Fundamentals of Industrial Oil Hydraulics and Pneumatics
By Professor R. Maiti
Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur
Module 4
Lecture 13
Critical Center Spool Valve Analysis

Welcome to today's lecture.

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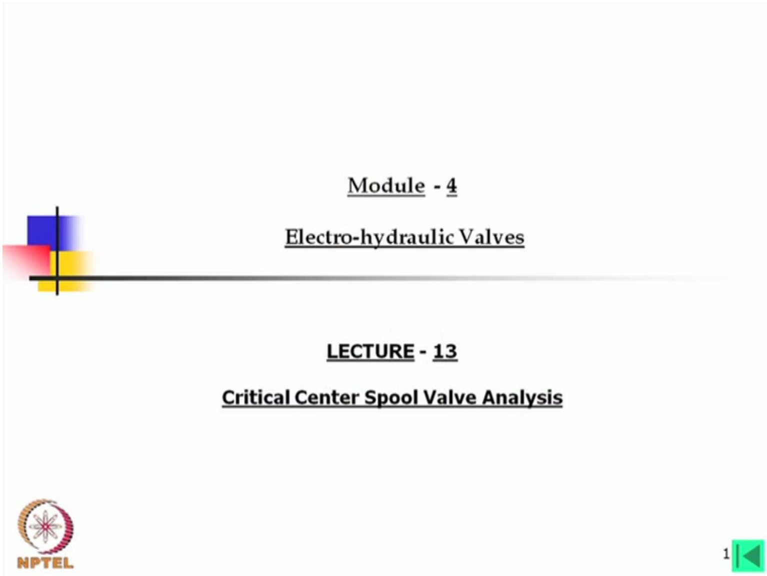

Lecture number 13 Critical Spool Valve Analysis, this is under Module 4 Electro-hydraulic Valves.

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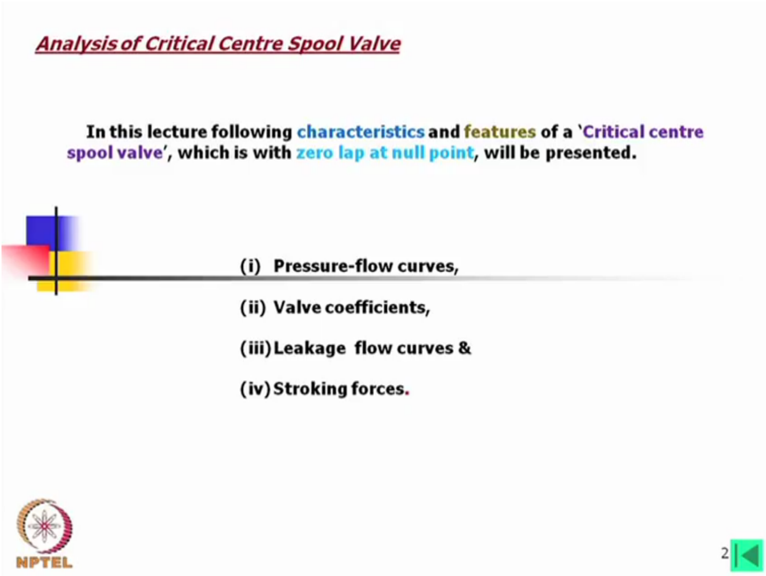

Now in this lecture the following characteristics and features of a Critical Centre Spool Valve which is zero lap at null point, will be presented. We shall look into first pressure-flow curves, secondly we shall look into valve coefficients, thirdly leakage flow curves and lastly stroking forces to complete all these analysis it may take another lecture where we shall discuss about more stroking force.

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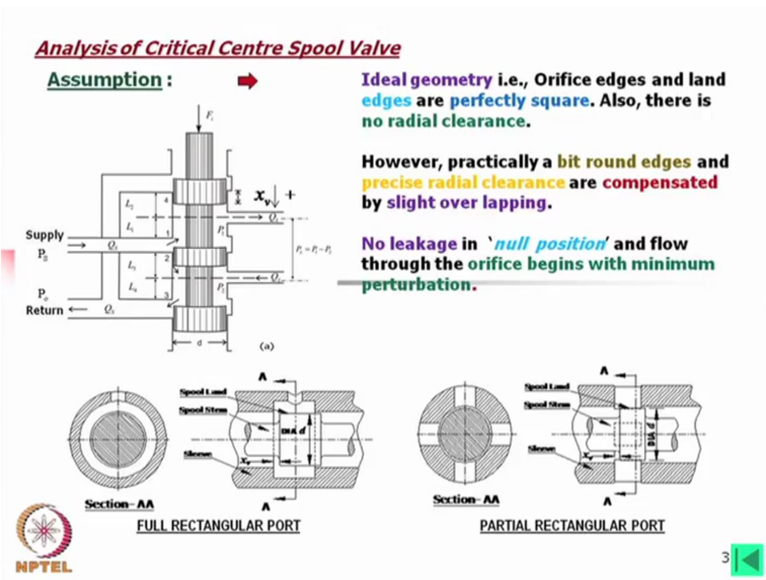

Now first of all let me explain what is critical centre spool valve, I have already explained but still with respect to this electro hydraulic valves or we should say that restriction spool valves we should know what is critical centre. In this case I mean in case of critical centre valve this dimension of these three lands are such that when this will be at the mid position or so called neutral position then the width of the land ideally equal to the width of the groove width of the port there, width of the groove ideally although it is not matching with this figure but it will be.

Critical centre means the width of this land will be equal to this and width of this land will also be equal to this height or this length and as well width of this one will be equal to this. Or in other words if I look into full rectangular port then when this land will be its mid position then this port will be completely closed and if we think of the nominal dimension, suppose this length is L 1, then this length will also be L 1 however, in practise it will be different which we will come later.

Now again I would like to explain this part, usually you will find that these three lands are of equal width however, it might be middle one is more or less but this will be equal to this port as well these two may be different from the middle one whereas these two are equal. Now for partial rectangular port also this width here or any grooves rectangular grooves made there is equal to the land width.

Now before analysis we make some assumptions these assumptions are essential for the analysis although it may not be in practise or in other words it may not be matched with the actual realistic data. Now ideal geometry, what do we mean by ideal geometry? Frist thing the I have talked about the width, then comes the orifice edges and the land edges are perfectly square that means this edge is serve I would say that what is there, what is the importance of making it serve, if there is any chamber or if these corners are round off then the flow pattern, what will be the flow to this valve will not help in the performance of this spool valve.

As well if there is a it is these corners are round or the chamber is there in that case there will be a slight opening even if ideally these widths are equal, also there is no radial clearance, ideally we have to assume there is no radial clearance, otherwise even if this port is closed at neutral position ideally through the radial clearance there will be leakage, we shall in this lecture we shall explain in fact it is slightly overlapped to make a critical centre valve it is made slightly overlapped but if there is overlapped you will understand that there will be delay in response time a little delay in response time.

However, optimum clearance, optimum overlapping can be designed, carefully calculated and can be designed. Now here in the next line I have described that bit round edges precise radial clearance and compensated by slight overlapping which I have described now. No leakage in null position and flow through the orifice begins with minimum perturbation. Now here I would like to mention in this assumption in this analysis first we shall consider there is no leakage at null position that means at the neutral positions.

Now this null position by definition it is the central position where valve is having no action however, suppose a valve is working at a flow rate say 70 litre per minutes to maintain something, some motion and we need to maintain that flow that means we have to design our control about that point then that point is also called null point but here unless otherwise mentioned we shall consider the null position means is the neutral position.

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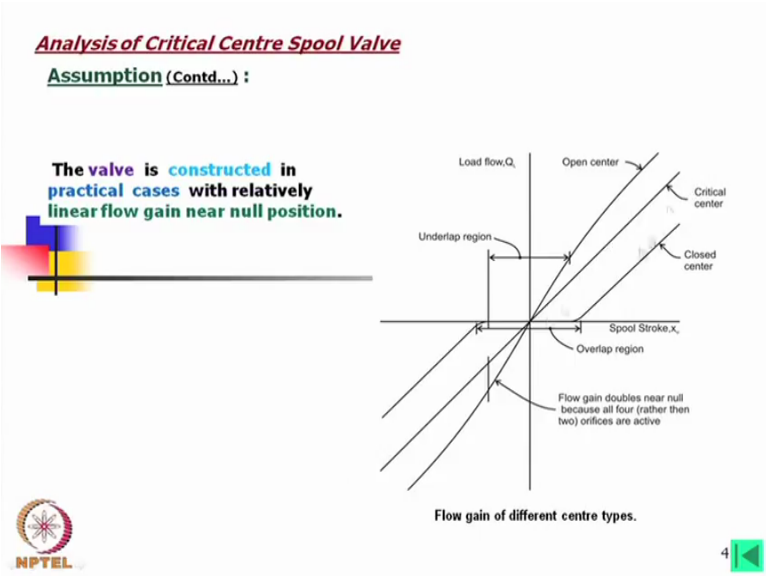

The valve is constructed in practical cases with relatively linear flow gain near null position, linear flow gain. Now look at this curve, what we find that so this is the flow, this is the load flow we have plotted here and this is the spool stroke or spool displacement, now about the 0 this may go in positive and negative direction spool and due to that there will be the load flow, the curve will be like this.

Now we have drawn three curves here the central one is for the critical centre this means that ideally we want this that here this should be a completely linear and it should cross this origin. However, if it is open centre that is underlap valve then what will happen that at the neutral position at the null point there will be flow in both the directions. So to gain a flow in any direction first of all we have to close that orifice, close that gap and then the flow will begin then the curve has to be like this sorry this curve will be like this, there will be this is the flow line so there will be flow even if at the 0 and then this will be this curve will like this.

Now what you find that it is not matching with this (())(10:06) not on the line or the flow line because of the reasons in that case this orifice is very small or opening is very small in case of open centre. So there is some flow which will with the stroke gradually which will increase that is why the curve is like that. On the other hand for the closed centre what we find at the when the valve is closed then the flow there is no flow at all until there is certain amount of the spool stroke or spool displacement but there is no flow means practically there is no flow so in that case this is matching with this line, okay.

So this is called overlapping region and this is underlapping region it is the region is called underlapping but the amount it is not (())(11:08) the amount of underlap. Flow gain doubles near null because all four rather than two orifices are active we should try to understand this, visualize that why this sentence is written, so this flow gain doubles near the null because of all four orifices are open. But today's study will be on critical centre valve for which we expect the curve put like this.

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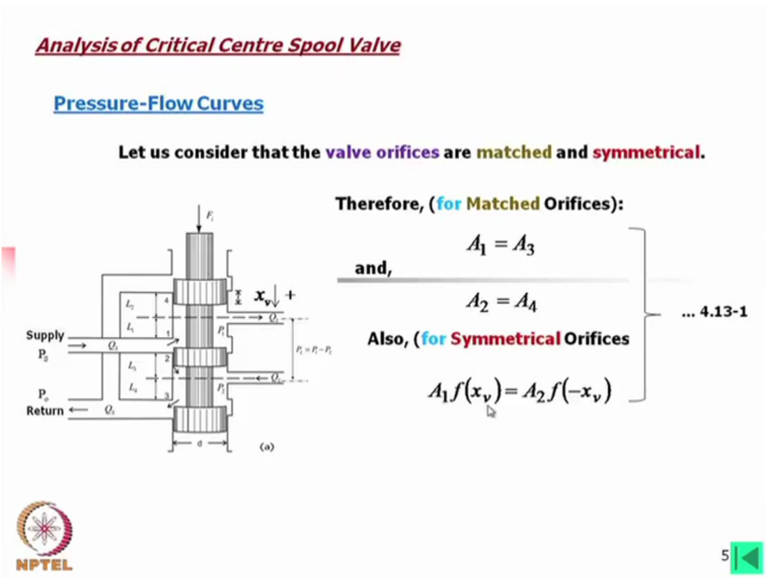

Now we shall derive the expression for pressure-flow curves, we have already learned that how to equate the load flow and the system flow we have already done it with respect to the load pressure as well as the system pressure and the orifices. Now let us consider that the valve orifices are matched and symmetrical I have explained what is called matched and symmetrical. In case of matched means we shall look into there are in any positions we must consider the four orifices 1, 2, 3, 4 we should write the equation in terms of all orifices even if apparently those might be closed if those are really closed then in that case we can put that flow 0.

But matched means A 1 will be A 3, this A 1 will equal to A 3 this will be identical area this will be of identical area. Look into this even if this width is smaller than this still it is possible because this diameter is same and the stroke length remains same and A 2 will be A 4 for matched one.

Now for the symmetrical one what we need with the displacement both in positive and negative direction A 1 the function of x v is equal to A 2 x v. So as for A 3 and sorry A 1 and A 2 which one actually it was closed A 1 is open. So this will be if you put this in the negative directions A 1 will be equal to A 2 with the displacement as well as A 3 will be equal to A 4.

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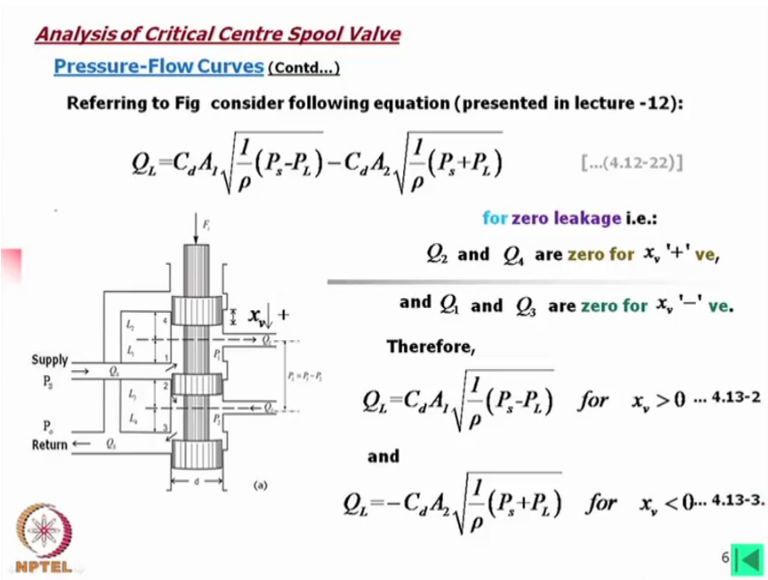

Again with referring to this figure consider following equations presented in lecture 4, sorry lecture 12 the earlier lecture we developed these equations, okay. As well here we wrote this equation for A 1, A 2, A 1 and A 2 that we are equating for load flow. Now for zero leakages suppose we are considering these equations and we consider there will be no leakage the Q 2 and Q 4 are 0 for positive x v plus v that means when this is the positive direction of the spool displacement, spool it is also called stroke for the positive stroke we shall consider Q 2 and Q 4 is zero, whereas if we give this stroke in the opposite direction that means in the negative directions then Q 1, Q 3 will be zero or in other words in this equation we can consider A 2 is equal to zero.

Therefore, we should we can write the load flow is equal to coefficient of discharge into the area 1, into 1 by Rho system pressure minus load pressure this is the standard equations for positive stroke. And for negative stroke we would write (C d A 2) minus C d A 2 1 by Rho system pressure plus load pressure for x v is equal to less than 0, that is negative stroke the negative sign has come due to this region for negative stroke, okay. Now here again I would say that C d except at the small opening C d can take an constant for all these orifices because they are same, they are matched and symmetric.

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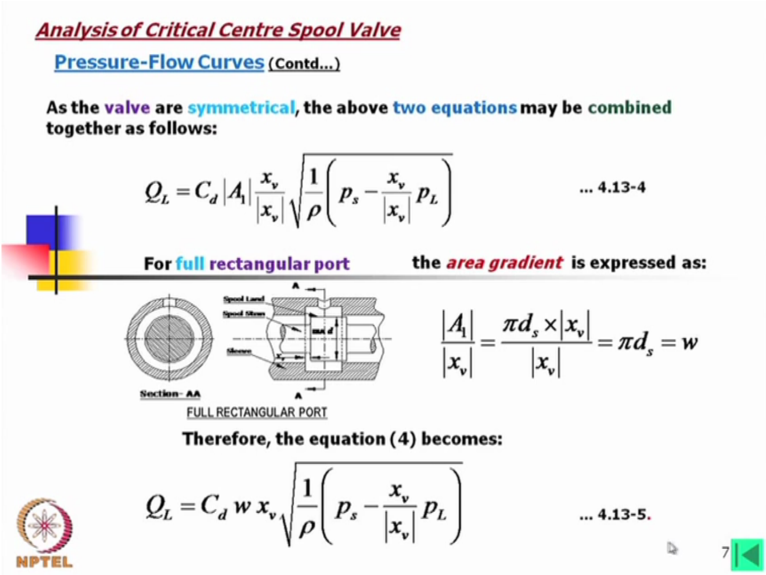

As the valve are symmetrical, and the above two equations may be combined together as well we can combine these two equations in this form. What we have written here that there in that equation we had C d area, C d into area and x v divided by modulus of x v. Now what we have taken in this form because this area is positive so we can write like this so whatever sign is coming for this one that will be here and then similarly also we can write in this form, this means this will when this is negative then automatically this will become positive and here also a negative sign will come if this is positive then here it will be positive and here it will be negative and we have considered that there is no leakage flow so that is matching with the equations just the two equations which we have shown the previous slides.

Now for full rectangular port we have we can write these equations as well this is also possible the if it is partial rectangular port but this is for rectangular port we have written. Now this for rectangular port what we can write area gradient is expressed as A 1 by x v so this is nothing but Pi d s this is d s means diameter of this spool, diameter of the spool. Here we have written d but this is spool d is the nominal dimension one is that bore and another is that spool so anything can be taken may not put s so Pi d s and then it becomes x v because this is always positive so x v divided by x v so this we get Pi d s which is nothing but the width of the rectangular port.

So therefore these equations finally we can write in the form, this we can replace by w and we can write in this form. Now we shall use this equation further for the analysis of the critical centre valve.

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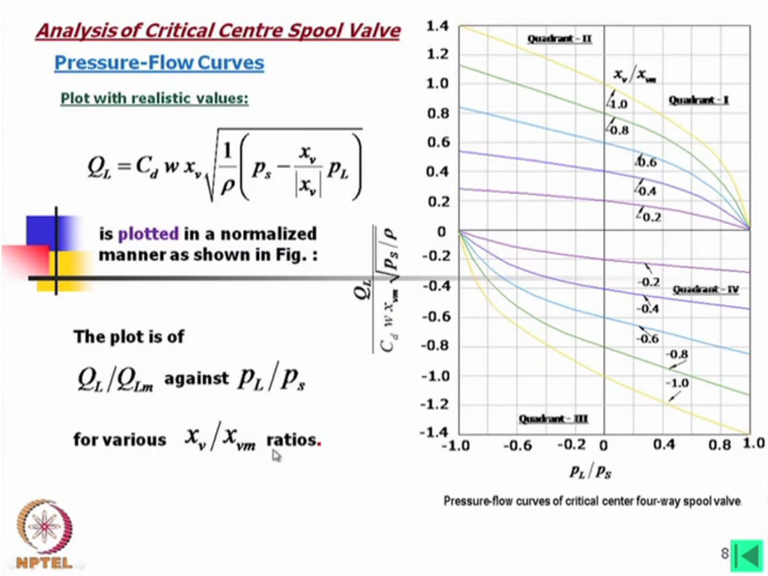

Now we shall plot this pressure-flow curves this equation what we have shown that directly gives the pressure-flow curves, okay. Now we are plotting this one in a normalized manner as shown in the illustration. Now this is a little difficult to concede because of the reasons here is the 0 lines but this is P L by P s then this is this ratio is negative in this direction, this ratio is positive in this direction, whereas here we have consider the load flow divided by maximum possible load flow which is at the maximum stroke, okay.

So this we have written this is also a ratio so this is dimensionless, in this case this is also dimensionless and we have plotted for various again dimensionless of the stroke divided by maximum stroke. Now this we have consider the four quadrants 1, 2, 3, 4 and then if we plot this one with a this value because this is the dimensionless value we if we can assume any value and for any maximum value of course it should be realistic and then we can get this sort of curve. Now the plot is Q L by Q Lm against P L by P s and for various x v by x vm that is the stroke divided by the maximum stroke ratios.

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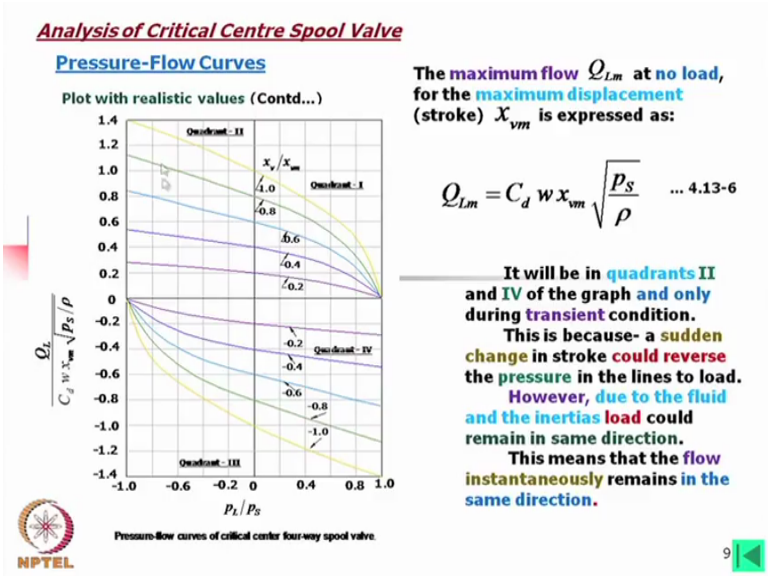

Now the maximum flow Q Lm at no load, for the maximum displacement that is the maximum stroke x vm is expressed as Q Lm is equal to C d the w the idea gradient and multiplied by x vm P s by Rho, now here the only at the maximum stroke we should consider that the system pressure that is the maximum pressure, the system pressure what might be the maximum flow we are comparing with this.

Now this curve if we for this Q Lm if we give some other definition that is through some other orifice, some other pressure then this curve will be different but that also can be usable because we can multiply with this value later to get actual Q L there. But this plot is made with these values. It will be in quadrant 2 and 4 of the graph and only during transient conditions.

Now this is this language it is written that if we consider quadrant 2 and quadrant 4, these conditions are valid if you think of the transient conditions because a sudden change in stroke could reverse the pressure in the lines to load in the lines to load that means if we think of this valve where the line is connected to the load then a sudden change in stroke will reverse the pressure immediately there but due to the fluid and the inertias load could remain in same directions or this is the filling of the load or this it will try to move in the same direction although pressure has changed.

So this we are plotting for the critical centre valve looking into their performance at the null point, so therefore in realistic value it might be slightly confusing that why it is in this directions why it is showing that when if the pressure is in the opposite directions that these negative values are in the quadrant I mean this is for the negative values and this is negative quadrant so this is in the positive quadrant and we have consider also two this is one is positive, another is negative for these values these are actually for the transient conditions.

That I think if we try to solve a realistic problem then only we will be able to understand what is the meaning of that but here we should keep in mind that one positive, another negative means the pressure has been reversed although the load is moving in the direction of flow. This means that the flow instantaneously remains in the same directions it will take some time to change the flow then again we will find the curve opposite quadrant that means these portion of the curves are valid only for transient conditions. (Sorry this is not properly load, okay.)

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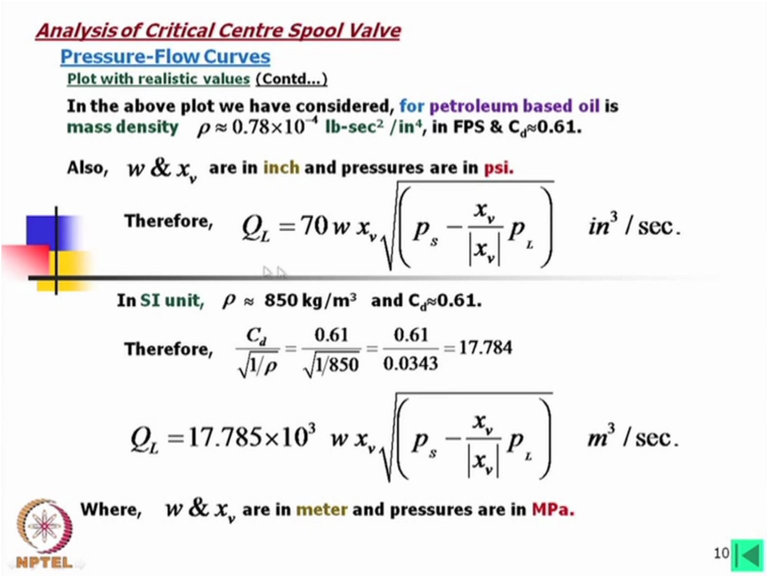

Now in the above plot we have considered, for petroleum based oil the mass density Rho is equal to 0.78 into 10 to the power minus 4 pound second square by inch to the power 4, w and stroke the width the what is called the (pressure gradient) area gradient sorry this is area gradient and the stroke are in inch and pressure in psi. So for that if we substitute this value thus we have consider the C d we will get this equation this is very often used you are following FPS system.

Now we use normally SI units, now SI units the petroleum based oil unless otherwise mentioned you may consider the density mass density is about 830 to 850 kg per meter cube, okay 830 to 850 kg per meter cube. Now let us consider we have consider the 850 kg per meter cube and the C d we have shown that for practical purposes it is around 0.6 to 0.62 like that 0.6 to 0.62 any value you can choose for a valve analysis.

Actual error due to this suppose the oil density is 830 kg per meter cube and C d may be closed to 0.62. Now the realistic value there will be you will find that the difference will be negligibly small, only thing that in case of servo valve these are automatically corrected whatever the (())(28:02) with these calculated values that are automatically taken care of, in case of proportional control valves the corrections are possible even if you take some data not exactly what is inside the valve particularly this with density may reduce with pressure and temperature or it will vary in not reduced it may little bit vary, okay.

So we need not be worried at this point but to have an idea we get that C d by 1 by Rho for SI systems 17.784, so first of all we have calculated without looking into the dimensions then if we put into the equation in SI system this will be 17.785 into 10 to the power 3 w x v P s minus x v by x v P L meter cube by second. Now in this case we should keep in mind that w and x v are in meter and pressure in Mega Pascal. Actually if you look into this 10 to the power cube if you take inside it, it will be 10 to the power 6, this means then this pressure will be in Pascal.

So if we write this formula that this is in Pascal in that case we should not write 10 to the power cube here, you can remember this formula or simply you can derive from the main equation but these are the realistic value who deals with such valves they usually directly use this formula instead of considering actual Rho and C d etc this will fit into the calculations.

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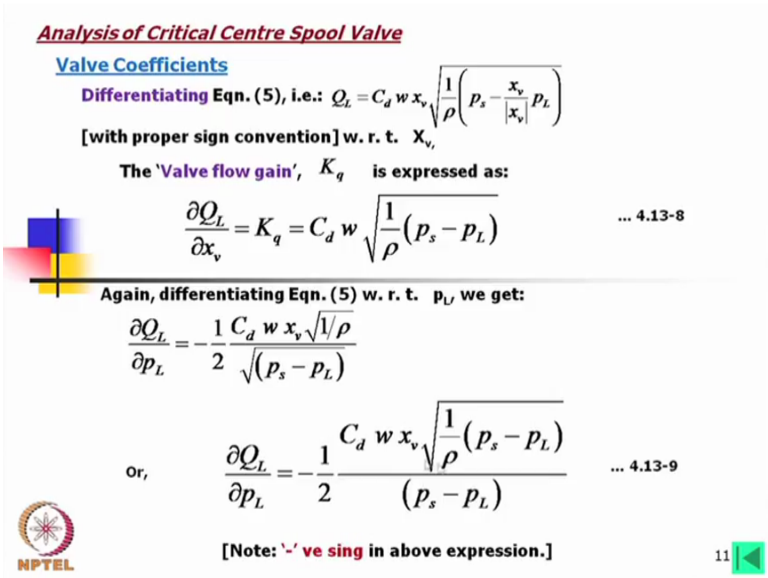

Now we are we will find what are the valve coefficients earlier in the previous lecture we have discussed one is that flow gain valve coefficients this is we have coming to this flow gain another is the flow pressure coefficients and then these are the two which we should find out from these equations then third one is the derived one that is the pressure sensitivity we will come to that.

Now we shall differentiate this equation with respect to x v, so this will give us the flow gain that is rate of change of load flow with respect to the change I the stroke. Now this is expressed by K q is equal to C d w if I differentiate this so this is a function of this is not a function of valve stroke therefore, simply this will be (d x v) by del x v by del x v which is equal to 1, so this comes like this.

Now again if you differentiate the same equation with load pressure P L then we get that del Q L by del P L is equal to half C d w x v 1 by Rho in the denominator root P s minus P L under root. Now this derivations you can say this if we del root 1 by Rho P s minus P L we can take 1 by Rho out so it will be here and this will be P s minus P L to the power minus half, okay to the power minus half.

So it comes in denominator and then this half will come over here, okay am I correct? And then del Q L by del P L of this function this becomes 0 and this becomes minus 1, so minus sign has come over here you understand this how we have derived this one, okay. So this is not difficult you can do it. So in this equation we can write with this equation rather it is written in this form which is we take this 1 by root over there, so we take it there 1 root so this becomes square of that so P s minus P L, okay multiply this denominator and numerator with root P s minus P L so it will become like this, okay so we use this formula.

Now look at this negative sign is coming over here so you should be careful why I had mentioned here many of us make mistake in this derivations and from there we go into wrong direction calculating this coefficients, okay.

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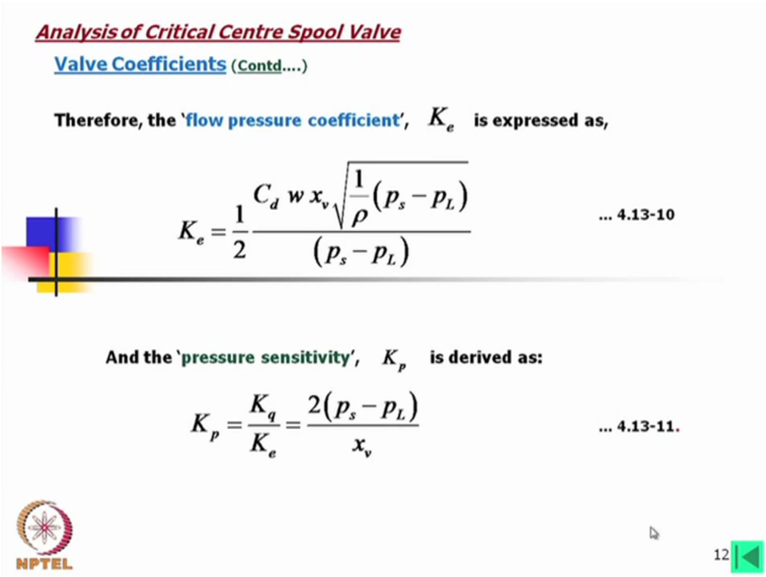

Now therefore the flow picture coefficient which we have derived like this K is expressed is nothing but the same equations. Now here you will find that minus sign is not there because in the K e already minus sign was there. So as minus sign is here so when we are writing in this parametric form there is no minus sign is here it is always actually this value is always positive because del Q L by del P L is always negative value with load increase in load pressure reduces with decrease in load pressure sorry with increase in load this pressure will decrease this is somewhat slightly difficult to concede but we can later prove that also.

And the pressure sensitivity the pressure sensitivity K p is derived as it is nothing but K q by K e so if you equate this equation 9 and 10 you will arrive into these equations. So this we have considered for zero leakages, okay.

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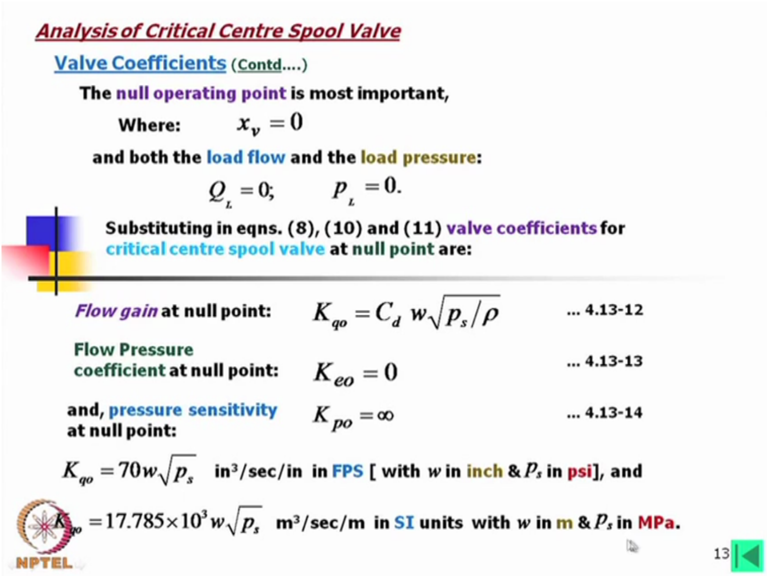

The null operating point is most important, where the stroke is equal to 0 and both the load flow and the load pressure are also 0. Now at the null position that means in this case we are considering the neutral positions not the null position about the operating point or it might be about the operating point because it is may be the motor the cylinder is running in both the directions. So in that case null point is the neutral position is the zero position there is no stroke.

So we shall consider now that Q L is equal to 0 there is no load flow as well as load pressure is equal to 0, this is true only for critical centre valve. Substituting in equation 8, 10 and 11 valve coefficients for critical centre spool valve at null point are that if we consider that K q0 in that equation you will find the other terms becomes 0, so this simply C d w into P s by Rho and you will find that K e0 that is flow pressure coefficient at null position Ke0 means at null position is 0.

And as the other one other coefficient pressure sensitivity is the ratio of these two then this divided by this becomes infinity so this will be the coefficients for an ideal critical centre spool valve at null point. But there is there will be difference because of the their will be leakage even if it is a critical centre valve we are coming to that but anyway this from the earlier equations that FPS system we can write this equation 70w into root P s, okay look into these dimensions and in SI units we can write this. So this also the fluid power practise engineer they remember these values.

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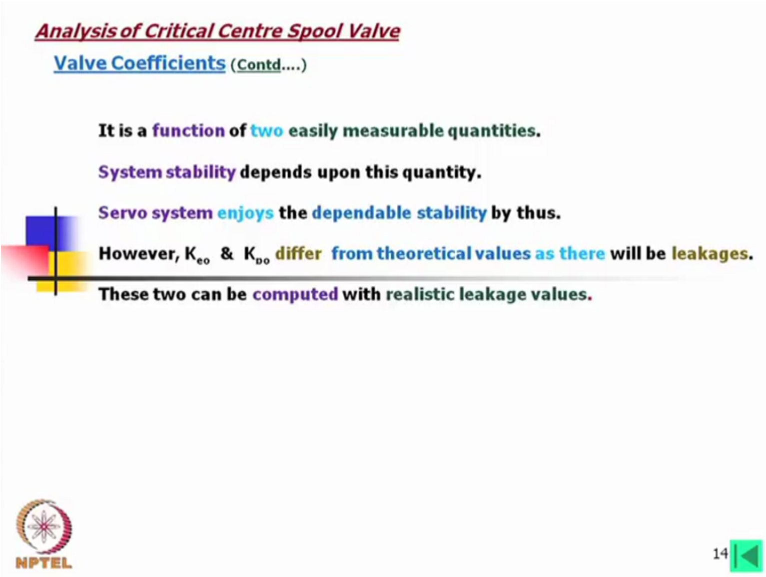

It is a function of two easily measurable quantities these quantities can be measured because we can put this valve in null position, we have to identify that this is the null positions looking into their outputs that is possible where it is tested that is possible that null positions. Now this I would like to mention here for servo valve this when we are using this valve it is before the actual activities on these valves null position test is done so that it is in the null positions and this performance will be identical if we give the set equal amount of set in plus positive directions and negative directions.

Say for example we are using a servo valve in a missile what is the life of this servo valve only one the missile when it will be it will complete its job the servo valve is gone. So these servo valves even if there is motor and everything is made for just only one use but these are accurately adjusted. Anyway these two functions we first we determine the null positions and then this will measure, how we do it? System stability depends upon this quantity because this is pressure sensitivity and stability there.

And fortunately servo system enjoys the dependable stability by thus this means that once we adjust and we make it then the stability will be maintained because of this zero point stability null point stability. However, these two coefficients differ from theoretical values as there will be leakages. Now these two can be determined other can be derived from these two, okay. So now we shall look into this how this can be derived at null positions.

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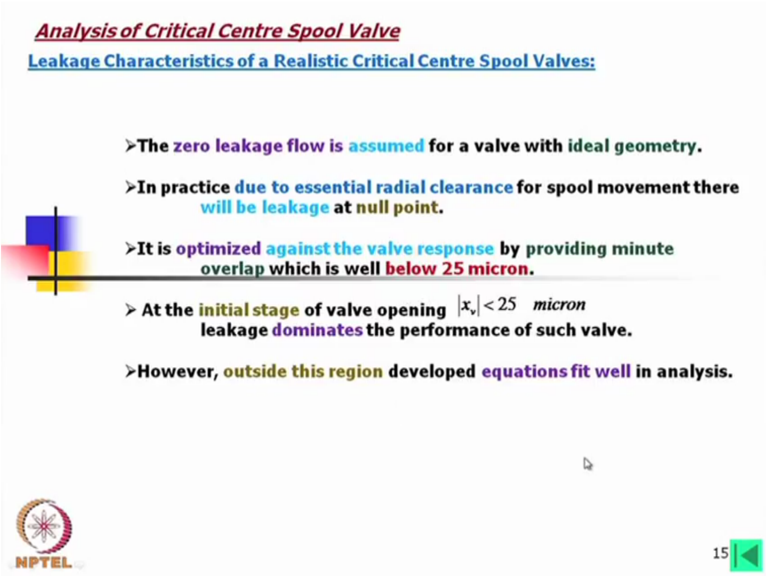

We consider some realistic values and then the zero leakage flow is assumed for a valve with ideal geometry we do it in practise due to essential radial clearances for spool movement there will be leakage at null point, what it is that the we I have told the land is slightly overlapped that is slightly greater than the port opening, the width of the land is slightly more than that in the tolerance range, okay.

Now what will be the tolerance? It is optimized against the valve response by providing minute overlap which is well below 25 micron these are usually in the order of why it is 25 micron because in the valve usually radial clearances are not more than 25 micron radial clearances are not more than 25 micron this is again irrespective of the valve size. If we consider a small valve say spool diameter is about 10 millimetre, say if it is a valve of 25, 30 litre per minute.

So we can manage with a spool diameter of 10 millimetre, whereas for large flow 100 litre per minute other may be it will be 20 millimetre it is not again linear the diameter and this you can see this area is very big and for very large valve again this full port opening is not very desired because there will be very high change in flow rates with a small stroke length.

So there we go for partial one, for small valve full port, for large valve you will find the partial ports are there again it is rectangular due to this linearity we w is a constant, either it is Pi d s or may be some angle into diameter of the land. At the initial stage of valve opening this x v that is the valve stroke is less than 25 micron at that stage leakage dominates the performance of such valve, okay the characteristics will be different from our desired characteristics, okay.

So in some cases you will find controlling over the null point is difficult, whereas slightly away from the null point you can control. Fortunately most of the performance is not at the null point we need the performance away from the null point. So if we can manage with the control at the null point then the rest of the control is not difficult. However, if as I told earlier also if we find that at the null point the valve is closed to stability then it will remain stable at other positions also.

However, outside this region developed equations fit well in analysis. So for if it is suppose we take another position where the 50 litre flow is there and we have to control over that then it is not difficult even if that might be then it will not look into the valve whether it is critical centre or the open centre or the closed centre, okay. But still critical centre is widely used because the motor is used it driven for the both directions and this is important we have taken this one as an example.

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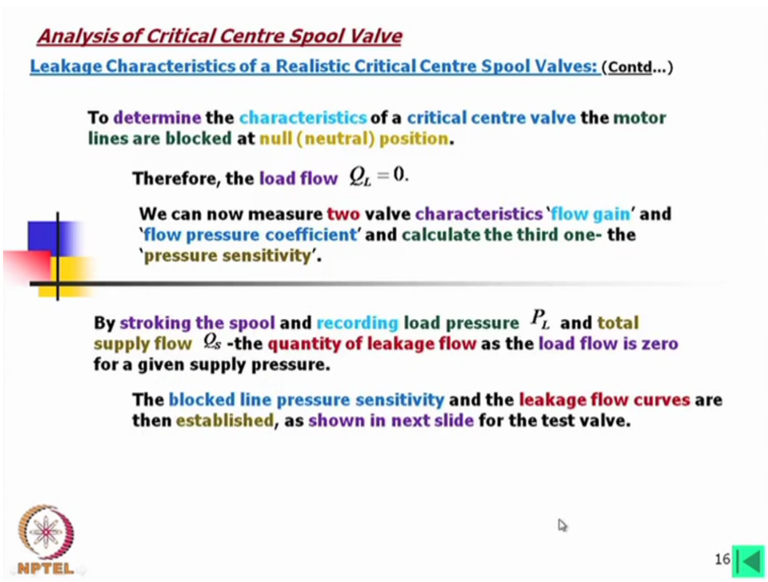

To determine the characteristics of a critical centre valve the motor lines are blocked at null positions. So what we do we simply close the load line, we block this that means load flow is trying to be initiated but there is no load there is it is away from the load, no load condition is different from blocked load we first of all we block the things and then we measure the leakages.

Therefore, the load flow becomes 0, okay. We can now measure two valve characteristics flow gain and flow pressure coefficient and calculate the third one the pressure sensitivity for null positions. By stroking the spool and recording the load pressure P L in that conditions we give a small stroke and we measure the P L, P L means other side of the spool if you remember this valve this spool figure and total supply flow Q S the quantity of leakage flow as the load flow is zero and given supply pressure this means that at that condition we measure the flow out flow out from the valve which is nothing but the leakage flow, okay.

The block line pressure sensitivity and the leakage flow curves are then established as shown in next slides for test valve, okay we will come into the next slides but here I would like to mention that we are allowing the flow in we are not allowing the flow to load but there is leakage through the all orifices Q 1 I mean there is 1, 2, 3, 4. So we should measure all these leakages separately, you will find that summation of all these flows equal to Q S but you will find this that pressure that P L of one side will differ from the P s at the supply side, so this we should carefully measure.

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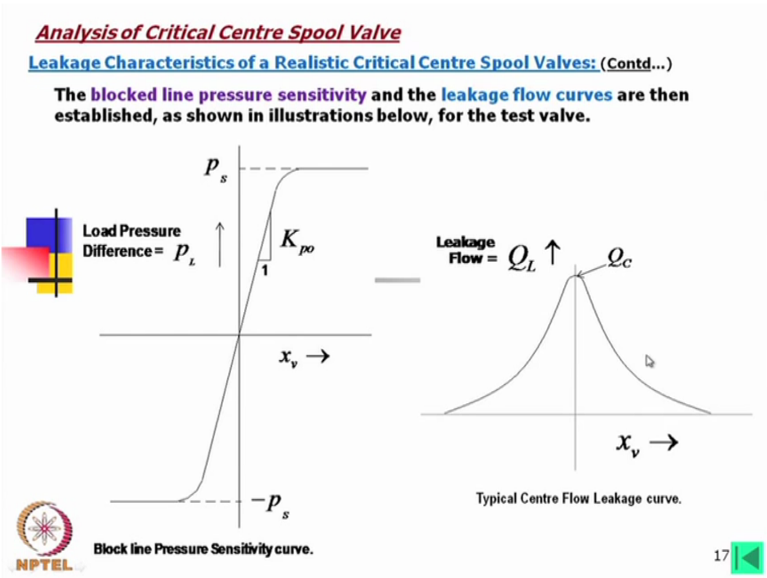

And then the block line pressure sensitivity and the leakage flow curves are then established, sorry this is I have repeated here again as shown in illustrations below. Now look at this curve so this is leakage flow curves we have drawn these curves we will get the curve like this, this is the system pressure and the minus system pressure and our curve will be something like this, this can be plotted from by testing a valve look but you should keep in mind this is at the vicinity of the null point very small opening we have done and we are trying to get this curve.

Now also there will be typical leakage curve there will be typical leakage curve which will look like this about this centre point there will be leakage like this, okay.

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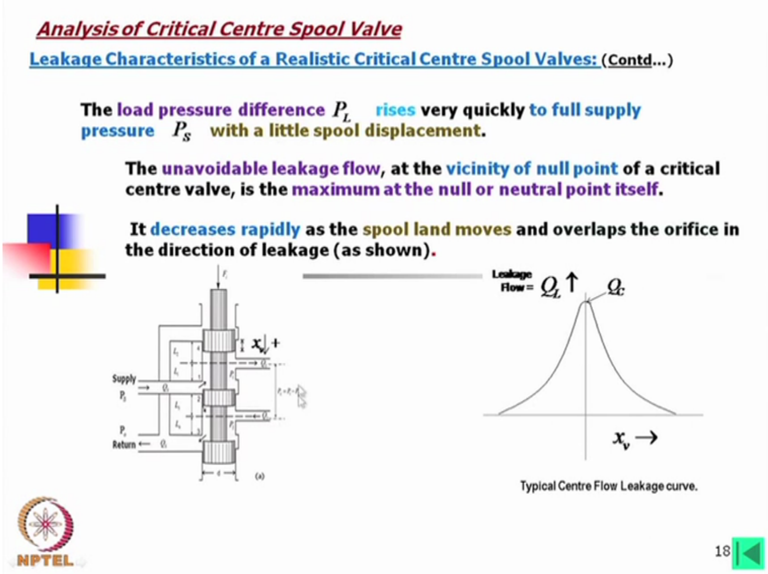

Now the load pressure difference P L rises very quickly to full supply pressure the system pressure this is obvious we have not used the load block there. so you will find when each slide opening there will be initial P L less than P s but it will very quickly will rise to this point because there will be no flow the flow will be stop there load side, leakage side there will be flow but the load side there will be no flow, okay.

So referring to this valve you can say that we have suppose these two are blocked so initially there will be some P L after that you will find we have opened a little bit here and then we are allowing the flow so P L initially it was some value but with small displacements gradually this very quickly it will become to the P s and in this case we cannot measure the flow because the no flow is going, so Q L will be 0, whereas this flow will be there which is leakage flow which ultimately all leakages flow will be equal to Q S.

Now so this is again I have shown this the flow curve leakage flow curve we will get and it decreases rapidly at as the spool land moves and overlaps the orifice in the direction of leakage, okay. Now the leakage flow also will reduce as the overlapping, this is we are calling overlapping with the solid portion increases that means this when this is now not actually orifice you should say after certain stroke length this will become a capillary package and at one point you will find there is no 0 no flow. So flow will be 0, leakage flow will be 0 and we can plot this one.

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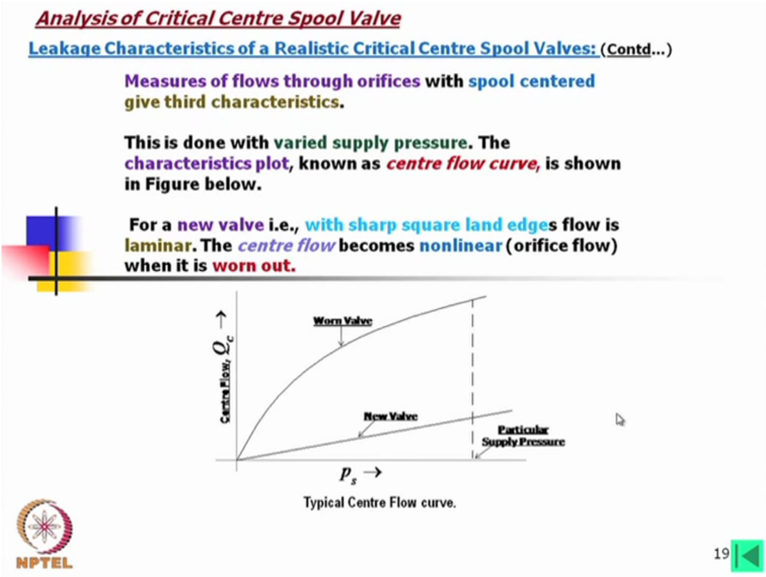

Then measure of flows through orifices with spool centered give third characteristics this can be derived. This is done with varied supply pressure. The characteristics plot known as centre flow curve is shown in figure below. Now this is called centre flow curve. So what we will find that we will find a curve like this but this is for new valve, this will be linear look at this this is possible only for the new valve when both the port edges and the land edges are very sharp, okay.

But when it will worn out we will find this type of curve so this is for the worn valve but if you look into this here so what was this load flow that is called centre flow Q c, Q c was this much with a new valve whereas Q c has changed to almost two to three times this is somewhat realistic data but you will find instead of that still this valve can be used still this valve can be used because this disturbance is only this will disturb the performance, this will make the valve sluggish at the near the null point but at a distance it is operating with some flow this value will not affect the overall performance very much only thing response will be sluggish and which again can be taken care of or else we would say that may not affect overall performance of the machine. But in case of missile you see valve when tested we will get line and we will never get this one because this will not return to us.

So for a new valve with sharp square land edges it is the flow is laminar and the centre flow becomes nonlinear when it is worn out it is called orifice flow. This is we call the laminar flow and this is orifice flow, I think this has to be continued now we will discuss further on the null point and then we will think of the stroking force in the next class this is essential to calculate the stroking force and we should look into the variation in stroking force which actually need to be controlled in a servo valve, okay thank you.