Water and Waste Water Treatment
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Module No # 11
Lecture No # 54
Nanofiltration and RO

Hello everyone, welcome back to the latest lecture session. After discussing water treatment or the conventional water treatment related aspects, we moved on to looking at some of the recent developments which are taking place which are applicable to water treatment. And some of which also applicable to waste water, in that context we looked at membrane process and we discussed about ultrafiltration and micro filtration and there the principle was primarily about exclusion based on size.

And then we looked at absorption and then ion exchange, next class is relevant to nanofiltration and osmosis or reverse osmosis where we looked at removal of dissolved ions too.

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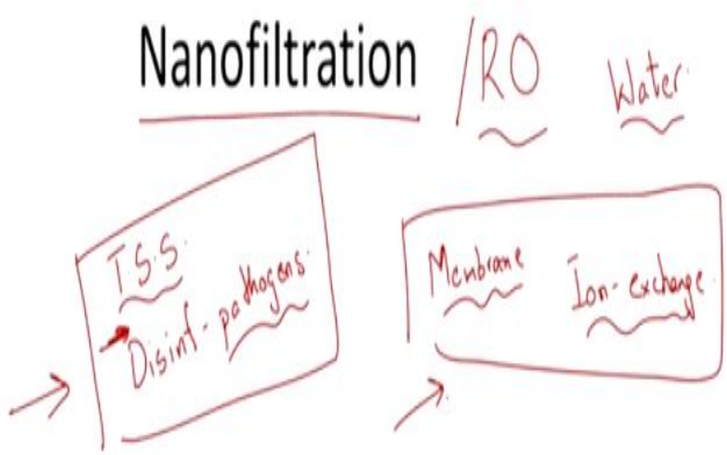

Nanofiltration and RO or reverse osmosis is what we will look at and with that we will end or wrap up water treatment related aspects. Just a bigger picture with respect to water, if we want to remove suspended solids, we looked at that sedimentation tanks, we looked at disinfection for pathogens. Depending on our requirements sometimes we will need to remove or look at applications of membrane filtration.

That something you will have either before or typically before disinfection or after to sometimes but typically before disinfection or ion exchange maybe in industrial process or in the context of waste water. These as you can see are not usually used in general we look at these 2 aspects for the conventional water treatment. But now due to industrialization and ever increasing stress on water,we are having to look at ion exchange, membrane process, adsorption so forth too.

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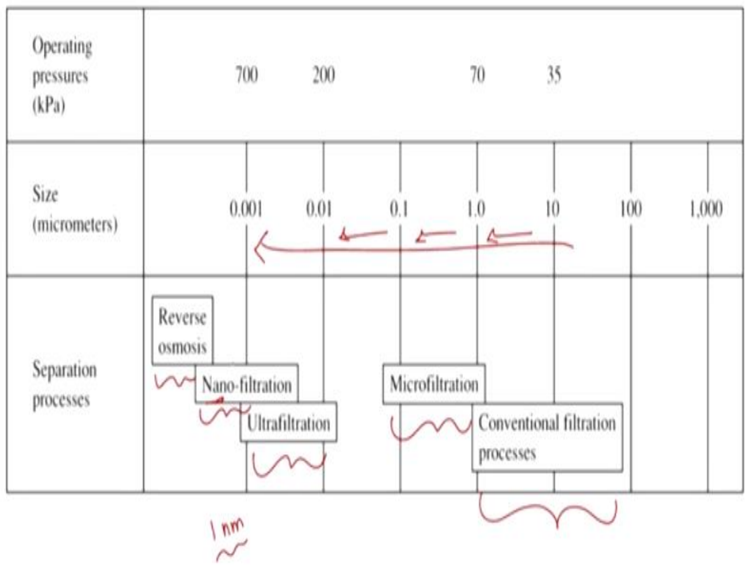

Let us go forth, nanofiltration so until now we have looked at conventional filtration, micro filtration and ultrafiltration. And then we are now going to discuss nanofiltration and reverse osmosis, what do you see here? We see that the sizes that we are talking about are decreasing drastically, each one is 10 times less than the preceding one. You can understand the sizes that we are talking about.

And nanofiltration, why did that name come about or why did it come about? Well the sizes were 1 nano meter and that is why people starting calling them nanofiltration, let us move forth.

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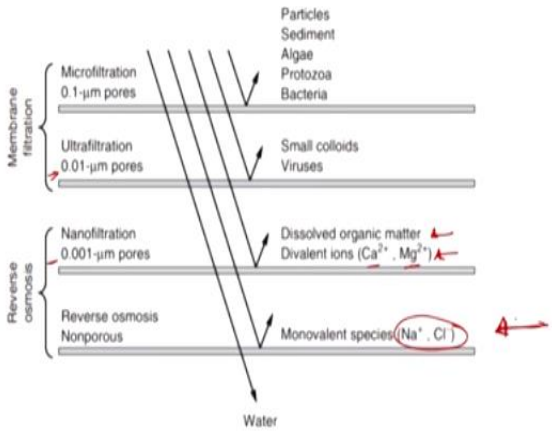

- Nanofiltration (NF), which is the middle ground, can eliminate the organics nearly as well, but not the ions (salts)

What is it that nanofiltration can remove? The size of the pores as you can see one order of magnitude lesser than that for ultra-filtration typically anyway. And what can it achieve or what can it remove it? It can remove dissolved organic matter and the divalent ions for example calcium and magnesium which are of interest of us. And then reverse osmosis, we can remove even the monovalent species like sodium and Cl- or chloride.

As you can see different sizes and different types of treatments, so depending upon what you want to achieve you look at that. Reverse osmosis, you would have seen this or most water treatment or household units have this. But it is not really necessary depending upon where you are living at but we will look at that later.

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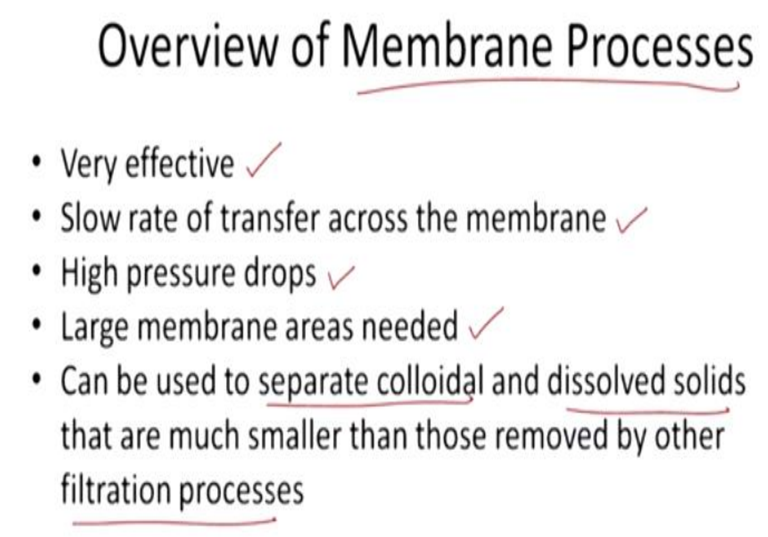

Overview of membrane process. What have we seen? Pretty effective, efficiency is pretty good but slow rate of transfer across the membrane and coupled with high pressure drops. And thus, we needed our relatively higher surface area but because they are packed really relatively well or per unit volume you have considerable area, that can be achieved. We are trying to separate the colloidal and dissolved solids that are much smaller though than those that are removed by the filtration process, that is a generic aspect.

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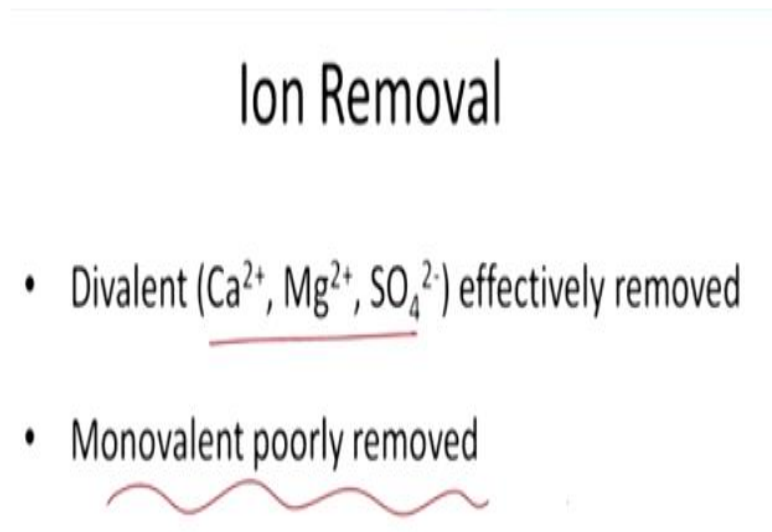

With respect to nanofiltration as mentioned earlier, we are trying to remove or we can typically effectively remove divalent anions or cations. Monovalent relatively poorly removed, so that is one aspect to keep in mind.

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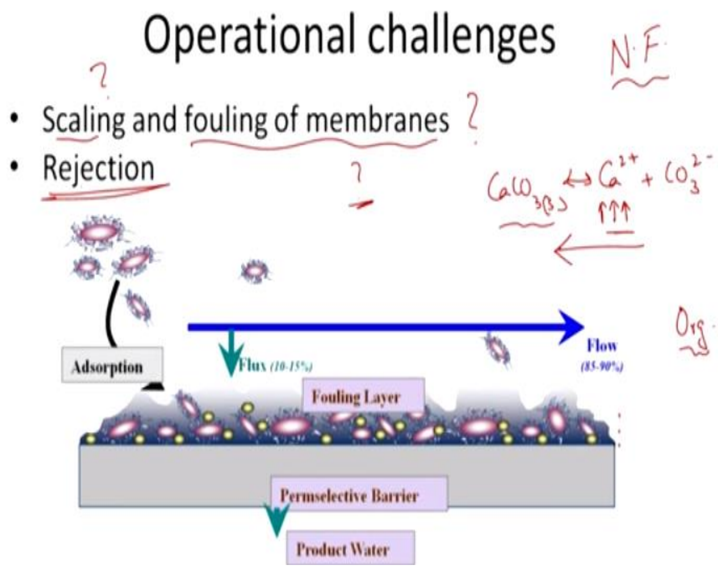

Operational challenges, when I am using nanofiltration either in an industry or for water treatment, what are the challenges that I will face? Scaling and fouling of membranes, what is this fouling of the membranes and what is this scaling of the membranes about? For example, think of this we know that calcium can precipitate out or let me write it as the dissolution reaction, this will be in equilibrium.

Near this membrane surfaces, especially this will be relevant to RO but let us discuss this now too. Near the membrane surface if the concentration of your relevant ion which can precipitate out is really high, what does that mean? For this particular reaction, the concentration is relatively high, at least for these products that backward reaction will be feasible. And you can have precipitation on the membrane, so that can lead to scaling of the membrane.

And fouling of your membrane. You will have either organic matter or typically natural organic matter which can be adsorbed on to the membrane surface and that will lead to fouling of the membrane. What issues is that going to lead to rejection? Rejection is going to be an issue and also greater pressures are required for the relevant water flux that you want to achieve, so that is an aspect to consider.

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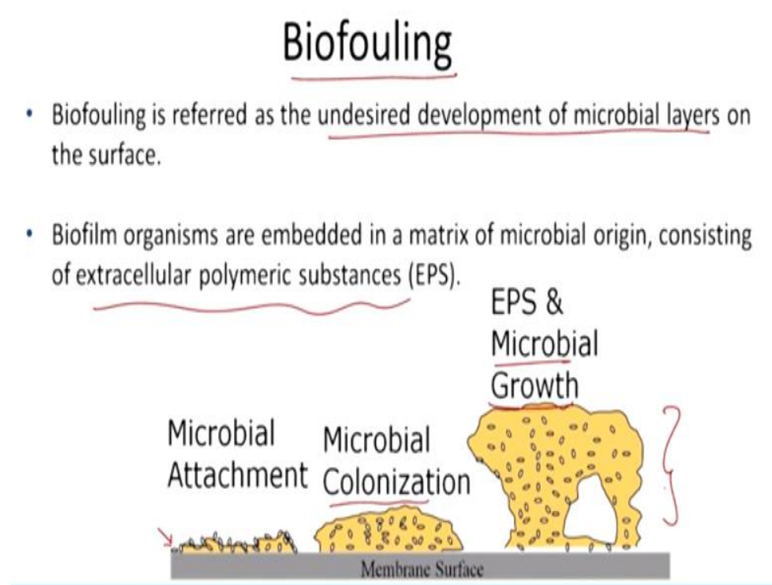

Let us move on Bio fouling, here we have undesired development of microbial layer. Initially you might have some microbial attachment and once the conditions are such that the microbes can thrive. Now you will have colonies being formed, microbial colonization and then microbial growth, extracellular polymers polymeric substances microbial attachment colonization and growth.

This will lead to bio fouling and issues with respect to rejection and higher pressures. These are the aspects that need to be considered or looked at.

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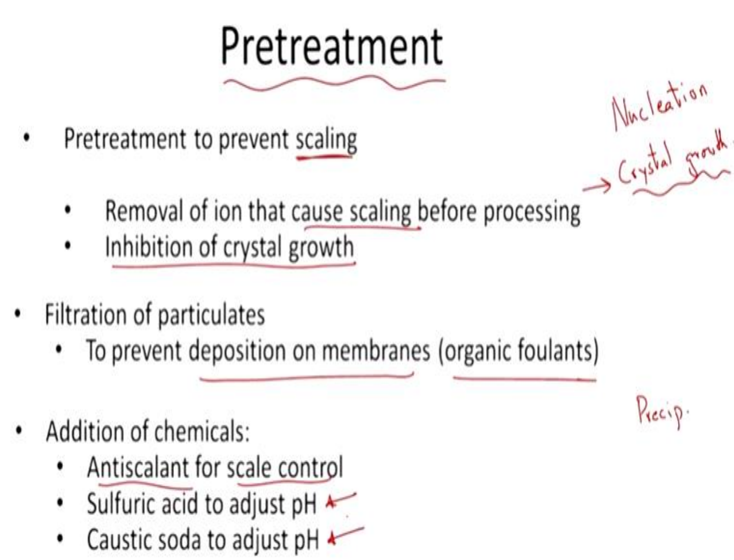

What are some of the ways to look at this? We are going to have to employ pretreatment. One aspect is to prevent scaling, so if I want to prevent scaling I can either remove the ion that causes scaling before it reaches the membrane of interest nanofiltration or the RO membrane. Or I can inhibit crystal growth in precipitation, there are different stages, one is nucleation the first step and the other one next one will be crystal growth and the agglomeration and so forth.

You can look at various ways to minimize crystal growth. One is concentration, one is surface area turbulence, that is one aspect to keep in mind so you can also filter out the particulate matters to prevent deposition on the membrane, this is relevant to organic foulants. Natural organic matter and so forth or we can also add chemicals, this is typically widely used in industries.

Anti-scaling agent for scale control. You want to prevent precipitation as we saw earlier precipitation I think where is that? If I add a ligand that makes calcium more soluble and free metal or free calcium in the solution is less, then this reaction will not proceed to the left. Even though the calcium total is still the same, the proportion of calcium total which is in the form of Ca2+ will be relatively less and that is what I am concerned here.

That is what we can take care of by adding anti-scaling agents or when you have metal or such and at relatively higher pH, most of them can precipitate out with the hydroxide or the relevant ligand, you can control the pH as required, sulphuric acid or depending upon requirements for increasing the pH you can add caustic soda so pH and anti-scaling agents.

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Desalination so you have saline water, relatively high ionic strength, relatively high salt concentration and you want to remove these salts concentration, how do I do that? first why? Well India along the coast, the people are in considerable water stress but they see water all around so that sea water cannot be used. Because high ionic strength, high salt concentration even if you take the water, it would not serve the purpose for which we take the water.

You are going to feel more thirsty if you take water, it is osmosis in a way. Let me not go there so we need to desalinate that water, why is it? Because we need water, we need more water requirements or every day we are increasing or we have ever increasing need for water, we are not managing water well, let us look at what we have, so need for more water.

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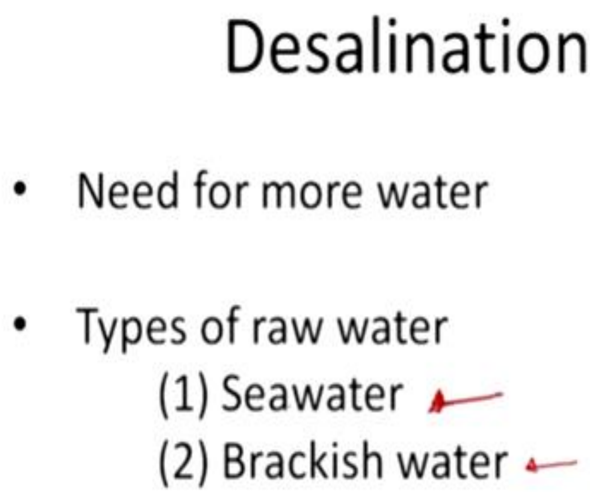

And what are the types of raw water, sea water or brackish water which is relatively less ionic strength, sea water and brackish water.

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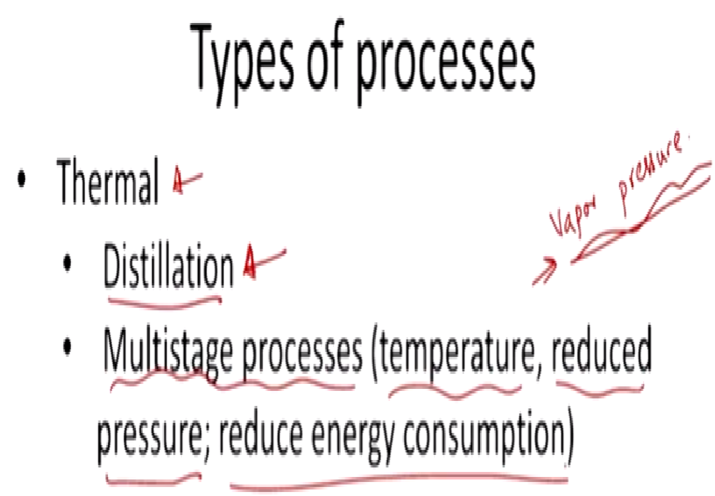

Different types, one is thermal distillation this is something that people would have come across, distillation typically energy intensive you need a source of heat that you can convert the water into water vapor and then as you pass it through though the relevant salts are not going to converted into the gaseous phase, they are going to stay as solid, the vapor can later be condensed and used for water.

Distillation, but the conventional way it is too costly, too much energy so what do they try to do? To my understanding they try to decrease the vapor pressure that even at relatively low temperatures the water can be boiled, so that is where the efficiency of the system comes into place. But in general, this is not widely used at least for desalination, that is one aspect to keep in mind.

And as mentioned here, it is multi-stage process, typically temperature and reduced pressure, why do we want that? We want to look at decreasing the vapor pressure. What is the key aspect because I want to reduce the energy consumption, if not I need to provide more energy for that heat of vaporization, that is the relevant aspect here.

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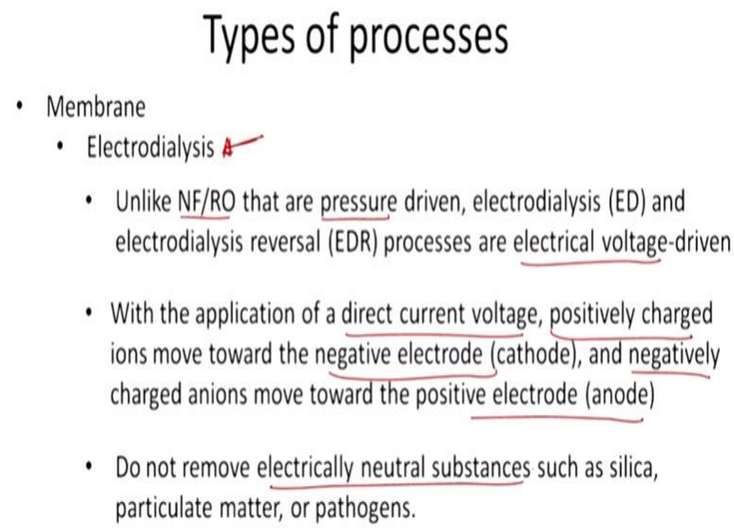

Types of process and one was distillation the other one is electrodialysis. You might have heard of dialysis with respect to kidneys. Well, we are trying to mimic that here in a way but unlike nanofiltration, RO where the driving force is pressure, here it is electrical voltage. That is something to keep in mind. We are going to apply a direct current voltage and that will bring about a movement in the relevant ions, we will look at the picture.

How is it going to happen? Negatively charged ions move towards the positively charged anode and positively charged ones towards the negatively charged cathode. And the issue is if we have electrically neutral substances then they will not be removed. Earlier it was vogue and then fell out of favor after RO. But I think it is coming back into the picture.

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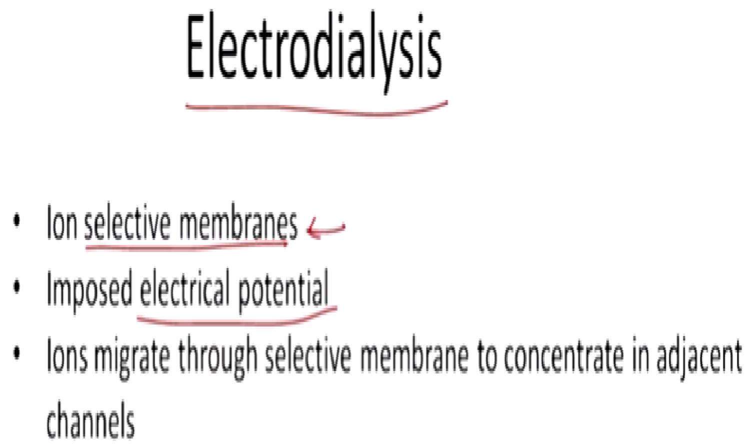

What are the key aspects for electrodialysis? As we mentioned we have electrodes and then we are going to apply a voltage so that positive ions move towards one negative ions towards one and then you will end up with relatively water that is free of charge species. But you need to have neutrality, you cannot end up with what that is charged, let us see how that is brought about.

You are going to have 3 major aspects here, ions selective membranes and I am going to impose an electrical potential and the key aspect is that the ions are going to migrate through these ions selective membranes. Let us see how it is done.

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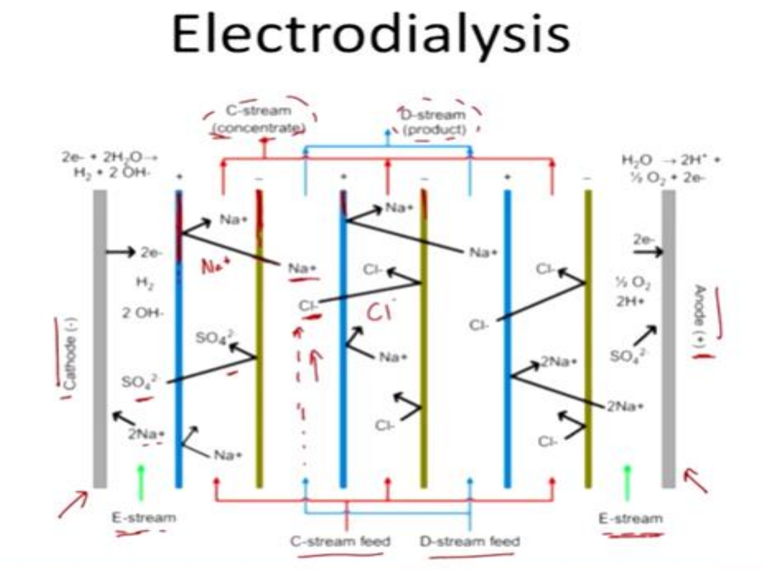

Here is a picture, here note that we have C stream and D stream is the one that I am collecting for my product and C stream is the one that is like the concentration or the reject you can think of it. And each stream it can be similar to or the same water as the one that you are trying to treat, that is for charge balance related issues if I am not wrong, what do we have here?

We have the negatively charged electrode and positively charged electrode, anode and cathode. Once I apply a potential, the relatively charged species are going to start moving to the oppositely charged electrode. For example, sodium will try to move towards cathode, sulfate will try to move towards anode. That is one aspect to keep I mind. What are the roles of these ions selective membranes? They will only let either a cation go or only an anion go through them or migrate through them, let us look at this.

This is specific to cations or it is not going to let cations through this is specific to anions this membrane it is not going to let anions go through. Let us follow the streams here so here is my water that I want to treat as it goes along, once the potential is applied this sodium will try to move towards cathode. But this one this membrane here will only reject or prevent migration of anions.

Sodium cation positively charged can go through that but then at the end of the day it will not be able to migrate through this particular ion selective membrane. We will end up having relatively high concentrations of sodium but water has to be electro neutral, that is why you see that SO4 2-

from this E stream moves into this particular stream here and then more or less you will achieve electro neutrality.

But what is happening to this particular stream that I have here? Na^+ was removed while migrating towards the cathode and Cl^- while migrating towards the anode will be removed similarly. Here Cl^- can migrate through this cation specific membrane. Cl^- will pass through that but not through this particular membrane. And now there will be an increase in concentration of Cl^-.

Thus, you are going to have alternating membranes or ion specific membranes and you are going to have potential and you are going to have a stream where the concentration of the ions is relatively high that is the reject stream and another stream where the concentration of the ions that you want to remove is relatively less. Same aspect when will this work fine? This will work fine when you have high concentrations of the relevant charge species.

And your final product that you want is not such that it requires very low concentrations of this charge species then it works relatively well. If not, it starts getting relatively costly.

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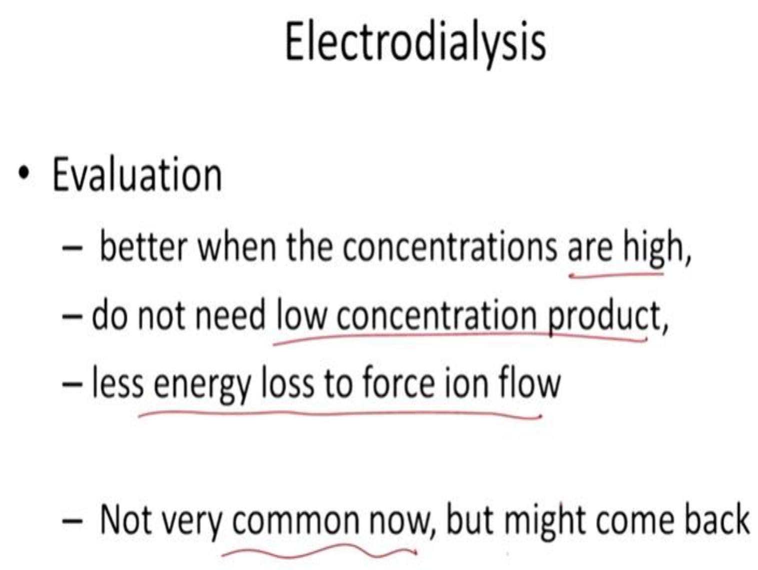

Better when the concentrations are high and we do not need low product concentrations leading to less energy loss to force ion flow, that is the relevant issue. But as mentioned earlier even though not very common now, they will probably make a comeback.

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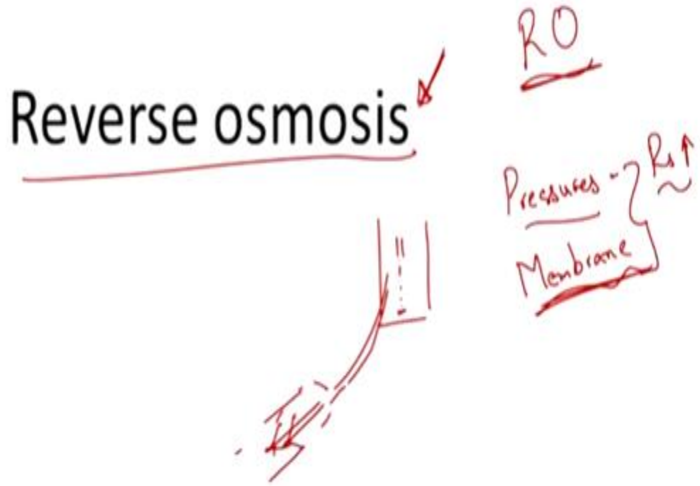

Reverse osmosis, you would have seen this in your household water purification systems. In general, whenever you collect the water from your RO systems at home keep in mind that not all the systems have RO. If you know the kind of water that is present in your locality and by understanding this course, you can look at whether you are fine with maybe an micro filtration membrane and maybe an activated carbon filter and maybe a UV.

You can play around with that but the company guy tries to sell RO because it is relatively costly and he can make more money of it. But I would urge caution, look at what is the quality of the water that you have and what is the acceptable and then go ahead and choose it, why is that? Because first you need to apply considerable pressures that is one aspect and more importantly you would see that.

This means that the costs are relatively high and also the membrane cost itself is pretty high whenever you have to change this membrane, we know that fouling takes place, different types of fouling. We just looked at that bio-fouling, organic fouling, scaling. And some of this scaling is irreversible too so then you have to change the membrane if not water will not pass through and you will have very little water coming through for the feed water.

These are the aspects that need to be looked at because of the cost and also more importantly note that whenever I have RO system here and I am taking the water here, you will see that there is a reject stream and there is considerable reject water that goes out into the sink. For each depending upon the system how old the membrane is or how much fouling occurred on the membrane.

You are going to see considerable reject water coming out, so for every liter depending on how old the system is you can maybe reject up to 2 liters or so of the water. But that depends so you need to consider these aspects regarding water wastage, let us move on.

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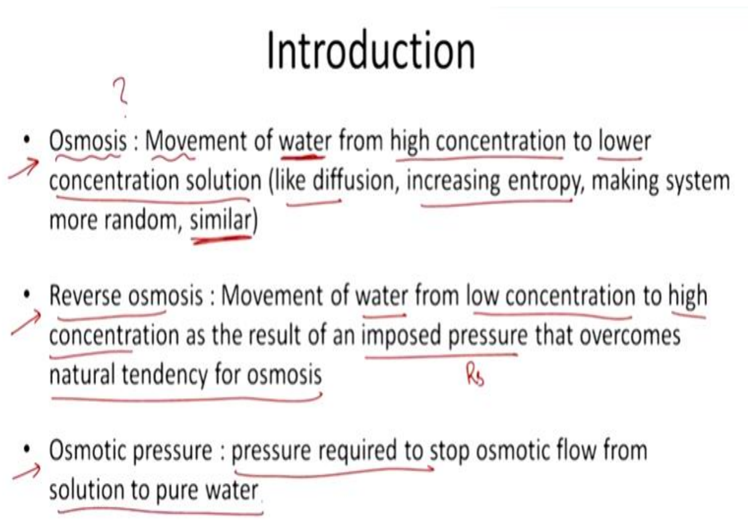

What is it that we are talking about reverse osmosis? What is this osmosis about? We will look at the figure but let us just look at the written statement that we have here. It is the movement of water, keep in mind. It is the movement of water not of the relevant molecules or the ions, where does it move from? It moves from higher concentrated solution to lower concentrated solution.

Why is that like, diffusion increasing the enthalpy making the system more similar so for example if I have highly concentrated solid solution here and relatively less concentrated solution here, relatively high chemical potential here and so I want to achieve equilibrium that is what the system tries to achieve. This is thermodynamics more or less so but for now let us limit ourselves to chemical potential to achieve the same potential.

What is it that water is going to do? The water is going to migrate from this relatively low concentration zone to the one with high concentration zones that the concentration in this high concentration zone also comes out to be low enough or relatively enough or low enough such that it is similar to the one in the low concentration zone, that is the aspect we are talking about water.

Osmosis, this is what usually happens but we do not want that, we want reverse osmosis. We want movement of water from low concentration to high concentration but this does not happen in nature that is why we want to impose a pressure this is what leads to the cause. And this has to be applied such that we overcome the tendency for osmosis.

And how can I understand that pressure, so it is osmotic pressure it is the pressure required to stop the osmotic flow from one solution or from the solution to pure water.

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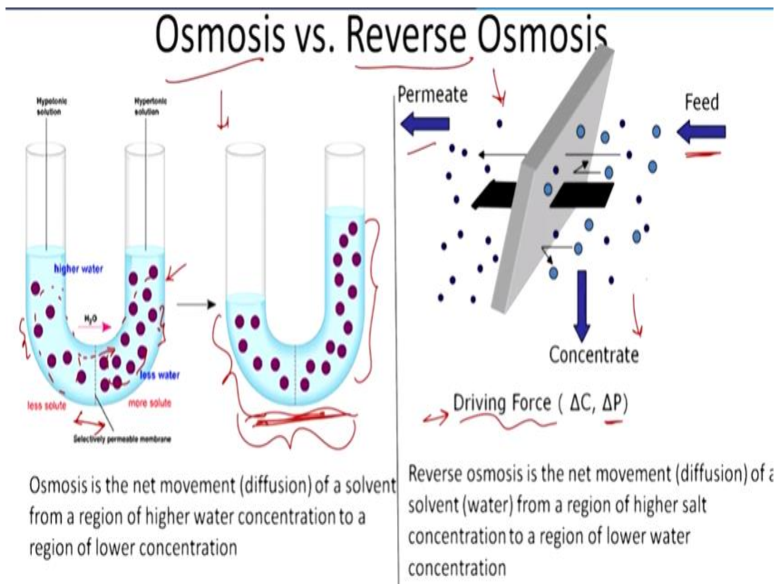

Let us understand why are the 2 figures that we have here? On the left, we see osmosis. What do we have here? If we have relatively high concentrated water here relatively low concentrated water with respect to the relevant salts or such,0 to achieve the same potential the water is going to go from here to here so over time the concentration here is going to increase and concentration in here is going to decrease to a level such that both are at the same concentration.

But what is it and so this is the final product so this is what more or less happens water will go to here and now the concentration here. And concentration here is the same but how will this help me? It does not help me because now the concentration is more or less high throughout all the water systems here, here I am going to apply a pressure to negate this reverse osmosis, this is osmosis so we are going to look at osmosis.

I am going to have feed and I am going to apply the pressure so there has to be a driving force. In general, if we look at classes, students will do what is relatively easier for them. If you want to make them do something or the majority of the students you have to force them to do that. You can think of the driving force in that manner so it is the pressure that you are going to apply.

In that way you are going to have permeate and you are going to have the concentrate or the rigid where the concentration of the relevant ions is going to be relatively high.

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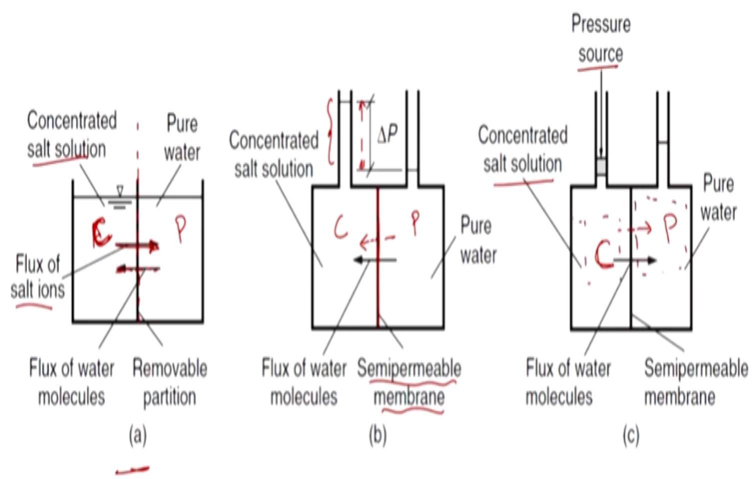

Diffusion sketch for reverse osmosis: (a) diffusion, (b) osmosis, and (c) reverse osmosis.

Let us look at the relevant picture, so here you can see diffusion, so if you remove this what do we have here. We have concentrated solution here and relatively pure solution here. And if I remove this removable partition, you are going to have movement of the salt ions. But before because of mass transfer and mass balanced you need to have also flux of water in this direction.

That is an issue but with respect to this membrane which will not let molecules go through, that is why it is the RO membrane, semi permeable membrane only water will be allowed to go through. What is going to happen here? We are going to have concentrated solution here and pure water here. To achieve the same potential, what is it going to happen? The water is going to go in this direction.

That is why you see this particular difference in the relevant pressure, but now I do not want that to happen. I have to apply this level of pressure source and then I will see to it that the concentrated salts solution. Water from the concentrated salts solution will move towards the pure water. Now I will have more of the pure water while I will have lesser of more concentrated water. That is what we are trying to achieve here, let us move on.

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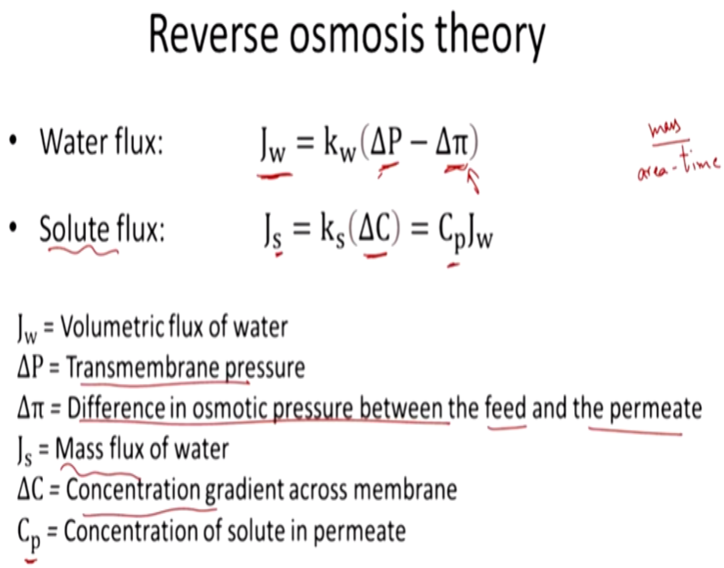

Theory is fine, let me not go into detail because this is a UG class. What do we said? Water flux depend upon flux is mass per area per time, typically you can look at the units and understanding that. In general, so this is the trans membrane pressure which is the case for every different kind of membrane and this is the one that deals with osmotic pressure. For solute, solute flux, it depends upon the concentration gradient.

Let us see what we have. Volumetric flux of water, trans membrane pressure and difference in osmotic pressure between the feed and the permeate. That is the aspect here, so mass flux of water, well not water it should be solute. Concentration gradient across the membrane, C p is the concentration of solute in the permeate. These are general aspects here.

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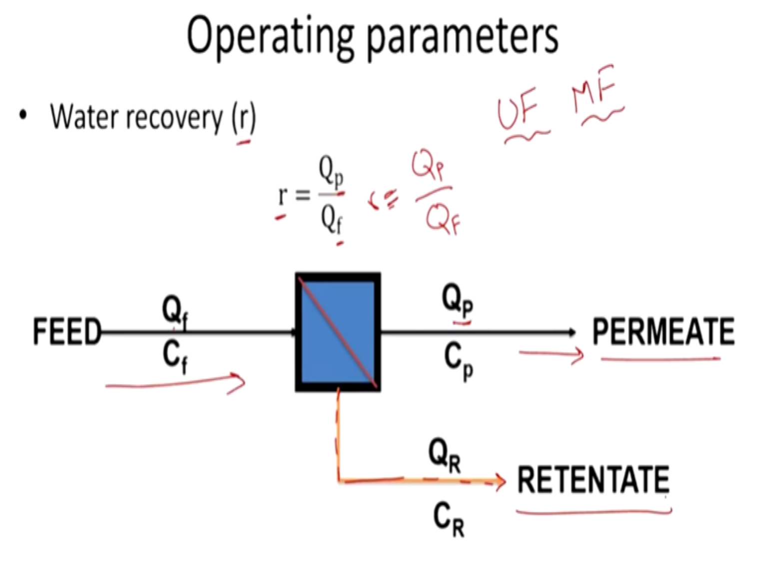

Operation parameters, this is similar to what we looked at earlier but let us look at 2 variables that we are going to look at. We looked at this in the when we are discussing ultra-filtration and micro filtration too. Here we have recovery, we have permeate and we have feed. Feed is what I am putting in, permeate is what I am going to use or is useful to me and retentate or the concentrate or the reject is Qr.

Water recovery is Qp, this Qp by Qf, so here if the water recovery is high that is good but after considerable operation of your membrane and fouling of your membrane, this recovery is going to decrease. And then your reject water flow is going to be relatively high, so that is something to keep in mind.

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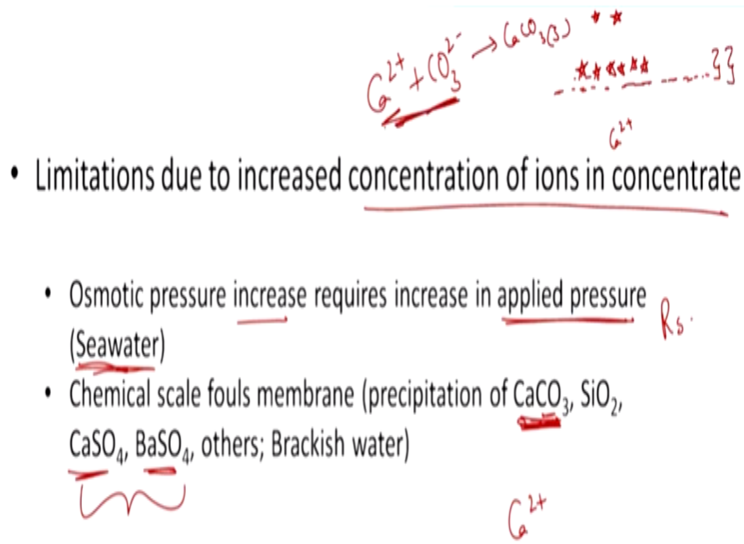

That is with respect to the water, so as I just mentioned the limitations are due to increased concentrations of ions in the concentrate. Osmotic pressure increase requires increase in applied pressure, this is the case especially with sea water. Osmotic pressure leads to an increase in applied pressure. And that means you are going to have cause chemical scale fouls membrane for example as we mentioned earlier in the case of nano filtration.

If you have calcium and this can be reversed because of pH, you can bring down CO_3^{2-} concentration. But $CaSO_4$, $BaSO_4$, these are everywhere, these lead to irreversible fouling, that is one aspect to keep in mind. This is reversible fouling this is irreversible fouling. How does this occur? As we mentioned this is the membrane, now here we have relatively low concentration of the relevant ions.

But here the concentration is very high, I am just using a star to denote that. If the concentration is very high then the conditions for this particular reaction to go forth or favorable. That is why even though in the bulk liquid solution, the concentration of the Ca^{2+} is not high. Near the membrane surface, the concentration will be high enough such that you can have precipitation of the relevant metals or such, that is something to keep in mind.

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- Solute rejection

$$1 - \frac{C_p}{C_f}$$

$$\text{Rejection} = 1 - \frac{C_p}{C_f} \qquad \frac{C_f - C_p}{C_f}$$

- Higher for highly charged molecules
- Higher for larger molecules

Solute rejection, what is rejection? Rejection is equal to (Cf – Cp) / Cf, feed and permeate or it is (1 – Cp) / Cf. Higher for this is with respect to the concentration of the relevant molecules, higher for highly charged molecules and higher for large molecules. You can understand that if it is relatively charged and larger, it is relatively easier to reject those particular compounds by RO.

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Typical reverse osmosis facility

Typical RO facility, this is called a stage, an RO element but this is what it typically looks like let us see.

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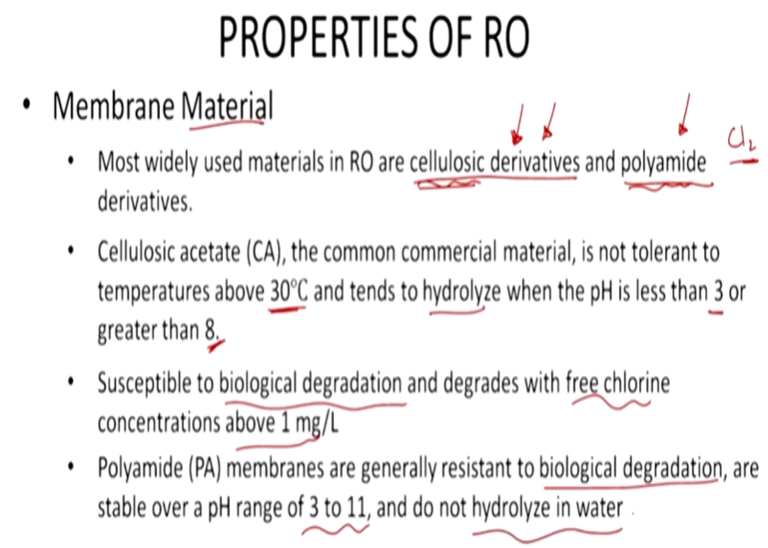

Let us look at different kinds of RO before that what kind of RO are we looking at. Membrane material, two widely used, one is the cellulose based and one is the polyamide based. This one is more hydrophilic, this one is more hydrophobic and this one though can degrade over time. Because it is cellulosic material but this one will be very reactive towards chlorine.

If there is any chlorine or such in water, that is going to cause considerable issue to this particular polyamide. Cellulosic acetate, very common but the issue is that it is not tolerant to temperatures above 30 degree centigrade and it can hydrolyze depending upon extreme pH, that is one aspect. It is also because cellulosic material, cellulosic acetate, it is susceptible to biological degradation and also this free chlorine too. That is one aspect to keep in mind.

Polyamide generally resistant to biological degradation and works over a wider range of pH and does not hydrolyze in water. But very susceptible to chlorine attack.

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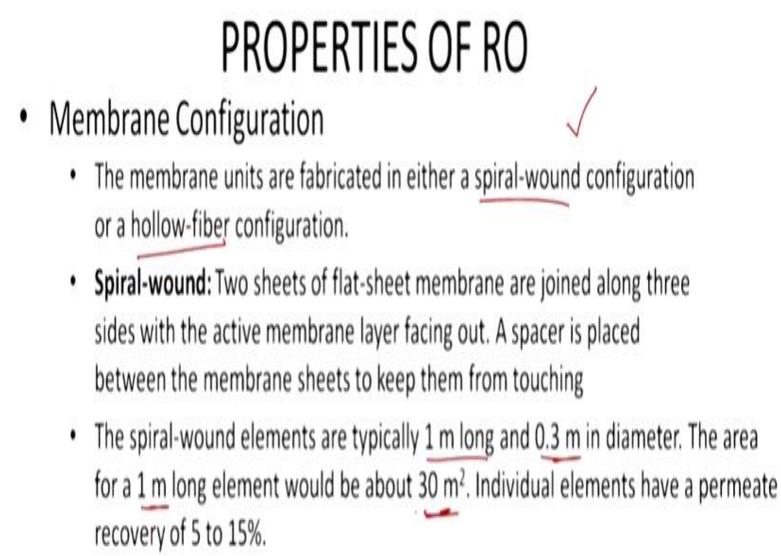

PROPERTIES OF RO

- Membrane Configuration
  - The membrane units are fabricated in either a spiral-wound configuration or a hollow-fiber configuration.
  - **Spiral-wound:** Two sheets of flat-sheet membrane are joined along three sides with the active membrane layer facing out. A spacer is placed between the membrane sheets to keep them from touching
  - The spiral-wound elements are typically 1 m long and 0.3 m in diameter. The area for a 1 m long element would be about 30 m^2. Individual elements have a permeate recovery of 5 to 15%.

Properties of RO, membrane configuration, let us see one is spiral wound. The other one is hollow fiber typically spiral form one, we looked at this in the context of ultra-filtration and micro filtration. Spiral wound, let me not read it out let us look at the picture as you can see typically one meter long elements with 0.3 meters in diameter, as can be seen within one meter long element, the area available would be around 30 meter square, that is something to keep in mind.

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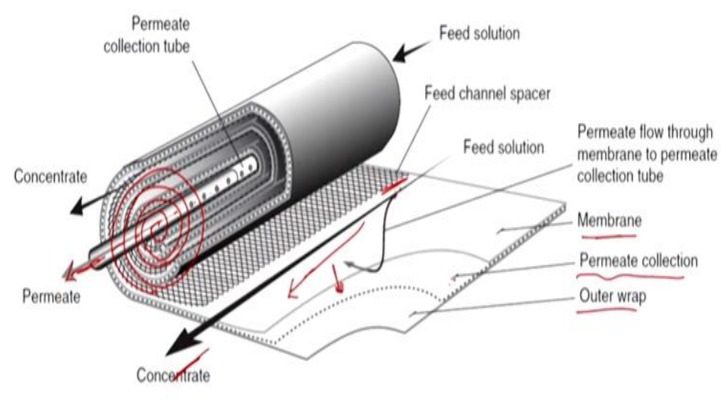

Spiral wound membrane

What is that we typically have or what happens in a spiral wound membrane, this is what you would typically see in your household RO systems too. If you want to open it up, so my feed solution is coming in. But note that my permeate or the water that I want to use is collected in the center. How is it that it comes out into the center? It has to take a spiral path.

Like this, it has to go through these elements and end up here, so what is it that we have? We have the outer wrap, that is not a big deal. This is permeate collection where permeate collects and this is the membrane. And the permeate flows through the membrane to permeate collection tube during this it is cross flow, more or less.

That is why it is also better to avoid scaling, so that is one aspect and also from between one membrane to the other, you are going to have this feed channel spacer. Feed solution, this is the concentrate or the reject, so it is going out in this way and the one that passes through the membrane, this spirally wound will end up in the permeate that is something to keep in mind.

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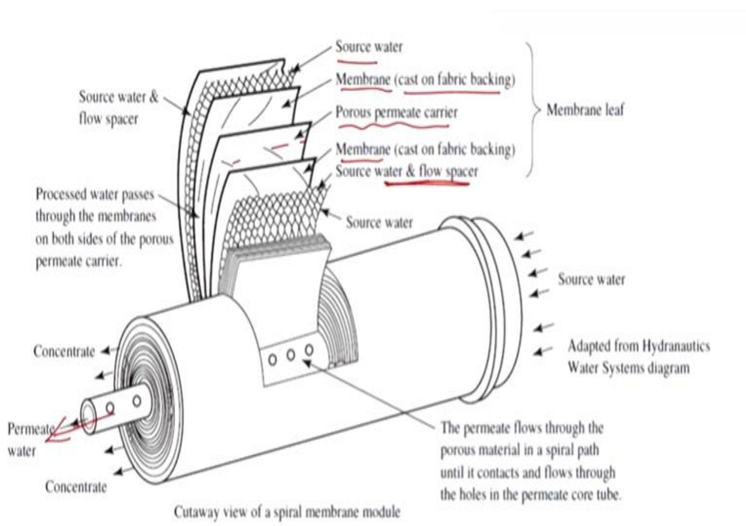

Typical spiral-wound RO membrane element

A different kind of figure to understand it, so water then the relevant membrane because it is so thin, it does not have its own strength. It is cached on fabric backing, porous permeate carrier, this is where the permeate go through and membrane. And as I mentioned earlier, water flow space, all this will end up in the central permeate water collection system or the tube.

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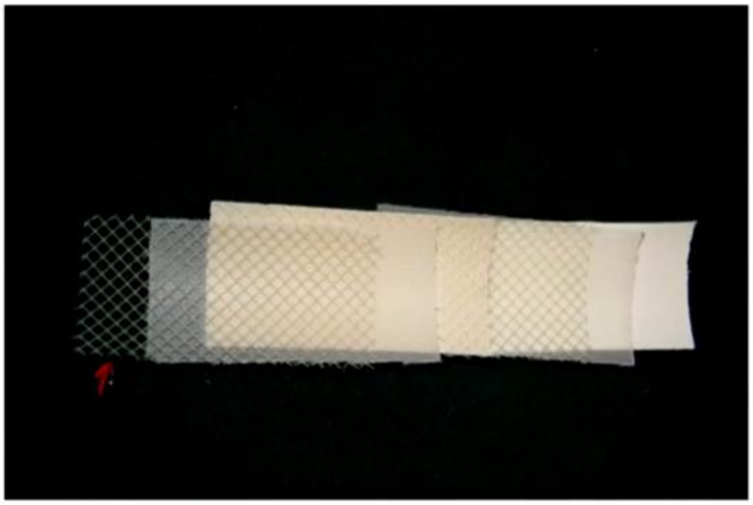

The layers of a spiral wound membrane

If you cut open your home made RO units too, this will what it should look like similar. Or this is what it should look like, the different membranes that we looked at, what are we seeing in the next picture? We are looking at this porous carrier, we are certainly looking at the membrane. And we are also looking at the water and the flow space relates these are the aspects that we are looking at.

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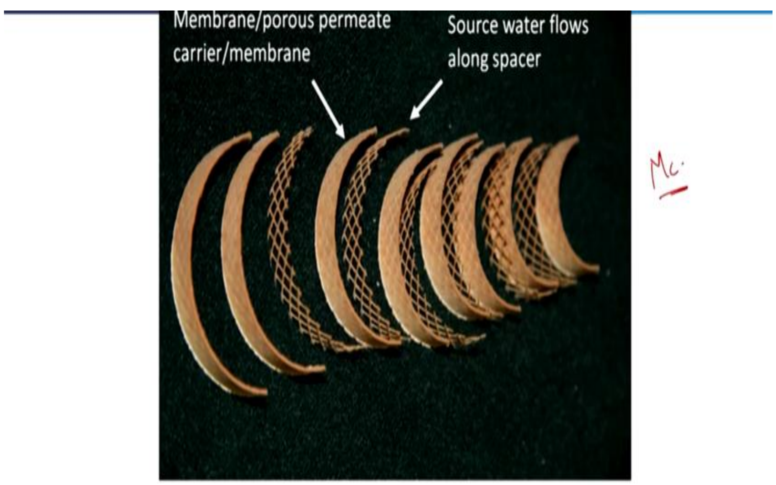

Layers of spiral wound membrane element pealed away. The "solid" curved pieces consist of three parts. The membrane is cast on fabric backing. Two membranes are separated by a porous permeate carrier

You can look at this picture, this is from Mckensey the student presentations. Let me move on so it is going to take spiral path, it meaning the water and reach your collection tube.

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PROPERTIES OF RO

- **Hollow-fiber:** The hollow-fiber element has several hundred thousand fibers with outside diameters on the order of 0.085 mm suspended in a pressure vessel.
- Permeate recovery is about 30% for each element

- The spiral-wound configuration is the most common for the production of drinking water from groundwater and surface water
- The hollow-fiber configuration is used extensively for desalinization of seawater in the Middle East.

And hollow fiber, not very much used, let us just look at that particular aspect. But where is it used for desalination of sea water? In the middle-east. But in general, people are moving away from hollow fiber.

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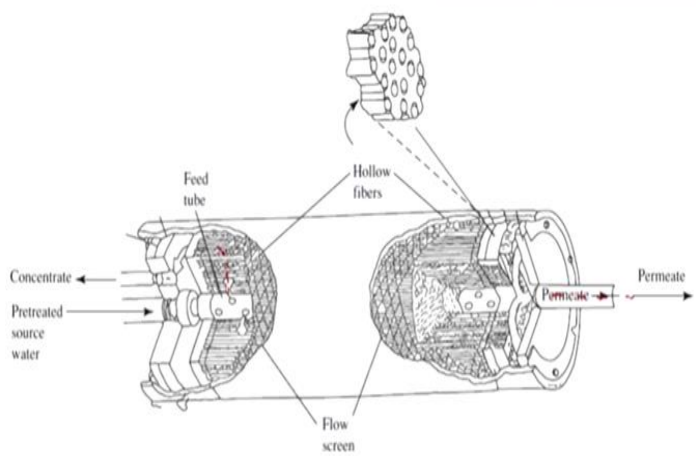

Typical hollow fiber RO membrane module

Hollow fiber, this is what it looks like and you can see that it is not a spiral. The pre-treated water comes here and permeates goes through here and you can see that this concentrate leaves this system here. At least certainly you see that it is hollow fiber.

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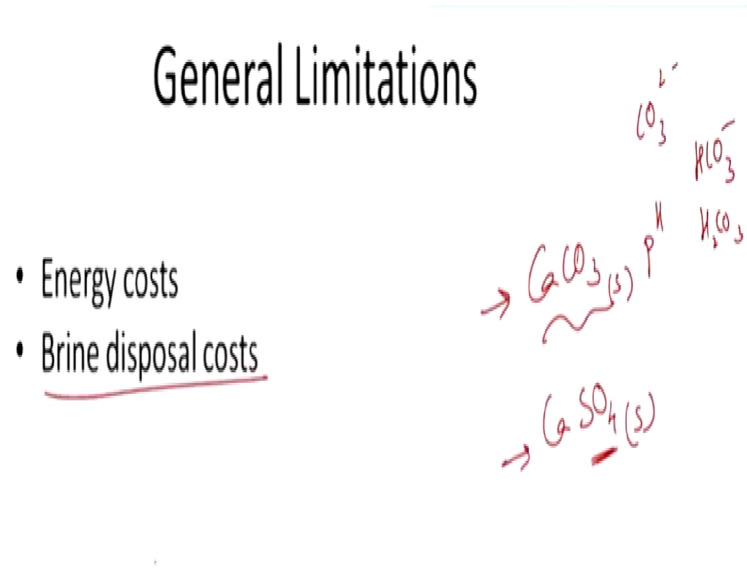

What are the limitations in RO? As mentioned, you will see that you need to apply pressure. Otherwise to overcome this osmotic pressure, so that itself a need for or considerable drain on the resources, that is one reason why the industries at least in India do not prefer to go for RO. Other reason is that before RO, if you do not have the well-functioning micro filtration or ultra-filtration system which does not remove those products which can lead to scaling or fouling of your RO membrane.

What will happen? You have to change your RO membrane pretty frequently and also for RO you need to add anti-scaling agents or relatively look at removal of these scales like CaCO3. This is reversible with pH. CO_3^{2-}, if I bring it down the pH, HCO_3^- or H_2CO_3. But if I have the solid precipitate out as $CaSO_4$ that at almost all the pH range, SO_4^{2-} will stay as SO_4^{2-}.

It is difficult to remove this, so this is irreversible fouling and reversible fouling so these aspects also need to be taken into account when you are looking at operating the RO. The costs are pretty high with respect to operating the RO and also with respect to changing the RO membrane, pretty high. And another aspect is you have the reject or the concentrate. The brine disposal cost, what to do with this? You can have a multi effect evaporator or landfill or such.

Brine disposal cost are considerably high, so with that we are done with water treatment. From the next session, we are going to look at the aspect related to the sludge or the solids that we have collected. Sedimentation tank, we are going to collect solids at the bottom, in the secondary sedimentation tank, in biological waste water treatment, we are going to collect sludge at the bottom, what do we do with them?

We cannot just dispose them. That is what we are going to look at in the next couple of sessions and wrap up this course. Thank you.