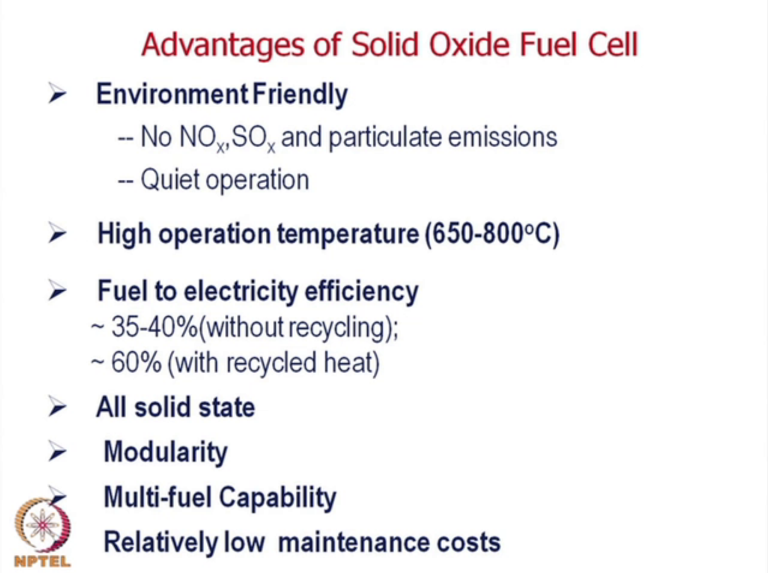
Advanced Ceramics for Strategic Applications
Prof. H. S. Maiti
Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur

Lecture - 29
Solid Oxide Fuel Cell
(Contd.)

Let us comeback to the discussion on Solid Oxide Fuel Cell. In the last class, we were discussing about specific advantages of the particular device.

(Refer Slide Time: 00:31)

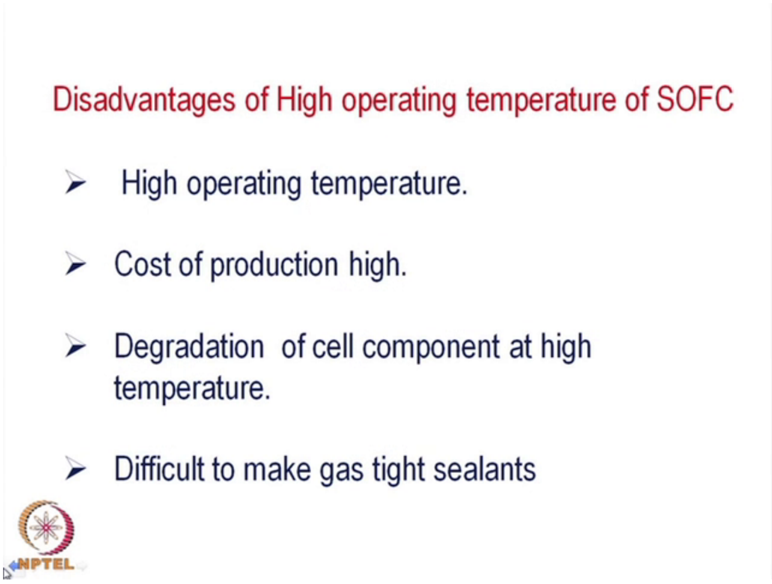


Just to continue with that, we have very high electrical efficiency up to 60 percent, particularly when the heat is also heat energy generated from the chemical reaction is also utilized, it is all all solid state that is all. Again advantage, the other advantage is modularity that is true of course for any kind of fuel cell, because a large the capacity - capacity can be enhanced by adding few modules.

So, there is a modularity, you do not need to have a very large capacity planned all the time, you can have few kilowatts to up to megawatts, whenever depending on the necessity, one can add different modules and enhance the capacity. Multi fuel capability is once again a very important advantage particularly for the solid oxide fuel cell, it operates at it is fairly high-temperature. So, there is a hydrocarbons, particularly hydrocarbons can be used in this case and large number experiments has been carried out with natural gas just the natural gas, which contains different kinds of hydrocarbons.

And there is a there is a in situ, there is a a in situ reforming what they call, there is a in situ reforming at the anode side or the fuel side. So, the hydrocarbons gets on the spot or on site break down into hydrogen and carbon monoxide and both of them can be used as a fuel in the system. And relatively low maintenance cost, because it is stable, the all the components of the fuel cell are ceramic materials and they are quite stable, their life is quite long. Of course, there is degradation it is not, that they do not degrade, because of the different kind of interfacial reaction, because of some of the high temperature chemical reactions, but relatively their maintenance cost is low.

(Refer Slide Time: 02:54)



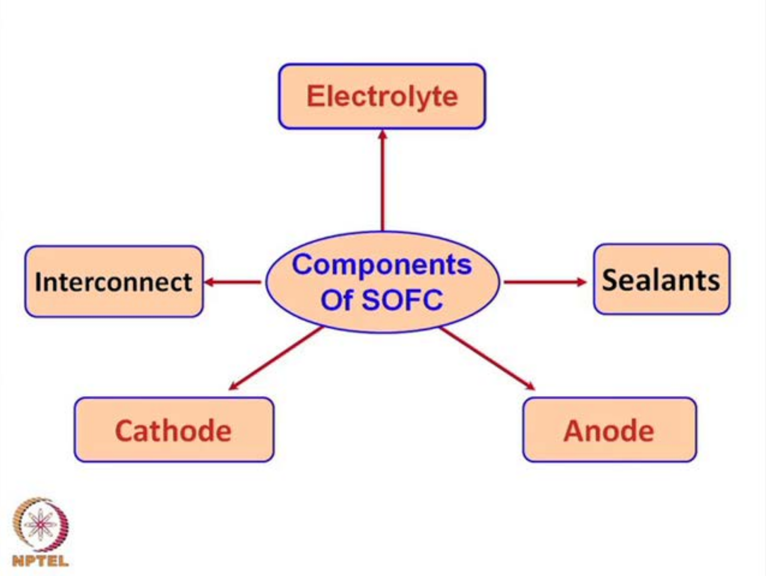
So, these are some of the great advantages of solid oxide fuel cell, why solid oxide fuel cell can be utilized for efficient power generation. However as I mention, there are also certain disadvantages, high operating temperature is one of an advantage, but it is also disadvantage. From the materials point of view, you cannot use all the different materials even if they have better properties, so far as the electrochemical activity is concerned. Cost of production sometimes is very high, although maintenance cost of the cell maybe low, because of the high life long life.

But, cost of production, fabrication of ceramics and requires high temperature and being a brittle material, cost of production is always high, that is true for any ceramic material.

Degradation of cell component at high temperature also is one of the problems, we will discuss that later on. Because, there is a chemical reaction, some of the ageing behavior is there, the structure gets change in, because two three different materials are in contact with each other and are maintain at a high temperature.

So, there is all that is inter diffusion, it is very difficult to maintain a clean clean interface. So, that kind of degradation is there, difficult to make gas tight sealants, that is another very important problem, so far as the SOFC design and SOFC fabrication is concerned, fuel cell fabrication is concerned, we look into that later on, difficult to make gas tights sealants particularly at a high temperature, so because you are talking about two different gases. So, and we do not want we do not want that the two gases combine or come in contact with each other except in the desired way. Desired way is the electrochemical combustion, but otherwise they should not come in contact with the each other. And therefore, we need to separate out to the two compartments and that is a very challenging task for any fuel cell developer.

(Refer Slide Time: 05:11)



Well with this, let us come to what are the different materials we need for making a SOFC fuel cell system. The major materials are three we have already discussed, we need an electrolyte, we need a cathode material, we also need an anode material. These are the main three components, but in addition, we also need another material like interconnect and is called sealant, we are just discussing about the sealant, sealant is a challenging task.

Electrolyte, cathode and anode, we have more or less discuss, their functions we have more or less will discuss, we will discuss further. But what is interconnect, interconnect is basically a a a material which connects the cathode of one cell to the anode of another cell. So, that is the purpose of that is why it is called interconnect, because the overall electro EMF for each cell a is within 1 volt within 1 volt. And therefore, if you are talking about a power system having 700 volts or at least 100's of volts and lot of sufficient amount of current has to be drawn.

Then, a large number of cells are needed, each cell generating less than 1 volt a power pack a power pack or a stack needs a large number of cells. So, the cathode of one cell has to be are connected to the another cell and this is the purpose of interconnect, we will see how exactly the interconnect works in different designs. And sealant is an important issue of one of the reasons, we will look into that or exactly and as I mention few minutes back, that the basic purpose of sealant is to separate the two compartments, the gas make the whole system gas type.

And so that, the fuel and the oxidant do not come in contact with each other, except through the electrolyte. So, that is the purpose of the sealants and since the whole system operates at fairly high temperature, we need high temperature sealants and stable sealants. So, it is it it is again a challenge challenging task for any ceramic engineer or materials engineer.

(Refer Slide Time: 07:44)

Specific Materials used as SOFC Components

	Electrolyte	Cathode	Anode
Physical Form	Gas tight Dense Layer	Porous layer	Porous Layer
Thermal Property	← Comparable Thermal Expansion Coefficient →		
Electrical Property	Fully ionic conductor	Electronic Conduction	Mixed Conductor
Available Materials	9 m/o YSZ Gd – CeO_2 (GDC) Sc stabilized ZrO2 (ScSz) Sr – Mg doped La-Gallate(LSGM)	La (Sr)MnO_3 (LSM) La-Co ferrite (LCF) (La,Co)FeO_4 (LCF) (LaSr)$CoFe_2O_4$(LSCF) (BaSr)CoFeo4 (BSCF) etc	Ni-YSZ Cermet Ni-GDC

All these are the different kind of materials and some of the properties required for the construction of the solid oxide fuel cell. The kind of the the electrolyte, these are the three headings the electrolyte, cathode and the anode and then what in what is the kind of physical form ,in which they are needed. Electrolyte must be a gas tight dense layer, they have gas tight dense layer is the is the form in which electrolyte is needed. Now, one thing also is important here, what will be the thickness of the layer, thickness has a very very important bearing on the overall performance of the cell.

Because, higher is the thickness higher is the resistances, which give rise to the higher internal impedance of the cell. So, one cannot draw a large current, if one wants to if the system if the thickness is large then the resistance is high and the current carrying capacity or the current density of the electrolyte or the system as a whole reduces. So, you cannot draw large currents therefore, there is always tendency to or the any design will have a very low thickness in the order of microns.

So, it is not millimeter, even the electrolytes are in the order of few 10's of microns so that is another requirement of the electrolyte, it has to be completely dense so making a dense ceramics as you as you can understand is always a little challenging task. So, one needs non porous material whereas, cathode and anode by design, they have to be porous. Otherwise, the gases both the both the reactants will not come in contact with the electrolyte and so there will be no chemical electrochemical reaction.

So therefore, they have to be porous whereas, the electrolyte has to be dense and it is thin, it has to be quite thin. Thermal property because, three of them are sandwiched together, the electrolyte, cathode and the anode forms basically a monolithic structure. So, their thermal expansion coefficients must match otherwise, there will be a crack and there will be bending and the whole system will not be stable, because there will be they are operating at higher temperature.

So, whenever there is a thermal cycling from room temperature to high temperature or high temperature to room temperature, there will be problem of cracking. So, one has to choose the material in such a way that, there are many other criteria's actually for example, thermal expansion is one of them. But the materials must be chosen in such a way that, there is no as such chemical reaction high temperature chemical reaction between these materials, which are in come which are in contact with each other.

So, the electrolyte, the cathode and the anode of course, the cathode and anode are not in contact with each other, they are separated by electrolyte. So, the electrolyte and cathode and and the electrolyte and the anode, they should not have any chemical reaction at their temperature operation. There are many different alternatives available for the materials are concerned, looking at these requirement basic requirements, the electrolyte of course, one of the major come. So, sorry, so far as the electrical properties concerned, alright I forgot to mention about that, the electrical property what is the kind of electrical property requirement for these three materials. Electrolyte as definition, it is fully ionic conductor and in this case, it is oxygen ion conductor. So, the conductivity is only through a movement of oxygen ions whereas, cathode and the anode, cathode must be electronic conductor, there is no need of no there should not be any oxygen ion conductivity here.

But there will be sufficiently conducting at the temperature of operation whereas, in the mixed conductor sorry the anode must have a mixed conductivity that means, partly electronic partly ionic, that is also another requirement for the anode. And in addition to of course, you have a thermal expansion coefficient in match with the electrolyte as well as the cathode. So, far as the materials are concerned, these are the alternative materials available to us.

Electrolyte, the most important electrolyte which is been use and is actually quite a stable material is 9 mole percent, Yttria Stabilized Zirconia, YSZ it is called so this is 9 mole percent yttria stabilized zirconia. It is a cubic fluoride structure so you have to stabilized the cubic fluoride structure so that, you get sufficient amount of oxygen ion vacancy and fairly large electronic fairly large ionic conductivity or oxygen ion conductivity. Some alternative materials are also there like gadolinium, gadolinium doped cerium oxide.

Cerium oxide is also known to be a cubic fluoride structure and adding gadolinium produces in sort it is called GDC and that also has a oxygen ion conductivity, it may also have some other properties, we will see later on. Scandium Stabilized Zirconia SCSZ, that is also used as can be used as a electrolyte, because it has a higher much higher conductivity compared to this one. But it is very costly and availability of scandium is also quite limited so there is some problem otherwise in principle, it can be used from the points of properties.

Strontium magnesum doped lanthanum gallate, lanthanum gallate is another compound which is supposed to have very high oxygen ion conductivity, but it is conductivity is quite high compared to YSZ or zirconia. Even at 100 degree and 150 degrees, we have the same kind of conductivity, what you get with YSZ at around 900 degree centigrade. So, the operation temperature can be lower down to a large extent for lanthanum gallate, but for various reasons, there is no compactable cathode or anode and their reactivities little high.

So, for practical systems, people are working on this kind of material, research is going on quite extensively of this kind of material, but no practical system, as really have come out or a demonstration system has not really come out, so far as the power (()) are concerned. Cathode, there are large number of possibilities, the most important cathode material is strontium manganite, sorry lanthanum manganite lanthanum manganite doped to strontium.

So, basically it is a lanthanum magnetite La MnO 3, a kind of perovskite kind of distorted perovskite compound and in which actually Mn is available in both 2 plus and 3 plus state and that actually, give rise to the electronic conductivity here. So, when you dope with strontium, it again gets stabilized a a a in the high temperature form, there are couple of polymorphic forms and it goes through a phase transformation somewhere around 600 degrees.

So, if you want to and the higher temperature phase is more electronically conducting than the low temperature phase. So, if you want to stabilize the low temperature high temperature phases, you can dope with strontium and the high temperature phase is get stabilizes and also the conductivity increases. In addition, there is another great advantage is the thermal expansion coefficient of lanthanum manganum is not exactly same as that of YSZ. And so you have by doping with strontium, thermal expansion can be matched with YSZ.

So, that is the reason, this is the most common is the most common and popular cathode material, one uses for both for research and for development of prototypes. There are many other ferrite kind of compounds have been tried and being tried like lanthanum dope cobalt ferrite LCF, lanthanum cobalt ferrite is a I am sorry these are repetition here, lanthanum strontium cobalt ferrite LSCF and barium strontium cobalt ferrite BSCF. So, these are actually the different kind of ferrites, also having a very good ionic electronic conductivity, these are all electronic conductors not ionic conductors.

So, all of them are good electronic conductors primarily, because you have a variable valency cations here. So, we have seen earlier that, most of the oxides having variable valency cations will lead to electronic conductivity or kind of semi conductivity. And all of them have a good semi conductivity at higher temperature and they are fairly stable at the operating temperature of the SOFC. So, these are some of the alternative materials or cathode materials, one can use and when it comes to anode, not many alternatives are there.

The most important one of course, is nickel YSZ, it is a cermet it is a cermet, in which nickel metallic nickel is there and YSZ is the same YSZ here. So, it is a mixture of the electrolyte material and metallic nickel whereas, it can be also used particularly with ceria adopt electrolyte, one can also use nickel GDC that means, the cermet of nickel at GDC. So, normally the principal is, you make sorry you make a cermet, a composite a composite of metal ceramic composite cermet of a nickel.

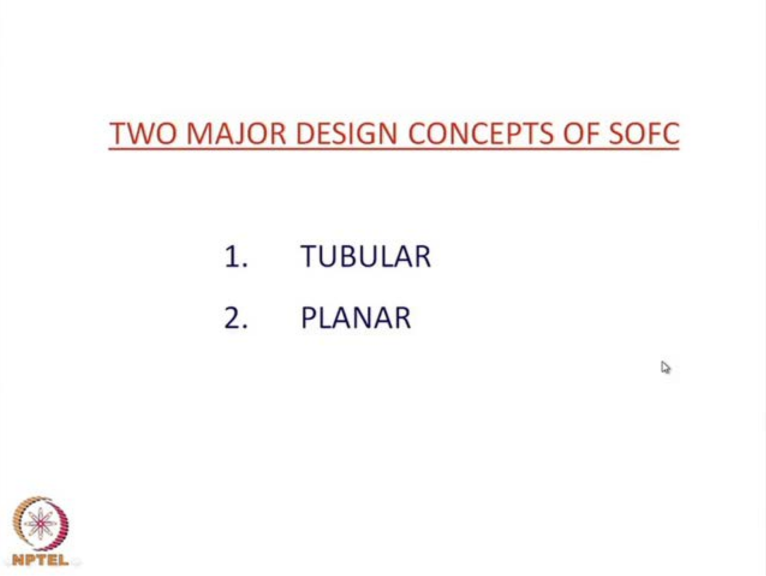
Nickel is normally the common material use, which is stable at fairly stable at higher temperature and relatively less costly and the electrolyte material. So, if you are using YSZ then make a cermet of nickel NYZ, if somebody is using GDC that is, the gadolinium dopes ceria as the electrolyte, the anode maybe the cermet of nickel and the electrolyte material. So, these are the this is the basic philosophy and the philosophy behind it is, it has to be a good electronic conduct mixed conductor in fact, this provides a ionic conductivity this also provides a ionic conductivity and nickel provides the normal electronic conductivity. So, that is how, it becomes a mixed conductor, but the more importantly why we need a cermet, if we are talking about the electronic conductivity then only nickel could have been used.

But the problem is, the nickel has a much higher thermal expansion coefficient, nickel as a much thermal expansion, because this is a metal whereas, this is ceramic. So, in general, metal have much higher thermal conductivity thermal expansion coefficient thermal expansion coefficient than YSZ or any other ceramics. So, to match the thermal expansion coefficient and also to maintain the electronic conductivity between them, between within the material, one needs a cermet.

A mixture of nickel and YSZ that is how, you match the expansion coefficient thermal expansion coefficient with the electrolyte, because it is in contact with the electrolyte. So, we need a electronic conductivity in the so nickel or the metal provides that and to reduce the thermal thermal expansion coefficient, one mix the electrolyte also with that. But obviously, the nickel has a much higher thermal electrical conductivity than YSZ so the overall conductivity gets reduced.

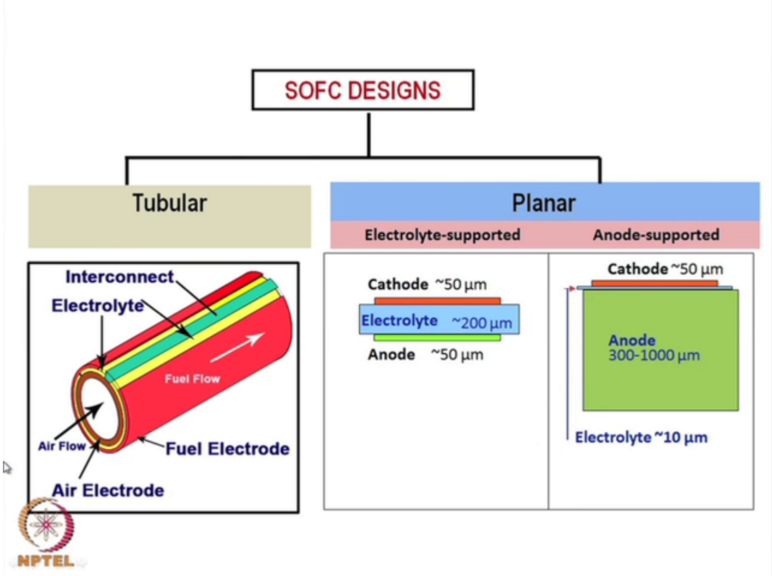
So, it is a one has to find out a compromise or optimize, how much percentage of nickel and how much percent of YSZ has to be used for this kind of cermet. We will discuss that little bit how exactly, what is the basic principle on which one decides or optimize the composition. So, these are the different material one have one has for the combination of or the three different materials of our interest.

(Refer Slide Time: 21:52)



With this, we come to another aspect of the solid oxide fuel cell that is the design, the design is, there are two major design, there may be different other designs. But, experimental designs, but these are designs which has been more or less standardized, one is called the tubular design, another is called planar design.

(Refer Slide Time: 22:16)



This is the basic difference in tubular design, you actually fabricate a kind of tube using the different materials of interest. So, this is a tube basically, if they have a support tube which is a cathode tube, air is basically a cathode so the support tube is a porous cathode maybe, strontium doped lanthanum magnetite. So, you make powders of that and then fabricate a porous tube, over that one deposits one deposits a thin layer the yellow basically, thin layer of electrolyte YSZ.

And then we have do have a another SOFC anode on top of that so this red one is actually the anode so this is the electrolyte, the inner one inner layer is the cathode layer or lanthanum strontium dope lanthanum magnetite or in sort it is called a LSM and the red one outside is the anode or zirconia nickel zirconia cermet. So, that is how, it is been made and then the interconnect is here, the strip the blue strip here is actually the interconnect.

So, there is a strip, which you can see the, it actually goes to the upto the cathode so there is a discontinuity of the electrolyte here and it goes directly upto the cathode and it is gets exposed to the surface. So, this interconnect we will see, how exactly it works, it actually connected here to the cathode, but the anode is separated out, so it is not connected to the anode, so there is a gap of the surface layer top surface layer.

Now, thickness is about sorry this is about 2 to 3 millimeter in diameter in case are, 2 to 3 millimeter in thickness, the electrode sorry electrolyte is few microns let us say about maximum is upto 50 microns. And in this case, it is deposited by electrochemical vapor deposition, it is called electrochemical vapor deposition, one takes a volatile matter of the zirconium tetrachloride and yttrium tetra chloride. Vapors are allowed to come from the chamber and then gets deposited on the surface of the porous cathode layer.

So, there are a complicated process, by which a completely dense electrolyte film can be deposited on this. So, this is your electrolyte and over top of that, one has to deposit the electrolyte, here the anode the zirconia anode, there are many techniques by which this can be done, one can do spray paint spraying or dip coating or plasma spray. So, there are many different techniques, by which one can do that and this of course, once again it can be deposited by a screen printing or plasma spraying.

So, these are the different techniques, by which a tube like structure basically, a tube like structure is made, but this tube is not a monolithic tube, it is actually a sandwiched structure. The tube wall is actually a sandwich structure and the tube wall acts as the M a M a or membrane electrode assembly. So, you have the advantage over here is, one can flow air, because cathode is inside so the air can be flown through the inside inside of the tube and the fuel can come in contact with the anode and it can flow outside.

So, there is no question, it is become easier for the two compartments to be separated once you have a tubular structure. So, that is one way, a a solid oxide fuel cell the whole tube acts as a cell and the fuel is flowing in the outside and the air is flowing on the inside. So, this has been in fact, was originally developed by Westing Siemens Westinghouse, originally by Westinghouse and then Siemens Westinghouse and 700 kilowatts of power plants have been already demonstrated and prototypes have been built.

And they have been operated at different countries particularly, in Japan with natural gas and so on upto 50 to 60000 hours of continuous operation has been demonstrated by this tubular fuel cells. There is another design, which is called the planar design and once again in a planar design, well it is a very simple thing, it is just a sandwich structure, the way we have seen it earlier.

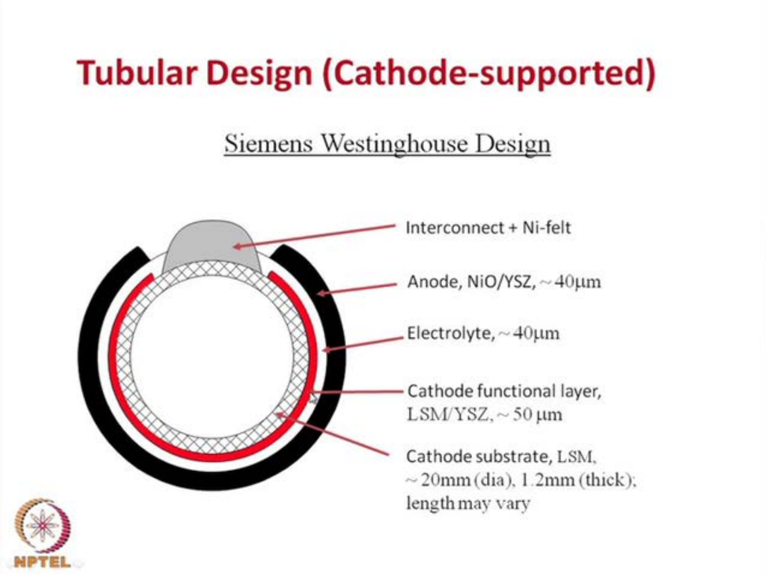
Instead of a tubular structure, we have just a planar structure and we will see later on, there are various various kind of designs once again within the planar structure, whether it is electrolyte supported or anode supported or cathode supported. So, these are these some kind of indicative figure, so far as the thickness is concerned, the electrolyte here you can see about 200 microns, which is about 0.2 millimeter, the anode is 50 millimeter, cathode is another sorry 50 micron and cathode is another 50 micron.

This is what we call the anode supported one, this is electrolyte supported, you can see, because 50 micron cannot be self supported, 50 micron cathode or 50 micron anode cannot be self supported, the mechanical strength is not good enough. So, you need another thicker material and in this case, it becomes electrolyte that is what, the the original designs was electrolyte supported. But later on, more efficient design have come up, these are anode supported what we call, the anode anode is much thicker here whereas, the electrolyte is much thinner and that is about around 10 micron well.

10 micron is quite thin, but normally, it is a about 20 to 30 micron, is quiet natural or quiet regular, cathode once again is about 50 micron. So, these are just sandwich structure, planar structure, but the problem here is, you have to separate out the the fuel side or the oxidant side and the fuel side. So, one needs a other kind of support structures

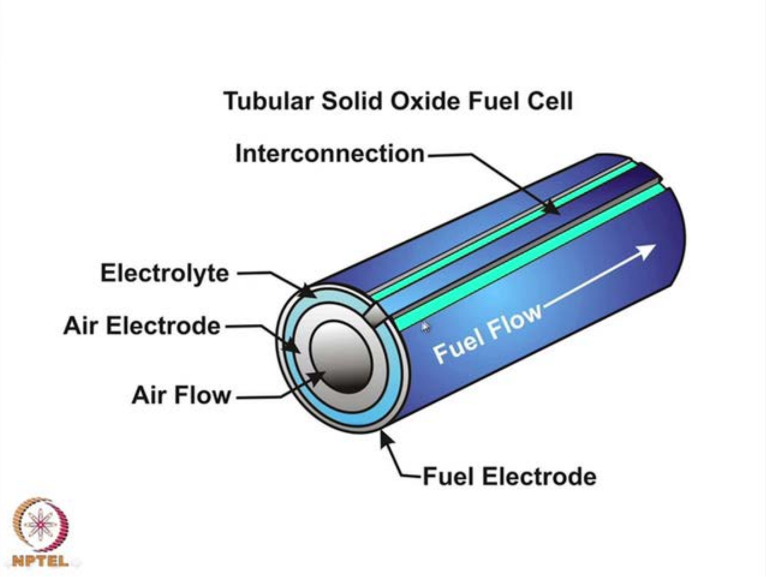
or the sealed sealed chambers so that, the two gases can flow and do not come in contact to each other so that is the challenge of course, we will see how it be done.

(Refer Slide Time: 30:08)



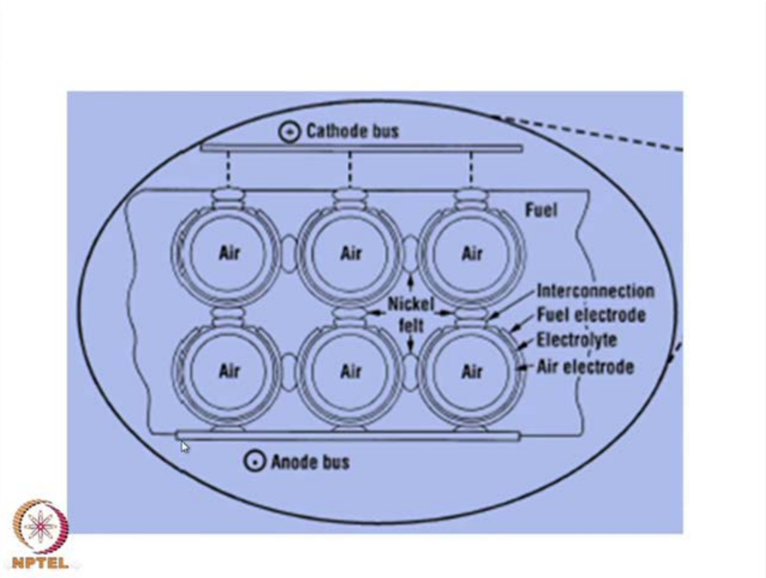
Well, this is the expanded view of the supported structure the tubular structure, this is the cross section of the tube, which we have already discussed alright. This is the anode, the white one here is the cathode and then there is a additional layer what they call, cathode functional layer well, we will come to that later on. What is the cathode functional layer, because in between the electrolyte and the cathode, one produces or gives another very small layer or thin layer of a different material, which which is advantageous from the point of view of drawing larger currents or higher current density. So, this is the cross sectional view of the tubular (( )).

(Refer Slide Time: 31:05)



This is the overall another view of the tubular structure, is little more exploded view, but the it is basically the same.

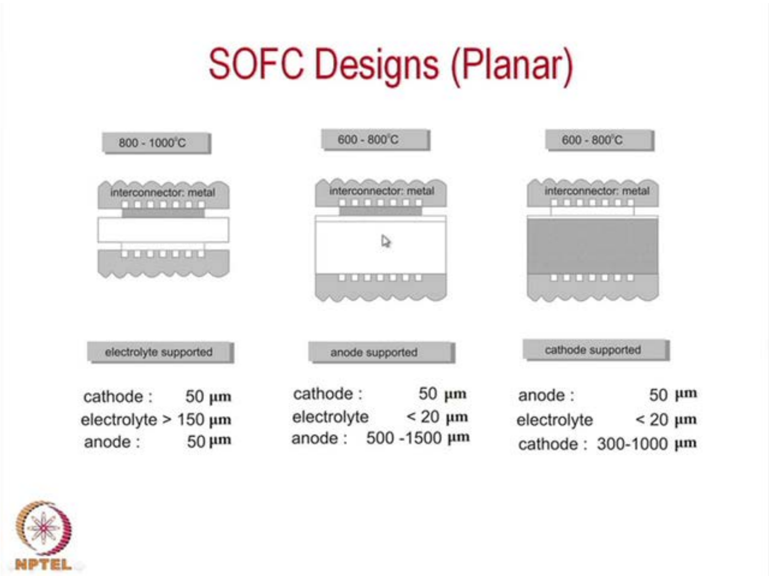
(Refer Slide Time: 31:19)



This is the assembly this is the assembly, by which the tubes are finally put together, this is one can have stacks. So that, you can see this is the cross section of the tubes again and these are the this is the interconnect so the the cathode is connected to the outside of the next cell so the outside is anode here and the inside is cathode. So, this is how, the interconnect walks, on this side of course this is a parallel connection, these are the basically their nickel nickel felt, a nickel mess is used to connect the anode to anode.

So, sidewise, they are connected anode to anode and the vertically, they are connected cathode to anode so this is a series circuit and this is a parallel circuit. So, the battery of large number of such tubes can be put together and finally, one can help a cathode bias cathode bias here and the cathode anode bias here. So, it is a positive charge here, the anode are connected parallely and the cathodes are connected parallely. So, by that process, you can have a battery of systems, battery of cells individual cells or battery of tubes basically a large number of tubes stack together so that, a power system can be fabricated.

(Refer Slide Time: 32:56)



These are the different designs, so far as the planar design are concerned, one can say this is an interconnect. Before that, this is your electrolyte, this is electrolyte supported, electrolyte supported anode supported and cathode supported, the basic difference is the dimensions of the three layers. Here, the electrolyte is much thicker, the white portion is the electrolyte, the here the inner it this is anode supported. So, this white this white is actually anode and this thin white thin layer of the white layer is actually the electrolyte and the other one is the cathode so the here it is cathode supported.

So, just the reverse of that, the cathode this is cathode has a thick, thicker area of is cathode, once again a very thin layer is the electrolyte and on top of that the anode is there. So, the dimensions are given here, the cathode is about 50 micron here, the electrolyte is hundred more than 50 micron, earlier we have seen, about more than 200 micron. So, it varies between 1100 and 150 to 200 micron, electrolyte is less than 20 micron here whereas, anode is much larger.

Anode is almost 0.5 to 1.5 millimeter in in thickness, here cathode is about 300 micron to 1 millimeter and electrolyte is still less than 20 micron, anode top layer is all the time 50 micron. So, whether it is a anode, whether it is cathode and here is also the cathode so that is how, this is the structure this is the sandwich structure of one single cell, is an… similarly, this is the design of the anode supported, this is cathode supported. The current train of course, is primarily the anode supported one so the anode is again porous alright.

Now, interconnect here is in a different form, this is an one interconnect in fact, because of the thin electrolyte used here, the operating temperature has come down. You can also notice, the operating temperature here is higher, because the electrolyte thickness is higher. So, to reduce the internal resistance, you have to heat it to higher temperature so the operating temperature 800 1000 degree centigrade. By reducing the thickness of the electrolyte, one can reduce the operating temperature 600 to 800 degree centigrade.

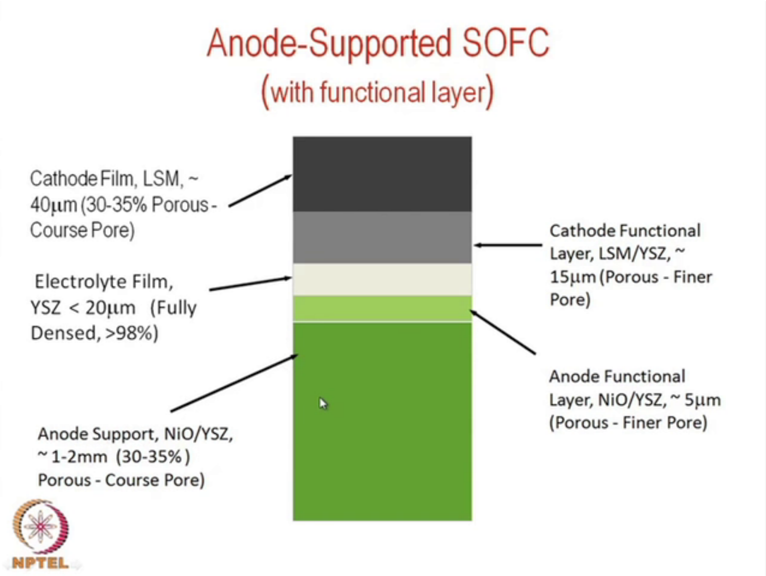
So, the anode supported, both anode supported and cathode supported where, electrolyte is much thinner is about 20 micron in thickness, the operating temperature can come down so this is one advantages of this. Now, interconnect here, it is in a different form, interconnect is there is one interconnect here, there is another interconnect there so there are two interconnects. And in the interconnect, you have some channels, these white spots, white groups are actually basically, there are some groups. And once it is in contact with the plane surface of the anode, it actually forms the channels.

So, these are the channels through which, the fuel gas fuel gas is allowed to pass through whereas, the on the other side, the channels are used for the… This is the this is the anode supported so the cathode so the oxygen or oxygen air is allowed to pass. So, these square, the white spots or the white square cross section spot are actually this channels through which, the gases are passing. So, on one side, you have a this is anode one so it is fuel and this oxygen, if this is cathode then this becomes oxygen and the other side becomes fuel.

So, the interconnect here in fact, in a different form so if you can stack, this is only single layer, if you can stack large number of layers one after the other then the the cathode side will be in coming in coming in contact with the anode side. So, the other side also, there will be some channels like that so this are plates actually, these are metallic plates in this case, because the operating temperature has come down to 600 to 800 degree centigrade.

So, some of the metals can be used, which is not possible when this the temperature operation is with little high. In this cases, there is no metal which can which stand more than 800 degree centigrade, but if the temperature operation is between 600 to 800, there are some metals particularly, ferritic steel, the high chromium steel can be used and being used these days. So, this is so the construction is different and one has to seal these part of the area so that, the gas is allowed only through the channels, either this channel or that channel and the gas does not come out outside. So, there will be some sealant, there will be some glass sealant has to be used to seal the interconnect with the either, with the anode or with the cathode. So, this is the different designs for the planar structures.

(Refer Slide Time: 38:53)



This is again a a a expanded view of the similar structures, only thing we have some material here, this is anode supported one, this is an anode where, 1 to 2 millimeter and 30 to 35 percentage porosity, coarse pores are there. And then you have the white white region, is actually the electrolyte, 20 micron thick and the density density is about 98 percent, fully dense. These are the cathodes films, once again about 40 to 50 microns in thickness and the porosity is upto 30 to 35 percent, coarse pores is called then there are two additional layers.

The three layer are normally the standard layers, but we have additional layers, one can say, cathodes it is called, whichever is in contact with the cathode and the electrolyte or in between the cathode and the electrolyte, this layer is called the cathode functional layer. Layer is called, it is very thin is about 10 to 15 micron, again porous, but these are finer pores, these are finer pores than the original cathode. Here also, you have another material which is called anode functional layer and the material, I am just coming to that and compared to this anode, which is a coarse pore, this has a finer pore.

So, there is a gradient of pores in fact, one is the material is slightly different, here you can see the cathode side is LSM YSZ. That means, the mixture of the basic cathode, which is LSM pure LSM and a mixture of something like a something like your cermet, what we have used a nickel YSZ. Instead of nickel YSZ, we are basically using here LSM YSZ, there is a mixture of the cathodic material and the YSZ, which is the electrolyte and the pores are much finer.

So, we have basically, if you go through across this two layers, the initially we have a coarse layer and then in contact with the electrolyte, there is a final layer. Same things happens here on the other side, the anode basic anode has a coarse pore and then the cathode anode functional layer which is NiO YSZ. This is in fact, it is it is not one can have NiO, because it is this is Ni and this is NiO YSZ which of course, under the reducing condition will finally, go to Ni.

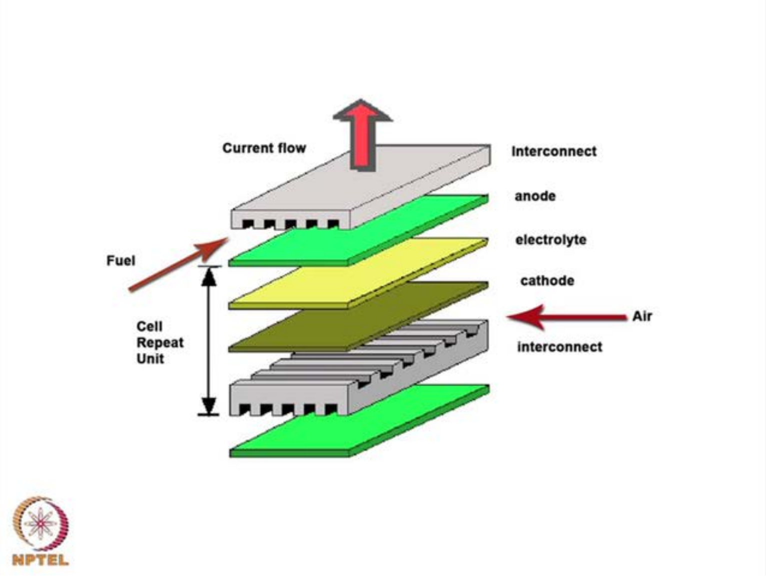
So, NiO is not that stable in presence of hydrogen so NiO will gets reduced to Ni, so finally, it becomes an Ni YSZ just like the composition of the the original anode material. But the more importantly is a finer pore size, so it has once again the gradient of pore size, coarser pore to the finer pore. Advantage of this is, to increase the current density I mentioned earlier that, we need a contact or what we call a triple phase boundary that means, a contact between the electrolyte, the anode and the gas phase.

These two must come in contact as much as possible so which is possible, which is the the contact area maybe enhanced by reducing the pore size. So, finer is the pore, this contact area or triple phase boundary area gets enhanced and so the number of reaction sites, number of the interfacial reaction site increases. And therefore, you can have a higher current density, you can draw more more current, more gas can pass through and more current can go through or pass through this circuit.

Same thing happens in the other side also, if you have a finer pore size in contact with the electrolyte, the triple phase boundary area of the triple phase boundary increases so you have a more reaction sites. So, the exchange reaction takes place much in a large number or number large amount nor large extent and then you get a higher current density. However, you cannot have all through this finer pores, if you if you have a very fine pore all through then there is a problem of gas diffusion.

So, the overall diffusion rate will reduce so that will restrict the movement of the gas and therefore, one can have a one would not have the enough reaction sites, no reaction sites will be there. But, the gases will not be available and therefore, the current density will reduce so it is always better to have a gradient of pores finer pores towards the electrolyte side and coarser pores away from the electrolyte side. Same thing happens with the both in the cathode as well as in the anode side so that is the reason, one uses a five layer model instead of a three layer model one can use a five layer model. And with a gradient of porosity and as well as sometimes sometimes these materials are different here of course, just a mixture of the normal cathode and the electrolyte has been used or a normal anode and the electrolyte has been used. But some different materials can also be used to enhance the electrode kinetics.

(Refer Slide Time: 45:03)

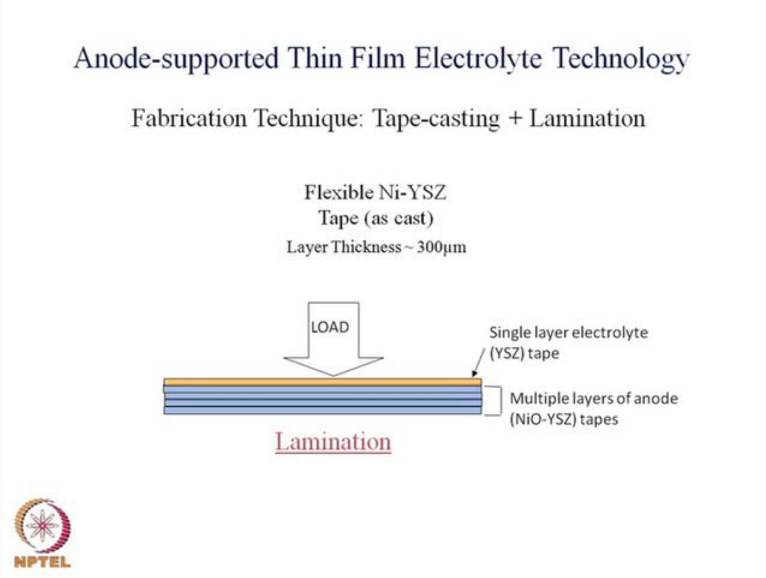


So, this is another way of designing, this is the this has been shown in a in a different view or this is a isometric view and this is the interconnect, this is the interconnect. So, there are two interconnects and one can see, this is the anode, the green one is the anode and the black one is the cathode, yellow one is the electrolyte. So, there are two anodes have been shown, this is the continuous, this is the start of the next layer, next unit cell, the next single cell so this is single cell.

So, these are the groups and normally, the groups as you can see, there are groups on either side of the interconnect so this is one gas so this is in contact with the cathode so this is oxygen side and below this is the anode side so this is fuel. So, on either side of they can in fact, it is connecting the anode from one cell to the cathode from the other cell, this is an conducting material and the metal is certainly good conductor so or alloy actually ferritic steel, so that is a good conductor.

So, it provides the electrical contact and also provides the channels for the flow of reactance or the gaseous reactance. And there is a cross flow, there is a cross flow design so the flow of fuel is in perpendicular direction to the flow of oxygen. So, oxygen in drawing flowing in this direction or air is flowing in this direction and the fuel is going along this direction. So, this is the stack, it is a kind of stack design one after other, one can stack a large number of cells then they can be connected parallely outside.

(Refer Slide Time: 47:10)



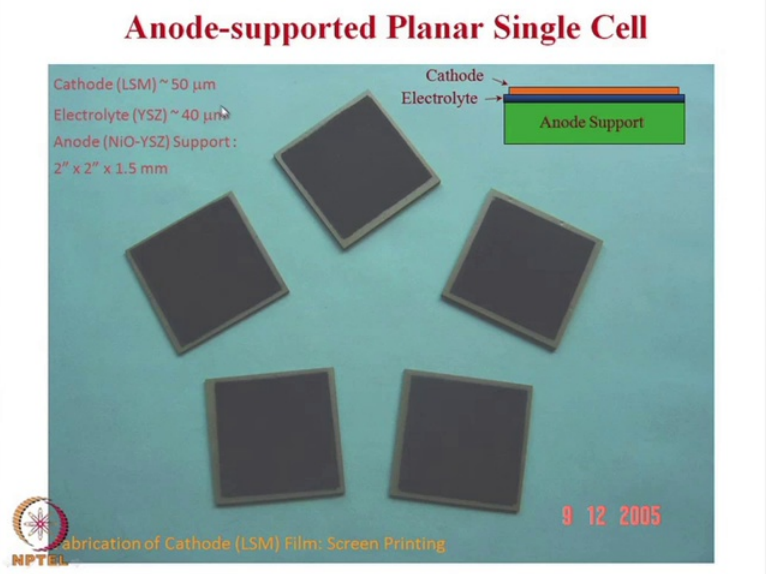
Well this is another thing in fact, how these cells are finally designed or fabricated, these are tape cast seats, flexible tape cast large, number of flexible tape cast seat are actually compressed together. This is the anode this is the anode material in the form of tape and then only one tape of zirconia stabilize zirconia. So, single layer of electrolyte is there and then large fuel depending on the thickness of the each individual tape as well as what will be the final thickness of the support tube, support anode.

So, these are nickel YSZ nickel YSZ tapes, which has been pressed together in the cold condition so while putting a load is actually compressed them and this is the multiple layers of anode nickel. In fact, one other thing need to be mentioned here, to start with, these compositions are basically nickel oxide and YSZ. So, we formed nickel oxide YSZ and then during it is use when hydrogen is passing is allowed to come in contact with this at a high temperature, the nickel oxide gets reduced to nickel.

So, finally, this stable form is nickel YSZ cermet, so by taking few numbers of the tapes actually, you can control the thickness. Since you need about 1 to 1.5 to several layers of such things can be compacted together in the cold condition and only one layer is put for the electrolyte or the only pure y s z. And then they can be cosintered cosintered that means, sintered simultaneously so that, the nickel YSZ gets sintered on the surface on the surface of this anode.

So, that is how, one actually makes so the flexible nickel YSZ tapes has cast layer thickness is about 300 microns so several of them and then fabrication of typecasting plus lamination to call the lamination. So, anode supported thin film electrolyte is actually one of the techniques, it is not the only techniques by which it can be fabricated. But, this is only one of the techniques, by which the tapes can be formed so single tape casting machine can be used for the same purpose.

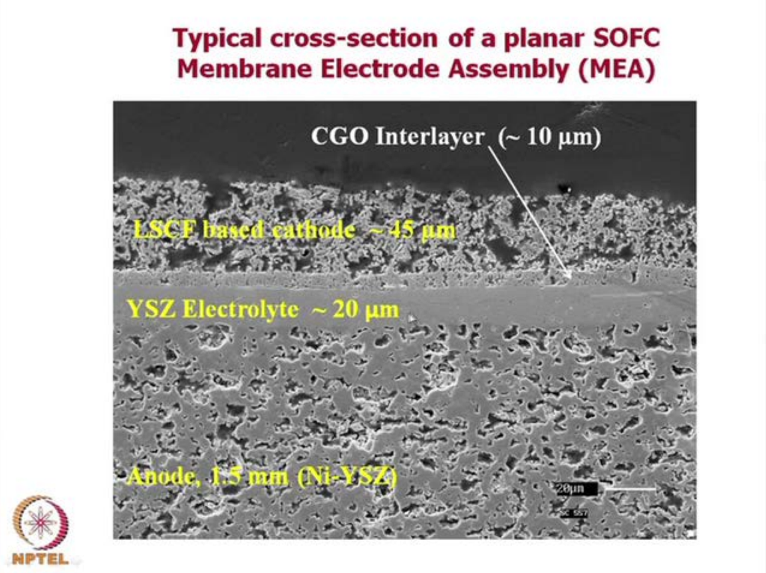
(Refer Slide Time: 49:56)



These are some of the examples of typical examples of cells made at CGCRI, in fact so these are the tapes made at CGCRI at some point of time whereas, there… So, these are basically nickel YSZ anode, this is basic structure, nickel alloys at anode and then this black one is actually screen printed LSM, the screen printed LSM is here. So, the typical dimensions are there, it is 50 by 50 sorry 50, these are 4 inches by 4 inches I believe, no these are 2 inches by 2 inches, 1.5 millimeter. Later on of course, the same group is also making 4 inches by 4 inches cells.

So, the electrolyte thickness is about 40 micron in this case and cathode is about 50 micron and this is about 1.5 millimeter. So, of course, there are that challenges of fabrication is, there are tremendous amount of challenge, because your sandwiching three things together and particularly, the electrolyte making a elect dense electrolyte on a porous substrate is always a very difficult job. And one has to find out, whether there are peen holes and so on, that has to be aborted so this is certainly a challenging fabrication technology.

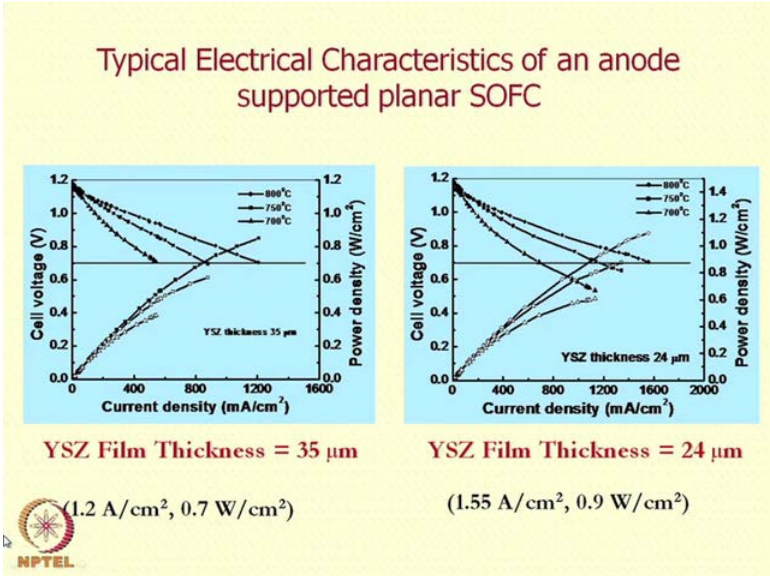
(Refer Slide Time: 51:36)



This is a typical microstructure, the cross section and one can see this the LSCF layer, they are actually a four layer here, the anode functional layer is not there. These are the anodes, this whole thing is porous anode, this is the electrolyte is about 20 micron in this case. These are the electrolyte dense electrolyte layer and then there is a LSCF, LSCF one of the cathodic material which is a finer pores, you can see this layer is finer and then much larger pores.

So, this is LSCF cathode, cathode is not LSM, it is LSCF, it is there and then CGO are the inter layer functional layer. The CGO has been about 10 micro, this is 20 micron, this is 10 micro and this is about 15 micron, this is about 1.5 millimeter. So, this a typical cross section and as you can see, to make a dense material within the porous material by a co firing technique is always a difficult job. So, this is typical cross section of a planar SOFC membrane electrolyte, electrode assembly, this we have seen what is happening alright.

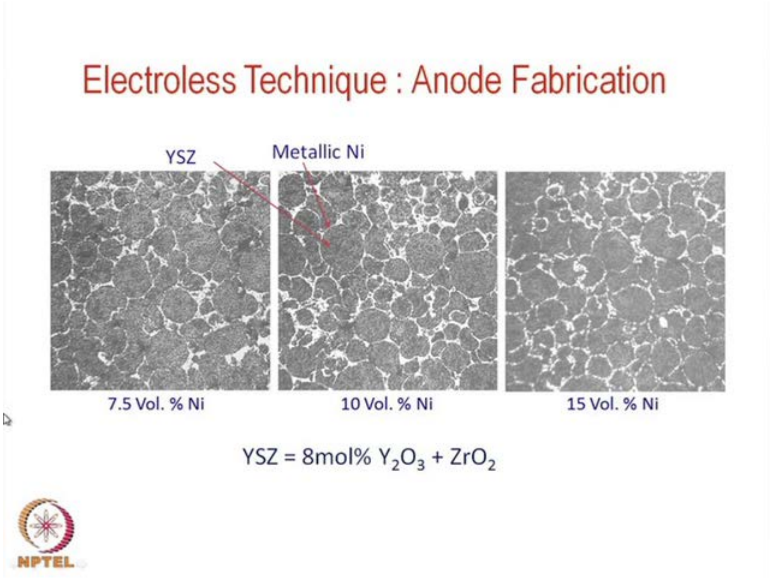
(Refer Slide Time: 53:06)



These are the typical current voltage verses current curves, current density curves you can draw different amount of currents at different voltages so these are the open these are the voltages across the single cell of course, these are all single cells. So, as you increase the current density, load is increased, more and more current get drawn and the voltage comes down. So, normally at 0.7 percent, 7 volt whatever the current dense we get so if the open circuit voltage, the current is low, voltages is high obviously, and as more and more current is drawn, the voltage comes down.

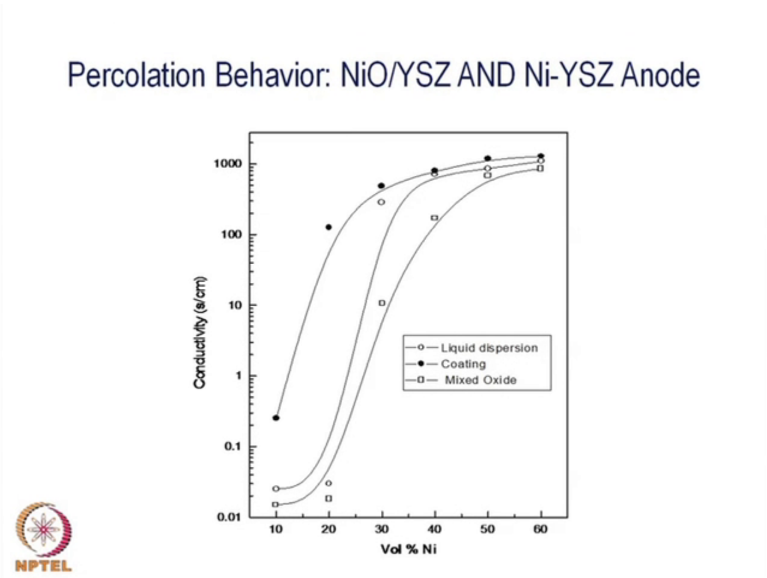
So, this is the thickness, these at kind of thickness dependence you can see, the YSZ film is here about 35 micron. So, you get a current density about 1.2 Ampere per centimeter square and overall voltage about 1.7 per centimeter square. Whereas, if you have a lower thickness of the electrolyte in the same structure, you have a higher current density 1.55 Ampere per centimeter square and 0.9 Watt per centimeter square, is the total voltage of the single cells of course. These are once again the data presented from this CGCRI group.

(Refer Slide Time: 54:39)



Well, I think I will not discuss it this time, we have some more interesting features need to be discussed.

(Refer Slide Time: 54:48)



But that can be discuss in the next class, for the time being let me stop here and whatever remaining, maybe we will discuss in the next class.

So, thank you for your attention.