Petroleum Reservoir Engineering

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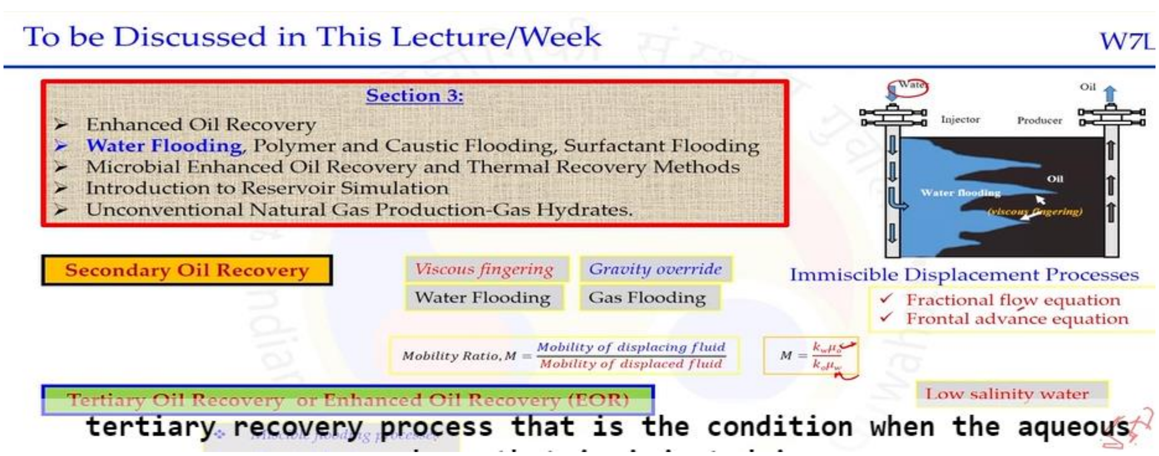
Lecture 19: Enhanced Oil Recovery Methods

Hello everyone. Welcome to the class of petroleum reservoir engineering. This is week 7 and lecture number 2. In the last lecture, we discussed about secondary oil recovery processes. We discussed both water flooding and the gas flooding process. The processes are having certain limitations that we discussed in detail about the viscous fingering for the water injection process and then the gravity override for the gas flooding process.

We discussed about the invisible displacement process given by Buckley and Leavitt that is having two components frontal flow equation and then the frontal advance equation. We discussed about how the water or gas injection flow through the reservoir domain and let the oil move towards the production well. As mentioned viscous fingering and gravity override are the two processes those put the limitations on efficient recovery of the oil by the secondary recovery process. The factor that is mobility ratio is used to understand the efficiency of the secondary oil recovery process later on the displacement efficiency in terms of the water saturation or the oil saturation was also discussed.



So the mobility ratio is the ratio of displacing fluid divided by the mobility of the displaced fluid. So, basically it is the ratio of the parameter where the mu o is in the numerator and mu w for the water injection in the denominator. So we can see the mobility ratio should be favorable when the m value is lesser than 1 and in certain cases when the viscosity of the oil is very high the mobility ratio is not favorable. Since the process need to be improved and that is come out as the new processes we call the tertiary process also called the enhanced oil recovery process EOR. There are various processes those are implemented after the secondary recovery process some of them are mentioned here like the miscible flooding process, chemical flooding, thermal flooding process and the microbial flooding process.

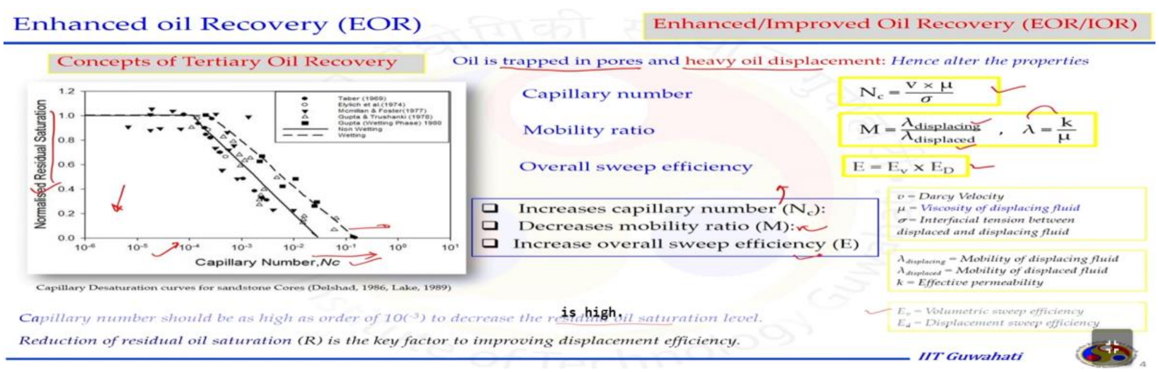
So we will discuss in today's lecture about the tertiary oil recovery process in detail. The concept of low salinity is also gaining lot of attention both for the secondary and tertiary recovery process that is the condition when the aqueous phase that is injected in the reservoir is having the low salinity compared to the formation water that is very high saline and that has given very good result in terms of the oil recovery process. So the crude oil production happens in these stages primary oil recovery, secondary oil recovery both accounts around 35% to 40% of the original oil in place at max. Hence significant amount of the crude oil remains in the reservoir. So we need to improve the recovery that is the aim how we can do that thing by improving the secondary recovery technique process.

As I mentioned the secondary recovery is water injection and the gas injection we can improve those processes by altering the properties of the inject state fluid. For example the water we can use the low saline water or we can include some chemicals in the aqueous phase. Similarly for the gas we can inject the gas at the condition when it is miscible with the crude oil and all those falls in the ER process. Implementing the advanced processes for further enhanced oil recovery process beyond the secondary process so altogether these falls in the ER process. The ER process can also be engineered or implemented in more efficient way to recover the oil process.

That is where the tertiary oil recovery processes are gaining lot of importance in oil industries to recover the trapped oil in the reservoir domain. So for the secondary recovery process this is the mobility ratio we can improve the condition in such a manner the mobility ratio is becoming lesser than 1 that is the favorable conditions. So the tertiary oil recovery process are very reservoir specific lot of data information need to be known before we are choosing which ER method should be implemented in the reservoir domain. So the reservoir geometry fluid properties like the porosity and permeability for the reservoir fluid property density viscosity of the fluid means the crude oil that remain in the reservoir reservoir depth at what depth we are having the crude oil and then the other properties of the rock like lithology and rock are also important and then the fluid saturation significant amount of the oil should remain in the reservoir to implement the tertiary recovery process. So the concept of enhanced oil recovery process can be understood with this diagram.

This diagram says the normalized residual saturation on the y axis and then the capillary number on the x axis. So after the secondary recovery process the oil remain in the reservoir is either trapped in the porous region small small region where the oil is trapped and then the rock is having the affinity for that oil. So when we are injecting the water, water is not able to enter in those pores because of the high capillary force. Hence the oil is still remain in the reservoir. So the oil is trapped in the porous region that is remain in the reservoir.

Second condition the oil that remains in the reservoir is very heavy oil means it is having very high viscosity and the density. Hence we need to implement the process in the EOR that can alter the properties. It can alter the properties of the fluid that is getting injected means an alteration of the properties of the crude oil itself also altering the properties of between the rock and the oil interaction. So this can be achieved by having the high capillary number. As this figure showing if you want the residual oil that remains in the reservoir to be very low means we are able to get the more oil recovered then the capillary number should be high.



If the capillary number is high the residual oil remain in the reservoir after the tertiary process will be low. The ideal condition would be when the residual oil remain in the reservoir is becoming 0 and that can be achieved with very high capillary number. Hence the capillary number should be high and that is the ratio of the viscous force to the capillary forces. We need to reduce the capillary forces or improve the mobility ratio that is the improving the mu w the aqueous viscosity. Second is the mobility ratio itself that is the ratio of displacing fluid mobility to displaced fluid mobility and the mobility is defined as k by mu.

So the parameter that is important second one is the mobility ratio third one is overall sweep efficiency. So for example if we taken out the oil from these small pores through the microscopic displacement process the oil is coming to the pool region from where it needs to be swept towards the production well. Hence the overall sweep efficiency also important to assess the success of the ER process that is implemented in the reservoir domain. The overall sweep efficiency is the multiplication of EV and ED. ED is the displacement efficiency that we discussed in the last class and EV is actually the volumetric sweep efficiency.

So to have the success of ER or recovery factor high we have to have the condition when the capillary number is increased, mobility ratio is decreased and overall sweep efficiency is increased. So capillary number should be as high as in the order of 10 to the power minus 3 and more to decrease the residual oil saturation level as we can see in this diagram. In this reduction of residual oil saturation is the key factor for improving displacement efficiency. So if the residual oil saturation is becoming low it means the efficiency of the displacement is high. So the important parameter and the mechanism of the EOR is the mobility ratio, interfacial tension and variability alteration.

These three factors becomes very important. Mobility ratio either increase the viscosity of the injected fluid or reduce the viscosity of the oil. Interfacial tension that is the between the two immiscible phases we need to reduce the interfacial tension and then the variability alteration that is the affinity of the rock towards a particular fluid. So if we can make the alteration in the variability that will be in the favor of recovering the more oil from the reservoir domain. If we talk about the efficiency of the system so several factors are there.

As already mentioned capillary number should be high. Capillary number is denoted by CA, NC or sometime NCA also. Interfacial tension between the two immiscible phases should be low. Displacement efficiency should be high. Mobility ratio should be low.

Efficiency should be high and then the variability alteration. We need to alter the variability from oil wet to the water wet. So the water can diffuse into small pores and replace the oil. The chemicals those are used in the process of ER which is the chemical ER. The adsorption of those costly chemicals should be low for the better efficiency of the system and then the reservoir heterogeneity that is very complex as less heterogeneous it is the favorable for the ER process and overall cost of the process that is also one of the parameter to assess the efficiency of the system.

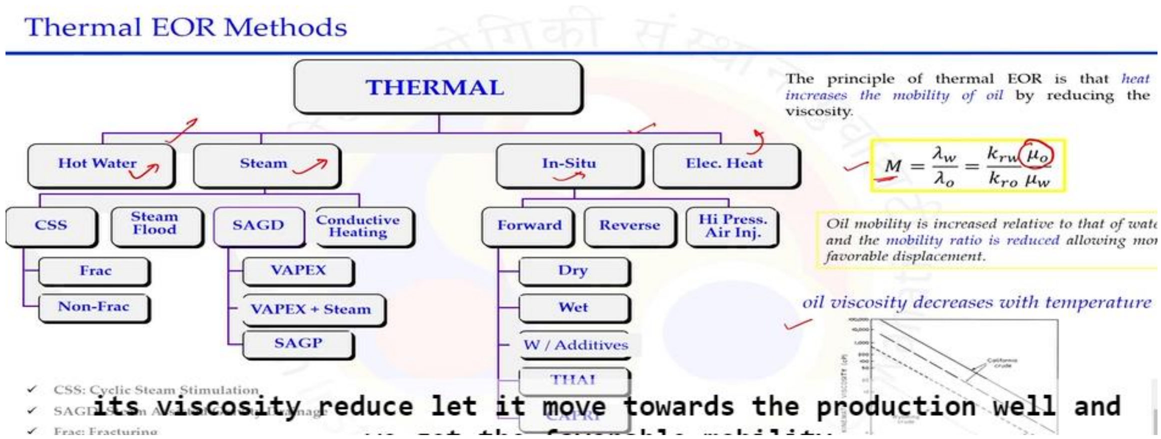
The recovery of the oil and the cost involved should be in the proportionality that is making the process cost effective. So the displacement efficiency that we talk about here is two types microscopic and the macroscopic. So the replacement of the oil at the pore scale is called the microscopic displacement efficiency and that is the factor depends on interfacial and surface tension forces, wettability of the system, capillary forces through which the oil is trapped in the region and then the relative permeability. Once the oil is ready to come out from those pores the competition between the rock between the oil and the water is determined by the relative permeability. Second displacement efficiency is the macroscopic displacement efficiency that is the bulk volume of the oil should be swept towards the production well.

So this is sweep out the volume of the reservoir oil towards the production well. Again this is dependent parameter on the heterogeneity and the anisotropy of the reservoir. Morality ratio is the primary factor in this and then the physical arrangement of the injection and the production well as discussed for the water flooding. Different types of the injection and the production well arrangement can be chosen that is how far the wells are, how they are arranged and how effectively they are communicating through the permeability will be one of the parameter that will determine the value of the macroscopic displacement efficiency. So these are the pre-requisitc kind of the conditions where the chosen EOR method will give us the better recovery process.

There are various types of the recovery processes. We can classify them broadly in two ways. First one is thermal process and another is non thermal processes. The thermal processes are further classified based on the scheme chosen to provide the heat to the system. The basic principle of the thermal processes is providing the heat to the crude oil that is trapped in the reservoir domain.

The heat will reduce the viscosity of the oil and make it more movable. As we can see from this mobility ratio expression if we can reduce the value of mu o we will be able to get the mu lesser and that is the favorable condition. So the oil viscosity as we know decreases with the temperature as can be seen in this diagram for different crude oil as we increase the temperature the viscosity decreases. So the overall objective of the thermal processes provide the heat. The heat can be provided by injecting the hot water to the domain or the injection of the steam in situ combustion of some of the crude oil in the reservoir domain by injecting the air and making the combustion process happen that leads to very high temperature.

At that high temperature some of the crude oil that is viscous will be cracked down and the mobility of the oil will be improved. So these processes are actually using the aqueous system where the water either in the hot condition or in the steam condition is injected while the other side we are having the process where the crude oil is burnt or electric heater are used to provide the heat to the crude oil. Further classifications are there for all these processes like for the hot water we are having the cyclic steam injection stimulation process. In this process what we do the single well is used for the cyclic injection of the steam and production. So we inject the steam let the oil viscosity reduce and from same well we produce the oil.



In steam flooding we do injection of the steam flooding from the injection well let this steam go to the crude oil the processes or the mechanism happen let those happens and we are getting the crude oil movable towards the production well. So we are not going in detail about all these processes I already mentioned here what sec the process what the fracture process could be understood from the literature. For example the fracture process we inject the steam that creates the fracture nearby the valve reason it means it increase the permeability in that reason. Similarly on the other side we are having the process called the thigh capry and the combination of thigh and the capry processes. So in thermal processes by any mean we provide the energy or the heat to the crude oil lets its viscosity reduce let it move towards the production well and we get the favorable mobility ratio.

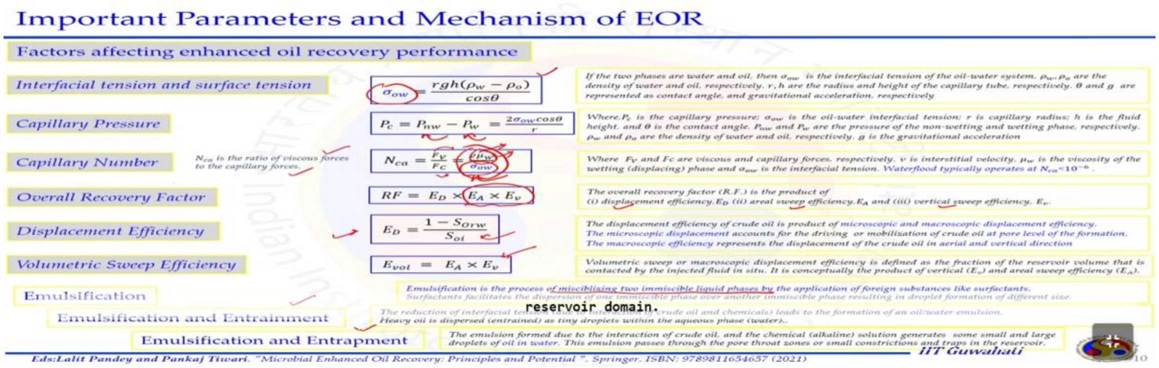
In the non thermal processes we are having the processes like the miscible injection of the gases chemical injection into the reservoir domain and then we are having the other processes also. So other processes include the MUR microbial ER process form process and then we are having this plasma pulse process or the ultrasound process by any mean as I mentioned we try to improve the three parameter that is increasing the capillary number reduce the mobility ratio reduce the interfacial tension and overall these factor include towards the displacement efficiency to be better. So for example we can see here in the condition of miscible injection there could be several cases where the gas is injected above the minimum miscibility pressure let that gas dissolved in the crude oil make it less viscous let it be flow towards the production well. In chemical injection polymer surfactant alkaline and combination of them are injected into the domain those alter the properties and let the oil flow. Other processes microbial ER is also similar to the chemical ER here we use the bio surfactant instead of the chemical surfactant.

So the application of the other processes like the ultrasonic and electromagnetic waves and the plasma pulse may be effectively to recover the oil and environmental friendly also but again depends on the complex nature of the reservoir domain. Here in this diagram we can see the chemical ER process is having the alkali surfactant polymer and their combination either two of them or three of them injected into the reservoir domain with the aqueous phase to alter the properties the concept of form and the nano fluid are also the part of the chemical ER process. So the improvement of the ER process by different means can be summarized quickly here we will discuss in detail in the coming slide. So the thermal oil process they are the high temperature process reduce the oil viscosity increase the oil mobility towards the production well steam injection in situ convection or some of the process. Chemical injected with the aqueous phase change the characteristic of the reservoir fluid improve the oil recovery mechanism chemicals may be surfactant alkali polymer combination of them as well as form generating a system or the nano fluid can also be injected along with the aqueous phase.

Missive gas injection we can inject the CO2 and N2 hydrocarbon gases they reduce the IFT between the displacing and the displaced food forms single homogeneous phase as they are miscible with the crude oil and becomes easy to let the oil flow from the original place to production well. As mentioned microbial ER is the concept of bio surfactant injection we can inject bio surfactant along with the chemical combination also it can be performed in in situ and ex situ conditions we will discuss those later on. So let us discuss some of the factor those improve the ER process or those are responsible to characterize the improvement achieved by the ER process. So the first and foremost important parameter is the mobility ratio in general the mobility of any fluid lambda is defined by the ratio of the effective permeability of the fluid to the fluid viscosity that we can see here for the oil lambda O is expressed like this similarly expressed for the water and the gas the effective permeability can be converted to the relative permeability. The fluid mobility lambda is a strong function of the fluid saturation through this relative permeability as discussed in last class also the permeability value or the relative permeability value for a particular phase will depend on its saturation.

The mobility ratio is defined as the mobility of the displacing fluid to the mobility of the displaced fluid mathematically we can say like this if we use the definition of the mobility ratio in terms of the mobility and further put in the terms of the relative permeability we are going to get this expression. This expression simply says to have the M value low increase the value of water viscosity this should go up reduce the viscosity of the oil improve the relative permeability of the oil and reduce the relative permeability of the water these are going to be the favorable conditions. So, M greater than 1 is the unfavorable condition for improving oil recovery process hence the condition should be M is lesser than 1 that is the favorable condition. Other parameter we already discussed in detail when we discuss about the properties of the rock and the fluid like those factors are interfacial tension and the surface tension that mathematically can be given by this. This is for the oil and water sigma ow is the interfacial tension between the oil and water.

Capillary pressure this is the pressure difference between the non wetting phase and the wetting phase capillary number that is the ratio of the viscous force to the capillary forces and mathematically it comes out to be like this. So once we put the viscous force and capillary forces in the mathematical term this will result in this form where it says mu w that is the viscosity of the water and in the denominator we are having the interfacial tension between the oil and water. So what we can do to have the high capillary number increase the viscosity of the water or reduce the interfacial tension. Overall recovery process is multiplication of the three factor that is the displacement efficiency ED, aerial sweep efficiency and the vertical sweep efficiency. Actually aerial and vertical sweep efficiency together called the volumetric efficiency.



So the displacement efficiency ED as discussed in the last lecture we can relate the saturation of the oil and the water. Volumetric sweep efficiency as mentioned is the product of EA and EV. Another aspect is the emulsion. So emulsion is the process of misplacing two immiscible liquid phases by the application of foreign substance like the surfactant. So when surfactant is added into the system in the aqueous phase so at the interface an emulsion is formed that emulsion can be of three types.

So the emulsion could be oil in water, water in oil or the mixed type of the emulsion. All these helps to create the emulsion reason or the thick reason that help the injected phase to overcome from the problem of gravity override, come out the problem of viscous fingering and letting the sweep efficiency be better. The emulsion could be associated with the entrainment and could be entrapment in the reservoir domain. So when it comes to the choice of EOR based on the factor we discussed along with those there could be some simple analysis before we are going to choose the method as one of the parameter is the crude oil that remains in the reservoir. So if it is light oil for example that is present in the reservoir domain primary recovery process itself can recover up to 25% because it is light less pressure energy is required to recover this.

And as this is light oil the secondary recovery process pressure maintenance process can also give us a good recovery and the remaining oil is the target for the EOR process. When this is heavy oil primary recover only 5%, secondary is also not effective because the oil that is remained is the very viscous or very heavy oil and that is not going to move with the help of just injecting the water and the gas. So the targeted EOR process is for 90% of original oil in place while in the case of very viscous kind of the tar sand liquid from the initial itself the primary and secondary are not going to help we have to think about implementing of the EOR process for recovering the entire original oil in place crude oil that is present in the reservoir domain. This result are published in 2008 by Thomas under certain assumption like the initial oil saturation is considered 85% of the pore volume and then the water is balanced by 15%. So when it comes to choose the thermal processes so high viscous oil low depth and low API is the target for the thermal processes when it comes for the gas injection the high depth and high API are favorable high API means less dense fluid.

Microbial for the lower depth lower layer and lower salinity are the condition where the microbial process should be implemented and for the chemical intermediate depth and the intermediate oil viscosity are the favorable condition and light to intermediate oil in terms of the density are also favorable condition. So when we can see in terms of the numerical value these are again collected from the literature so the value may vary but for the steam injection the depth should be in this range viscosity means very viscous oil we have to implement the steam process or the thermal processes. So if the oil is really very viscous the chemical injection gas injection microbial injection are not going to help we have to start implementing the thermal processes itself from the first point. Alkali, surfactant, polymer they also having certain criteria to be chosen when we are implementing those to recover the oil and similarly for the CO2 for CO2 the condition of the reservoir depth should be greater than 3000 depth feet because if we want CO2 to inject in the reservoir domain it should be in the miscible condition and then miscible condition can be achieved when the minimum miscibility pressure is crossed in the reservoir domain and as we know when we go deep in the reservoir pressure increases so the 3000 feet depth could be the condition when CO2 injected in the reservoir domain will be miscible with the crude oil. Again other factors are there the types of the crude oil and the other factor but these are some general criteria to choose the or implement the EOR method.

So let us discuss one by one some of the methods like thermal EOR method we can discuss just one process steam flooding process this is a continuous injection of the steam in the reservoir domain so where the crude oil is there as mentioned the very viscous crude oil is there if we are injecting the steam, steam is providing the heat to the crude oil reducing it viscosity but over the time the steam also get converted into the hot water and as the front is moving further this will get converted into the water as temperature will reduce temperature will reduce in two manner first it is providing the heat to the oil heat transfer is happening second heat loss is happening because the steam is also in the contact of the reservoir domain it also giving the heat to the rock. Another problem with the steam injection when we are injecting the steam this is in the vapor phase the gravity over right problem will come into the picture. So the reservoir domain where the injection and production well are at a sufficient distance the steam will get condensed from the hot water and then the water that will be the favorable condition. So all together steam flooding reduce the oil viscosity as the steam loss heat energy it condenses to yield a mixture of steam and hot water because of pressure gradient towards production well the oil bank that is formed here up front of the steam will move towards the production well. In general steam reduces the oil saturation in the steam zone to very low value all the processes of you are having certain limitations we will discuss some of the limitation of all the process one by one.

Let us say the limitation of the steam flooding process oil saturation must be very high if there is not significant oil the gravity over right of the steam as well as the sweeping efficiency will be less and the condition of the page on thickness should be around 15 feet thick for injecting the steam flooding that will reduce the loss towards the rock. Lighter less viscous crude oil can be steam flooded but that is not the condition we should implement because lighter crude oil or less viscous crude oil can also be recovered just by the water flooding. temporary application of the steam flooding viscous oil in massive should be there high permeability in sandstone or unconsolidated sand should be there. Steam flooding in general not implemented in the carbonate type of the reservoir and cost per incremental barrel of oil is high in this case because we need to produce the steam injecting that steam to certain depth in the reservoir domain will cost a lot and another problem with the steam that I said the mobility ratio could be in the adverse condition and then the oil might be flowing towards the injection well or the steam wave forming the channels and not making the contact with the oil because of the gravity over right it is passing through and reaching towards the production well. So the technical screening criteria in terms of the reservoir properties and then the crude oil properties are listed here.

So for a steam injection high value of permeability and porosity are desirable net page on thickness should be greater than 15 feet permeability should be greater than 10 milli Darcy depth should be significant and then the oil properties. So the more viscous oil like say greater than 20 centipoise is the more favorable condition for injecting any thermal processes including the steam flooding process also. The second process for enhanced oil recovery is the chemical ER process as mentioned earlier capillary number needs to be improved or should be high and that can be achieved by reducing the interfacial tension because that term interfacial tension sigma OW is in the denominator of the capillary number and that can be achieved the low value of the IFT by injecting the alkali and surfactant along with the aqueous phase. Increasing the overall oil displacement efficiency that can be done by having the condition where the emulsion formation is happening and surfactant does that job it reacts at the interface of the aqueous and the crude oil form the emulsion that could be oil in water water in oil or the mixed emulsion condition. Third one is the mobility control mechanism that can be achieved by increasing the viscosity of the water and that can be done with the help of including the polymer in the aqueous phase that will increase the viscosity of the aqueous phase.

So if we see the similar thing we listed earlier also high capillary number reduced interfacial tension reduced mobility ratio and alteration of the wettability are the primary factors those should be considered for chemical ER implementation and in case of the surfactant the surfactant are very costly the cost incurred by the surfactant injection can be very high if the surfactant are getting adsorbed on the rock surface. So the selection of the surfactant should be done in such a manner the adsorption is very less or it can be done in other method also like choosing some sacrificial agent those are getting adsorbed on the rock surface before we are injecting the surfactant aqueous phase and overall we are reducing the surfactant adsorption in the process. Similar diagram the chemical ER could be implemented by alkali alone surfactant alone polymer alone or their combination or at the end we are having the alkali surfactant and polymer combination. All these alkali surfactant and polymer are having different features as listed here also and the combination of all these three together will contribute towards improving the oil recovery significantly. Further the ASB flooding also modified in terms of injecting the nano fluid or nano particle along with it or making some system while injecting the gas along with the chemical to generate the form in the system.

So what happens the oil is trapped here between the rock surface and we are having the strapped oil if we can reduce the IFT by using the surfactant or the alkali that can also form the in situ surfactant the trapped oil will be having the tendency to move through this small channels towards the production well from original place towards the other place that is where we can mobilize the oil by reducing the interfacial tension. In case of the nano particle for example silica nano particle there could be some other nano particle like TiO2 could be chosen. So this is our oil droplet polymer and nano particle can alter the condition at the interface of the oil droplet. So for example polymer and oil they are creating the emulsion here and the silica nano particle can adder on the surface of the oil bubbles. So by injecting both together then this kind of the emulsion form and that is more stable and more effective.

So let us discuss one by one the different types of the chemical UR processes what are the advantages and the challenges associated with these processes. So for example first one is the alkali flooding alkali injection along with the aqueous phase into the reservoir domain first it forms the in situ surfactant. So due to the in situ surfactant the alkali component that is injected reacts with the acidic component of the crude oil that is present in the reservoir domain and form the in situ surfactant. That surfactant reacts like the similar to other surfactant. So this is the primary advantage or the foremost condition for injecting the alkali but for that condition to be present in the reservoir we should be having the acid value of the crude oil that is in the reservoir domain.

Once surfactant form it reduce the IFT it alters the wettability and emulsion also get formed. Displacement efficiency will increase and the forms emulsion for mostly heavy oil compounds the alkali and the alkali could be chosen like NOH, Na_2CO_3, KOH and some other also. These are very inexpensive and very effective to recover the oil if in situ surfactant can be formed. So in this diagram we can see the alkali flooding mechanism this is having the emulsion and entrapment of the oil emulsification and entrapment process, wettability alteration reducing the wettability and the IFT reduction. So what happens alkaline solution with the crude oil form the in situ surfactant reduce the IFT and the emulsification process happen that eliminate the viscous fingering and finally we get the additional oil recovery by this process.

What are the challenges with this process because of the alkaline nature the corrosion will be there and it can also damage the formation? Third one is the IFT reduced by alkali alone or even by forming the in situ surfactant are not effective. As mentioned earlier ultra low value of IFT is required and that can be achieved by injecting the surfactant. So in surfactant flooding we inject the surfactant. The surfactants are the compounds which have the ability to reduce the interfacial tension or the surface tension between two immiscible phases.

Surfactant molecules contain two group hydrophilic head and hydrophobic tail and disperse as monomer at very low concentration. Lower IFT value can be achieved with the help of the surfactant it also help to alter the wettability and overall improve the microscopic displacement efficiency that is the advantage of having the surfactant once it reduce the interfacial tension once it alter the wettability the pore volume that is occupied by the oil initially the water or the water plus surfactant solution can enter in those pores and replace the oil from there and that is where the microscopic displacement efficiency can be improved. So the reduced interfacial tension between the oil and water interface forming the collision drops which lead to the increase in oil saturation forming oil bank and mobilize the residual oil from original place towards the production well because of the pressure gradient. The surfactant could be of four types broadly classified like anionic, cationic, zitaryonic and nonionic. So there are different features of each type of the surfactant very carefully the surfactant should be chosen again depending on the interaction of the surfactant with the rock formation in the domain.

So the anionic surfactant are chosen preferable for certain reasons but again depending on the geological formation and the interaction of the surfactant with the crude oil makes the surfactant selection appropriately it should be chosen. So lot of research need to be done specifically how much lower interfacial tension is achieved and how much wettability has been altered like how the contact angle is reduced from a high value to very low value and that is where the surfactant flooding could be chosen and the types of the surfactant could be chosen. Another aspects of the surfactant flooding is CMC value. So the surfactant are having the tendency to form such kind of the micelles and those micelles once are formed the extra concentration of the surfactant are not going to help reducing the interfacial tension. So the CMC is defined as the lowest concentration above which monomer cluster to form micelles and when micelles are formed the extra concentration is not going to participate in the IFT reduction or something.

So the IFT does not change much after the CMC value but it reduces dramatically with increase in the surfactant concentration below CMC. So if we are injecting very low concentration of surfactant that is also not going to help in the flooding we should find out the CMC value of that surfactant and the surfactant should be injected near around that CMC value to have the effectiveness of the surfactant injection in terms of the lowering the IFT value. The challenges associated with the surfactant flooding is adsorption of surfactant at the rock surface they are expensive and IFT drops up to CMC value only and does not much change beyond the CMC value. Third aspects of the chemical ER process is the polymer injection. Injection of polymers such as PAM or the biopolymer in the aqueous phase are chosen there are certain other types of the polymer like the Gentangum, Gorgum could have been chosen depending on the cost and of course how they are going to improve the mobility of the water.

Polymer means improving the mobility of the water means reducing the mobility of the water and reducing the mobility ratio. Polymer flooding main objective of the polymer flooding is creating the favorable condition for the mobility ratio that is mobility ratio is lesser than 1. As we can see in this diagram if we are having the oil and we are just injecting only the water the viscous fingering will happen all these are having the fingering effect. So when we are having the water and the polymer injection we can inject the aqueous phase along with the polymer that is having the high viscosity and that will create kind of a bank and not let the water secondary water or chase water injection to bypass the oil and reach to the production well. So that is where the mobility of the water can be controlled by having the polymer injection and the chase water will be utilized for pushing this bank formation towards the production well.

So polymer in aqueous phase what it does increase the viscosity of the injected water reduce water permeability increase the volume efficiency favorable mobility ratio and ultimately we receive the higher value of the oil recovery. Polymer phenomena as shown here we can see here the polymer flooding is not having much viscous fingering it reduce significantly and we are having the favorable conditions. When it comes to polymer flooding that is in which viscous fingering as I mentioned again the selection of the polymer will depend its viscosity its adsorption and the retention on the rock surface what concentration should be injected along with the aqueous phase what its molecular weight and these are the condition at the reservoir. So the salinity and the temperature so polymer degradation should not happen polymer at the high salinity should also be effective in maintaining the mobility ratio. So the challenges is degradation of polymer at high temperature so if temperature is very high in the reservoir domain polymer may get degraded and will not function effectively they are also expensive.

Hence these are some of the challenges in polymer flooding process. So the combination of alkali surfactant and polymer in different combination can be implemented so each process is giving its benefit towards the overall oil recovery. So for example alkali we are injecting alkali that is forming in situ surfactant helping the IFT reduction surfactant can reduce the value to ultra low IFT so when alkali surfactant are combined together we can achieve the ultra low IFT value increase viscosity of the aqueous phase by the polymer injection lower the mobility ratio alter the wettability so all these factor that we discussed are included here in terms of the benefit of ASP flooding. The last one as mentioned is economical process so the alkali are not costly they can be sacrificial agent for the adsorption at the surface so we can reduce the adsorption of the surfactant at the rock surface. Nowadays the nano particle and chemical flooding are also getting introduced to provide the favorable condition like this stability of the emulsion generated as well as increasing the viscosity of the aqueous phase. So when we compare the process of two crude oil from Ahmedabad and the Chinese crude oil we can see the efficiency should be better for the ASP flooding so that is happening in both the cases but as we know the alkali roll is only to form the in situ surfactant but we can see here the in situ surfactant form is comparable in both the cases but in case of Chinese it is little bit more and the primary reason could be the Chinese crude oil is having significant high acid value and that acid value is forming more in situ surfactant that is why the recovery is better.

When we compare the second that is the surfactant recovery and in surfactant recovery we can see the Indian crude oil from Ahmedabad is giving better recovery compared to the Chinese and that is the reason because the viscosity of the crude oil is very high in case of the Chinese crude oil compared to water. So the in situ surfactant formation or the surfactant injected is able to reduce the IFT but because of the nature of the crude oil that is very viscous it is not able to displace that oil towards the production well. So hence several factor with respect to the oil properties with respect to the injected fluid properties as well as the rock properties are essential to understand the process of choosing different chemical combination at different concentration also to formulate a chemical sludge that is effective for a particular type of the reservoir. For example nowadays the surfactant are being chosen those are also having the polymer signature so the viscosity can be improved while surfactant is reducing the IFT and altering the wettability. Similar concept with respect to the nanoparticle so they are making the more stable emulsion and increasing the viscosity means reducing the mobility ratio.

The limitation of chemical ER process, adsorption of the chemicals is very detrimental to decide the process. High temperature may lead to degradation of the chemical. Best result are obtained when alkali reacts with the crude oil and that is the case when the crude oil is having the significant acidic component in the composition of the crude oil. High amount of the anhydride, gessom and clay are undesirable for the chemical ER process. High heterogeneity may lead to the failure of this process because of the channel formation in the heterogeneity region of the reservoir domain the injected chemicals may get lost.

So the reason of the failure is the low oil price in the past so the cost is involving chemical those are costly. So the crude oil price should be high then only it may be the beneficial to inject the chemical based ER process. Insufficient descriptions of the reservoir geology so lot of the information is required with respect to the properties of rock, fluid to implement the process. Excessive clay content may be very undesirable in that case high water saturation should not be there and then the fracture should not be there that is related to heterogeneity and inadequate understanding of the mechanism may lead to the failure of ER process. Unavailability of the chemical in large quantities so we are talking about injecting in the aqua space in billion barrels and we are talking about injecting of water aqua space in a large quantity in a particular concentration these chemicals should be added to from the chemical slush so their availability should be ensured.

The technical screening criteria even the viscosity even if it is high but it should be lesser than 170 poise to implement the chemical ER process and the other criteria are like depth, thickness, permeability should also meet and the temperature should be lesser than 200 degree F to reduce or to avoid the degradation of the chemicals. So the next process is the microbial ER process the microbial ER process for the recovery of the oil uses the microorganism indigenous or injected into the reservoir and their metabolites those alter the properties similar to the chemical injection and we get the better ER process. This is little bit history about when the MER process was implemented in 1926 when the first field trial was done in Arkansas USA in United State the field trial of me I started with pure or mixed culture of bacillus, pseudomonas and others so the mixed bio surfactant were implemented it was also concluded that anaerobic bacteria present in the oil can mobilize it also has been concluded that the anaerobic bacteria present in the oil can utilize oil to form gaseous product. So they also help to create the pressure generation in the domain and letting the oil post towards production well. So the advantage of microbial ER process or the features are bio degradability, low toxicity, lower CMC value is required so compared to the chemical surfactant very low CMC value is required in case of the bio surfactant.

Ablability of raw material should be ensured and antimicrobial activities should be assessed before implementing the microbial ER process. Microbial ER process can be implemented in in-situ condition or ex-situ condition. In in-situ conditions the metabolites is produced inside the oil reservoir itself so we are having the microbial community we supply the nutrients let them grow and the metabolites should be produced metabolites are the product of these microorganisms when they degrade. So the metabolites are produced inside the oil reservoir we do not take them out we do not grow them in the laboratory the reservoir itself becomes to let the metabolites form. While in the case of ex-situ MER the metabolites are produced outside the reservoir and then injected into the reservoir domain for their function.

So the ability to produce effective surfactant at a low price may make it possible to recover substantial amount of the residual oil. So the bio surfactant are similar to the chemical surfactant only difference is they are produced through the microbial route and the MER relies on the microbes to ferment hydrocarbons and produce byproduct and those are useful in the oil recovery. So microbial growth can either within the oil reservoir as I mentioned in the in-situ condition or those can be done in the ex-situ condition providing the nutrients. So the nutrients such as sugar, phosphate and nitrate frequently must be injected to stimulate the growth of the microbes and at their performance. So the role of different byproducts in the microbial metabolite process are listed in this table so we are having for example biomass, biogas, biosolvent, biopolymer, bioacid, bio surfactant all these are the byproduct when the degradation of the fully grown microbes happens and they are having different mechanism through which they contributes towards the ER process.

Most of them are similar to in the nature of the chemical substance for example they are contributing reducing the IFT the bio surfactant does that it reduce the IFT viscosity reduction happens, emulsification process happens and some other. The biogas can help to maintain the pressure and then the biopolymer can have the favorable novelty ratio and then the biosolvent they can be sacrificial agent also in the reservoir dormant to reduce the bio surfactant adsorption on the rock surface. So the bio surfactant could be produced commercially or could be the indigenous microbes those are already present in the oil field can be utilized to produce the bio surfactant. The advantage of using the indigenous microbes they are already exposed to the harsh condition of the reservoir dormant like the salinity temperature and pressure. So their survival chances are high the fact we do is providing the nutrients those microbes and letting them grow to a substantial growth rate and then those fully grown microbes are going to produce the metabolites.

So for in situ ER process the microorganism must not only survive in the reservoir environment but must also produce the chemical necessary for oil mobilization and that is as I mentioned the advantage if we choose the indigenous microbes. In some reservoir beneficial microbes are indigenous and only need nutrients to stimulate growth the growth is exponential in the nature. Studies have shown that several microbially produced bio surfactant compare very favorably with the chemically synthesized surfactant. So either we can replace the chemically surfactant by the produced bio surfactant or we can form a combination of the bio surfactant chemical surfactant in such a manner they are creating the situation those are favorable for the oil mobilization. The conditions are reducing the IFT, reducing the mobility ratio, increasing the sweep efficiency and increasing the capillary number.

Then features are listed here those are the screening criteria temperature should not be high otherwise the bio surfactant will not function properly the pressure range, oil viscosity, salinity and pH are also important in case of the bio surfactant and then the analysis like the batability, alteration, IFT can be achieved with the help of bio surfactant similar to the chemical surfactant. The advantage of bio surfactant is it is having the lower CMC value. So the next one process is the gas based ER process. So the gas injection is the second largest enhanced oil recovery process next to the thermal process used in heavy oil recovery process. So the mobility ratio which control the volumetric sweep between the injected gas and the displaced oil bank in gas process is typically highly unfavorable due to the relative low viscosity of the injected phase.

So the gas is having the low viscosity, density is also low, it will be having the gravity override phenomena. For that purpose the gas can be injected in the condition when it is forming the miscible region. So the miscible gas injection is actually the secondary oil recovery process but miscible and immiscible together are also part of the EOR process. So in miscible gas injection process mass transfer occur between the oil and gas forms a transition zone to displace the oil effectively.

Miscible gas injection gives better displacement efficiency. Immiscible gas injection improve recovery by soiling and the oil viscosity reduction only. While the miscible region that is more favorable in terms of the displacement efficiency of immiscible gas injection is less than the miscible gas injection. We can see the miscibility or immiscibility condition of the gas injection will depend on the temperature and pressure condition at the reservoir. Hence the reservoir depth, temperature, pressure at that conditions are important to assess the gas injection is happening in the miscible zone or immiscible zone. So for example very high pressure above the minimum miscibility pressure is required for the miscible displacement process to occur.

While in this region the immiscible displacement process will occur and that happens because of the swelling, viscosity reduction or the crude oil vaporization in this region. While in the miscible displacement the interfacial tension becomes 0 for the practically 0 for the miscible displacement process and that is the favorable condition because if interfacial tension is very very low that we want and so the capillary number will be high and then the residual oil remain in the reservoir domain will be less. The limitation in fact with respect to the gas based EOR process the minimum depth is set by the pressure needed to maintain the miscibility. So if you want to inject the gas at the minimum above the minimum miscibility pressure and that minimum depth should be available in the reservoir domain. Mass fingering result in poor vertical or horizontal sweep efficiency that can be again improved by having the miscible injection of the gas.

Injected hydrocarbon gas should be available so the gas could be CO2, N2 hydrocarbon gas or some flue gas. So if we are talking about the hydrocarbon gas that should be available for the injection. Recycling of the produced gas may reduce the total gas requirement. So every time from the injection well we are injecting the gas into the reservoir domain.

From production well we are getting the gas plus oil plus water let us say. So the gas can be further recycle after separation. So there could be several types of the gas there could be several type of the combination for the gas injection we will discuss some of them. So for example CO2 flooding process in this we inject the CO2 because of the gravity the CO2 will be pushing or contacting some of the oil but as the gravity override will be more dominating the gas will bypass through the upper zone and there will be a significant portion of the oil that is un-swept and at the production well we are getting the oil, water and gas but very early breakthrough of the CO2 will happen and later on we will be getting only the gas produced at the surface. Hence this process is not very effective because of viscous fingering and the gravity override. What are the application of CO2 flooding when it can be implemented? It can be implemented light to medium wise it can be done in immiscible condition depending on the temperature pressure condition.

How it does work by the soil swelling, viscosity reduction as it reduce the viscosity and vaporizing gas drives it vaporize some of the lighter component of the oil. The challenges associated with the CO2 as mentioned viscous fingering, gravity override and then the early gas breakthrough. As it is bypassing the gas breakthrough will be very early stage and that is undesirable. The technical screening criteria are listed here in terms of the crude oil properties and the reservoir properties.

The primary requirement is pressure required for achieving the miscibility of the oil and the gas. So to overcome with the problem of gravity override and the viscous fingering the solution could be alternate water gas injection. In this scheme what is done the water and gas are injected alternatively. So we inject the gas then the water then the gas and then the water. So what happens the water and the gas are moving from injection well towards the production well and they form certain kind of the pockets or the banks and as this is moving towards this one the CO_2 will not be having the over right phenomena gravity over right phenomena. It will mix with the crude oil form a oil bank and that oil bank will be post by the water or the water CO_2 combination towards the production well.

So this CO_2 wag process called the water alternative gas process is more beneficial compared to CO_2 process. Similar to CO_2 the application could be in controlling the CO_2 mobility that will give us the better sweep efficiency. Gas injection increase a displacement efficiency it can also done in the miscible or immiscible condition. The challenges associated with this is oil recovery around only 10% of original oil in place. Water blocking may happens unfavorable mobility ratio is still there and the gravity segregation is still there because it is just water and gas and both are having the problem of viscous fingering and the gravity over right.

Although the combinations are formed in the cyclic manner but still the challenges remain same. So here we can see if we are injecting just the gas the viscous fingering will be more dominating when we are having the water and CO_2 for example here in the cyclic manner viscous fingering is reduced but still it is there to control that thing the chemical can be injected chemical along with the water we can inject some chemical. For example if surfactant is introduced we are able to reduce the mobility control of the water and we are having the front that is having the less viscous and that happen because the surfactant produce the stable emulsion that is not let the water and gas bypass and hence we get the better. When we are having the alkali surfactant and CO_2 further it can be improved in terms of mobility control and then the pushing of the oil bank could be better. One more aspect here in case of CO_2 work process in this case the CO_2 get enough time before it is getting breakthrough to get mixed with the oil and then the oil viscosity can be reduced by CO_2. So several combination of water gas injection can be implemented they could be in the tapered up process tapered down process means the ratio of the water and gas injection could be in the increasing order or could be decreasing order again depends on the geological formation crude oil properties and crude oil properties.

Some other modification are done in the gas injection process so the chemical enhanced as mentioned in the previous slide also so water and gas injection can be augmented by introducing the chemical. So the WAG improved by adding chemical additive to the water slush chemical could be surfactant, alkali, co-surfactant, salt, polymer, nano particle the gases could be CO_2, nitrogen, flue gas and the natural gas. So the types of the process could be sag process where surfactant is introduced, peg process where polymer is introduced, ASEG process when the alkali and surfactant are introduced or ESP alternate gas where the chemical slush mixed of alkali, surfactant and polymer is supplemented along with the water injection in the alternate water gas injection process. For example here we can discuss about the sag process so the alternate injection of the surfactant slugs and the gas is done result in form generation in the reservoir preferred over continuous form injection process because here we are having the gas and the surfactant that is in the pocket form.

We will see in the next diagram. The challenges of sag process is the adsorption of the surfactant by the reservoir rock otherwise the other factor like reduce IFT, better mobility control, improving the sweep efficiency, reducing the viscous fingering are some of the advantage of the sag process. The other process like ASEG is listed here in this alkali and surfactant are introduced alternate injection of A slug and gas is done alternative to ESP flooding. So in ESP we wanted polymer to be injected to control the mobility while the mobility can be controlled by alternate injection of alkali surfactant and then the gas. Mechanism how it does work in-situ form generation, improve mobility control, achieve ultra low IFT value because of the surfactant, CO2 dissolution with crude oil reduce the viscosity of the crude oil, formation of microemulsion could be type 1, type 2, type 3 on the VINSR chart, miscible ASEG or immiscible conditions both the condition we can implement this thing.

So CO2 sag process diagram that is the form flooding process also. So in this you can see the CO2 and then the surfactant, CO2 and the surfactant and this is the chase water actually the water drive is implemented in the cyclic process. So up front you can see the form generation is happen that form generation is not letting this CO2 to bypass or the gravity override is stopped and this form is actually stable form is generated that is pushing this oil bank that is formed up front of the injection towards the production well. Hence the CO2 sag process could be very effective. As we are adding the more chemical into it we are making the process more effective because the individual chemical added into a water alternate gas process will be more efficient by contributing its own mechanism towards the oil recovery. So the form stability that form here depends on the gravity and the capillary drainage, Morgan effect, disjoining pressure and gas diffusion.

So let us not introduce many of the term the form can be prepared in such a manner it is stable it is not letting the gravity override happen and pushing the oil towards the production well. So these are some of the screening criteria listed for all the processes we discussed. So steam process, combustion process, ASP plodding, polymer, alkaline, surfactant, CO2 miscible condition and CO2 immiscible condition as well as microbial flooding condition. So with respect to the oil properties with respect to the reservoir properties are listed here. You can see some of the properties like page on thickness are not critical for many of the things except for the steam flooding process.

There should be significant page on thickness to reduce the loss of the heat towards the surrounding. Similar the viscosity should be significant high then only we should implement the steam flooding otherwise the other processes for the low viscous well could be effective. But the steam flooding is very efficient when the oil viscosity is very high. In fact if the oil viscosity is very high the steam flooding or the thermal ER process either by heating rod or by combustion process or injecting the steam should be implemented because other processes will not be effective. So in terms of the reservoir properties and the oil properties I listed out several ER process these could be the guidelines not the final decision to choose the ER process to be implemented because the ER process selection depends on several other factor just not only the factor those are listed here.

These are certain kind of guidelines or preliminary criteria those can be utilized to screen some of the process. As I mentioned if oil is very viscous steam flooding is going to work other processes are not going to work. If the temperature is high then the microbial and chemical processes are not going to work. If the depth is too high the depth is too much of the reservoir then the gas injection could be favorable because at that high pressure condition the gas will be miscible with the crude oil. So in the summary of today's lecture we discussed several ER processes miscible, chemical, thermal and microbial process in terms of their application mechanism how they do work challenges associated with these processes and then the screening criteria. Although we did not discuss in detail but the preliminary idea of all these processes towards the ER selection processes are discussed in today's lecture.

The tertiary oil recovery process are reservoir specific so lot of the other factor and as much as information is available with respect to the reservoir, crude and the injected fluid that will be beneficial to choose appropriate process. And if we look towards the global perspective ER represent only 2% of the global oil supply these data are from 2017 and around 375 ER projects operated in 2017 and they produced 2 million barrels per day capacity. If we look different category of these 375 ER projects so the ER method implemented thermal, gas, chemical and microbial and if we see here the microbial is very less only sharing 0.

61% while the major part is the thermal and then the gas ER process. Chemical is also just only 11% of total project. Within the thermal processes if we see the major share is towards the steam injection and the in-situ combustion injection also. I think some mismatch is happened in this figure. In chemical ER process the polymer process is preferred because of improving the mobility ratio that is along with the water as done in the secondary recovery process polymer is injected into it to improve the process. And here if we see on the gas side the miscible gas injection has been implemented in the field to recover the additional recovery and out of this 40% 35% is miscible gas injection while here this part is the steam injection is sharing the major part. So the ER process are having the potential to get the recovery of the trapped oil that is trapped in the porous region that is also viscous in the nature not able to get mobilized by the secondary processes.

So the scope are there so the ER process can be effective but lot of research with respect to information of reservoir and the oil properties are required to choose the process and also advancing this process by improving or engineering this process to meet the requirement. For example the chemical ER process that is using costly surfactant can be augmented with the bio surfactant in the process to reduce the cost. So with this I would like to end my today's lecture. In the next lecture we will continue discussion about section 3 of our slavers. So we discuss this part, second part and then the third part we will go to discuss the introduction to reservoir simulation in the next lecture.

So the next lecture will be about introduction to reservoir simulation. Thank you very much for watching the video. We will meet in the next lecture. Thank you.