk of conductivity that is a aspect that we should be alert to, that there are conductivity of different species possible and therefore, in a particular circumstance you may have any one of those species being conducted or more than one species being conducted. So, there are materials where you can have a mix of both electronic as well as ionic conductivity, you can also have materials where you have only ionic conductivity you can also have materials we have only electronic conductivity.

In a typical circuit which involves a power source of this nature where you are having either a battery or a fuel cell you want only ionic conductivity in the electrolyte and only the electronic conductivity in the external circuit. So, that is the basic thing that you want to do. You want only electronic, I am sorry only ionic and only electronic; If you have electronic conductivity in the wrong place. So, in the context of this circuit I would I would be referring to the possibility that you have electron transfer also occurring through the electrolyte.

If you have electron transfer also occurring through the electrolyte then you have what is referred to as a internal short circuit. It means you are providing the electrons are very easy path to complete the circuit and they do not go through the external circuit instead they simply cut across the electrolyte from anode to cathode, and that completely waste the energy that is available in the fuel ok.

So, the summary of what I am trying to describe here is that in a typical circuit that involves a power source of this nature there are parts of the circuit that have to have electronic conductivity and other parts that are supposed to have ionic conductivity. And you have to be careful to ensure that the you know the the material such as the electrolyte or components such as the electrolyte must not have ionic conductivity. Sometimes as the material deteriorates for various reasons it may develop electronic conductivity and that is considered bad, ok. In various ways there may be other processes which may occur which may create a a pathway for internal short circuit and that is considered bad and its even considered unsafe. So, you have to be careful about that you have to be aware of that.

So, as I mentioned this is a very important distinction between what is ionic conductivity versus what is electronic conductivity. And the fact that when you look at a circuit there are regions that should have one and not the other, and if you if you have a mix then you are doing actually then your device is actually not performing, correctly.

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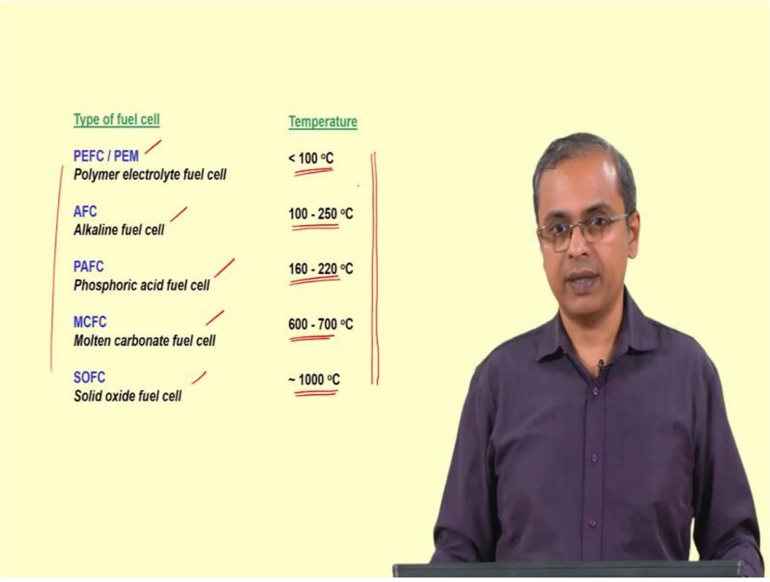

As I mentioned the fuel cells are of variety of types ok. So, fundamentally a fuel cell is going to have a supply of fuel which is typically in most cases the standard fuel that people discuss in the context of a fuel cell is hydrogen. You can have other fuels, but most often we talk of hydrogen as the source of energy, or source of as a as a fuel, being used in a fuel cell and typically the oxidant is just oxygen or air. So, on the anode side of the fuel cell you will supply hydrogen, on the cathode side will supply air or oxygen and that's a typical kind of setup in which you are looking at fuel cells. But you have a wide range of you know possibilities with respect to how the fuel cell deals with this fuel air combination and how it operates.

In fact, as I told you very interestingly even though you actually have the electrolyte not being critical in actually generating any power for you I am going to show you now that the range of fuel cells that are possible. Actually differ fundamentally in the choice of electrolyte that exists in the fuel cell. So, it is not so much the difference in the anode or the cathode although those also have differences, but fundamentally the differences arise due to a difference in the selection of the electrolyte. That makes a lot of other decisions for the fuel cell and that then decides what the fuel cell can do, what are its advantages, what are its disadvantages what are its limitations. So, all of those are decided by the choice of electrolyte.

So, in the table that I am going to show you I am going to look at a few different types of fuel cells and in each case the primary difference is the electrolyte. So, on the left hand side of your table that you see here you see different types of fuel cells, the one that is right at the top is what is referred to as a polymer electrolyte a fuel cell or a proton exchange membrane fuel cell, a PEM fuel cell which is a proton exchange membrane fuel cell. As you go from the top of the table to the bottom of the table the electrolytes keep changing and one important characteristic which changes as a result of this change of the electrolyte is the temperature of operation of the fuel cell which is what you see here ok.

So, the temperature of operation of the fuel cell changes as you change the electrolyte and this is one important parameter that is being changed because of the selection of the electrolyte. It also then impacts other parameters of the fuel cell such as the catalysts being used and also what kind of fuel can be used in the fuel cell you will see in this technology. That for different types of fuel cells there are particular chemicals which may be present in your reactant stream the reactant could either be on the air side or on the fuel side both are reactants although the fuel is the oxidant and I mean. So, fuel is the fuel and the oxygen is the oxidant. So, you have those two combinations of what you are sending into the fuel cell and they are generally being referred to as reactants.

So, it will turn out that many of the reactants based on the source from which you are getting the reactant. So, for example, you can get high purity oxygen which will be coming straight of our tank or you could be just taking air which is just you know ambient air. Now, if you take ambient air you have oxygen, you have nitrogen, you will have some tiny amounts of carbon dioxide, maybe some extremely tiny amounts of you know other gases, maybe there is some other vehicle that is nearby. So, it may also be giving out some you know carbon monoxide or nitrous oxides of different kinds. So, various things can enter your fuel cell.

Now, some of those ingredients in the gas stream can either affect the anode or affect the cathode or affect the electrolyte. And if it affects them in a negative sort of way then one of those components will stop functioning and that will impact the overall you know functioning of your fuel cell right. So, therefore, it is very important to understand which parameter which reactant is you know good for a fuel cell which reactant is sort of being described as a poison for the fuel cell because it is destroying the functioning of the fuel cell.

So, if you look at the different types of fuel cells as I said the you know the one right at top on the top of your table is a proton exchange membrane fuel cell. Typically the electrolyte there is a polymeric in nature it that is the standard electrolyte that I used and usually these operate at less than 100 degree C.

Now, if you shortly going to look at the reactions that occur in a fuel cell, but one of the main products that you get of a fuel cell is is water. So, the hydrogen reacts with oxygen and generates water. So, if you are below 100 C in temperature this water is going to be in liquid form ok. So, its liquid water just the just the just the way you would have water in a glass of I mean glass holding water etcetera. So, it is not in vapour form it is not steam at that point in time is just sitting in liquid form. So, this may not seem like much, but basically in this technology the state of water defines some of the operational difficulties that the fuel cell may face as you operate the fuel cell over a period of time okay.

So, that that is something that you have to be aware often as you understand this technology more and more you will appreciate these nuances associated with the state of water. But I am just alerting it you to it that you know this particular kind of fuel cell operates below 100 degree C typically and therefore, it means that the water is now in liquid state.

The next type of fuel cell here is the alkaline fuel cell and as you can see here it operates between 100 and 250 degree C. And from here on forward here on downwards on this table you have fuel cells which are at progressively operating at progressively higher temperatures and therefore, in all of these fuel cells the water is typically not in the liquid state ok. So, it is in vapour form that you are dealing with water unless you pressurize it, but basically it is sitting in a vapour state.

So, alkaline fuel cell is the next one the at even higher temperatures between 160 and 220 degrees C, you have phosphoric acid fuel cell. So, that’s even higher temperature of operation. If you go to 600 to 700 degree C there’s something called as the molten carbonate fuel cell or rather. If you select the molten carbonate as your electrolyte the operation range of temperatures that you have to go to operate it is 600 to 700 degree C.

And finally, you arrive at the solid oxide fuel cell where you are looking at a temperature of operation of 1000 degrees C or more.

Now, I have just mentioned some names and I have mentioned some temperatures. So, it is of interest to understand why these names result in these temperatures. So, the first thing is the names that I have mentioned to you which whether it be proton exchange membrane fuel cell or alkaline fuel cell or a phosphoric acid fuel cell or molten carbonate fuel cell or solid oxide fuel cells all of these fuel cells the name refers to the material that has been selected as the electrolyte ok.

So, in in a polymer electrolyte membrane cell fuel cell, it's a polymer electrolyte, polymer based electrolyte, alkaline fuel cell uses OH ions KOH kind of material as the electrolyte. You have phosphoric acid being used in a phosphoric acid fuel cell, carbonate ions in the form of molten carbonates are being used as electrolytes in molten carbonate fuel cells and finally, in solid oxide fuel cells you have ceramic materials which have oxides. So, Yittrium stabilized zirconia we are going to see that Yittria stabilized zirconia etcetera are used as the electrolyte.

So, these 4 5 fuel cells that I have shown you here differ in the material that has been used as the electrolyte and that also defines the name of the fuel cell. Well, that leads you to the next question okay. So, what? So, you are selected a different electrolyte. Why you should that make a difference to the temperature of operation? As I told you to complete the circuit you have to have ions travelling through the electrolyte right. So, you have electrons travelling through the external circuit and you have ions travelling through the electrolyte.

Now, when you draw current from the circuit, when you draw current that is effectively the rate at which you are drawing electrons from the circuit ok. So, you have some load, you are putting some load there and let's say it is a 5 amp circuit or something like that you know let's say we usually do not draw 5 amps even though it is a 5 amp circuit we are drawing much less than that. So, in any case let's assume you are drawing half an amp. So, in half an amp you can actually calculate how many coulombs per second it is and therefore, how many electrons per second it is ok.

So, once you figure out how many electrons per second are required to handle that half an amp. So, the reaction has to occur at that rate ok. So, in other words electrons have to be generated at the anode and introduced into the external circuit at that rate, electrons have to arrive at the cathode and the same rate and the electrons have to be consumed at the cathode at the same rate only then you do not have a build up of electrons, only then you have a continuous flow of electrons.

Now, I only spoke about a release of from the anode travelling through the external circuit arrival at the cathode. The ions also have to cross from the anode to the cathode or cathode to the anode depending on the type of ion which we will see shortly, at the same rate to ensure that the circuit is always completed. If they don’t cross over at the same rate you will have a build up of charge it means not enough ions are arriving to complete the reaction. So, the electrons just arrive there and they are waiting for the ions. The few that have a come they have completed the reaction the rest of them are just sitting around waiting for the ions to come. If they sit around and wait they are building up charge, if they build up charge they stop further current in the circuit.

So, it is important that the ions also move through the circuit at a acceptable rate. In fact, at exactly the same rate, except you know looking at the charge of the ion. I mean after you factor in the charge of the ion it has two more the same rate. So, if it is a 2 minus ion you can have half as many ions move across as you have electrons moving the external circuit so that the charges being balanced. But the point being they have to move across.

Now, it turns out that in most of these materials which have some ion being conducted the rate at which you can move the ion across that material is dependent on temperature. In other words the conductivity the ionic conductivity of most electrolytes, ionic conductivity of most electrolytes is dependent on temperature its temperature dependent. And typically it means, typically it is seen that if you raise the temperature of the electrolyte then the ionic conductivity improves okay so in fact, in this manner in in this in this context it is very different from electronic conductivity.

If you take any wire, any metallic conductor which is conducting electrons if you raise the temperature of that material it will typically increase in resistance because it it increases the number of you know collisions that the electron will face as it tries to move through their conductor and therefore, it slows down the electron. So, typically this is seen in the in the form of an increased resistance to the flow of electrons in the external circuit. So, this is what you will see when you have any metallic conductor. In all ionic conductors, in fact, it is the opposite. In ionic conductors the pathway of for the ionic conductivity is such that and the process is such that if you raise the temperature it actually happens faster. So, you have better conductivity at faster for these ions as at higher temperatures.

So, that is the reason why the choice of the electrolyte affects the temperature at which you are operating. The choice of the electrolyte affects the temperature at which you are operating because only at that temperature this material is able to conduct ions at an appreciable rate. So, you can take a solid oxide fuel cell and try to operate it at room temperature.

So, reactants are the same your going to send the same reactant at the anode and the corresponding reactor at the cathode. So, the reactants are not different they are exactly the same independent of the temperature of operation for a solid oxide fuel cell. But at the room temperature the conductivity or the ionic conductivity of the solid oxide electrolyte will be so low it with so many orders of magnitude low it could be like you know 6 7 orders of magnitude lower than what is available in the external circuit that you cannot draw any appreciable current from it; Even though you are sending sufficient reactants on the anode side and sufficient reactants on the cathode side.

And as you raise the temperature of the solid oxide fuel cells gradually correspondingly the ionic conductivity rises and when you arrive at about 1000 degree C of operation you have sufficient ionic conductivity that it matches up with whatever is required in the circuit and therefore, you can draw appreciable current.

So, you can see that the choice of the electrolyte directly impacts the temperature at which the fuel cell can operate primarily because it impacts the conductivity the ionic conductivity of that electrolyte as a function of temperature.

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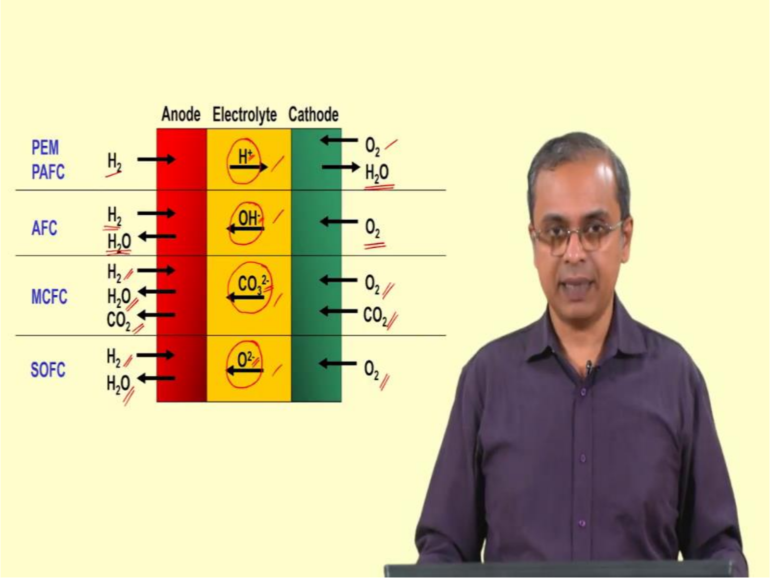

In the table that you see here for the various fuel cells the you at this point I only put the abbreviations down here, but they correspond directly to the types of fuel cells we saw previously. You can see here what reaction happens at the anode or what reactants arrive at the anode or what are possible reactants that can be used at the anode, what is the ion that goes across in the electrolyte and what are the possible reactants that are available for you at the cathode.

So, if you look at the PEM fuel cell or the PAFC fuel cell phosphoric acid fuel cell they are all fuel cells where the ion being transferred across is the proton. H plus ion, H plus ion is basically a proton and that is the ion that is being transferred across to enable this and so the conductivity of the electrolyte is the electrolyte conducts protons. It’s called a proton conductor and that is why sometimes they call it proton exchange membrane fuel cell ok. So, that is a proton that’s the H plus ion.

And the reactant that arrives at the anode is H_2 and at the cathode the reactant that arrives is O_2, and the reaction once it is complete you have product water which is being ejected from the circuit from the fuel cell on the cathode side. So, this is what happens any in a PEM fuel cell or a proton exchange membrane fuel cell.

If you go to the alkaline fuel cell as the name suggests it’s an OH minus ion that is involved in the process of completing the reaction and it is the ion that travels through the electrolyte ok. So, an OH minus ion is involved here. So, you can see here also because it is a negative ion as opposed to the H plus that you see here, this is a plus and this is a minus because it is a negative ion it is actually going in the opposite direction it is travelling from the cathode to the anode, the H plus was travelling from the anode to the cathode ok. So, direction of flow of the ion is different. So, a OH minus is travelling from cathode to the anode. You still have oxygen arriving at the cathode, you still have hydrogen arriving at the anode, but now the product water is actually formed at the anode ok. So, product water is being formed at the anode because of the direction in which the ion is moving.

So, you can see here clearly even in these two examples that the choice of the electrolyte has made a big difference in what is happening within the fuel cell ok. So, again maybe for a first time a person being exposed to the idea of a fuel cell for the first time maybe the location of water is not a big deal. But in actual operational conditions of a fuel cell as a technology that people are trying to deploy in some you know in some end use the location where water is coming out, and what other you know parameters or components are impacted by the water being present there is very important to you know understand, to respond to, and to handle properly ok. So, this is something that you see here.

The molten carbonate fuel cell you have the CO_3 2 minus carbonate ions being involved again it is a negative ion negatively charged ion. So, you can see here 2 minus is the charge therefore, it is actually travelling again from the cathode to the anode, so that is the direction of flow of the ion. Here it turns out that you can actually send oxygen you send oxygen as the reactant on the cathode you also include the CO_2, this CO_2 also shows up at the anode side. You have product water being formed in the anode side and of course, the reactant hydrogen that is being introduced in the anode side.

So, you have hydrogen here, oxygen here, and based on the you know flow of gases I mean reactions that are occurring you have CO_2 you showing up at both places and then you have this CO_3 2 minus ion which is going from the cathode to the anode.

The last fuel cell that is on our table for discussion is the solid oxide fuel cell. As the name suggests its oxide solid oxide. So, it is a solid electrolyte in this case typically a ceramic material. So, it is brittle how to be careful with it, it breaks very easily and it is a it conducts oxygen ions. So, O_2 minus ions are being conducted here again you can see here it is negatively charged, so once again it travels from cathode to anode.

So, if you see these 3 selections here the alkaline fuel cell, molten carbonate fuel cell and solid oxide fuel cell, in all these 3 cases the ion is negatively charged and it moves from the cathode to the anode. Only in the proton exchange membrane fuel cell you have a positive charge and therefore, it is travelling actually from the anode to the cathode ok.

So, if you look at the solid oxide fuel cell again oxygen arrives at the cathode, and hydrogen arrives at the anode and you have product water being delivered at the anode. So, this is the set of reactions that are occurring, I have still not shown you all the details of it we will see in the next couple of slides more details about these fuel cells. But you can see here through this table already that you know there's lot of detail involved in it.

And you are still not spoken about the materials themselves what kind of materials and what you know issues are there with respect to these materials. This is just what are the broadly, what are the reactants arriving, what is moving from where to where, what are the conditions under which it is moving and how is that impacting the overall selection of you know reactants and you know where the product will appear etcetera.

And incidentally these you know 5 types of fuels cells that I am discussing with you are really the main most important or most prominently known types of fuel cells. There are a lot of other types of fuel cells that people are working on which could you know which are the some variations of these or maybe when newer versions of these that are being looked at. So, this is not a completely exhaustive list of every possible fuel cell that is you will certainly find things like you know molten sorry, I am sorry a direct methanol fuel cell.

You can also have other types of fuel cells that are present which which do not appear on this table, but whatever I am discussing here are you know basically the ideas that you can just extend to extend a little bit and you will find that they apply just as well if with other types of fuel cells including the direct methanol fuel cell.

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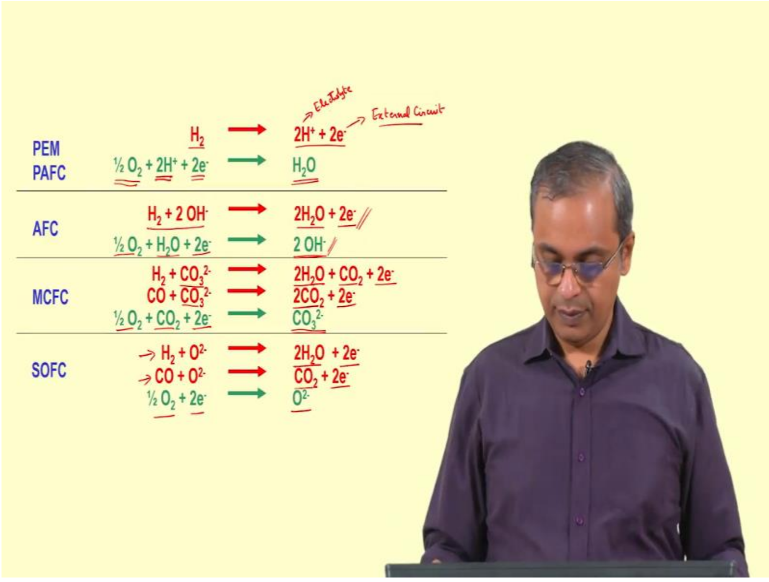

So, in this slide you will, I am I am also detailing the reactions that are occurring. Previously I simply show told you that you know something arrives at the anode, something arrives at the cathode and then you have a reaction.

So, for example, if you take the proton exchange membrane fuel cell you can see here the hydrogen arrives at the anode and then it splits to 2 protons plus 2 electrons at the anode this goes into the external circuit and this goes into the electrolyte. So, something goes into the external circuit and something goes into the electrolyte and through the electrolyte this arrives at the cathode.

So, through the electrolyte it has arrived here at the cathode and the through the external circuit this has arrived at the also arrived at the cathode after, having done its activity of you know powering some device etcetera. There at the cathode the proton which arrived through the electrolyte and the electrons that arrived through the external circuit react with the oxygen that is now present on the cathode side and generate water. So, this is how the reaction is occurring.

This is how the various steps of the reaction occurring. Some gas arrived at the anode it split, one part went as an ion through the electrolyte, another part when does the electron through the external circuit and they both arrive at the cathode side one through the electrolyte, one through the external circuit and at the cathode additionally another gas arrived.

So, now these 3 ingredients the second gas that has arrived there the electrons that are arrived to the external circuit and the ions that have arrived through the electrolyte all of them react and get you your product water. So, that's what has happened on a PEM or a phosphoric acid fuel cell both of them have this general you know layout of activities set up the way I just described. In an alkaline fuel cell as I mentioned in the in all the other fuel cells the ion is moving from cathode to anode and that's sort of what you see here.

So, here for example, the hydrogen is reacting with this OH minus ion that has arrived through the electrolyte and gives raise to your water. And it now releases an electron as a result of this reaction that electron comes to the cathode side reacts with water that is present there and the oxygen that is present there and gets you these two OH minus ions.

So, the exact sequence you can just go over again and see, but basically it's the same thing that is happening. In all these cases you find electrons are travelling through the external circuit some ion is generated in this case it is generated on the cathode side, whatever I have written in green in the slide is the reaction that's occurring on the cathode side. So, in the cathode side this ion is being generated which goes through the electrolyte and then you have some other reactions occurring at the anode.

If you look at the molten carbonate fuel cell again you know as the name suggests it is the carbonate ion that is involved here. So, CO_3 2 minus is the ion. So, on the anode side actually two possible reactions are there you can supply hydrogen or you can also supply carbon monoxide. Both of them can react with this ion CO_3 2 minus and will either generate water or they will generate CO_2. So, interestingly in a molten carbonate fuel cell you can actually use carbon monoxide also as a fuel ok. So, if you have polluting carbon monoxide from somewhere and you stream it off into a molten carbonate fuel cell you can actually clean it up it will just convert it to a CO_2 ok.

So, first of all you don't want to collect CO anywhere. So, it is not the same gas to be working with, but what I am saying is you know if there is a stream which already has some exhaust stream from some other plant which has some CO you can send it of into this and it will convert it to into a CO_2 and also generate some electricity in the process. So, that's how you are getting this CO_2 and H_2O here you also get some more CO_2 here and then in both these reactions electrons are released ok. So, in both these cases oxidation has occurred electrons have been released they are being released into the external circuit. And in the external circuit again they travel all the way around to the cathode side where you have oxygen, you have some carbon dioxide being supplied there on the cathode side and the electrons that have arrived through the external circuit and they generate the CO 3 to minus ion, ok.

So, CO_2 is continuously being generated on the anode side. So, you have to keep re-circulating it and bring in bringing it back to the cathode side only then you can keep this reaction running because CO_3 2 minus is moving across. So, you need to keep that in supply right. So, this is the way it works on molten carbonate fuel cell.

Finally, we have the solid oxide fuel cell where also the same you know the same point is true on the anode side you can use both the hydrogen as a fuel as well as CO as a fuel. Actually you can use a variety of different fuels, but these are two that I am highlighting here. Both of them will react with oxygen in this case and generate either water or CO_2 and in both these reactions as a result you also have electrons spring released. These electrons again as usual travel through the external circuit complete some reaction on the some some activity the external circuit and arrive at the cathode side that these electrons react with oxygen gas and generate the O_2 minus ion. That’s the O_2 minus they travel through the electrolyte ok.

So, in all these cases that we have just seen you have some reaction occurring at the anode, some reaction occurring at the cathode and depending on which reaction generates the ion that ion correspondingly goes through the electrolyte and then completes the reaction on the other side, in all cases electrons go in the external circuit from anode to cathode. So, that is some things are common about all of these reactions and some things are slightly different because of the nature of the ion being used and which direction it travels. And as a result of the choice of the electron which is also depend which also impacts which iron is travelling and in which direction it is travelling the temperature of operation of these fuel cells also changes.

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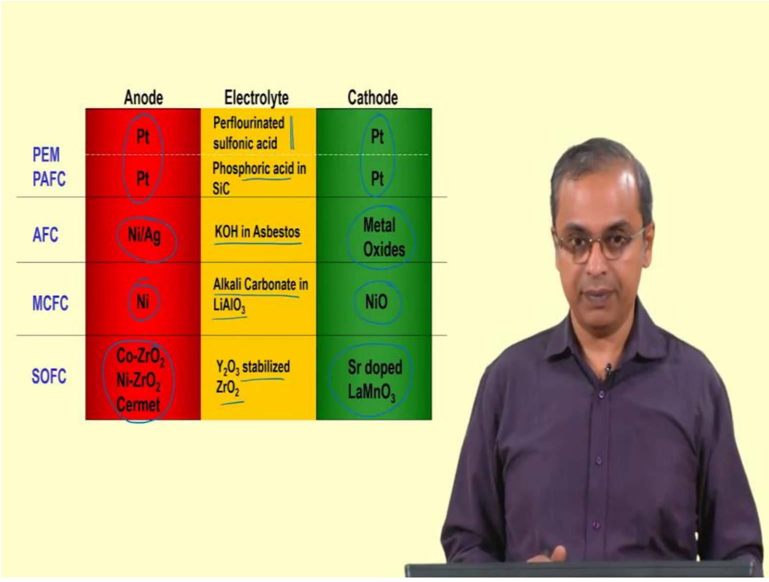

I mentioned a little while earlier that you know once you select this fuel cell based on this you know temperature of operation it also impacts many other things that are present in the fuel cell. One of the most important things that are that is impacted by this choice of the electrolyte and therefore, the temperature of operation is the material that can be used at the anode as a catalyst and the material that can be used at the cathode as a catalyst.

So, the lower the temperature of operation you tend to need much more expensive materials which are typically precious metals to be present at the anode as well as the cathode, to catalyze the reaction ok. So, they provide much better sites active sites for the reaction to occur and so they become necessary at lower temperatures to enable the reaction to occur.

So, for example, in a PEM fuel cell as far as the in a phosphoric acids fuel cell which are all operating you know just under 100 degree C or just over 100 degree C at the lower temperatures the catalyst material that is used at the anode as well as the cathode in the lower temperature fuel cells happens to be platinum, both at the anode as well as the cathode. And that is the largely because the temperature of operation is actually you know around 100 degree C or less maybe marginally more if you go to higher temperatures. So, alkaline fuel cell or molten carbonate fuel cell you suddenly find that you can get away with vastly cheaper materials.

So, things like nickel, okay silver is still an expensive material, but it is vastly cheaper than platinum, you know you can easily go and buy you know significant amount of silver for the same amount of money that you would pay for a few grams of platinum. So, it’s vastly cheaper than platinum, it is still it is a expensive metal, but you can use nickel as well. So, nickel and silver can be used various kinds of metal oxides can be used which are you know which are all going to be much much cheaper.

Again as you go up in temperature you have nickel here, nickel oxide here, again very cheap relatively cheap materials. And then when you go to much higher temperatures these are not necessarily cheap materials, but they give you some other advantages so that is why they are still being considered Strontium doped lanthanum manganate and and different kinds of you know metals with ceramics like cobalt with zirconia and nickel with the cornea these are called cermets. So, both ceramic materials as well as metals are being used.

The electrolyte as I said this series of materials that I am showing you here one is this is referred to as a perfluorinated sulphonic acid we will see this in some detail later in the class in involved in the other classes. This is a phosphoric acid in silicon carbide is the electrolyte that is used for PAFC phosphoric acid fuel cell.

For alkaline fuel cells you have KOH which is held in a in asbestos I mean these were the primary designs that have there that had been explored and investigated for a long period of time. If you really look at literature you may find you know much more you know some variations on these materials or some newer materials that are being used for electrolytes. But fundamentally these are the kinds of materials that people studied for long periods of time. And so, a lot of understanding is there of these systems using these materials and that is why I wish to highlight them.

You can have for a molten carbonate fuel cell, alkali carbonate in $LiAl\ O_3$ as the typical kind of electrolyte combination that is used. And Yittria stabilized zirconia is another electrolyte that is used commonly for solid oxide fuel cells. Solid oxide fuel cells also use things like cerium oxide, samarium oxide, geranium oxide, doped materials of that nature wide range of oxides are used. So, this is just a sample of what kind of a material can be used for an electrolyte in these systems and this is not the only material that can be used. So, that is something that you have to keep in mind.

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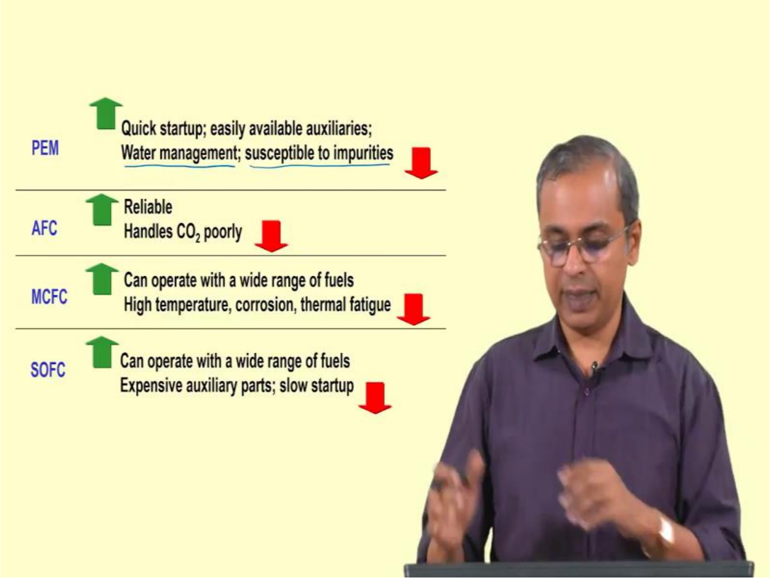

Just a couple of slides as we close this class; The, I would like to emphasize again that the electrolyte is actually a very critical part of the fuel cell even though it is not the one that generates the power. And primarily it is because it affects the temperature of operation of the fuel cell and that impacts many many things about the fuel cell.

So, for example, many of the advantages and disadvantages of each type of fuel cell is actually directly related to the temperature of operation of the fuel cell. So, if you look at PEM fuel cells proton exchange membrane fuel cells, so these are basically since they are operating at low temperature they are very easy to start. So, typical automobile application requires you to have the ability to do what is called or what is referred to as a cold start. So, you come out of your house your car sitting in the garage or sitting out in the you know maybe in rain, maybe in snow depending on which country you are in or which region of the country you are in and then you go to start it.

So, the engine is sitting at you know close to 0 degree centigrade could be or at room temperature maybe 10 20 degrees centigrade from there the engine has to start. So, if the fuel cell is actually operating at a relatively low temperature it it it is able to handle the start from a you know temperature which is basically room temperature. So, therefore, its quick to start. But as I said the water is available here in liquid form and therefore, this water actually can you know collect inside the fuel cell and block the reaction from occurring. So, water management is a is what is it is referred to how you handle that water, how do you make sure that the water leaves the fuel cell and leaves the path clear so that fresh reactants can occur there come there. So, water management is a very critical aspect in these PEM fuel cells.

Also since they are at low temperatures they are susceptible to various types of impurities, various types of impurities will go and just sit there, they will not leave they will block the path of the catalyst on the surface of the catalyst. Typically for example, carbon monoxide is one of those things that can sit on top of a catalyst particle and block that site from reaction, and once it blocks the site from reaction recation will not occur there. Then slowly you lose the ability of generating current from the fuel cell.

So, at lower temperatures they sit much more effectively and therefore, this pem fuel cell is more susceptible to impurities which means you have to have fairly pure stream of reactants going into the fuel cell. So, that adds to the expense associated with the fuel cell.

We can have alkaline fuel cells, they are very reliable, but they actually handle carbon dioxide rather poorly and that's a little bit of a problem because you will have some carbon dioxide in even in ambient air there is going to be some tiny bits of carbon dioxide always present in ambient air. And that carbon dioxide can be it becomes a problem with alkaline fuel cells because it reacts with KOH and forms potassium carbonate. And then the KOH which is present in the electrolyte is no longer there it has reacted with CO_2 and formed potassium carbonate and then you don't have KOH and then no longer the you know there is the ionic conductivity, deteriorates very fast and then it stops working even though you have the right temperature of operation. So, therefore, it is a problem.

If you go to molten carbonate fuel cell you are going up in temperature. So, it can operate with a wide range of fuels. So, carbon dioxide is not a problem, CO is not a problem, the things that are problems at both alkaline fuel cells and PEM fuel cell are not problems here, water is not a problem. So, all those things which we are problems are no longer problems, but because you have gone to a higher temperature you can end up having you know corrosion which means unwanted reactions can also occur fast, reactions that you want will occur fast reactions that you doN't want will also occur fast.

So, various materials that are present in the fuel cell can degrade faster. So, this is a issue with higher temperature fuel cells such as molten carbonate fuel cell.

The last fuel cell that's up here on your slide is the solid oxide fuel cell. It can again operate with a wide range of fuels it is not the aspect of you know this idea that CO will poison it or CO will be poisoning it in some ways does not exist you can send almost any kind of fuel into it it will just work just fine. It is just that because it operates at 1000 degrees C the main disadvantage is that every component associated with it is not easily available, you have to make special components each component has to be able to handle 1000 degrees centigrade or something very close to that and therefore, these auxilary parts that are these are all the parts that go with the fuel cell to make it work are all also getting complicated.

So, even something as simple as you know you want to seal the fuel cell you put some kind of you know sealant on the fuel cell that sealant will break down and then once it breaks down you have gas leaking all over the place. So, that's again dangerous and it is also a waste of energy plus it is also not a safe way of operating the fuel cells. So, that becomes a problem.

So, you can see here that each type of fuel cell has some advantage and some disadvantage and therefore, you have to when you select a type of fuel cell the you have to understand that there is a package of issues associated with that some bright and some not so bright.

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So, if you look at international efforts on fuels cells largely they are on two types of fuel cells, the proton exchange membrane fuel cell and the solid oxide fuel cell. These are the two types of fuel cells that are significantly researched internationally and interestingly they represent two extremes of the issues faced with fuel cell applications, the fuel cell work and fuel cell applications. And they are typically suited for completely different end uses.

So, if you look at the world today in terms of energy usage and where they would like to apply fuel cells, largely they look at automotive sector or they look at stationary sector which could be household, buildings, hospitals of different kinds ok, so buildings of different kinds.

So, now, if you look at stationary applications the power is typically consumed on a steady basis. So, the issue of start up and shutdown is not so high ok. So, you have many houses powered using a fuel cell that fuel cell can sit operating comfortably for a long period of time. So, there actually having a solid oxide fuel cell works very well you can set it up I mean or that potential is there it still has issues, but the potential is there because it can all be set at a high temperature and can remain there. You don't have repeated you know start up and shutdown cycles that are occurring on the fuel cell.

On the other hand for a automotive application it is the PEM fuel cell that works best because it is at a lower temperature of operation and you can you know do a start up and shutdown vastly more easily that in a SOFC and it does not have any of the major issues that SOFC faces with this start up and shut down kind of cycling.

So, therefore, they are two different types of fuel cells, they are again people researching these fuel cells, trying to use them for all sorts of applications and they are really pushing the boundaries by trying to do that and that is a nice thing about doing science or research in these areas. But these are the limits of these capabilities and limits of these types of fuel cells and therefore, you have to be aware of them as you try to use them.

So, as I conclude this class I would like to again highlight that in this class we have looked at the range of fuel cells, different types of fuel cells that are present. We have looked at you know what are what are positive aspects of mode each of these fuel cells what are some negative aspects about these fuel cells or rather what are their capabilities and what are their limitations and so with that I would like to conclude this class.

KEYWORDS:

Types of Fuel Cells; Anode ; Cathode; Electrolyte; Stack; External Circuit; Oxidation: Reduction; Fuel Cell Types; Fuel Cell types based on Electrolyte; Ionic Conductivity; Electronic Conductivity; Polymer Electrolyte Fuel Cell; Proton Exchange Membrane Fuel Cel (PEMFC); Temperature of Operation of the Fuel Cell; Fuel; Oxidant; Alkaline Fuel Cell; Phosphoric Acid Fuel Cell; Molten Carbonate; Solid Oxide Fuel Cell; Proton; Cermets; Cold Start; Disadvantages of Low Temperature Fuel Cells; High Temperature Fuel Cells; Low Temperature Fuel Cells.

LECTURE:

The concept of fuel cells is introduced in this lecture. Their classification based on Electrolytes and Operational temperature is discussed in detail with respect to their chemistries, pros and cons.