Non-conventional Energy Resources
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Lecture – 30
Battery Testing and Performance

Hello. In this class we will look at Battery Testing and Performance. In our previous class we looked at some of the basic concepts associated with batteries as electrochemical devices. So, we will build on it and we will look at battery testing and performance. This is very important to understand because whatever as we mentioned you know whatever renewable energy source we use; often batteries are there as part of the overall scheme to enable you know more uniform delivery of power or at least delivery as required by the customer.

And in this context you will always find so many manufacturers of batteries who are selling different chemistries of batteries, who are selling you know even with the same chemistry somebody will claim that their battery performs better than somebody else is battery and so, on.

So, we need to understand what is the process by which we test a battery and you know what are some parameters; we should look at when we think in terms of performance of the battery. So, that is the kind of issues that we will look at in this class.

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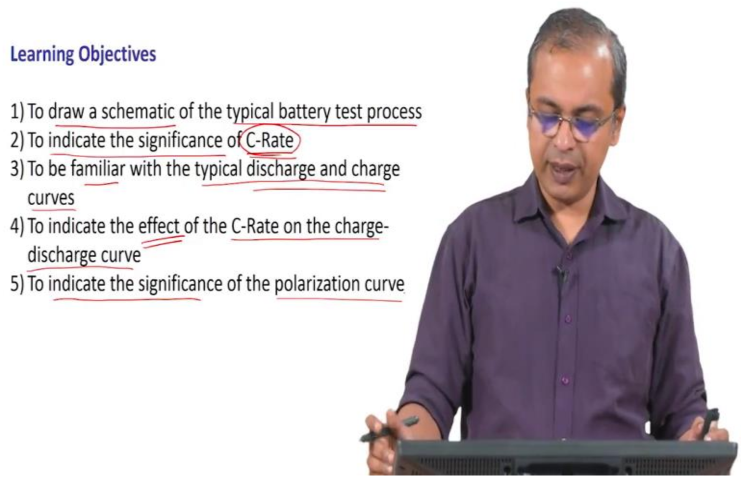

So, what we will do is we will in this in terms of learning objectives; what we will do in this class is we will first draw a schematic of the typical battery test process. So, the typical battery test process we will draw a schematic and just get an understanding of what happens during a battery test process. And then we there is something called a C-Rate. So, we will try to understand the significance of the C-Rate; what is the C-Rate, how is it indicated and what is the significance of it and how does it matter? We then become familiar with typical discharge and charge curves.

So, you can call it charge discharge curve or discharge charge curve whatever way you want to call it. So, there are such curves that are generated for batteries. So, we will try to understand; what is a typical kind of a curve for it and I mean how do we you know understand it and utilize it? Then we will also since we have learnt about the C-Rate here and we have learnt about this discharge and charge curve,, we will try to understand the effect of the C-Rate on the charge discharge curve.

So, we learn C-Rates independently, you will learn charge discharge curve independently then you understand what is the interaction between them. What happens if you change the C-Rate, what happens to the charge discharge curve?

So, that's something we look at and then we will also try to understand another parameter which is the polarization curve. So, what is the polarization curve and again how is that used to keep track of what a battery does and understand water battery does. So, these are all our learning learning objectives schematic of the battery test process, C-Rate, charge discharge curve, effect of C-Rate on the charge discharge curve and the significance of the polarization curve. So, this is what we will cover in today's class.

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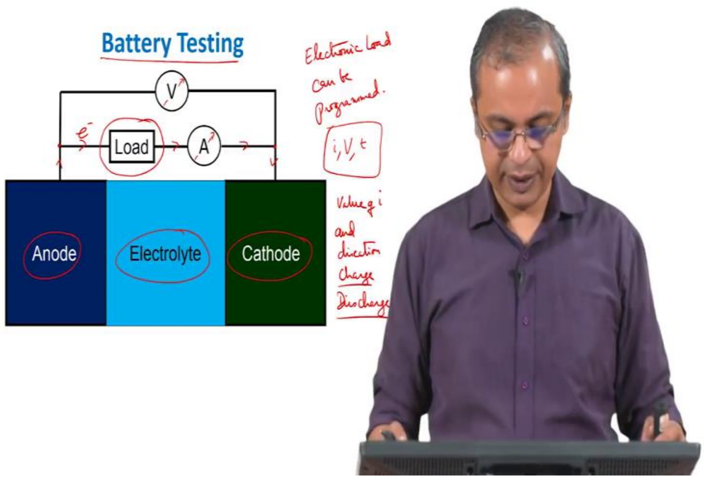

And so, let's start with the first point here which is the schematic of a typical battery test process. So, battery as we saw has an anode an electrolyte and a cathode. So, that's the three major parts of battery; so, you can simply draw it that way a battery anode cathode electrolyte the three rectangles and your all set.

So, when we buy a battery and we put it you use in anything, you could put it to use in a toy, you could put it to use in a remote remote for some you know television or whatever it is that you are putting it useful. What happens is during the life of the battery; so, you buy it new and then it you know let's say it lasts for a month and then the battery eventually drains out.

So, during this time we are actually making a wide range of different demands on the battery at different points in time. So, there may be a point let's say your I mean let's say it's a toy that you are using. So, then at some point you are putting the toy to go through a steady run for a period of time; at that point the demand from the battery is something. Then suddenly you get it to accelerate to much higher speeds, during the acceleration process the demand from the battery is different.

Then you stop the toy for some time and only leave the lights of the toy on. So, if you if you leave the lights of the toy on; that the demand on the battery is different. So, in this process you have used the battery in different ways for the let's say the; for the 15 minutes that you have been playing with a toy. Same thing with the remote control; so, most of the time the remote control is sitting idle except maybe doing some internal you know testing or internal electronics you know some kind of you know charging up that's going on internally.

You press some buttons at that point some signal goes. So, at that point it is you know more actively consuming battery power, you are continuously changing channels; so, then again battery power is getting consumed. Then you stop and then nothing is happening from the battery, again you press to increase the volume or decrease the; again you demand something different.

So, the point being whether you are using a remote or using a toy; typically when we use it as you know as a end user using the device which has batteries in it, we are not ensuring any kind of steady usage of the battery; we just have the moments when the battery usage is high other moments when the battery usage is slow and it completely varies. Maybe you played with your toy for 15 minutes, a friend of yours had exactly the same kind of a toy and they used it only for 10 minutes; somebody else played with it for an hour etcetera.

So, there is a extremely wide variation between our user profile from person to person even within a person from day to day and so, on. So, when somebody tells you; I bought those batteries and I put it into whatever they were playing, let's say its you know some radio that they were playing; they put it in portable radio that they were putting it in and then they say that it lasted a month.

That information is not really useful to you because we don't know how they used it for that month right. So, they might have used it very sparingly for a month in which case the month is not a significant number, they may have used it extensively for the month; in which case the month may be a significant number. So, even somebody says that I; I put this battery and it lasted me a month; that does not convey any information to you about what would happen if you bought exactly the same battery and put it in there exactly the same device in your house.

Because you may use it totally differently than the other person right. So, therefore, this kind of a comparison although it is called anecdotal comparison; I mean because they are just giving their experience to you and so on. This kind of a comparison is not particularly useful; unless you then you know enquire how much did you use? And they tell you know every day I have been using from morning to evening and something like that then; then then it starts conveying to you something.

If they use it only half an hour a day doesn’t convey much to you, it means for 30 days they have used it only for 15 hours. If they used it for 10 hours a day; then in 30 days they have used it 300 hours. So, there’s a huge difference between 15 hours and 300 hours. So, telling you that it lasted a month doesn’t mean anything.

So, therefore, we need to test batteries under somewhat standard conditions. Or at least we should be able to report it in some standard way so, that somebody else can look at it and make a decision whether or not that is acceptable to them; this is what a battery manufacturer would have to do. They would have to give you this kind of information so, that you can make a judgment if whether that that particular battery is useful to you or not. So, to do that what they do is essentially you have a battery and anode, cathode and an electrolyte.

So, we make connection; we make connection to an external circuit where there is something important here called the load. Normally the load is whatever end use you are putting the battery to. So, if it’s a toy then the load is the toy, but in a battery test situation you will have a test you know test station so, to speak. So, it will be one electronic structure I mean a instrument which has lot of electronics in it, where the specific purpose is you can specify some current and it will draw that current from the battery steadily.

So, you can start the test in the morning and say you know draw 0.2 amps, it will draw a 0.2 amps from the battery continuously. So, the question of you know you using it for 15 minutes, somebody else using it for 30 minutes is not there for; it will draw 0.2 amps continuously unless you give another instruction saying now change it to 0.3 amps or something like that. So, it will steadily draw the current. So, this load this electronic load is typically programmable ok; so, can be programmed. So, it can be programmed you can change the you know the amount of current you are drawing from the cell to whatever value you want to do.

So, you can set different levels of load and it will follow that load etcetera and in series with it you have. So, the current which you are drawing sort of does this. So, electrons are going this way the; so, you know the conventional current is going the other way, you have an ammeter. So, you have some ammeter here which tells you what is the current ok.

So, in a in a rudimentary setup you can have an ammeter there which you which you can read and you know note down the values from, but in the modern day setups there are automatic you know data acquisition systems, which are present inside this test station which will record the current. So, whatever load you set to you know you say you say 0.2 amps it will draw 0.2 amps from the battery and it will also record the 0.2 amps in the test station; in the data acquisition system.

So, you will have a value of current; current i is being recorded and you also have a voltmeter attached in parallel which now tells you the voltage. So, you record current I; you record voltage V and of course, you have a duration for the test which is time t. So, really these three are the important parameters that we record; current, the voltage and the time.

And the test setup will usually also have some safety features thrown in saying let's say you are drawing constant current 0.2 amps. You will also set a voltage window you will say that this battery supposed to operate at 1.5 volts; I don't want the voltage to change to drop below 1.3 volts and I don't want the voltage to go above say 1.7 volts. So, 0.2 volts I will put on either side that is just a decision you have to make based on the battery you are testing.

So, you will say that it should stay voltage should say between 1.7 volts and 1.3 volts. So, as long as the voltage is between these two keep drawing 0.2 amps and then the moment it touches one of these things, you switch off you don't draw further current or maybe if you are if we are talking of a rechargeable battery and let's say the voltage is dropped to 1.3; you use that to make a decision that it has actually reached the end of its you know discharge and now we need to recharge it or charge it right. So, therefore, you will say now if it reaches 1.3 volts stop the test and reverse the direction of the current and put the same 0.2 amps in reverse direction. So, that is the way in which you would set up; so, you will say how much current and direction value of i and direction. So, that will ensure whether you are doing a charge or a discharge.

Charge or discharge; so, this is how the testing is done. So, you connect the battery to the station, you program all this information in and you let it run. And if especially if it is a rechargeable battery; you can even say the number of cycles you can say that I want to do 10 charging and 10 discharging. So, it will just you can set it up in the morning and you can come the next day and maybe it will even give you an alarm; it will send you an alarm by SMS.

Or something saying that you know it has finished its 10 cycles or if there is an error in some sort that stopped for some reason it will tell you that right. So, this is the basic idea you measure the current, you measure the voltage and you measure the time. So, you either set a current; measure the voltage or set a voltage measure the current and then you check the time. And this data is collected and this way you ensure that the battery has been tested uniformly.

So, now if I take two manufacturers batteries and I put them under this condition; test condition and I gave the exact same cut off limits point you know 1.7 volts to 1.3 volts and I say drop 0.2 amps current. And now if a battery runs for 10 hours and another battery runs for 15 hours, you can confidently say that the second battery is better than the first battery for from the perspective of how long it will last right. So, that is the way in which a standard test is done for a battery and this is the idea behind the battery testing ok. So, this we will keep in mind if necessary we will revisit it, but this is the basic idea ok.

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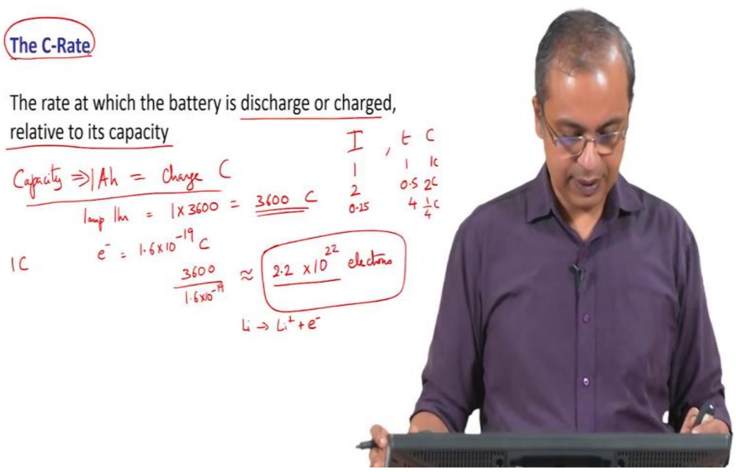

So, now I also mentioned there is something called a C-Rate ok. So, this is the rate at which the battery is discharged or charged relative to its capacity ok.

So, what is capacity? I spoke to you yesterday I mean even in the last class we spoke about ampere hours the capacity being measured in ampere hours. So, it is actually in in coulombs ok. So, it is basically charge in coulombs. So, in coulombs is what we are looking at right. So, so if I draw let’s say 1 amp for 1 hour so, that is your draw it 1 amp per second is a coulomb.

So, this is basically 1 into 3600 equals 3600 coulombs that is the amount of charge that is available in that battery 3600 coulombs what does that mean? So, now, if you have let’s say; if you look at because we always talk of electrons flowing the circuit right. So, an electron is each electron is 1.6 into 10 to the power minus 19 coulombs 1.6 into 10 to power minus 19 coulombs.

So, what does this mean? It means 3600 coulombs divided by 1.6 into 10 power minus 19. So, that is let’s say this is you will have; so, this is 3.6 into 10 power 3. So, this is 10 power minus 19 become 10 power plus 19. So, this is 10 power 22 3.6 divided by 1.6. So, we will say 2.2 let’s say something like that approximately 2.2 into 10 power 22 electrons. So, when you have drawn 1 amp for 1 hour, you have actually I mean consumed or flown 3600 coulombs of charge which corresponds to this many electrons having gone through a circuit between anode and cathode ok. So, that’s basically what you have done.

Now, so, this is in some ampere hour; so this is the idea. So, this basically represents this is significant this charge, this ampere hour, this capacity which is given in terms of ampere hours is significant because it represents the amount of chemicals present in the battery. So, battery as I said is an energy storage device. So, all the chemicals that you require for the battery are present within that battery right.

So, in terms of quantity itself they are present there in terms of quantity. So, the charge or the capacity that is available the capacity that is available which is now you know I am counting this as number of electrons. So, when when we say that it is 1 ampere hour 1 ampere hour; it means 1 ampere can be drawn for 1 hour ok. So, 1 ampere hour if I say then that corresponds to this many electrons. So, that it means; so, let’s say it’s a univariant. So, let’s say is lithium battery. So, lithium will become Li plus plus e minus correct?

So, that is the lithium reaction occurring the anode; lithium becomes lithium plus ion plus electron electron goes in the external circuit, lithium goes through the electrolyte lithium plus ion goes through the electrolyte. So, if you have 2.2 into 10 power 22 electrons going the external circuit that the same number of lithium ions is going through the electrolyte. And therefore, this is a direct measure of the amount of lithium that is available in the system.

And let’s say this if it means it if it says that the battery is 1 ampere hour this is all the lithium that is available in the battery. So, at this point you have consumed all the lithium available in the anode of the battery and the battery will stop functioning. So, the capacity is a direct measure of the amount of chemicals that are present in the battery and tells you how long the battery will operate under the same operating condition ok.

So, two batteries having double; one having double the capacity of the other if they are put to use in the same operating condition, the second battery which is double the capacity will last twice as long that is the basic idea. So, so that is capacity; so, that is a fixed value for given a battery for a given battery you have a fixed value.

Now as I mentioned you can draw 1 amp for 1 hour and that is 1 ampere hour, you can also draw 0.5 amps for 2 hours that will also be 1 ampere hour. So, we have various combinations here you can have 1 amp. So, if I just write current here and I write or will put capital I here; I write capital I current here and I write time here. So, I can have 1 amp, I can have 1 hour, I can have 2 amps; I can have 0.5 hours; I can have 0.25 amps and in that case this will last for 4 hours so, that the product is always 1 right.

So, clearly based on the current that you draw; the duration that it will last it will vary the other things being equal; assuming it is all operating ideally based on the current that you draw, it will last different durations of time. So, this is the idea that is captured by the C-Rate what is the current relative to the capacity that it is being used. So, for example, if I use if it’s a 1 ampere hour battery and I draw 1 amp, then you will consume this entire charge in 1 hour that is called 1 C-Rate.

So, this is for example, if I call this if I write the C-Rates here ok. So, this would be a 1 C-Rate if I draw 2 amps and it is going to get consumed in half an hour. So, we will call it; so, 1 C-Rate this will become 1 by 2 C-Rate and if I consume it in the 0.25 amperes 0.25 I am sorry this is 2 C-Rate two C-Rate.

It’s a it’s a inverted relationship. So, if I draw if I draw 2 amps of current for a point 0.5 hours’ it is twice the capacity twice of the capacity of the battery. So, it will last only half an hour; so, that’s a 2 C-Rate and if I draw a 0.25 amps; so, that is you are drawing much less than the capacity in terms of ampere hours. So, it will last longer; so you you will get 4 hours out of it. So, we call it 1 by 4 C-Rate ok.

So, it is an inverse of this value this time or it is basically an inverse of what you are seeing here with respect to the 1 hour of usage ok. So, so 1 ampere hour with respect to 1 ampere hour, if you can finish it in 1 hour it is a C-Rate, if you finish it in half an hour you are actually consuming; consuming the charge twice the rate; so, that’s called 2 C-Rate. If you take 4 hours to consuming it consume the charge; that means, you are drawing the charge at one fourth the rate. So, that is 1: 4 1 by 4 C-Rate.

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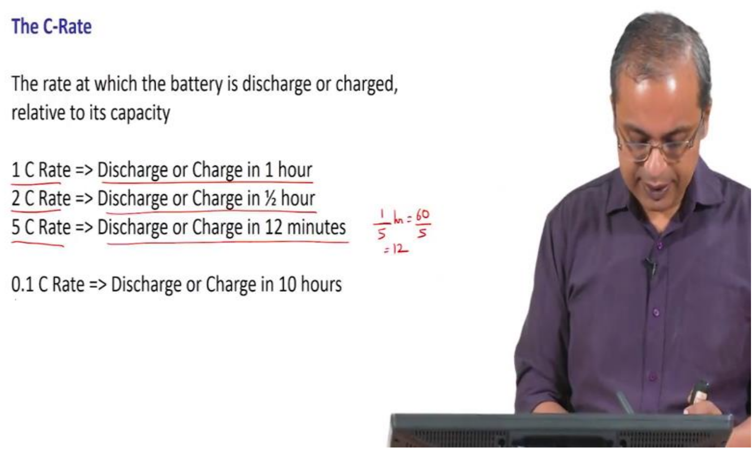

So, just to sum the same information I am summing up here. So, 1 C-Rate is discharged or charged in 1 hour, 2 C-Rate is discharged or charged in half an hour and 5 C-Rate for example, is discharged or charged in 12 minutes; 5 C-Rate means so, 1 by 5 of an hour that is 12 minutes. So, 60 by 5 that is 12 12 minutes is what it will take to do this in when; if you do the discharge or charge in 5 C-Rate.

Similarly you can go down in scale you can do 0.1 C-Rate very slowly you are drawing current out of that battery ok; in which case? Because it is 0.1 if you do 1 by 0.1 you will get 10 hours; it will the battery will now last you for 10 hours. So, the same battery can be tested under various conditions, you can test it at point 1 C-Rate, 0.2 C-Rate, 0.3 C-Rate etcetera C-Rate, 2 C-Rate, 3 C-Rate, 5 C-Rate etcetera.

So, normally in battery testing they do that; they do that to understand what is this battery capable of if I draw if I try to draw a lot of current from it; can it still sustain itself will it last how will it last, how will it perform? That is the reason why we do it in different C-Rates and then on that basis. And we always compare the C-Rate with the original capacity rated for the battery ok.

So, it may actually perform lot worse than that ok. So, for example, I am telling you here that if I do 2 C-Rate, it will consume the charge will get consumed in half an hour. But really that is only under ideal conditions right. So, supposing the battery were not ideal; so, the 2 C-Rate may actually consume the charge in let's say instead of 30 minutes, it may consume the charge in 20 minutes itself; which means you did not consume the charge completely, there was some charge that was unused.

And that is the reason why even though you said 2 C-Rate and you normally expect you to finish in half an hour; it is not finishing in half an hour; in 20 minutes itself it is out of it it has hit the you know boundary that you have set; you set 1.3 volts as the boundary, it has already hit the boundary beyond which you don't want the voltage to drop; so, you have stopped the test.

So, many batteries; so, that is why the C-Rate is always with respect to the original capacity. Because you may not be drawing the original capacity, when you draw high C-Rates and; so, you cannot keep on changing this you know the meaning of the C-Rate. So, it is with respect to the original capacity of the battery, the rated capacity of the battery which you which we know from the amount of chemicals that we have put in.

And then correspondingly we set the set the set the C-Rate and see how long does it last; it may not last half an hour, it may lost less than that. If you go to slow current densities it may last the whole distance. So, that is how you have to think about it. So, that's the idea of the C-Rate.

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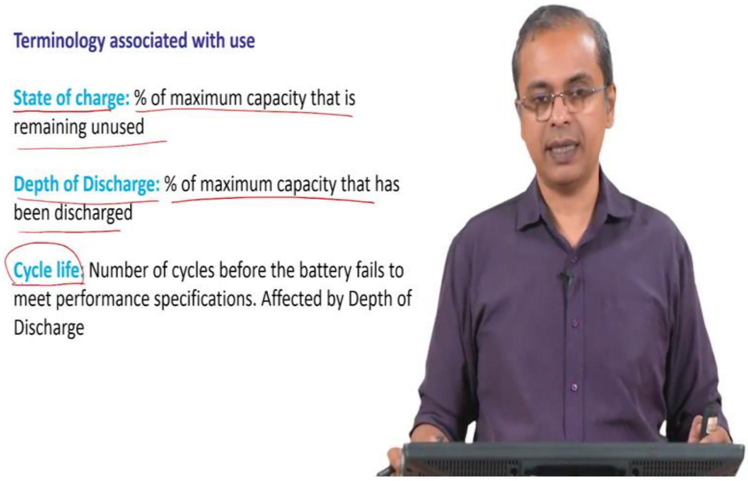

So, now we will look at some incidentally since we talked about charge and discharge a couple of few small terms here that we have to keep in mind. One is the state of charge which is the percentage of the maximum capacity that is remaining unused. So, if you have say you have completed you know 20 percent of the batteries capacity has been used. So, state of charge is 80 percent is remaining 80 percent remains in the battery that you can still use.

So, if you were using 1 C-Rate. So, the you know every 6 minutes is 10 percent. So, you have consumed 20 percent charge means 12 minutes of battery usage you have completed and the remaining 48 minutes remains in that battery which you can still use so; that means, that's the that is the way you compare the state of charge; assuming a particular C-Rate to how long the battery will would last.

Depth of discharge depth of discharge basically means percentage of maximum capacity that has been discharged. So, sometimes you know when we use a a rechargeable battery typical rechargeable batteries, let's say you use it for some particular purpose often what will happen is we will not use it for till the complete end before you recharge it right. So, you are using in a in your camera, you have a rechargeable battery you are you are taking photos etcetera and then at some point you know evening you are back at your home or your hotel room and you want to recharge your battery.

So, at that point the battery may not have completely discharged; it might have you know completed only three quarter of its discharged and that point you recharge it. The same is true with our mobile phones we you know whenever we get time we reach we recharge it, we don't necessarily wait till the battery completely you know winds up.

So, this extent to which it has been discharged before; you recharge it is the depth of discharge ok. So, depth of discharge is percentage of the maximum capacity that has been discharged. So, it is sort of the inverse of the state of charge. So, what remains is the state of charge, what has been completed is the depth of discharge. Cycle life this is actually relevant from the perspective of rechargeable batteries from the perspective rechargeable battery cycle life is important. Because it is the number of cycles before the battery fails to meet some performance specification ok.

So, it means. So, let's say typically recharge batteries rechargeable batteries; you may want it to run 1000 cycles, people try to advertise like that it runs 500 cycles, it runs 1000 cycles etcetera. So, why does it not run 2000 cycles when it is stopped why are they saying only 1000 cycles or why not say 1100 cycles? The reason being they have set some minimum performance limits.

So, they say that you know it should at least last you if I am drawing say 1 amp; it should at least we are usually not drawing one amp, but let's say we are drawing 1 amp it should last you at least 7 hours. Let's say some idea like that they have; so, when they keep on doing the cycling you know of charging, discharging, charging, discharging slowly the chemicals in some way deteriorate.

So, some deterioration happens in all the chemicals that are present there or even the structure inside the battery deteriorates in some way. And then the capacity which was perhaps originally the battery was originally able to last 10 hours, slowly starts decreasing with progressive cycling; it draw drops to you know 9 and half hours, 9 hours, 8 and a half hours, 8 hours and so, on it keeps on dropping.

So, by the time it reaches the 1000th cycle; it has probably reached 7 hours of discharge and that is all its able to discharge before it stops the it has already hit the cutoff and then it starts to having to recharge. So, and we set the standard we say that you know at least 7 hours it should last or some such thing we decide the number 7 is just an example I am giving you.

So, at 1000 cycles it has already we hit that 7 boundary of 7 hours; if you cross 1000 cycles it starts decreasing in capability below 7 hours; it becomes 6 and a half hours or whatever you know 6 hours 50 minutes something like that and we decided that it is not acceptable to us. So, once you set that acceptability limit saying you know at least this much long it should last; this point of performance it should give. Then you can give a define a cycle life.

Because technically, if you don't define that performance you know guarantee. So, to speak what is the minimum performance if you don't define that; you can keep on charging and discharging a battery in indefinitely you can do it; it may not last you 10 minutes and then after 10 minutes you will have to recharge it, again 10 minutes clearly that is going to be very annoying if you put that kind of a battery in your mobile phone right.

So, you don't want to keep on charging 10 minutes to use it for 10 minutes; you really want to be in a situation where you can charge it for maybe an hour or half an hour on an hour and then you want this battery to last for you for the day right. So, something like that is what we are used to. So, we are really expecting at least about 10 hours of service from the battery; I ideally at least 10 I mean ideally you may be on 24 hour service, but at least 10 hours 10 to 12 hours is what we are looking for; for us to feel comfortable.

So, 7 hours is actually on the lower side. So, so some criteria you have to set and with respect to that we decided as cycle life because you can figure out how long it how many cycles it will do before it hits that performance limit. So, again this is something that the battery test station will do for you. We cannot do this on an actual you know you cannot distribute battery to 100 users and figure out when they start feeling uncomfortable about it. In a battery tester you can set the current, you can set the voltage boundary and you can ask you to keep cycling and you can also say a cycle till you get the 7 hour mark and tell me when that happens.

So, once you set this up; it will continue to do that I mean it will continue to do the testing for you know 100 cycles, 200 cycles etcetera and then at some point it will stop and then you can take the data and you can plot it and you can see what is happened ok. So, this is the meaning of this cycle life ok.

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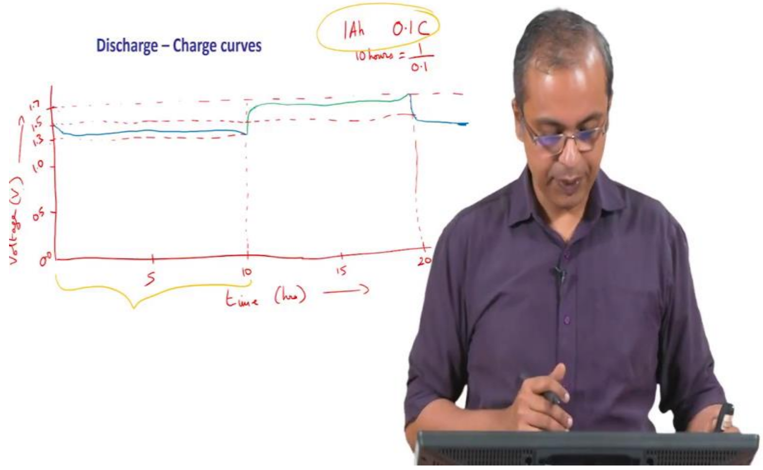

So, I keep talking of charge curves and discharge curves. So, now, we will briefly look at what is this charge discharge curve; how does it look what is it that we can understand from it. So, for that we will make a plot; so, on our y axis we will have the voltage we always talk of voltage with respect to a battery. So, we will put voltage here ok; so, and let's say you know most common value that we keep hearing is you know you go and buy batteries in a shop, you will see 1.5 volt battery. So, just for example, we will take 1.5 volt battery; so, I will put 1.5 here. So, let me say this is 0 have the x axis here. So, this is 0; so, I will say this is 1 and this is 0.5.

So, this is 0 volt 0 I mean 0.5 volt 1 volt, 1.5 volt. On our x axis, we will plot time in hours ok. So, that's what we have plotted on time; this is voltage in volts that's sitting up there right; so, voltage. So, this is what we have plotted; so, normally what would happen is. So, we will just put some time here I will I will just put some numbers here. So, I will just say let's say this is 10 hours and this is 20 hours roughly.

So, this is 15, this is 5 ok. So, some sometimes it is some such numbers we have. So, now, if you start taking this battery and you discharge it and let's say we have a 1 ampere hour battery and I do 0.1 C 0.1 C-Rate discharge charge discharge, but that's what I have put into the system. So, this means this battery will now last 10 hours or it's you can expect it to last 10 hours ok.

1 divided by 0.1 the capacity divided by the C-Rate will give you how long it last ok. So, that is how we are getting this value; so, so roughly I can expect that it last about 10 hours and I set some limit I say you know 1.3 volts somewhere here 1.3 I say it should not go below 1.3. So, that's one value as I set here.

So, what you will see is that what you will see is basically a curve that starts off around 1.5 and then decreases little bit in voltage and then sort of stays stable more or less stable and then begins to fall like this. This is roughly the kind of performance that the battery will show; it will start off, at some voltage the open circuit voltage that you measure then the voltage will drop a little bit as soon as you start drawing current from it.

Then it is stay at that lower value for a steady distance of time I mean period of time and then as you get close to its end of its capacity; it voltage will start dropping again and you have said this cut off at 1.3. So, your test the battery tester will stop testing it at that point; then we will say that we are you know recharging it. So, at this point you have finished the charge; so, you want to recharge it.

So, when you recharge it you reverse the direction of current. So, usually what it will do is suddenly the voltage or climb up. So, I will say again I will set another value here 1.7 volts ok. So, we will set that also just a moment; I have just seen that there. So, we have let's say 1.7 volts there; so, that's the value we have and I have set that value that is a guideline I have there. So, if I now do the recharge what will normally happen is it will it will suddenly shoot in voltage it will cross the 1.5 and then it will start recharging and this is how the curve looks recharge curve.

It will it will again stay flat more or less for the whole period of time; till we are getting close to this 20 hours and at that point it will do that. A voltage will start climbing up kind of steeply and you will see at that point know it will hit the 1.7 volt boundary and it will stop.

So, generally by the way; so, if you look at this curve what we see is that the recharge will happen at voltages which are typically; if if I draw a guideline here this is the guide line that I will draw here for 1.5 volt. So, what you will typically see is that the discharge is happening even though you rated the battery at 1.5 volt; discharge happens at values just below the 1.5 volt 1.2, 1.3 I mean I mean not 1.3 we are keeping above 1.3 say 1.4 volts; at 1.4 volts most of the discharge happens at 1.4 volt one and then when you do the recharge most of the recharge is probably happening at 1.6 volts.

So, this is because of you know various inefficiencies that are present in the system including IR resistances and so, on. So, you end up having to draw put more voltage when you are trying to recharge the battery, you get a little less voltage when you discharge the battery. So, that is always a gap there is always a gap there that represents the inefficiency that is what this curve shows you ok.

So, this is how this curve would look and I can also tell you that you know this is one way. So, normally when you do a charge discharge curve; so, it will continue to do this. Supposing I say do this for you know 100 cycles; so, this is like 20 hours. So, beyond 20 hours again you are you know this blue curve will repeat after that. So, for example, it will continue doing this; so, from here if you do the discharge, it will come down and it will fall down back like this and then you will continue this.

So, this continues indefinitely; so, you can keep doing this many times and then do it. Of course, this means you will have an indefinitely long graph because you were 100 of cycles you will have. So, that gets a little messy to look at; so, another way in which they represent this is the instead of you know continuously keeping it as a linear scale that’s continuously going on endlessly on our right hand side, we keep since we know that we are doing a point 1 C-Rate; we basically you know that this test can you know any cycle whether it is a charge cycle or a discharge cycle, it is only going to last about 10 hours it may last even less than that, but typically it will going to only last 10 hours.

So, we can just stick to this part of the curve. So, we can just stick to this 10 hour part of the curve and plot everything within this 10 hours. So, we can have all these charge curves as well as the discharge curves within the same 10 hour period; repeatedly is resetting this to 0. So, all; so, whatever you see here between 10 and 20 hours, you should simply shift it back by 10 hours and you can plot it between the 0 and 10 hours.

So, that’s another way in which you can plot. So, that your entire plot stays between 0 and 10 hours you see multiple curves; each representing 1 cycle of charge and now one cycle of discharge; so, this is the way in which we have plotted. The other point we have to keep remembering is that I have we have just seen here that we have used a particular C-Rate. So, what happens if you use a different C-Rate. So, this is the point one C-Rate it took us 10 hours to do the charge or discharge and this is what we saw right. So, we can also plot this in terms of capacity this is the time that I have plotted I can also plot this as capacity.

So, I will have on the x axis capacity in that case. So, in so, the the point being that if I plot it as time then clearly the C-Rate will simply keep on changing the time dramatically just because the C-Rate is different. So, if I instead of you know 0.1 C; if I use 0.2 C; that means, I am doubling the current; that means, the the battery will last only half as long in terms of time. So, automatically that itself means that the test will end in 5 hours if even if everything were idea.

So, by simply going from 0.1 C to 0.2 C to 0.3 C etcetera you will keep on changing the time anyway, but the original capacity of the battery is the same. So, therefore, it may it may make sense to plot multiple different C-Rate information with respect to the capacity so, that you can see if there is a difference in terms of you know behavior because of the C-Rate. So, for example, we can plot it like this.

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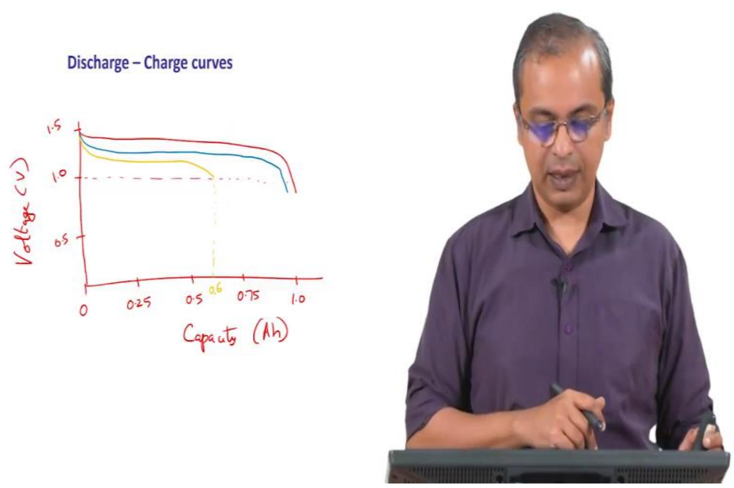

I will have again voltage here and I will have capacity. So, I have 1 ampere hour. So, this is 0 this is 1 ; so, this is 0.5 0.75, 0.25. So, this is capacity this is in ampere hours. So, the capacity is unaffected by what C-Rate you are doing right. So, the capacity of the battery is the same; the C-Rate simply tells you what how quickly or how slowly or withdrawing this capacity and using putting it to some use.

So, here I will have voltage 1.5 volts. So, this is 1, this is 0.5 ok. So, now, based on the C-Rate we will have you know different-different capacity. So, let's say my the first I draw it at some particular C-Rate I get this capacity; then I draw at some other C-Rate a higher C-Rate higher C-Rate will usually mean it will perform a little worse because your drawing current much faster and you may not even reach the full 1 C; you may even before the one C is reached you may hit some boundary.

In fact, I have kept a much lower boundary here let's say I am setting a 1 volt boundary here as the test condition; I can do some other C-Rate which may be even higher performance higher rate. So, you will see that the higher the C-Rate you do you may actually never completely reach the full capacity because inefficiencies are such that you will hit a hit your cutoff boundary before you even reach the complete capacity of the battery.

So, this means for like for example, let's say this is 60 percent let me just say that this is 0.6 it means only 60 percent of the battery I used; I already hit the boundary for that whatever I set as the cutoff limit for the voltage and saying I don't want to go below this voltage. So, because it may damage the battery or it may not be useful for the end activity that are in putting it to use for.

So, for those two reasons I may set a cut off voltage and so, it hit this 1 volt cutoff voltage in this case I set it at 1 volt let's say and it is hitting this one more cutoff voltage at only 60 percent of capacity. So, it is not really helping us. So, so the point is you can draw it I you have to understand. So, that therefore, different C-Rates, the performance can be different you may not completely get the full capacity out of it.

And you need to understand this for your battery so, that you can tell clearly whether or not this battery can be put to use for some purpose or not. Or if you get a new battery that you want to put it for some experiment, for some end use you know what usage that induces how much current it will draw.

You can test and check whether your battery can actually handle that activity right. So, this is the way you do that test.

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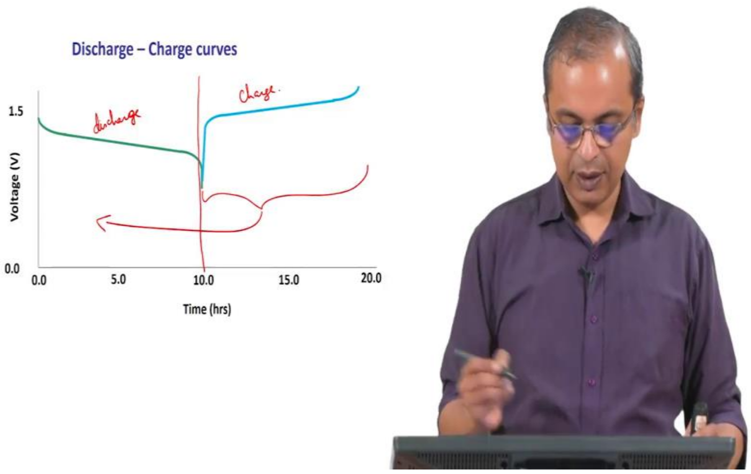

So, the same information I am just showing you here in these plots here; this is a discharge curve here and this is charge or recharge this is what we just discussed. And then the same thing as I said you know instead of you can just take this part of the curve and push it back into this part of the plot; so that the whole plot stays within 10 hours and so, that is exactly what we have done here.

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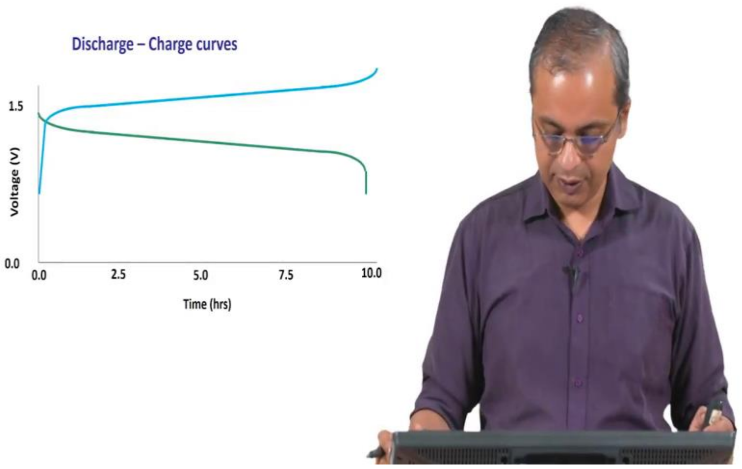

So, I have just plotted it all within 10 hours, I have shifted the charging curve also within this 10 hour window. So, there everything now shows up between this 0 and 10 hours.

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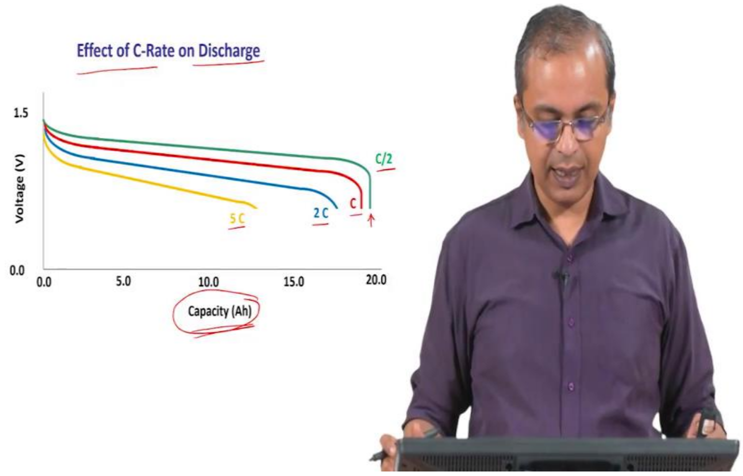

And the as I said you know we can have capacity here if you want to look at the effect of different C-Rates on discharge possibility.

So, I have a C by 2, I have C, I have 2 C and 5 C; as you can see the rate at which I am discharging the battery is getting higher and higher and higher. So, the speed with which I am pulling something out of it is higher; usually this is what happens the closer you are to you know doing it, the more slowly you do it the more completely you can extract the charge out of the battery.

The faster you do it before the full charge comes out of the battery; it starts showing you bad performance and then you stop the test. So, clearly that is why C by 2 gives you much better performance than C and which performs better than 2 C, which perform performs better than 5 C. And as I said it makes sense to keep capacity here because only then you can you know at a glance; at a glance you can compare these C-Rates.

If you put time here it is very misleading because anyway the C-Rate guarantees you that the time is not going to be the same. It is only the capacity that’s the same across the batteries across the; I mean across the various tests even though you are drawing different currents, the capacity is exactly the same.

So, an ideal battery would be something there where even at 5 C-Rate you will get the full capacity that is that you are getting from C by 2 rate; that would be a beautiful battery. You make a battery where you start at C by 2 rate, you go up to 5 C-Rate or even 10 C-Rate, you will still keep getting the full capacity of the battery out that would be a very nice battery to make; usually that is not the case the higher the rate at which you draw the current, lower is the capacity that you are able to extract from the battery. So, this is the effect of the C-Rate on the charge or discharge.

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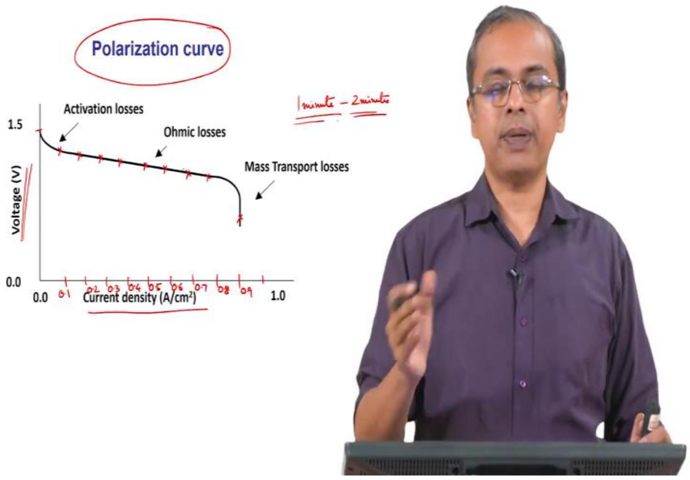

Also I pointed out that please remember we keep on having voltage on the y axis, but there is will have different things on the x axis; we already saw time as one one parameter we can put on the x axis, we saw capacity as another parameter that you can put on the x axis.

Now, I am going to show you something called a polarization curve where on the x axis we have current density ok. So, please keep in mind the curves look similar, but the meaning or the significance is very different. So, this and so, whereas, the previous curve that we saw here this kind of a curve is taking 10 hours to complete because you are completely extracting all the you know chemicals out of that system. A polarization curve actually happens in the matter of minutes; so, you may take 1 minute to record this curve. So, this is a sort of an instantaneous snapshot of the state of your battery. So, what happens is you stop the test, you measure what is the open circuit voltage ok. So, that is 1.5 volts then you draw let me just say this is 1.

So, I will I will just put some values here. So, I will say let’s say 1, 2, 3. So, let me say this is 10 amps ok. So, that’s 1 current densities 1. So, let’s say this is 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 1 amp per square centimeter. So, you change the current to point 1 amp per square centimeter; you measure the voltage and this will take you just about say 10 seconds to do.

So, then you immediately change the current to 0.2 amps current amps per square centimeter, measure the voltage like that you continue. You set the current, measure the voltage and do this only for about 10 seconds then you get all these points. So, you are not even actually able to reach 1 amp per square centimeter well before that you see this curve; so this at any given point in time; if you continued at this point in time’ if you continued at this particular 0.5 amps per square centimeter and did a long test in that would correspond to a C-Rate.

So, each of these points correspond to different C-Rates right. So, these are different C-Rates that are being momentarily tested you switch on the battery, you are sitting at 0. you raise the C-Rate to point 1 C-Rate and then you check what is the voltage and current relationship’ immediately change it to 0.2 C-Rate, 0.3 C-Rate like this you continue till some C-Rate which is high enough and that the battery is unable to support it and then you get this curve.

So, this tells you at a given instant in time what is the current you can get a different C-Rates at that point in time. So, that is called the polarization curve and it is usually a very good indicator of what is possible in the battery ok. So, you can take the nice idea the nice thing about a polarization curve is that as I said it only takes about a minute to record to measure minute or 2; it will take only that much. So, if you have about 10 points here and each point is going to take 10 seconds so that’s only about 100 seconds. So, less than 2 minutes is you; you can record this you can record this curve.

So, as opposed to curves such as this this is going to take 10 hours right 10 hours to completely charge a battery and another 10 hours to completely discharge the battery. And if you are going to do 10 cycles; so, that is the each charge discharge cycle together is 20 hours, you are going to do 10 such cycles that is going to be 200 hours. So, that is a very long test right.

So, that's 8 days of testing right 24 hours a day; so, about 8 days of testing you are looking at. This testing on the other hand is 2 minutes; so, 1 minute to 2 minutes ok. So, this is a very useful test that way the charge discharge test is more representative of what it will do long term, but this gives you a very good snapshot of it very good snapshot of it, it tells you what is possible it may not fully capture all the details at the charge discharge curve gives you, but it does tell you what's the possible with the with the battery, what is the state of health of the battery even after what after about you know you have used the battery for you know 10 hours. You just want to check what is the state of health of the battery you can do a polarization curve and you can compare it with the polarization curve that was there at the start of the batteries life.

So, you can also use this to compare multiple batteries because you can also do the full charge discharge curve and say you know this battery lasts at 100 cycles, another battery lasts 150 cycles and then you can say this therefore, the second batteries better than the first battery, but in the process you have consumed a huge amount of time to figure that out a polarization curve as I said only it takes about a minute or 2.

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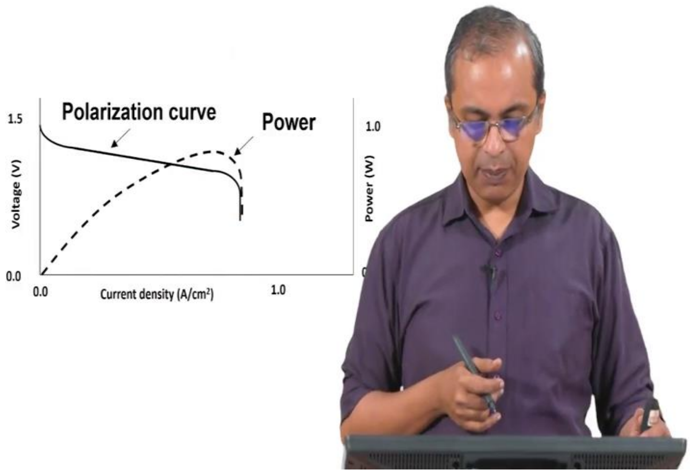

So, for example, if you look at this you have two different cells here cell A and cell B and I have done a polarization curve for both those cells. You can see here clearly that cell B is giving you much lower voltages for any given current density compared to cell

A. And we use current density because then you can you know compare even cells of different sizes.

So that is the reason you can you know normalize for the size larger; so, if you have one electrode which has some area and another electrode which is twice the area; then clearly you know it one electrode the first electrode has some chemicals, the second electrode has twice as much chemicals.

So, if you draw 1 amp from here it is the same as drawing 2 amps from the second battery. So, that is why you have to divide the area by 1 amp this divide this area by 2 amps you will be sitting at the same current density that way you can compare them that's the idea. So, now, you can see here that cell B has a polarization curve that is lower than cell A; so, you can say that cell A is better than cell B.

This may also be that for the same cell at different points and time you can see that you know it is deteriorating, how it is deteriorating etcetera. So, therefore, this is a very useful curve to have a polarization curve for any electrochemical device and certainly for batteries this is useful.

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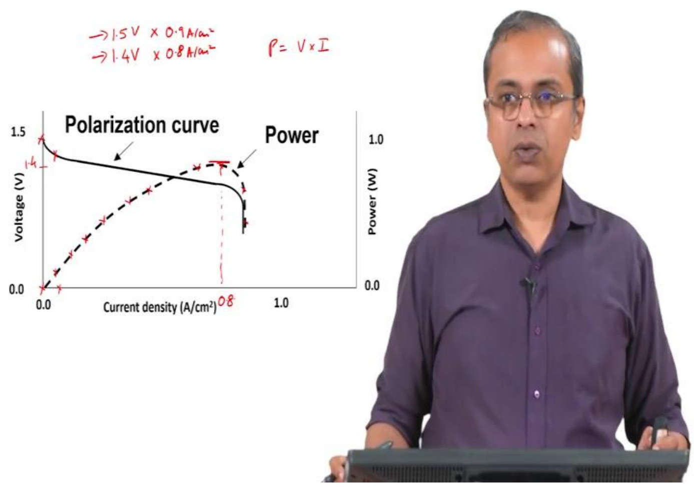

And from the same curve you can also find out the power curve; power as a function of current density. Because for example; when you are at open circuit voltage the current density is 0. So, therefore, the power is 0 V power is equal to V into I.

So, you can multiply by the area if you want or you can just do power density here power per unit area in that sense and then you can get. So, for every value of voltage you find out what's the value of current and then you get this product. So, similarly you do various points on this curve and then you will get this curve. So, it tells you; what is the point at which you are getting the maximum power.

So, just like you know we spoke about solar panels with maximum power point; battery also has a maximum power point, ideally you would like to use this battery close to the maximum power point or at least it tells you what is possible with the battery. If you if you put it to use with a camera for example, and that camera requires more power than this; this is the maximum power, this is the absolutely the maximum power that this battery can give you. So, if the camera requires more power than this it is it means it needs at 1.5 volts, it needs more than whatever this current is; that means, this battery cannot support that camera even though you know the camera fellow will say you put the 1.5 volt battery.

So, you put a 1.5 volt battery, but the battery he is using gives you let me say whatever this is you know this is let me say this is.0.8 ok. So, let me say; so, the he is he is expecting that it will deliver at least 0.9 amps per square centimeter for the camera, but your battery is only able to give 1.5 volts it's not even giving you 1.5 volts it is only giving you whatever 1.4, let's say is giving you 1.4 volts and at that it is giving you only 0.8 amps per square centimeter that is the best performance that your battery is giving. He is expecting 1.5 or the camera manufacturer is expecting 1.5 volts and 0.9 amps per square centimeter, you are able to deliver you are the battery that you have is delivering 1.4 volts and 0.8 amps per square centimeter.

So, clearly this is less than what is being desired and therefore, even though you may go to the shop and buy a 1.5 volt battery, as soon as you put it in the camera and you switch it on it will immediately say low battery ok. So, a brand new battery you put into the camera it will say low battery. So, one manufacturer's battery when you put in; it will say low battery.

Another manufacturer is battery when you put in; it will say full charge full charge is available you can use. Because that battery has a better polarization curve than this and therefore, the the camera is able to say that yes I can use this battery and so, it says it is full charge. So, that’s the reason why you see this variation from battery to battery that’s the science behind that variation ok. So, so, this is what we saw here.

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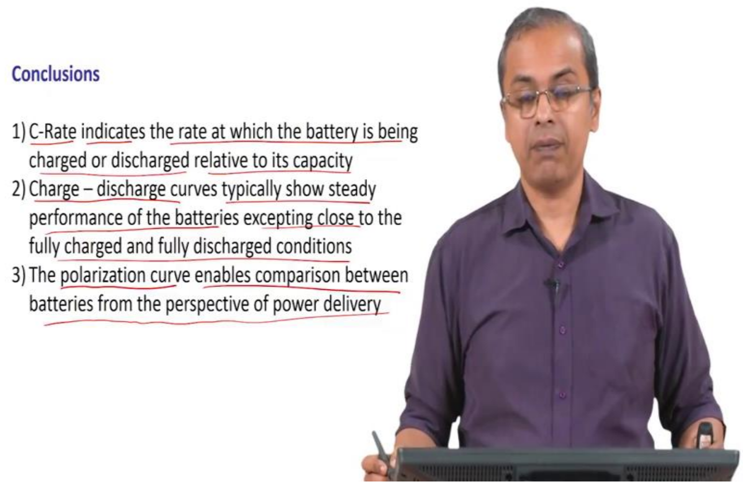

So, in conclusion we see that there is something called a C-Rate, we saw how the battery testing is done and in that context what is C-Rate it C-Rate indicates the rate at which the battery is being charged or discharged relative to its capacity.

So lower the C-Rate longer is the testing process 0.1 C-Rate will last 10 hours test 1 C-Rate will last a 1 hour test a 2 C-Rate will last half an hour test something like that roughly. Charge discharge curves typically shows steady performance of the batteries accepting very close to the fully charged and fully discharged condition. So, we saw just as you start discharging the performance drops; then it stays stable for a pretty long period of time and then when you get close to fully discharging the battery the performance will again drop and that is when you cut off the battery and that is how.

In fact, that is exactly what you are you know mobile phone or any other device that you use is doing; when it says battery is you know 0 percent; they are looking for that dip when that when it reaches the dip they say that it is reached 0 percent and then you can do the recharge. And similarly when you it says 100 percent when you when it sees that climb when it sees their thing climbing; it will say 100 percent or it can even meter the amount of charge that’s going.

So, that is exactly what is it doing. The polarization curve enables comparison between batteries from different from between batteries from the perspective of power delivery. So, how much power it will deliver and at various C-Rates what is the performance it gives you a snapshot; in 2 minutes you get a very good idea of the health of the battery, the capability of that battery and that is why the polarization curve is exceptionally useful, you can use that to compare brand new batteries of different manufacturers, same battery at different you know age conditions and so on.

A variety of things can be judged from the polarization curve. So, that those are our major conclusions and this is our class on testing and performance of batteries. And these are the major what we discussed today are all the major factors that help us get a very good idea of the state of the battery. And it also looks I mean we also discussed the manner in which we do the testing to get this information.

So, with that we will halt for today.

Thank you.

KEYWORDS:

Performance of Batteries; Battery Test Process; C – Rate; Discharge & Charge Curves; Polarization Curve; Test Station; State of Charge; Depth of Discharge; Cycle Life; Rechargable Batteries; Power Density; Current Density.

LECTRUE:

The standard procedure to test, to compare a battery and the relevance of C-Rate with with testing procedure is explained. The Charge and Discharge curves along with the polarization curves and its significance is discussed in detail with respect to Battery Technology.