Petroleum Reservoir Engineering

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Lecture 16: Well Testing and Performance-I

Hello everyone. Welcome to the class of petroleum reservoir engineering. This is lecture number 1 of week 6. In this lecture we are going to continue our discussion of inflow performance relationship that we developed for oil and gas reservoirs. We will understand the utilization of IPR or developing IPR in a true sense with respect to productivity index, concept of absolute open flow condition and then some empirical correlations those are based on the field test or the actual data set those could be single point and the multipoint data set. Two empirical approaches back pressure approach, forsemer approach will be discussed in today's lecture followed by well testing of the gas well.

So let us quickly recap what we did in previous week. We established the inflow performance relationship for different conditions. The reservoir could be producing the fluid that we broadly can classified into four part. First one is the number of the phases present in the reservoir.

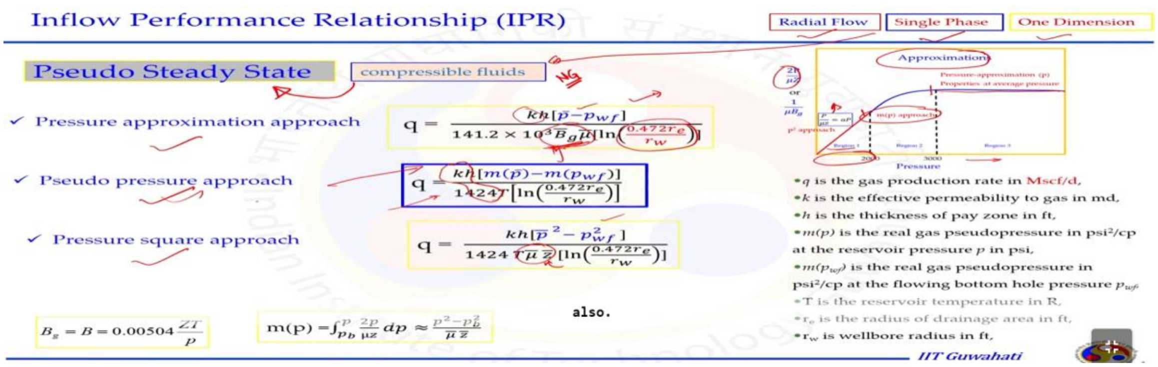
There could be possibility of the geometry of the reservoir that could be radial, linear, spherical and hemispherical. Mostly we discussed about the radial flow system. Next one is the types of the fluid, incompressible, slightly compressible or compressible fluid. So the oil and gas are covered within this classification of the reservoir fluid and then next comes under what condition the reservoir fluid is getting produced. Based on that we developed the IPR equation and later on the two important factor, first one is the skin effect, second component is the non-Darcy flow.

So near the wellbore region or specifically in the case of the compressible fluid means in the case of the gases the fluid is having higher velocity near the wellbore region because the radius reduces and the condition of Darcy law are not quite applicable specifically the laminar condition and that deviation from the laminar condition is considered by including non Darcy coefficient into the expression. So at a constant flow rate when we start producing from the well initially what happened pressure changes drastically under the transient condition. Later on it follows the late transient condition. In this condition the pressure is adjusting and these phenomena mostly happen near the wellbore region and when the pressure waves reaches to the boundary condition or towards the boundary condition we reach the semi steady state condition. That is actually the ideal condition or the condition most of the lifetime of the reservoir well is producing under the semi steady state condition.

So under transient condition or semi steady state conditions are the condition where we can relate based on the fundamental understanding and the analytical expression that we obtained in the previous lecture can further be utilized to establish the true IPR equation inflow performance equation. Important aspect is here when we are in this region we have to use the IPR that is established for the unsteady state flow condition and when we are in this region we have to use pseudo steady state flow IPR. So let us consider the case of one dimensional flow single phase fluid under the radial flow condition and that single phase fluid we can consider is a compressible fluid and our compressible fluid is natural gas. So in today's discussion mostly we will discuss about natural gas and then the condition that is pseudo steady state condition we can pick up as one of the case to understand how analytical expression that has been developed can be utilized to establish the IPR equation. So for compressible fluid under the pseudo steady state condition we get this kind of the expression.

This expression is achieved by doing the material balance in the system using the Darcy law for the transportation equation considering the compressibility concept for compressible fluid and setting up the boundary condition for pseudo steady state condition. Now we know for the compressible fluid the IPR equation under either steady state condition pseudo steady state condition or transient condition can be expressed in terms of three approaches. These three approaches are adopted based on the pressure region certain parameter those appear in our basic IPR equation how we can make the approximation to count the effect of the pressure on those parameters. So for example in the region 1 P by Mu z that is here is a linear function of the pressure when we are beyond 3000 psi the P by Mu z factor is having the constant value with respect to pressure and in between this 2000 and 3000 psi we are supposed to use the MP approach because neither linear or not constant relationship is there. Similarly, MP approach that is real gas pseudo pressure approach is more accurate approach because it can be applied for any pressure range implicitly MP included the change in the properties of the fluid for example viscosity compressibility constant how these properties are changing with respect to pressure.

So it has been included only complexity with the MP approaches we need to apply the integration method to calculate the parameter MP in the pressure range we are considering. So let us not go to in that discussion we are having three equations for the P approach pseudo pressure approach and then the pressure square approach. These three equations are having certain part common like this one that is the radius relationship of reservoir and the valvore radiation and the valvore radius. Now we will see here in pressure approximation we are having the different terms compared to pseudo pressure approach and then the pressure square approach. All these three equations are having different terms because that is the way the approximation are assumed and then the equation has been established under certain assumptions.



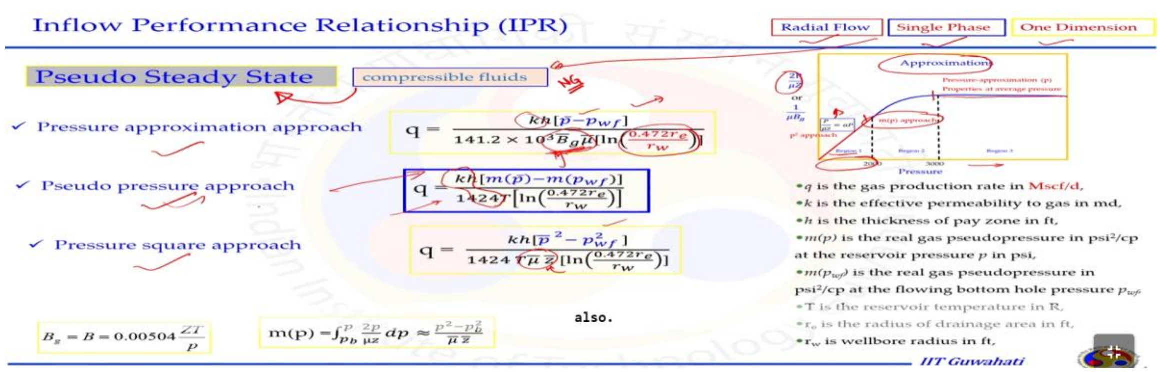
For example in the pseudo pressure square approach we are not having any parameter that is relating to the fluid properties. K, H and T these are the properties of the reservoir domain while in case of P and P square approach we are having the reservoir properties as well as property for the fluid that is viscosity compressibility factor and then BG volume formation factor. So the expression could be different but we can understand this expression can be transformed to some empirical correlation that we will discuss later on. So let us assume we want to have some numerical equation or the equation that is applicable to be utilized to understand the behavior of the compressible fluid flowing under radial conditions from a reservoir. If we choose any of the approach depending on the pressure range we have to have certain parameter to be included in this expression.

For example we are using the pseudo approach we need to know what is the permeability of the formation, what is the page on thickness, what is the temperature. Most of the time this information are not available or they may change over the time also. Similarly, for the pressure approximation we are having the fluid properties also. Fluid properties can be correlated with respect to the change in the pressure but the reservoir properties are something those need to be evaluated very effectively accurately to include in this expression. So the accuracy of this model will depend on how accurate that information is available to include in this expression.

Another approach could be transferring this approximation equation into some empirical correlation. So there are several correlation developed to understand the IPR relationship that is the relationship between the flow rate and the pressure drawdown. Pressure drawdown is actually the difference in the reservoir pressure and the bottom hole pressure that is also called the sand phase pressure. There are several correlation developed for the compressible fluid. We will discuss two approaches back pressure approach and the Horsman approach in detail at the later stage.

So let us see when we start producing the reservoir there is some more phenomena happens around that reservoir. So what happens with respect to time and then the value of the bottom hole pressure that is here Pw that changes initially when we are not producing at this condition the reservoir pressure is actually equal to the Pwf. So the Pwf value is equal to Pi but when we start producing Pwf start decreasing and then some sudden change happens in the value of Pwf. This happens because of the Valvore storage effect. So far we did not consider what Valvore storage effect are in the next slide we are going to discuss that thing.

After certain time when the effect of the Valvore storage can be neglected we will be in the transient region that is actually unsteady state flow condition and when the deviation from this straight line happens it means we are shifting the flow regime from transient flow region to pseudo steady state region. In pseudo steady state region the value will be producing for longer time. So let us consider the case of the compressible fluid within this reservoir domain we are having the equation for this transient flow condition that is the infinite acting radial flow condition. We could develop this analytical expression using the fundamental understanding. Now if we see here Pwf at any time during this change can be evaluated by using this expression.



Now this expression again records some of the parameter to be included and then including the value of Q. If we want to truly transfer this equation to the relationship when we want del P versus Q that is actual IPR equation or Q versus del P in more appropriate form. This transient flow will happen up to certain time only how long this is going to sustain can be calculated the time to reach the pseudo steady state conditions here when the deviation from this straight line is happening with respect to time we will be having the time could be calculated using this expression. That expression is having reservoir properties as well as fluid properties and this time is having the unit of hours. Similarly in the case of pseudo steady state flow region when we reach there we are having the IPR equation that is applicable for boundary dominating radial flow condition.

In these two equations we are having the fluid properties, reservoir properties, geometry of the reservoir that is considered radial and we can utilize the concept of IPR to get the relationship between pressure drop down versus the flow rate. In both the equation we did not consider skin effect and non-darsic coefficient. So under certain assumption these two equation could be utilized. Now these two equation will further be simplified to get the empirical correlation. Before going through that discussion let us consider what is bellwor storage or after flow condition.

So actually the production rate that is controlled in the reservoir is done from the surface not at the sand phase, sand phase means bottom hole condition. So what exactly happens because of this bellwor that is having some fluid already present here so if we are doing the draw down test or the build up test we will see what draw down test or build up test later on. Let us see when we are just starting the production at a constant flow rate. So it is kind of step input function we had given with respect to Q. So initially Q value was 0 we started the production at any Q value and that we are measuring at the surface.

So now at the sand phase what is going to be the flow rate is not suddenly going to change to the new value it will be having this S shape kind of the curve. So it will take some time to reach that value although after certain time this will reach to the same value that is measured at the surface condition and this happen because of the fluid already present in the bellwor. Similar phenomena will happen for the second case when we are producing the well at a constant flow rate and suddenly we are setting the well or we are changing the flow rate. In that case also mathematically we had given the function that is suddenly step down function from Q to 0 value but the flow rate will change like this at the sand phase condition. So this happens for some initial time after certain time the situation would be the same at the surface condition and the sand phase condition.

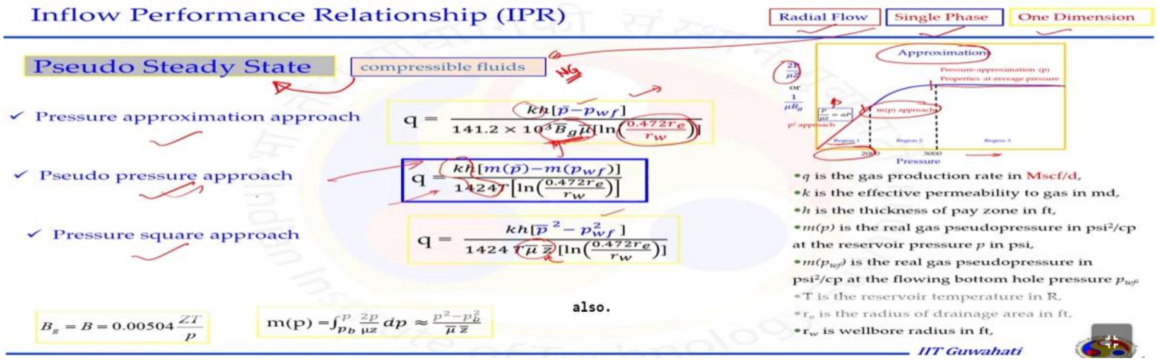
Most analysis often ignore the wellbore storage and after flow condition but for the better accuracy of the IPR equations these phenomena can also be included. These phenomena happens because of the fluid expansion within this wellbore or changing the liquid level within this wellbore and both the conditions should be included for the better accuracy but for the general understanding of the wellbore performance analysis we often ignore these two phenomena. So let us discuss the concept of productivity index. So the factor that is characterized the particular well one of the factor is productivity index and productivity index is defined by a parameter J that is equal to flow rate divided by pressure draw down. So if we see the pseudo steady state equation for the compressible fluid that is given here in the form of pseudo pressure approach we can adjust this equation keeping this Q in the numerator and bringing this pressure draw down in the denominator.

Sometimes you will see P reservoir is written sometimes just P bar all are same and then other side we will just left with KH and this term that is here. So this 0.472 is actually the adjustment for minus 0.75 in the logarithmic form. So if we compare this equation and these two equation we got one parameter that is J that is the ratio of flow rate to the pressure draw down now we got one parameter that characterize the reservoir.

So whenever we are talking about the reservoir engineering with a particular well the productivity index is one of the important parameter that is actually tells about at what rate the reservoir is producing. So the concept of productivity index can be included and the resultant equation is the new form of the IPR. In this equation you will say J is only one parameter that is need to be known to see the IPR equation. Now in this IPR equation at different PWF I can calculate the value of Q or at different Q I can calculate the value of different PWF only things need to be known is J instead of knowing the physical properties of the fluid or the reservoir geometry and reservoir properties we just need to know the value of J. So this J is called the productivity index how it can be obtained so the running the well at two different conditions we can get two different points with respect to pressure.

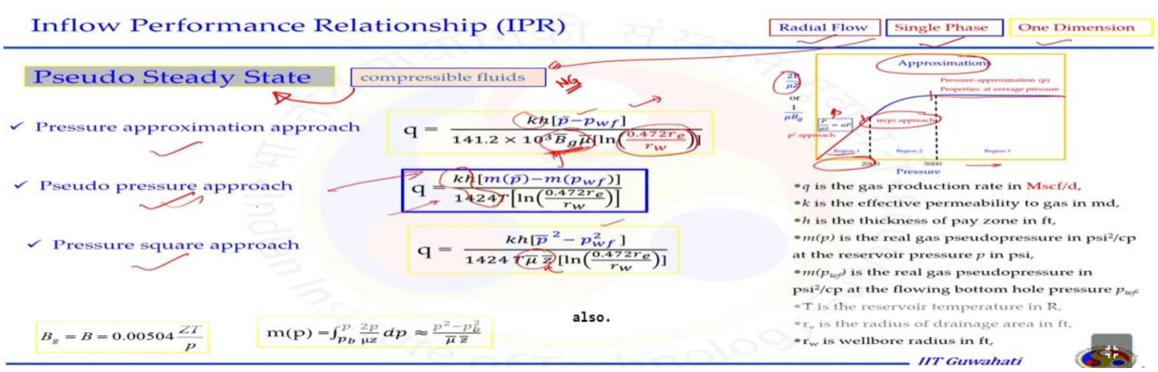
So the two different point could be first one is here that is reservoir pressure so when we are not producing anything Q is equal to 0 the well is in certain condition we are going to get the PWF that is MPE. So this is the plot of PWF versus Q in the pseudo scale for the pressure. Now this situation PWF is equal to MPE and then the flow rate is 0. So when we get two point on this scale at different flow rate we are getting the different value of the PWF we can draw the straight line and that the resultant straight line should be having the slope of minus 1 by J. So with this slope we can get the value of J and now we are having the value of J we got our IPR equation.

Now this IPR equation can further be extended extrapolated that is the purpose of drawing the IPR equation because once we are having the IPR equation we can utilize this IPR equation to understand the extended flow rate or the future production of the well. So the situation when we are having this MPE is equal to 0, 0 in the absolute pressure condition or the atmospheric condition or other way PWF is equal to 0 that is the situation here. In this conditions the flow rate is AOF that is the maximum flow rate we can obtain from that particular well when the PWF is equal to 0. So although this is a conceptual situation where we want to know the potential of the reservoir at what rate the maximum production can be achieved within the reservoir and that is absolute open flow condition assuming the situation where this is PWF is equal to 0. So the unit of J that is productivity index the unit of J will depend on the approach or the approximation approach is chosen to establish the IPR equation.



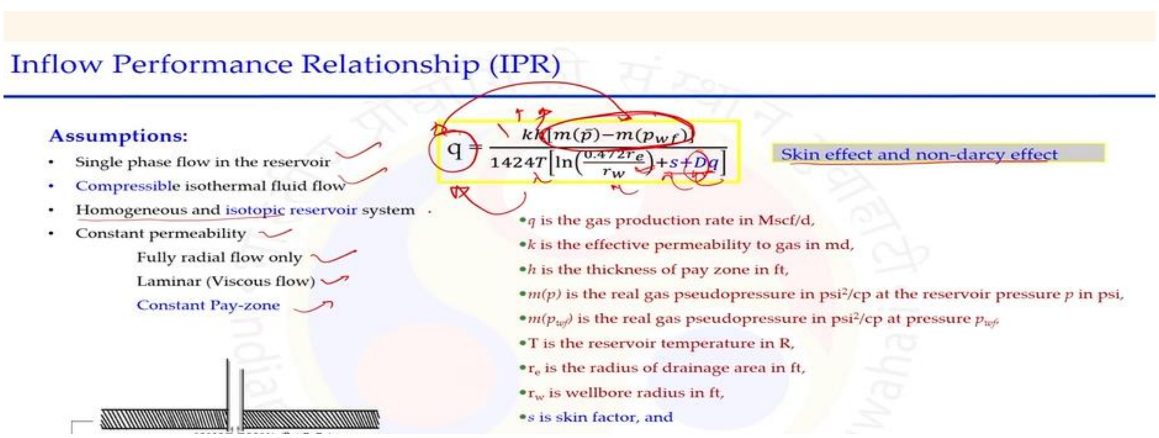
So for the compressible fluid we can have the P, P square and MP approach. Now the productivity index in the case of MP will depend only on the reservoir condition while for the other cases P approach and P square approach the property of reservoir and the fluid will also affect the value of J. But for a particular reservoir for a particular fluid production J is a good indicator about assessing the performance of that particular well and the absolute open flow potential can be obtained for that particular reservoir well by using the J concept. Now similar approach as is shown here for the P can be done for the pressure approach and then the P approach. Once we get our J value based on that we can calculate the Q max value.

Now the J value is also not required if we understand what is the maximum production is happening and at what pressure it is happening. Of course this Q max will happen when PWF is equal to 0. Now using this equation 1 and the other equation 2 we can relate the flow rate at any particular PWF with respect to the Q max and the reservoir pressure. Now the resultant equation using these two equation going to give us single point data equation. So now the reservoir well just need to have just one set of the data if we know at PWF we are flowing we can calculate the Q value directly without running the well without testing the well or other way we are flowing at a particular flow rate using this single point data we can calculate what is the value of PWF at the sand phase.



If we extend our discussion of the productivity index for the case where the skin effect can also be included in the expression. So the S will be appearing here all the things will remain same and in that case the value of J will only be change and that is actually the comparison when the deviation of J value is happening compared to the previous case if we are setting up here and if the J value is changing it means we are having the skin effect near the wellbore zone and we should use this equation which is also including the effect of the skin in the form of S. Otherwise everything will remain same the minus 1 by J will be the slope and the bottom part that is the pressure difference will be changed only here. The unit UAF condition everything will remain same similar to the previous case IPR curve based on the single point can be established use different value of PWF calculate the value of Q and then we can get the IPR relationship for that. So the productivity index is only good when we are having normal ideal flow condition without skin and without non Darcy flow condition or even with the skin effect it is good.

But when we are having the non-Darcy coefficient the definition of productivity index is not going to be that simple because in that case we will be having additional term dQ and that dQ is going to make this equation quadratic in the nature and then the definition of J flow rate divided by pressure draw down requires more complex thing. So the productivity index is good for the ideal condition as well as skin effect not for the non Darcy coefficient. So let us discuss more about this IPR equation for the compressible fluid with the skin effect and then the non Darcy effect. Certain assumptions are taken to establish this relationship that is the single phase compressible fluid isothermal condition reservoir is homogeneous and isotropic so the K value is not changing and the permeability is constant fully radial flow condition laminar and viscous condition whenever the deviation is happening from laminar condition near the valvore the d will account for that and then the constant page on thickness that is h. Now this equation can be adjusted in a more simple form.



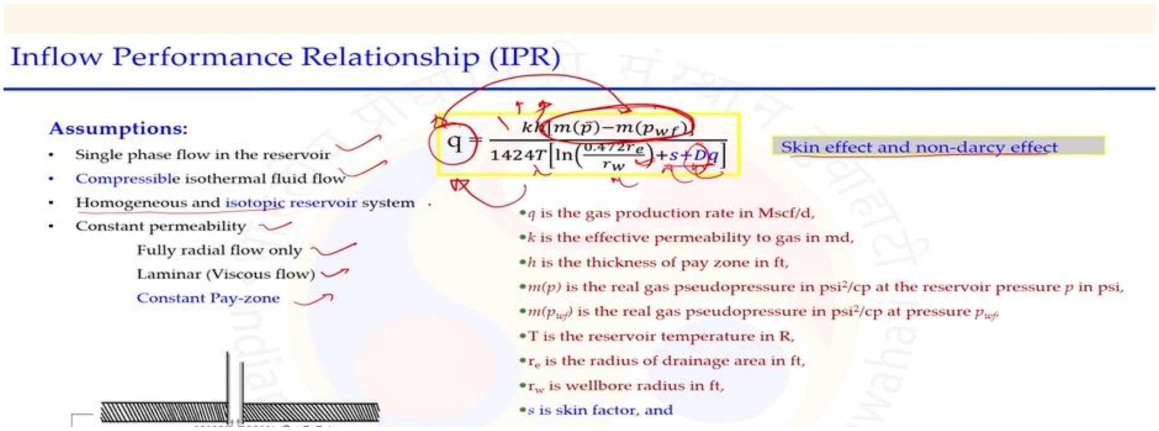
So what we can do if we see we can take this as a one parameter and then Q is the other parameter. So the Q versus this is actually the IPR equation as I said earlier to get the simplified form of the IPR equation numerical form we need to know all these rW, re, temperature, K and h for the MP approach for the other P and P square approach we need some fluid properties also. In this case the situation is not that simple we have to adjust this equation in some form those can be related to the empirical things. So the empirical methods for the IPR equation are the force smear model these models are good for the gas well testing and that is why we are discussing this model force smear and the back pressure model they are established for the gas well testing. For the oil well testing we will discuss in the next class.

So the force smear model actually first time established that near the valvore region it is not only the laminar flow but the inertia and turbulent phenomena are also happening and in that case the LIT model laminar inertia turbulent model is proposed by the force smear. That is actually is the quadratic form of the equation that says pressure drop down the difference in the reservoir pressure and the sand phase pressure is equal to quadratic relationship with respect to flow rate. And that is actually we are having here the basic IPR equation has been transferred to IPR for the pseudo steady state condition for the compressible fluid here. Now here if we adjust this equation we are going to get the similar expression. So what we can do this Kash T and something we can just consider as one parameter and then this is another here.

So what we are going to get let us say Q is equal to if I just say this is equal to X MP minus MPWF divided by ln 0.472 RE by RW plus S plus DQ. Now we can take this also this side so we are going to get Q multiplied by ln 0.472 RE by RW plus S plus DQ square and on right hand side we are having the same thing if we divide this by the X on the right hand side we will left with MP minus MPWF. Now whatever is in the multiplication of Q that is going to be the constant for a particular time we are evaluating the performance of the reservoir and that we can say A multiplied by Q.

Now here DYX that we can say is B and then Q square on the right hand side we are having the same term MP minus MPWF. So the analytical expression is actually having the basis of the Fords-Mears model which is the quadratic relationship of the flow rate and the pressure draw down. Now this equation if we see here we need two parameters A and B to be known. So without knowing the physical properties of the fluid and then the reservoir properties and other parameter if we know only two condition what is A and B we are okay to have our IPR equation. How to get those two condition A and B? We can run the well at two different conditions.

So let us say we are running the well at PWF1 condition and then PWF2 condition. Both the condition the flow rate can be estimated at this condition it is Q1 and at this condition it is Q2 or other way at flow rate Q1 we are running the well we can estimate PWF1 and flow rate Q2 we are having PWF2. Now the two equation we can get for the same this is and then two unknowns are there A and B. We can solve that equation to get the value of A and B. So this B is simplifying this equation at two condition and once we know the value of B we can calculate the value of A.



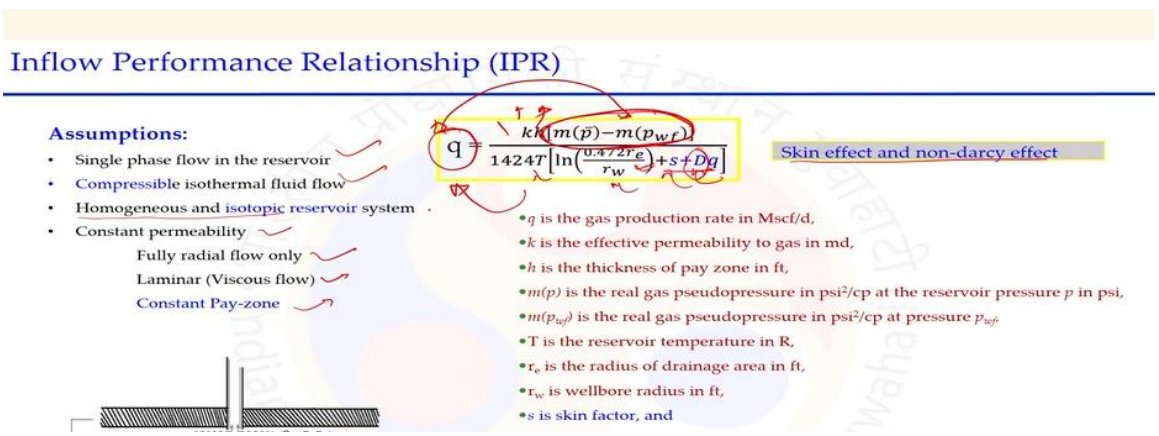
Other way could be we are having the graphical approach we are having the flow rate versus pressure here. So now this flow rate and versus pressure plotted here for the P square approach instead of MP approach because the similar analysis we can do for the P approach P square approach and MP approach. So let us say the equations are given in the form of MP approach while the graph is given for the P square approach. The analysis will remain same. So in that case what we are going to do let us this is our IPR equation if this equation is divided by Q on both the sides so we will be having this del P by Q is equal to A plus B Q this del P could be P minus PWF could be PE square minus PWF square or MP minus MPWF depending on the approach we are choosing.

So what is the point here divide this pressure draw down by Q on the Y axis and then the Q on the X axis you will get the relationship is Y is equal to MX plus C. So the M is actually B here that is the slope of this linear equation and A is actually C that is the intercept of this equation. So in the case of pressure square approach we are going to get some data we are running the well minimum two conditions are required having more condition will give the better accurate linear fitting and in that case the intercept and then the slope can be calculated and knowing this value we can put it here and we got our IPR equation in the Fors-Mere model. So now another empirical method that is the back pressure model also called the deliverability model so for the pseudo pressure condition for the compressible fluid we are having the same equation as in the previous case. Now the back pressure model based on several data set utilized to have this relationship can also be correlated with the analytical expression.

So first let us see what this correlation is that correlation says Q and the pressure draw down is related to C and N. C is actually accounting for the ideal condition where the non Darcy effect is not there in fact C can also account for the skin factor but for the non Darcy effect the N is taken on the power side. So lot of the data were established and then this relationship came out. Now this relationship is also having the basis with the analytical expression as I mentioned earlier. Now whatever is here in the multiplication of pressure draw down we can consider that C except taking out this dQ outside other than dQ whatever is there is actually C and for this dQ that is non Darcy effect the power N will take care for the non-Darcy coefficient.

Now this expression is similar to previous condition we need two data set to find out the two unknowns that is C and N. So if we can run the well at minimum two conditions we can get the value of C and N or if we are having the data set at two condition of flow rate and then the Pwf we can calculate the value of N and C. How we can do that thing we can take this equation to the log form. Now if we plot the Q versus pressure draw down on the log log scale we are going to get the linear relationship. In this case we are having this pressure draw down on the y axis and then the flow rate is on the x axis of course this is log log scale.

So the linear relationship that is coming by running the well for multiple data set we are going to get the slope that is equal to 1 by N and then the intercept will be C. Again similar to the previous case the equations are given in the form of MP while the graph is shown for P square approach. There could be a situation similar to the previous case where we can get the absolute open flow condition that is the maximum flow rate condition and in that case the N is not considering into the factor and then the C that is equivalent to the productivity index of our productivity definition that is Q divided by pressure drawn. But in that case non Darcy effect should not be there. If non Darcy effect is there as mentioned earlier productivity index concept cannot be implemented.

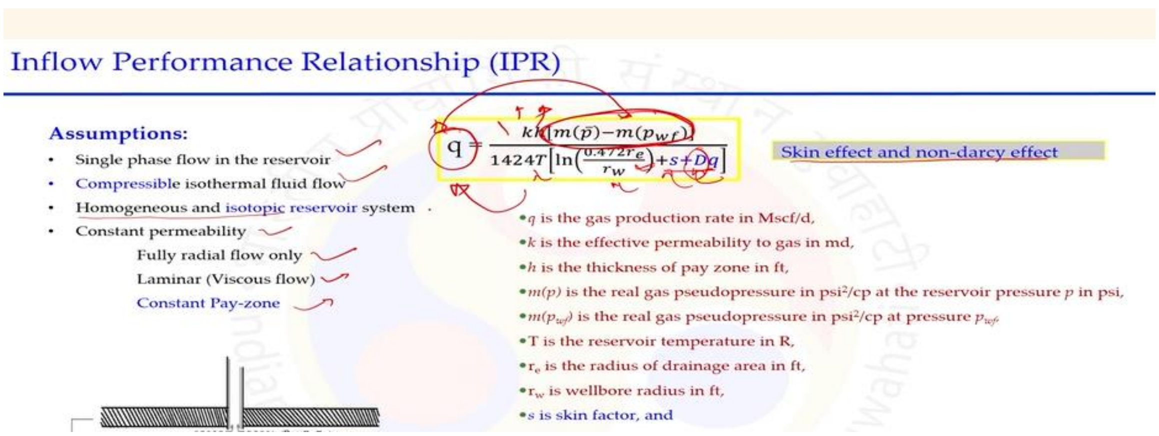


But in this case also we can calculate once we are having the linear equation we can extrapolate the data and we can obtain the condition when the maximum flow rate can be obtained with this model. Now the value of N if the value of N is equal to 1 this is similar to the case of back pressure model equation when the non Darcy effect are not important. If the non Darcy effect is significantly important then the value of N will be 0.

5. So the value of N will vary from 0.5 to 1. So let us summarize this LIT and then the deliverability model we are having the equations and these equations can be solved with two conditions to get the value of A and B for this force smear model. For the back

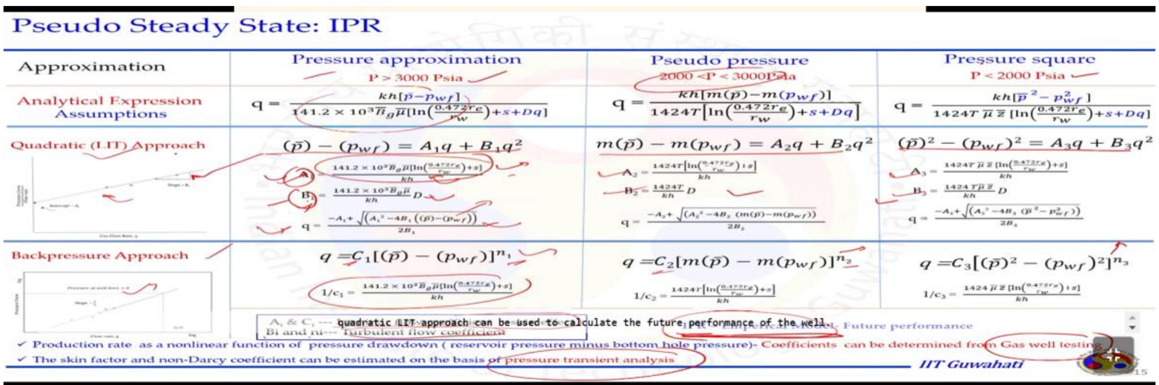
pressure model B can get the value of N and C just running at two different condition that I was saying. So let us say under the pseudo steady state condition this is our analytical expression for the pseudo steady state condition for the compressible fluid and that is if non Darcy effect is not considered this will be simple this equation and when the non Darcy effect is considered this is force smear model quadratic relationship and then this is back pressure model. Now the similar that what we did for the pseudo steady state case we can do for the transient case also.

Here the equations are shown in p square form. Now in the transient case also we can get the similar kind of the analysis that we did for this quadratic relationship or LIT relationship we can do under the transient condition also. In the transient condition what we can do we can split this log T and then remaining term is log. Now our pressure draw down is here and then the flow rate is here. So we can take this pressure draw down on one side and then the other side we can adjust in such a way and whatever is coming into the multiplication of this log T log T will be having this term multiplied by log T.

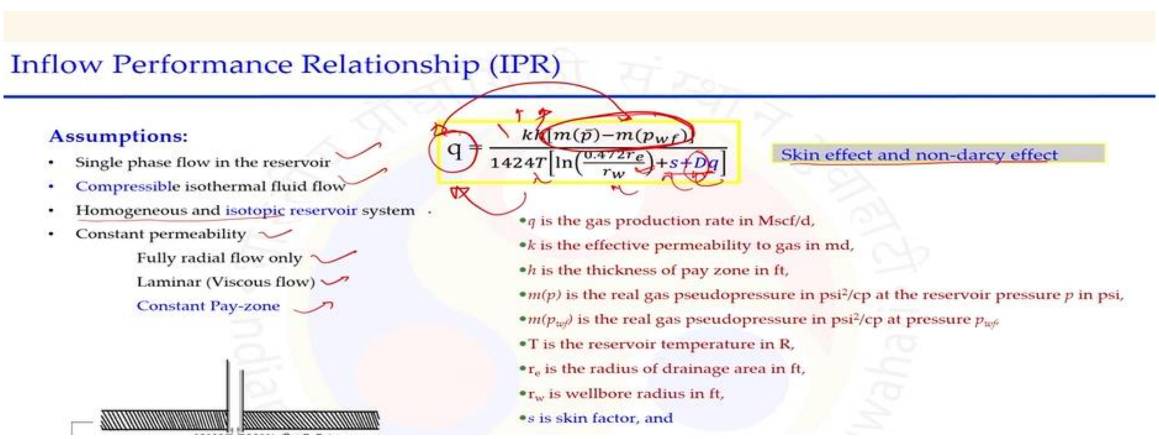


So this is M log T this we can say is M. So now this equation can be transferred again into the linear form where the non Darcy effect are not considered here otherwise it will become quadratic in the nature. So for the transient condition we got pressure draw down is equal to Aq plus M log T. So in the pseudo steady state case we are not having any time dependent things while in the transient we got the term that is accounting for the time. So we compare this equation with this equation the additional term is coming here. When the non Darcy effect is there we are getting the quadratic equation here similar here we will get the quadratic equation now this A that was in the multiplication of Q will be including the this log T term also there because this dQ and this Q will become dQ square and some multiplication here that will go in the form of B here and whatever remains in the multiplication of Q that will be A but that A will be the function of time.

Here in the case of non Darcy effect is not important the A is just constant while here it is having the time dependency. What about the back pressure model? In back pressure model we are going to have this CT not time dependent. So everything other than this part will go to the exponent and then the remaining will be as a CT that is in the multiplication of this Q. So actually that will be 1 by CT and then 1 by CT can be taken to the pressure side to get this relationship. So we got our equation for the pseudo steady state case either in the transient condition or the pseudo steady state condition.

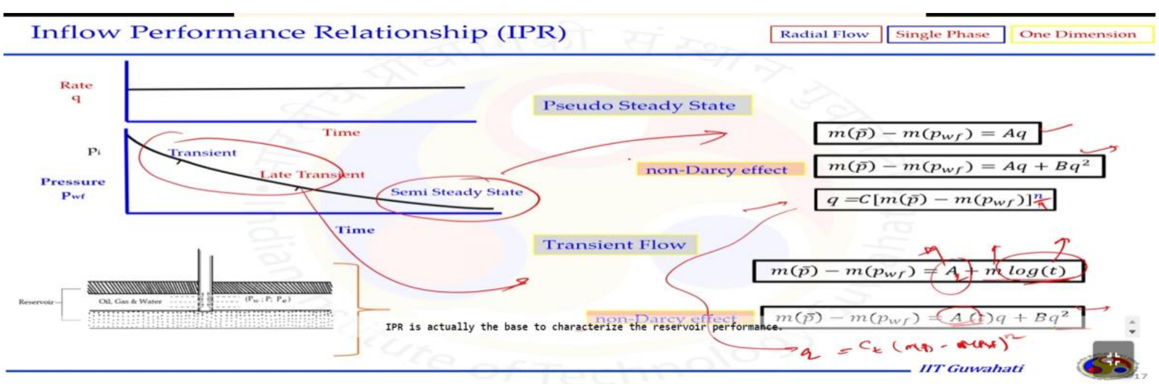


Now this equation also including the S and dQ those are the additional term that comes near the Van Gogh region. So let us summarize for the pseudo steady state IPR condition we are having the three approximation pressure greater than 3000 P approach, pressure lesser than 2000 P square approach in between pseudo pressure approach. We are having the two method LIT approach and in all the cases the parameter A and B those are appearing they are relating different properties of reservoir and the fluid. So by performing the method at two or three condition we can get the value of A and B from this slope and intercept.



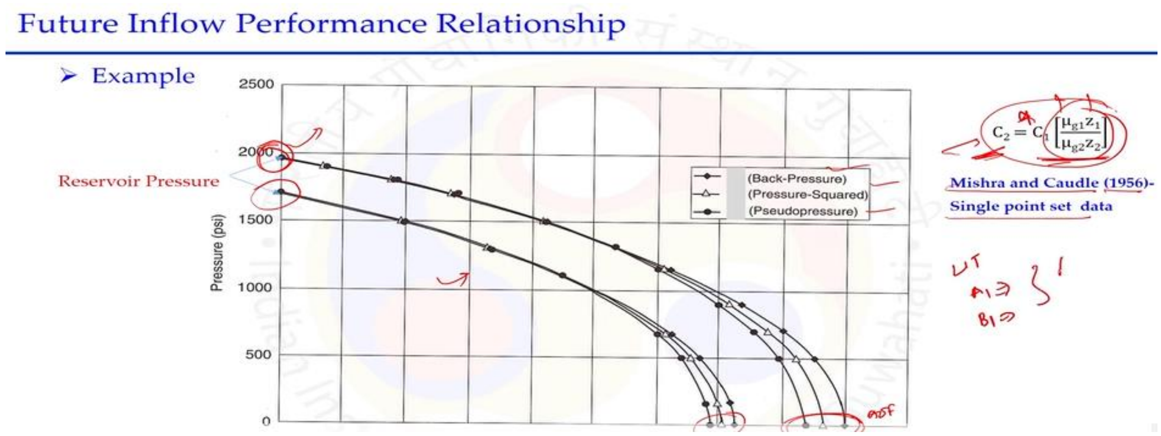
Now this A and B are having some reservoir and fluid properties. Now the A and B are having the properties relationship so the unknown property can be calculated with the help of this expression. Similar for the MP and P square approach or once we know the A and B we can calculate the flow rate at any PWF using this quadratic solution or we can do with the help of this graph also. Similar to back pressure approach we are having the C and N they will be different for different approaches and N will remain same because N is counting for the non Darcy effect only while the C will be adjusted as per the approach and then this 1 by C will be equal to what is here in the expression. So in that case again we can get the value of C and N either from this graph or solving for two different condition. So this IPR based on the empirical correlation the empirical models back pressure and the quadratic LIT approach can be used to calculate the future performance of the well.

So when we talk about the future performance of the well we can do with respect to different approaches so we are going to get the reservoir pressure here and that reservoir pressure will decline and the condition of EOF can also be calculated. Now these are based on the empirical models so all the models are almost following the same thing but at the end the EOF value is little different because the way the equations are set up. The important point to be discussed here is after certain time the reservoir pressure will decline. So let us say when we start our analysis there could be the point when we are here at 2000 psi if we start our analysis at this condition then the parameter calculated at 2000 psi reservoir condition may not be applicable or there will be a deviation from the values because the viscosity and compressibility factors they are the function of pressure they should be corrected to new pressure value. So again we need to run the well to get the IPR equation and then extrapolating that IPR equation to get the EOF value this is very cumbersome job for that it is suggested in the literature specifically the suggestion given by Mistra and Caudell 1956 for a single point data set it says like whenever you are changing the condition or you are going to evaluate the well performance at the new condition instead of calculating the IPR parameter again by running the well to different condition you can adjust that parameter C in the back pressure model by this kind of the relationship where the mu and z calculated at one condition mu 2 and z 2 are calculated at second condition.



So the C2 in the revised or the new back pressure model equation can be placed by using the previous C and then this factor. So this is the way the single point data set can be calculated for adjusting the pressure condition similar for the LIT model the A1, D1 can be utilized to calculate the A2, B2 at the new conditions that new condition is here.

So for the pseudo steady state flow condition we got this equation this equation simply saying no non Darcy effect when Darcy effect is there this will become the quadratic

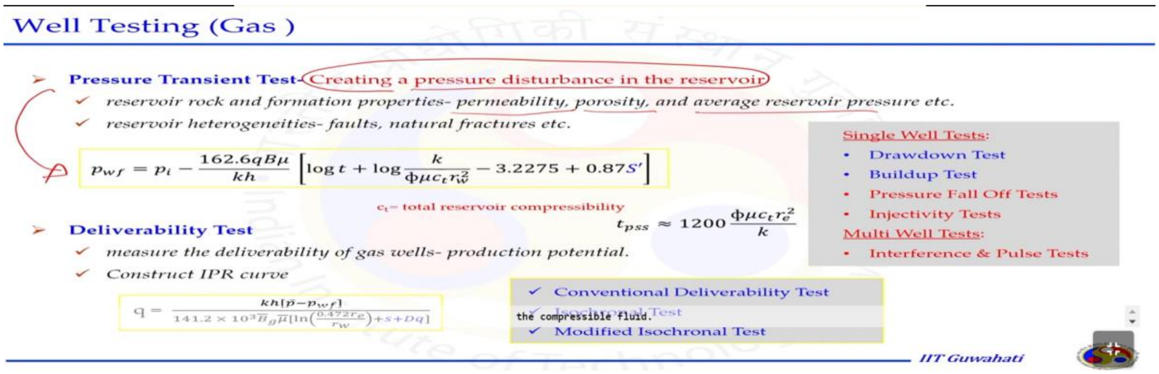


equation and then this is the back pressure model where the N will not be there if it is not having the non Darcy effect N will be there if the Darcy effect is there. Similar for the transient case we are having this Aq should be there we are having the Aq plus m log t so this t is actually going to take care of the measurement taken at different time and then the non Darcy effect equation this A will become the function of time and then we are having the quadratic relationship while for the case of the transient flow conditions this equation can also be written here. So now we got our equation we are running the well either in this condition we will use this equation when we are running this condition we will use this equation we can characterize the reservoir performance get the IPR.

IPR is actually the base to characterize the reservoir performance. So based on this basic understanding about setting up the equation in the different form we can go ahead now to perform the well testing. This is a useful tool to analyze the performance and understanding the future productivity of the gas well. Today's lecture we are discussing about the well testing for the gas well only. Why we need to perform this well test? The foremost condition is we will get the IPR equation. That IPR equation is required to understand the future production or the near future production also.

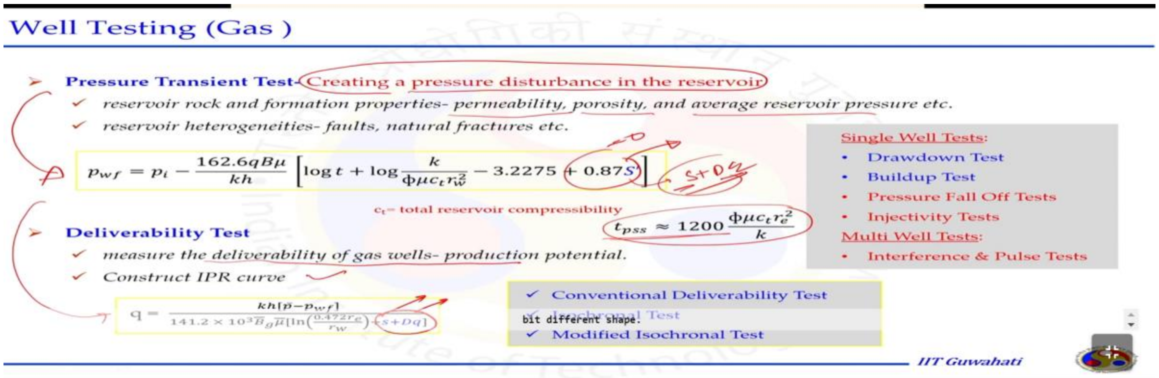
Second with the help of this gas well testing we can calculate the static reservoir pressure condition. The second is the flow potential of the reserve means the EOF condition what is the total reserve of the gas within the reservoir we can calculate with this. We can calculate the formation permeability by establishing this relationship we will get the constant in the equation those can be utilized to calculate the reservoir properties k page on thickness and other. We will also get rate versus pressure depletion data or to estimate the value of formation permeability including k skin factor or damage. So by performing the well testing we can understand is there any damage happen near the wellbore region or any stimulation happen or any improvement in the permeability happen.

Because if something happen in the skin zone that will be reflected in the IPR equation. Similarly non Darcy effect is important or not now it will be important in the future or not that can also be assessed by the IPR equation by performing the well testing to understand the nature of the equation. The result and information gathered during the testing are also utilized not only by the petroleum reservoir or the production engineer but certain regulatory bodies to estimate the gas reserve within the field domain and at what maximum rate the gas can be withdrawn from that field for the estimation of the gas reserve and projecting gas well deliverance. In the preparation of the field development how many new wells should be installed in that area can also be assessed by doing the well testing on already adjusting well. In the design and gathering of the facilities those are required to process the gas or the fluid at the surface.



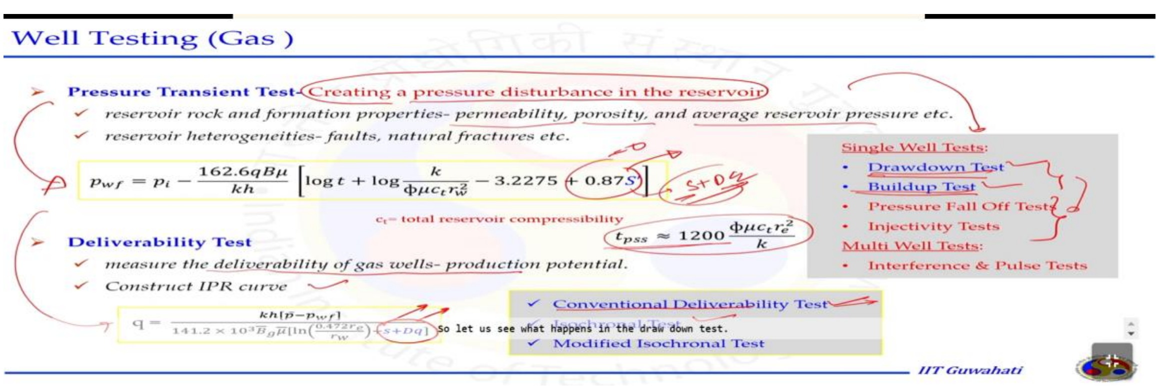
So two types of the test are done pressure transient test and then the deliverance test. So with the help of the pressure transient test we can get the skin factor and non Darcy factor because the pressure transient test done with respect to time and what happened near the wellbore region is assessed. While the dilutely test primarily are utilized to establish the IPR equation. So let us see what those tests are in more detail. Pressure transient test that is for creating a pressure disturbance in the reservoir. So by creating a pressure disturbance in the reservoir we understand how the pressure is changing with respect to time that is the pressure transient test.

Reservoir rock and formation properties as mentioned earlier also can be calculated with this pressure transient test. The reservoir heterogeneity can also be assessed with this pressure transient test because if sudden change is happening some of the established IPR equation parameter it means some fault or some fracture has been created or something happens. So that pressure transient test is done based on this transient IPR equation that is for the compressible fluid. Here S prime is including for both S plus dq and also called the total skin effect that is counting for skin as well as non Darcy factor that is actually near the wellbore region.



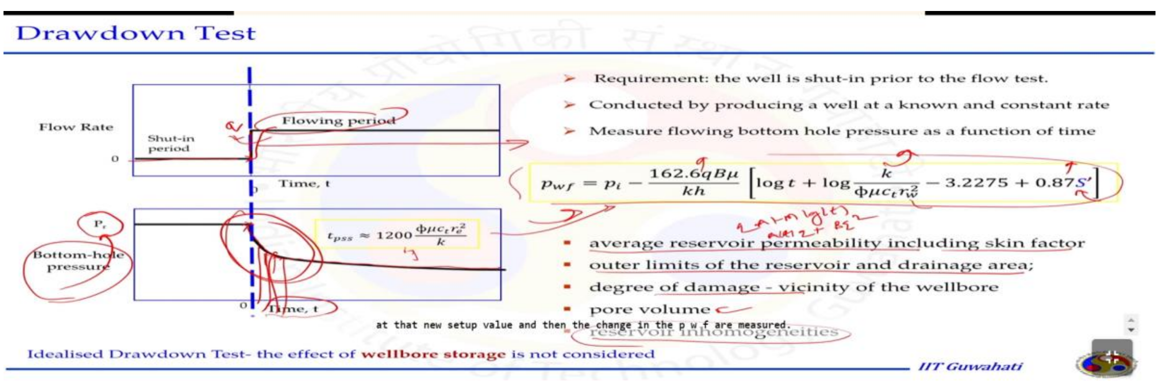
If both are absent then this term will be 0. The time to reach the pseudo steady state condition can be calculated from this equation. In the deliverability test we measure the deliverability of gas well it means the production potential of the gas well and we construct the IPR curve. In that case we use this pseudo steady state equation that is established for the compressible fluid similar to previous case S and dq are near the wellbore region and if they may be there or may not be there. If they are there we have to include in the equation and then the equation will take little bit different shape.

So on the pressure transient test we are having single well test or the multi well test. There could be a big list of those test we are just discussing briefly about some of the test. So in the single well test like draw down test and the build up test analogous to these test are the two other test. In the two other test what we do we inject the fluid from the outside and see the similar effect as we see in the draw down and the build up test. While the multi well well testing method they are done in the field where the one well is considered as the active well where we are performing the operation and second is observation well where we are seeing the effect of the operation done on the other well. So the connectivity between these two well can be assessed with the help of that test and how these two wells are communicating within the subsurface can be established.



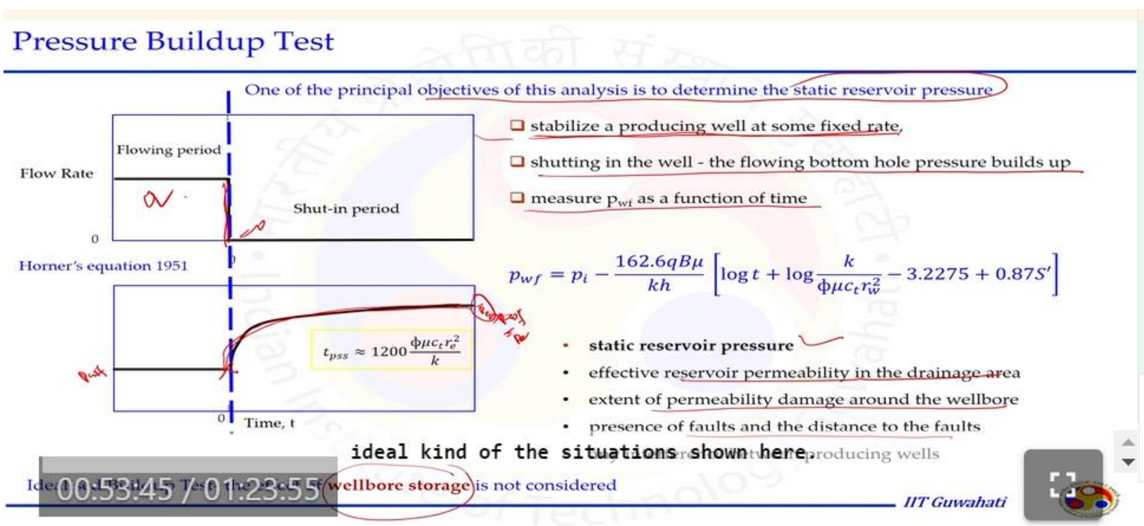
We will discuss only the draw down test and the build up test for the pressure transient test that will also we are going to discuss briefly about what those tests are. In the dilutely test that is for constructing the IPR equation there are three methods or three types of the test there. A conventional dilutely test also called the back pressure test or flow after flow test, isochronal test and then the modified isochronal test. So let us see what happens in the draw down test.

We are having the reservoir that is placed under the certain condition for a significant time. Significant time to make sure the bottom hole pressure has reached to the reservoir pressure. What will happen? The Pwf that was at the reservoir pressure when the flow was not happening when just well is open to flow the pressure value at Pwf will decline and this will decline and then reach to the pseudo steady state condition. The time required to calculate the pseudo steady state condition can be calculated with the help of this or simply by measuring the bottom hole pressure we can see when the change is not happening significantly the pressure is almost reached to the pseudo steady state condition where the change is happening with respect to time but at a constant rate. Now in this region where the pressure is changing non-linearly with respect to time we can use this pressure equation that is for the transient condition and can relate certain parameters. So at different time we can get the value we required only two but we can get multiple data set and then flow rate Q is constant we can put in this equation to calculate the unknown those are appearing in this equation.



So this draw down test that is very simple test simply says when the flow rate start the pressure will decline and that decline is in the pressure can be measured with respect to time and this kind of the analysis is going to give us the average reservoir permeability including the skin effect because that is appearing here in this expression. Outer limit of the reservoir and drainage area those are the radius R w and R e degree of time is in the vicinity of the wellbore if there is a deviation from that equation as we had seen that include like there is some time is happening at the wellbore region we can also calculate the pore volume and the reservoir in homogeneity how much heterogeneous the reservoir is near the wellbore region we can calculate with the help of draw down test. Idealized draw down test the effect of wellbore storage is not considered as mentioned earlier in this kind of the analysis there should be some delay in the flow rate and that flow rate delay should also be reflected in the pressure but that is actual condition we are considering the ideal condition we started step input in the flow rate flow rate is achieved at that new setup value and then the change in the p w f are measured. Similar to pressure draw down test there is a pressure build up test so this is one of the principle objective of this analysis is to determine the static reservoir pressure. Reverse to pressure draw down test what is done in the build up test the well is producing at a constant flow rate Q it is under the flowing condition.

Now the pressure here at p w f that was also established within the time window we are observing and now suddenly the pressure observation are made when the flow rate is set to 0 means the well is put under the certain condition. So our well was producing at a constant flow rate suddenly it is put under the certain condition what will happen p w f value will change and then p w f value will change slowly slowly and it will reach like this. In fact it should reach to p e reservoir pressure value. So in the pressure draw down we shut down well is put in the production condition in pressure build up test producing well is put in the shut down condition. In pressure build up test it is stabilized producing well at some fixed flow rate Q shutting in well the flowing bottom hole pressure will build up we measure the p w f as a function of time and at the end means after doing this certain condition for a longer time whatever the p w f value that is equivalent to the reservoir average pressure.



So the static reservoir pressure can be calculated in this manner effective reservoir permeability in the drainage area and then the permeability damage around the well bore can also be calculated. Similar to the previous test the fault and then the distance of the fault how far those fault are can also be assessed by running this for a different condition because if the pressure is getting build up in the pressure build up test or is declining in the draw down test depending on the geological formation near the well bore region. So if any faults are there any damages there that will be reflected in the change in the p w f value. Similar to the previous case well bore storage is not considered this is also one of the ideal kind of the situations shown here.

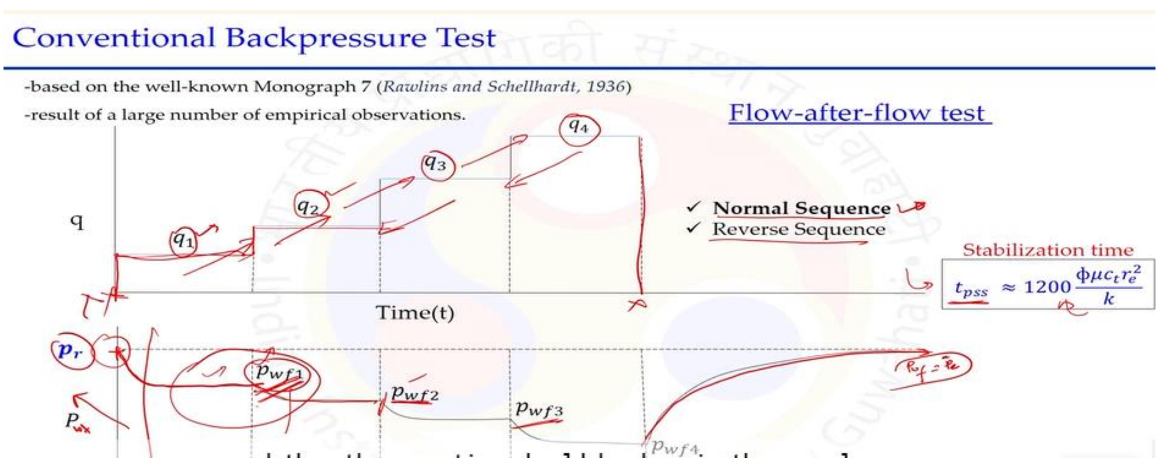
So let us come to the dilutely test those utilize this pressure draw down and pressure build up test. Dilutely test are done to construct the IPR equation the dilutely test are designed primarily to measure the dilutely of the gas well. The measure the availability of the gas to flow against various pressure conditions wake pressure means p w f. So when we said different p w f condition what is the flow rate can be achieved from a particular well evaluate wells production potential under specific condition of the reservoir and p w f productivity indicator j and A o f absolute open flow condition can also be established with this dilutely test it generate the IPR equation that is the foremost important for us. Here it is shown for the back pressure model similarly we can do this for the LIT method also. Several dilutely testing methods have been developed for the gas well let us consider only the three cases flow after flow it is also called the conventional back pressure test second is isochronal test and then the third one is modified isochronal test.

We will discuss one by one all these three cases so let us say conventional pressure test that is done flow after flow for multiple point test data. In this test the well that is there it is flow at selected constant rate until the pressure stabilize or we reach the pseudo steady state condition. What does it mean we are having this well we started producing through this well at a particular flow rate let us say q and then the pressure will change at p w f because of the pressure draw down we will wait till this p w f is reaching to pseudo steady state condition. It means it is passing the transient condition reaching the pseudo steady state condition and then once it reach the pseudo steady state condition that also called the stabilized condition.

So when we say stabilized condition means the well reach to the pseudo steady state condition. So the stabilized rate and then the pressure at that conditions are recorded. The rate is then changed to the new condition and again the similar thing we waited till the pressure reaches to pseudo steady state condition or to a stabilized condition. We again record the pressure and the flow rate data and then do it again. The process is repeated for total 3, 4 or 5 times depending on the well conditions or how long the well can be put under the testing condition. So let us say in this conventional pressure test data that I mentioned the steps in the previous slide it is flow after flow test the time we required to do this test every time we are changing the flow rate we need to wait till the situation is reaching to pseudo steady state condition that we can calculate with the help of this formula.

So now let us say we are having the flow rate q 1 the pressure will decline what does it mean we are having this flow rate q is equal to 0 at this condition and this p w f is equal to reservoir pressure. We started producing from this well at a constant flow rate q 1 this is similar to the pressure draw down test what will happen the pressure will decline at the p w f or the sand phase condition also initially it will pass through the transient condition late transient condition and reach to the p w f 1 condition. What is that p w f 1 stabilized pressure condition or the pseudo steady state conditions at the sand phase. In this case we run this well for a significant time till we make sure the pseudo steady state condition has been reached or not. We can do that by measuring the p w f for a significant time when the value is not changing significantly it means we reach the pseudo steady state condition.

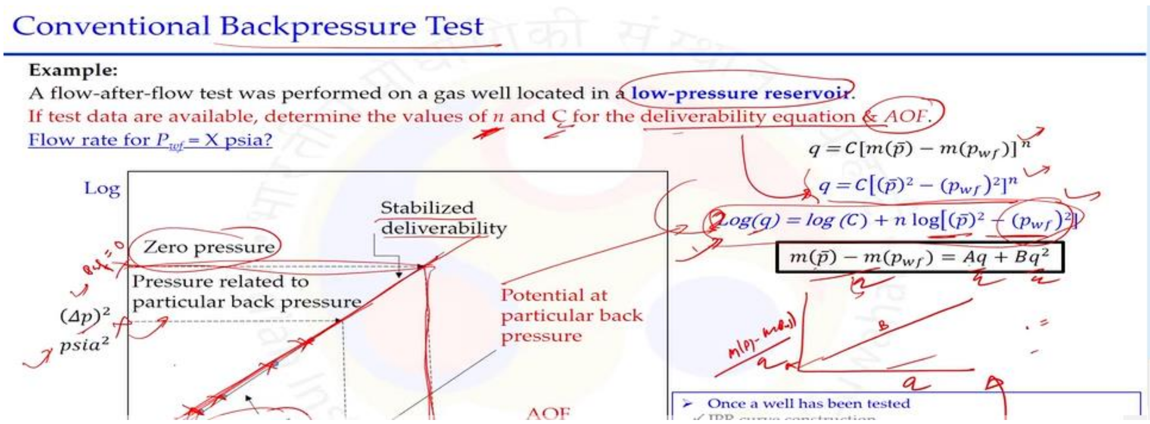
Now this test is done for several steps because now we got only one data set at q 1 flow rate the bottom hole pressure is p w f 1. So if we are using the productivity index we know the productivity index one data set is good enough if we are using quadratic equation two data set are good enough but for the better accuracy we will do it for three four five times. So what we did in the next step the q 1 flow rate it was flowing for a significant time we reach the pseudo steady state p w f 1 when we made sure p w f 1 is achieved pseudo steady state condition is achieved at this point we give another increment in the flow rate we reach to q 2 condition that is higher flow rate. So what will happen the pressure will further decline similar manner drawdown test transient followed by the pseudo steady state we will reach p w f 2 condition and then the values run for a significant time similar to the q 1 condition. We got second data set q 2 versus p w f 2 after assuring we reach the pseudo steady state condition q 3 flow rate is set up that is higher than q 2 we will get further change or drop in the sand phase pressure and it will stabilize at p w f 3 similar we do for the q 4 and at the end q 4 we can put it under the certain condition similar condition as we were having previously and in that case what will happen the reservoir pressure will be attained at the sand phase so p w f will reach the reservoir pressure.



So by doing this back pressure test we got the data set with respect to flow rate and then the p w f that is also at the stabilized condition because the transient condition transient equation will be used at the stabilized condition we will be using the pseudo steady state equation. Now the sequence that we followed here we consider every time from q 1 to q 2 we increase the flow rate from q 2 to q 3 we increase further flow rate and then q 3 to q

4 we increase the flow rate that sequence we adopted is called the normal sequence in this manner we increase the flow rate and see the further drop in the p w f value the reverse can also be done but the data says normal sequence is much accurate compared to the reverse sequence and then the operation should be done in the normal sequence. So let us take the example for the conventional back pressure test a flow after flow test was performed on a gas well located in a low pressure reservoir low pressure reservoir means we can use the p square approach. If data set are available determine the value of n and c for the dilute equation and calculate the e w f maximum flow rate condition as mentioned earlier we can use the m p approach p approach a p square approach but as the low pressure reason is given we should choose the p square approach this back pressure equation can be converted into log form and in this log form we are having the q versus this pressure data. So the reservoir pressure is given to us at different condition we are going to get different p w f what those different conditions are different q and then we can use either this back pressure equation or the l i t equation to calculate the parameter but in the problem we were asked to calculate for n and c so let us use this equation.

So what we will do on the log log scale for pressure square approach we will plot pressure draw down versus the flow rate and the data point at 3, 4 condition given to us will be plotted and a linear relationship will be established because this equation says on the log log scale the q and the pressure draw down should be having the linear relationship and now all this data in the conventional back pressure test are obtained when the pressure reaches to the stabilized condition means it reaches to pseudo steady state condition that is why the resultant equation here is the stabilized dilute equation. Now the slope of this equation will give us 1 by n and knowing the value of n we can calculate the value of c another condition that we can have this condition when the maximum flow rate can be obtained at this condition so we can also obtain that condition where the p w f is going to be the atmospheric pressure or the value in the absolute term is going to be 0 in that case the pressure draw down will be the maximum and that maximum pressure draw down will give us the maximum flow rate. So the conventional back pressure test is similar to testing the well at 2, 3 condition that we discussed previously in this lecture about force mere model or the back pressure model we can do the similar thing here we can pick only 2 data set here establishing the condition calculating the a and b or c and n depending on the model chosen just only the 2 value but having more value and the graphical approach can give us the better explanation in terms of the fitting the straight line calculating the value of e o f from the graph at that condition when we are going to get the maximum pressure draw down. So this is the way the conventional back pressure test can be utilized for the gas well analysis this condition is called the zero pressure when p w f is equal to 0 we will get the maximum flow rate condition a o f at any particular pressure we are flowing the well we can relate this at what will be the flow rate if the pressure is set to some other value p w f is set between 0 to reservoir pressure somewhere we can get the this condition if the pressure is set here means the reservoir pressure means we are not producing the flow rate is also 0. So once a well has been tested IPR construction can be done future inflow performance relationship can be obtained viscosity and compressibility factor of course changes we need to change the value of this a and b or c and n in the equation that is I mentioned about how to do that we can just change those coefficients those are responsible for this viscosity and factor those are including viscosity and the z factor like the c 1 or the a 1 in this model.

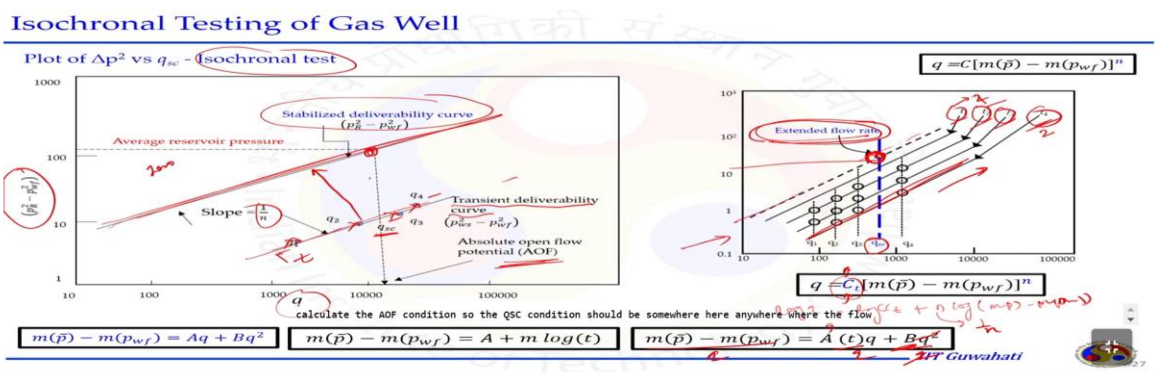


So that is the way we can do now here I am showing the log log form of the graph where this formula is used we can do similar for this one on the Cartesian coordinate system where the pressure change divided by q versus q because we can take out q from both the sides that will also give me the linear relationship and then the slope and intercept can be calculated to get the value of a and b. So the slope will be b and then the intercept will be a and this can be done for p p square and the MP approach. So the conventional back pressure test is actually having the drawback because every time when we are going to change the flow rate before that we have to wait till the pseudo steady state condition is not reached that may take several hours and it is a time consuming process and when we are saying time consuming process it is also costing us because the well is under certain condition for a significant time it is not producing it is under the testing condition it is not producing at the desired or the set flow rate. So the limitation of the conventional back pressure test is taken care by the isocronal testing of the gas well. In this isocronal test well what we do similar thing having the flow rate versus the pressure at the sand phase with respect to time we monitor it and what we see when we are having the flow rate that is 0 means we are not producing we are having the p w f value is also reservoir pressure.

Now we produce at q1 flow rate the pressure draw down is happen similar to the previous case so we reach p w f1 and this is done for a significant time to see the pressure is declining and reaching to some stabilized value not necessary it is reaching to stabilized value but we fix some time through that time the change in the pressure is monitor and then the well is put under the certain condition. So this is first step is like the pressure draw down test second step when we shut down the well for some time the pressure at sand phase will grow up will build up and it will reach to the same reservoir pressure. In second step the increased flow rate is set up at q2 value and then the well is flowing for a certain time and then the value of p f w2 is achieved. In that case what is happening the p w f2 will be lower than the p w f1 because the flow rate q2 is higher than the q1 and when we shut down the well after some time then the pressure will come back again to the reservoir pressure. And this kind of the steps q1 q2 q3 q4 flow rate are done in the increased manner or not necessary in the increased manner we are doing but if we do in the sequence in manner we will get better fitting in the equation.

Let us say q1 q2 q3 q3 are giving us the pressure draw down p w f1 p w f2 p w f3 p w f4 happening in the reservoir at the sand phase and at the end we get one extended flow rate. What do you know extended flow rate we set up flow rate to certain value and at that condition we see what is the pseudo steady state or the stabilized pressure is going to be we measure this flow rate let us say it is q5. So, in this case of the isocronal test closing in the well until a stabilized or very nearly stabilized reservoir pressure is reached that is the condition here the well is flowed at a different rate for a set period of time that is the time here t here going to be same the flowing bottom hole pressure p w f at time t being recorded. So, every time when we spend time t we record the pressure when we spend time t we record the pressure when we spend time t we record the pressure and we record the pressure. Let us see in terms of actual conditions so these are the pressure value when we shut down the well and we measure the p f w1 p f w2 p f w3 and p f w4 we can take the value at any time we can fix like 2 hours at every conditions when we are having this flowing condition we can say every 2 hours we are taking the data let us say and here also or we can take at 3 hours or 4 hours it means we can fix any particular time within this flowing condition for all the flow rate and can use the transient equation to get the IPR relationship.

Now let us see that IPR relationship under the transient condition is complex so what we do we fit these Q versus p w f data at same time and then get the graphical approach to find out the equation or the relationship or the linear relationship that is not actually true stabilized condition but that is the transient condition. Let us see in the next graph we can see so when we are having this pressure drawdown versus flow rate on the logarithmic scale for this isochronal test logarithmic scale means we are considering the back pressure model not the LIT model but similar analysis can be done for the LIT model also. So the pressure drawdown versus flow rate now at a particular time that I was mentioning here we can see the data collected for different flow rate at this time or at this time or at this time so the time can be fixed even could be 2 hours every time when the flow rate is changed every after 2 hours the value of the pressure is measured or it could be 3 hours 4 hours kind of the thing so this could be lower time this could be the higher time and this is our extended flow rate extended flow rate means the time when we left the well for a pseudo steady state condition and then the pseudo steady state condition has been reached we obtain the pressure value and corresponding the flow rate and that data is taken here. So this is the extended flow rate now here you will see all the equation with respect to time they are taken at different times are having the same slope and that happens because if we see in this equation also the value in the logarithmic form if I take the log of this log Q log CT that is time dependent for a particular time that will be same plus N log MP minus MP WF. So in this equation if we see we are having the pressure versus this log Q data the slope is going to be the same and that same slope will be applicable for all these conditions similar to if we are using the LIT model in that case also when we are plotting this so the value of B will remain same similarly here the value of 1 by N will remain same for the same time data set only the intercept here will change and here the value of CT will change.



So the slope is going to be the same and that is the basis of isochronal test and the extension of this equation that is passing through that flow rate condition or PWF condition will give us the QSC condition means the flow rate at that condition if we can measure the PWF5 that we measured here PWF5 now we can calculate what is the extended flow rate actually this is the true condition that is the stabilized condition and that stabilized condition is actually the IPR equation. So in this case what we are going to get the we tested the well let us say at a particular time we fixed time and at that time for Q1 Q2 Q3 and Q4 we got the data and at that time we plotted this Q data with respect to pressure on the logarithmic scale we got this linear relationship this called the transient diluteability curve and then parallel to this we can draw a line that is passing through the point that is actually the extended flow rate condition so PWF5 condition this is for example let us assume it and flow rate at that condition could be the stabilized flow rate QSC condition the slope will be 1 by n and then the intercept of course will be different because that depends on the time and by doing this we got this is a stabilized diluteability curve or the IPR curve. Now using this equation we can calculate average reservoir pressure the absolute open flow conditions so the average reserve pressure for example here the zero pressure condition and at that condition this is intersecting here we can calculate the AOF condition so the QSC condition should be somewhere here anywhere where the flow rate where the PWF is there this is the condition on the line is for the zero pressure condition. So the transient diluteability curve is established first using the extended flow rate the actual stabilized diluteability curve is obtained by the isochronal test. In this method also if you see every time when we are flowing for a constant time and putting the well for a certain time that certain time is actually depend on the reservoir condition how fast it is coming back or pressure is building up under the certain condition to reach the reservoir pressure PR.

If that reservoir pressure PR takes longer time to reach then we are spending too much time to do this test every time we are waiting till PR is reached hence this is also little bit time consuming test compared to modified isochronal test. So in the modified isochronal test this is similar to the isochronal test the length is certain period not required for pressure to stabilize does not yield a true isochronal value but it is good approximation towards the true value and can be considered use approximation like isochronal test are modeled exactly modified isochronal test are not modeled because it use certain approximation in this case what we do we fix certain time before the pressure reach to the reservoir pressure back we start the new flow condition widely used because it saves time and money of course if the longer time is required for the testing means you are losing the money and prove to be the excellent approximation to true isochronal test. So it is widely used because it saves time and money and prove to be excellent approximation to true isochronal test. In this test what we do similar to the isochronal test the length is certain period is reduced and in this case we are having the similar condition Q1 Q2 Q3 and Q4 as the conditions where in the isochronal test we are flowing the well at the Q1 condition from the zero flow condition pressure will decline in this flowing well condition when the well is certain and leave it in the certain condition for certain time the pressure will build up now in this method we are not waiting till this pressure is building up to the reservoir pressure what we did we fix this time del T del T del T constant in fact we can fix the same time for the flow condition and same time for the certain condition del T can be kept constant. So we flow the well pressure decline the pressure build up in the certain time new flow rate new pressure build up so in the Q2 condition we will get again when we open the well pressure will decline and that will reach to PWF2 we are again not waiting till pressure is reaching to the reservoir pressure we started the next condition and this is the way every time when the certain time is reached that we already set up the next flow rate is starting and at the end we do the similar extended flow rate condition to find out the stabilize flow rate and pressure relationship.

If we see in this case all the time between these steps certain and the open condition can be kept constant so by doing this at different flow rate we are going to get different PWF value those we got here and this is that extended flow rate again the same concept the line should be parallel to the transient condition and then the extended should pass through the extended flow rate condition to get the stabilize deli will take up. So we got the transient deli will take up by using this data and parallel to this line we got this stabilize deli will take up this is the EOF condition similar to the previous case we can also get the slope 1 by n we can calculate the intercept C for the true stabilize condition and we got the IPR equation that is for the stabilize flow condition. So now the well is running under the stabilize flow condition we are having the IPR equation we can use that equation to predict the future of the well. Now these dilutely test when we should perform them there are certain conditions under those these test should be performed although there is no certain restriction but the preference is given for the flow after flow test when the high permeability for mission is present in the reservoir this means the time to reach pseudo steady state condition is not going to be large because the significant permeability is there it will reach in a lesser time compared to the tight permeability formation as the flow after flow test or the conventional and the conventional back pressure test should be performed that is actually this is directly durability or stabilized durability analysis while the other method they go to the some transient curve and parallel to that we get the stabilized curve. But if the permeability is low in the formation then to save the time we should do the isochronal test because in this test we do not wait till the pressure is reaching to pseudo steady state condition we can fix some time and after that the well is put under the certain condition the pressure of at the PWF will come back to the reservoir pressure.

But that is also like taking little time to compensate that time modified isochronal test is done and this is done for the tight permeability formation where the time to reach the pseudo steady state condition time to reach come back to the reservoir pressure condition is high then we should do the modified isochronal test and that situation happens in the tight permeability formation conventional back pressure has limitation like the tight formation it will take longer time to get the pressure coming back to the pressure to reach the pseudo steady state condition isochronal modified isochronal test to shorten the test time but again they are first use the transient curve and then take the transient curve to the stabilized pressure condition. So, actually the well is run under the stabilized condition only one time hence the applicability of these different test will depend on the conditions. So, in summary of today's lecture we started with the IPR equation those developed in the previous lecture we learned the productivity index and the absolute open flow condition this productivity index is J absolute open flow condition is the maximum flow rate condition it means the PWF is 0. We discussed two empirical method in detail back pressure approach that is C del P to the power N del P could be P square and MP approach and the force mere model that is AQ plus BQ square is equal to del P this is like this and then we discussed the well testing method like the back pressure method isochronal method and the modified isochronal method.

Again this discussion is done for the one dimensional flow under the radial flow condition. So, in today's discussion we discussed mostly the gas well testing. So, in the next lecture we will continue our discussion about well testing and the performance. We will understand the performance of the oil well and the system when the field is having multiple wells and then another good technique to understand the well performance that is decline curve analysis that we will discuss in our next lecture. With this I would like to end my today's lecture. Thank you very much for watching the video.