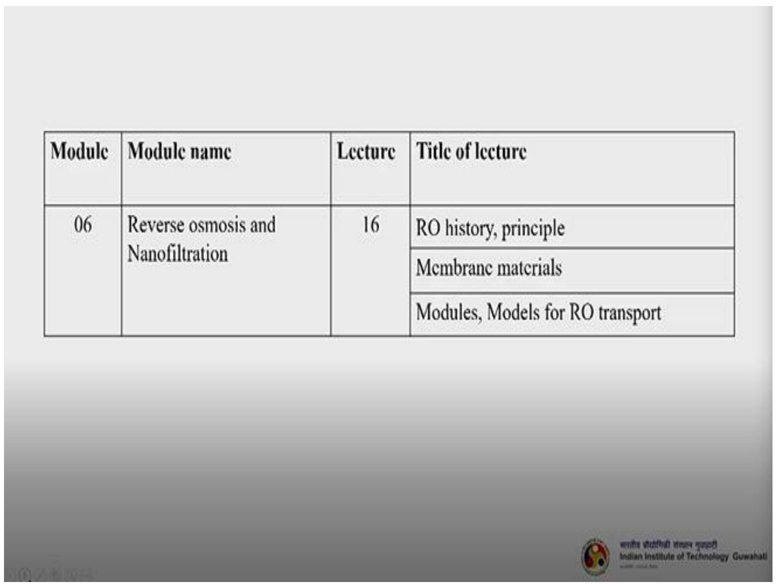
Membrane Technology
Prof. Kaustubha Mohanty
Department of Chemical Engineering
Indian Institute of Technology, Guwahati

Lectute-16
HP and LP RO, membrane materials, modules, models for RO transport

Good morning, students todays lecture 16 of our module 6. So, as you know that we have been started.

(Refer Slide Time: 00:38)



Module	Module name	Lecture	Title of lecture
06	Reverse osmosis and Nanofiltration	16	RO history, principle
			Membrane materials
			Modules, Models for RO transport

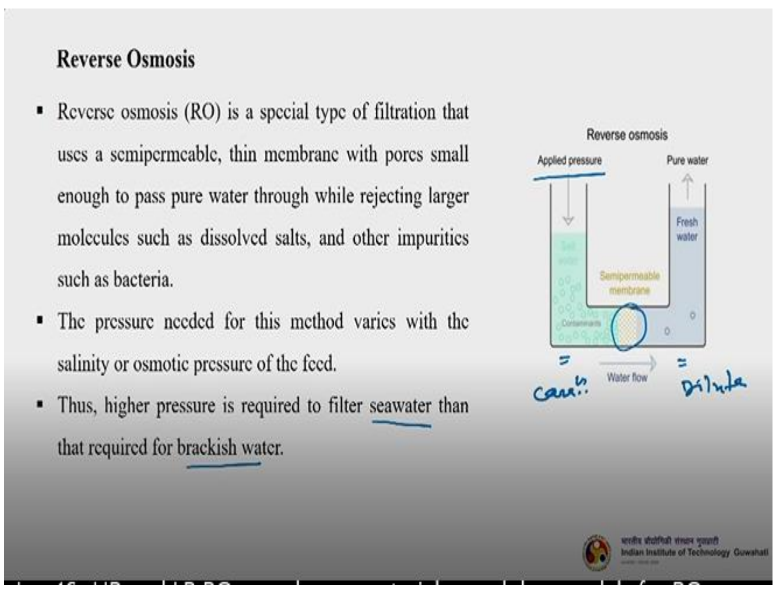
From this module onwards, will be discussing mainly about the different types of membranes and their applications basically. So, today we will discuss, about RO, its history, principle membrane and materials, their different types of modules and the modules that is required for the RO transport. Now, henceforth most of the modules. Later on in our lectures will be discussing like we are starting with RO.

Then we will discuss ultrafiltration, microfiltration and then other membrane processes like electro dialysis, pervaporation. So, one thing you will find that may be little common is about the membrane materials and the membrane modules. Now, you know, materials and modules who have discussed in general. In one of our or two of our classes and the membrane material properties.

And the modules different types of modules, its advantages and disadvantages. How about nevertheless, it is very important that all these two things like membrane and materials and modules has to be read again under subsequent membrane processes such as RO, microfiltration, ultrafiltration and other things. So it is important as to understand that all the membranes and materials and all the modules are not going to be used universally for all processes like RO microfiltration, ultrafiltration.

That is why it is required to be repeated, so do not think that it's getting repeated. It is not so it is needed to understand that what are the materials and modules are fit for particular membrane applications. Now, today we will discuss about the RO, and its membranes, materials and modules so before that we will discuss little about the principle.

(Refer Slide Time: 02:31)

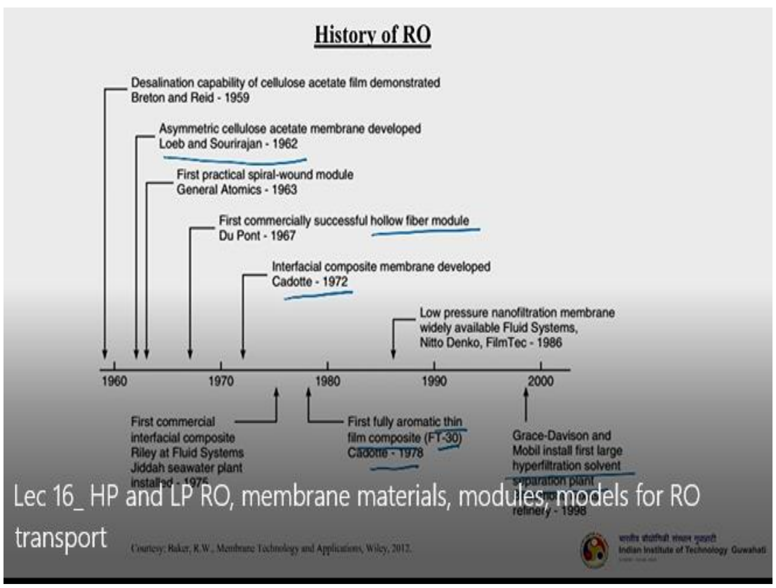


So, you know, RO is a special type of filtration that uses a semipermeable thin membrane with pores small enough to pass pure water while rejecting larger molecules such as dissolved salts and other impurities such as bacteria. In our last class we have discussed about the principles of osmosis and reverse osmosis, and we have understood how osmosis works and how reverse osmosis works.

So just quickly we are going through what we have discussed earlier, so you know that we the semipermeable thin membrane here this is the concentrated phase, and this is the dilute phase, right? So, as you know that in RO, we need to apply the pressure which should be sufficient enough to overcome the osmotic pressure right? So that is why they applied pressure whatever we are applying here must overcome that delta pi or osmotic pressure difference .

So, that the flow of water from the concentrated side, will go to the dilute side. Okay against this chemical potential gradient .So that is why we need to overcome the osmotic pressure difference. Now, higher pressure is required to filter seawater, then that is required for the brackish water. Okay? The reason is that seawater is more concentrated almost 35,000 ppm. I am just looking out the sodium chloride concentration brackish water it is less 5000,6000.

(Refer Slide Time: 03:54)



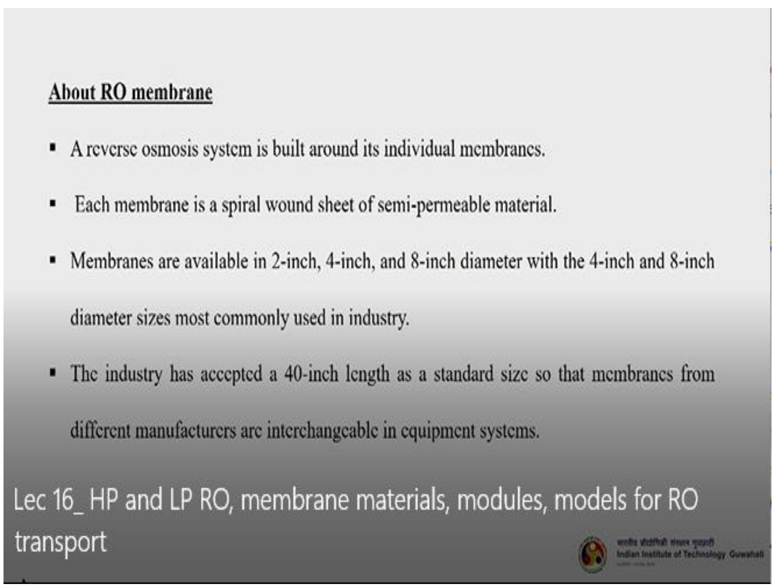
So let us understand the history of the reverse osmosis. So you can see that 1960. It started actually desalination capability of cellulose acetate thin film demonstrated by Breton and Reid in 1959. So in 1960, it was adapted. Okay, then asymmetric cellulose acetate membrane and developed by Loeb and Sourirajan you know this is one of the most important breakthrough in the membrane science and technology that is in 1964 or 65, if I correctly remember.

Then first practical spiral wound module was designed by General Atomics in 1963. Then a Du Pont has successfully fabricated the first hollow fiber module in 1967. And again, these are all applied for the desalination processes. Then the most important breakthrough again come, which is the interfacial composite membrane development. Cadotte has developed this type of membrane in 1972.

Then first commercial interfacial composite membrane was proposed by the fluid systems and commercial application own was successfully demonstrated for the seawater plant in Jiddah Saudi Arabia 1975. Then, first fully automatic thin film composite okay the TFC membrane, which is the brand name is given by FT30. Okay, was invented by cadotte in 1978, then subsequently, so many other developments has taken place like low pressure nanofiltration membrane and proposed by Nitto Denko and film tec in 1986.

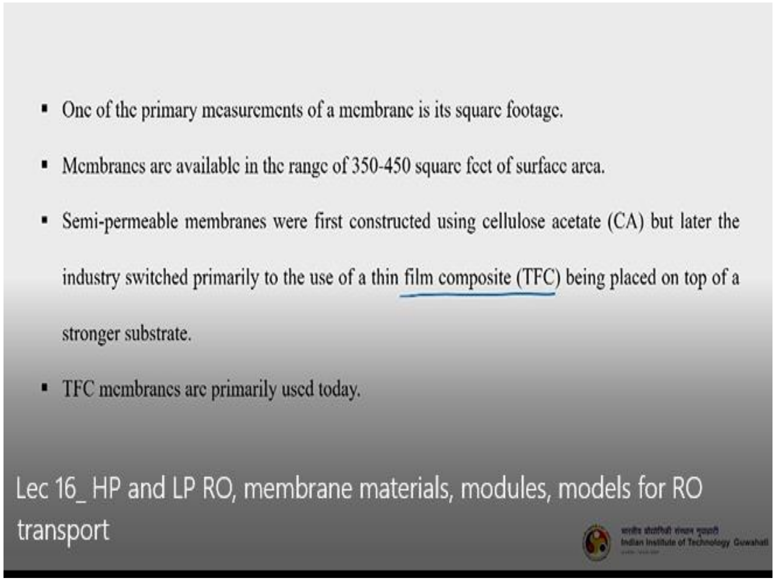
Then in 2000. Grace-Davidson and Mobil install the first large hyperfiltration solvent separation plant in Texas refinery okay, in 1990 so this one of the major developments which is out side of the desalination systems.

(Refer Slide Time: 05:57)



So a reverse osmosis system is built around its individual membranes . Each membrane is a spiral wound sheet of semi permeable membrane. Membranes are available in 2-inch, 4 inch, and 8-inch diameter with the 4-inch and 8- inch diameter sizes are most commonly used in industry. The industry has accepted a 40-inch length standard size, okay so that membranes from different manufacturers are interchangeable in equipment systems.

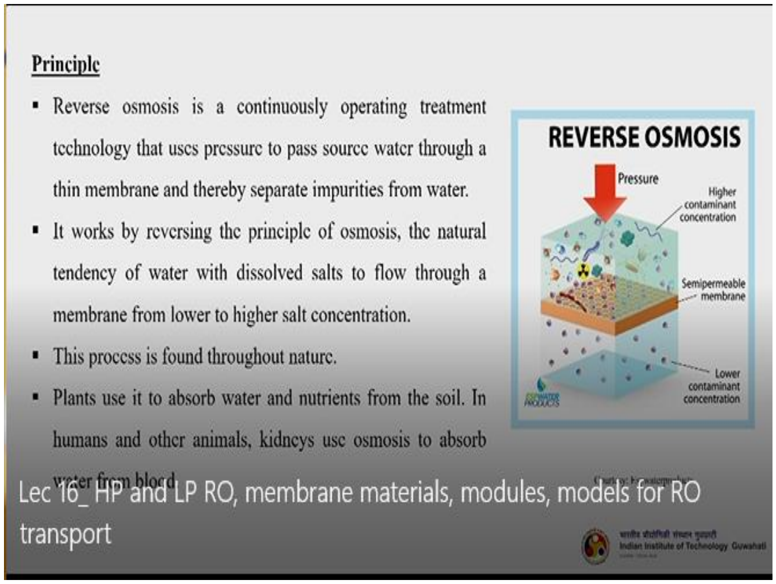
(Refer Slide Time: 06:24)



So this is all membrane manufacturing companies who are making especially RO membranes, have agreed that 40 inch size is the maximum length for the RO modules, okay so that if you dont have a particular company make membrane also ,you can interchange it with another company make. So the length will not create any problem. So one of the primary measurements of the membrane is its square footage. So membranes are available in the range of 350 to 450, square feet of the surface area.

Semi permeable membranes were first constructed using cellulose acetate(CA), but later the industry switch primarily to the use of the thin film composite. Okay, this we have discussed in detail about the thin film composite when we are discussing about membrane preparations being placed on top of a stronger substrate. Now most of the membranes RO membranes which we have seen today available commercially around TFC, not all but subsequently the measures the majorities are of TFC membranes.

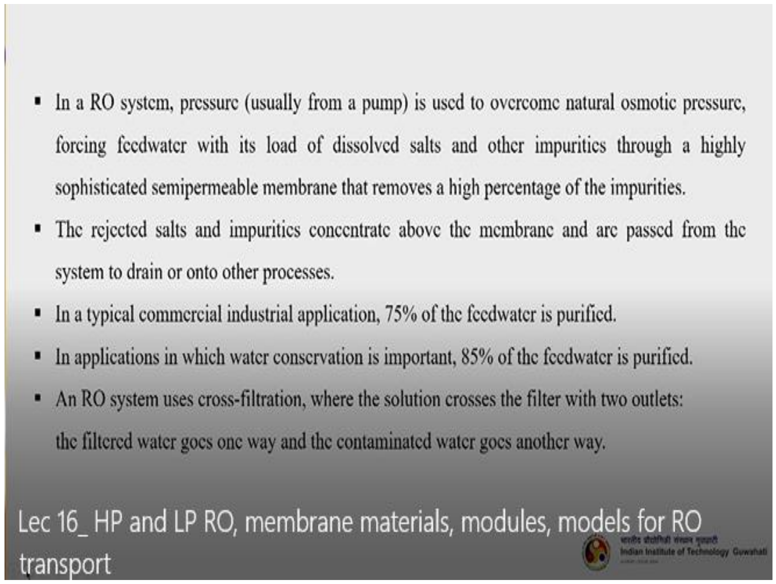
(Refer Slide Time: 07:27)



So, let us understand the principle little more than we'll go ahead and discuss about the modules and materials. So RO is continuously operating treatment technology that uses pressure to pass source water through a thin membrane and thereby separating impurities from the water. So you have just applying the pressure to overcome the delta pi the osmotic pressure, so that flow from the contaminated water or concentrated water will go inside, or will pass through the membrane, and then will move to the lower contaminated or lower concentrated side.

Here we are talking about contamination because we are talking about sea water desalination or brackish water desalination. The major application of the reverse osmosis. It works by reversing the principle of osmosis the natural tendency of water with dissolve salts to flow through a membrane from lower to higher salt concentration. This process is found throughout nature, the plants use it to absorb water and nutrients from the soil in humans and other animals kidneys use osmosis to absorb water from blood.

(Refer Slide Time: 08:33)

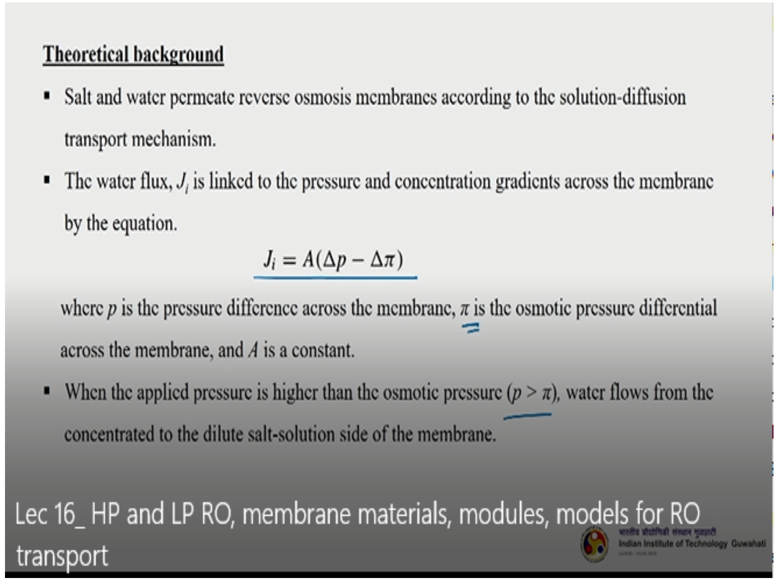


In RO system pressure, usually from a pump is used to overcome natural osmotic pressure, forcing feed water with its, load of dissolved salts and other impurities through highly sophisticated semipermeable membrane that removes a high percentage of the impurity. Now, it is worthy to mention here that whenever we are talking about the salination of seawater and or brackish water, it is important to note that they do not only contain the sodium chloride okay their contain so many different things you know sea water contain so many different things.

There are so many, bacteria's presents or the microorganisms presents and there are other components who will who will actually foul a lot, immediately they will foul so by fouling is a problem. Okay. Apart from that there are other smaller and higher molecular weight sources so it is not that only it is sodium chloride. Okay. So, all these things, needs to be taken into consideration when you are actually designing RO membrane right? For a desalination purposes.

The rejected salts and impurities concentrate above the membrane and are passed from the system to drain or onto other processes. Now, in a typical commercial industrial application 75% of the feedwater is purified. In applications in which the water conservation is important, almost 85% of the feedwater is purified. In RO system, usually uses crossflow filteration mechanism, but the solution crosses the filter with two outlets. The filtered water goes on one way and the contaminated water goes in the other way in the opposite direction, basically.

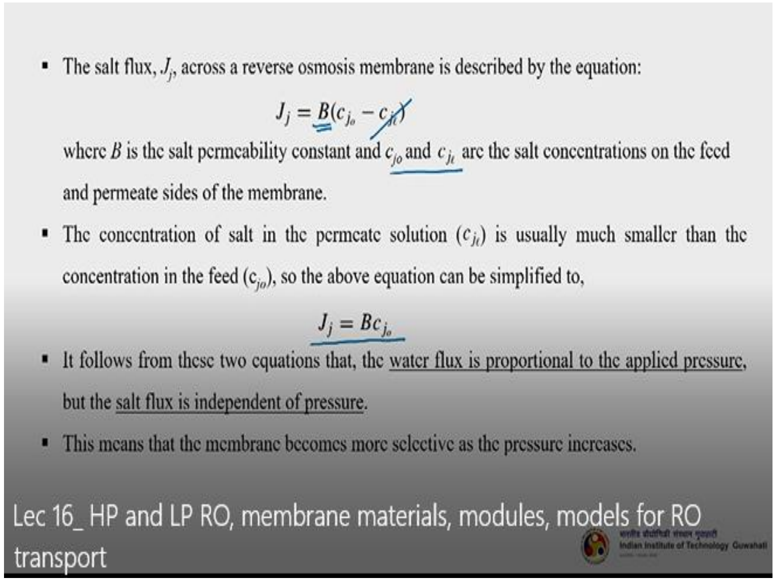
(Refer Slide Time: 10:11)



So, salt and water permeate reverse osmosis membranes, according to the solution-diffusion transport mechanism. We have discussed solution diffusion in detail today also we will just briefly touch it. The water flux is linked to the pressure and concentration gradients across the membrane by the equation.

Okay, so J equals to A into delta p minus delta pi. So p is the pressure difference across the membrane and pi is the osmotic pressure differential across the membrane and A is a constant proportionality constant of phenomenological composite whatever you can call it. So, when the applied pressure is higher than the osmotic pressure so P is greater than pi water flows from the concentrated to the dilute salt solution side of the membrane.

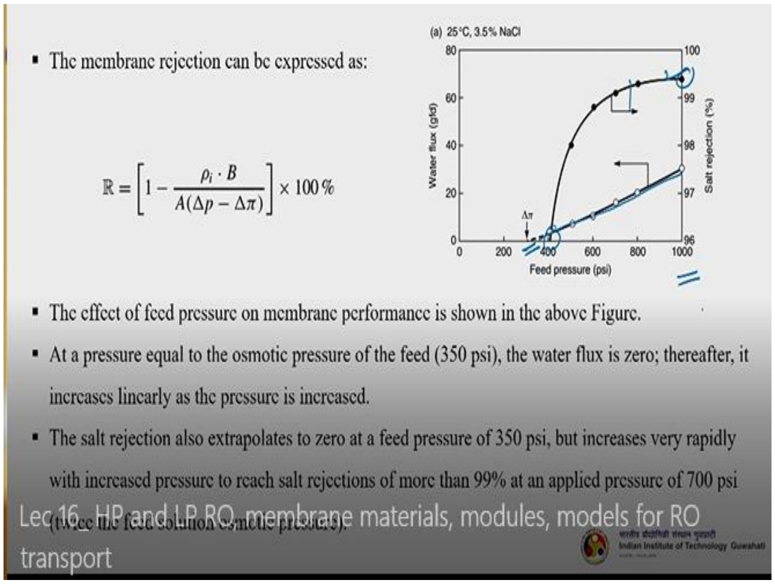
(Refer Slide Time: 10:53)



The salt flux across a reverse osmosis membrane is described by the equation. Jj equals to B into Cjnot minus cjl , so B is the salt permeability constant and cjnot and cjl are the salt concentratin on the feed and permeate sides of the membrane. Now the concentration of salt in the permeate solution is usually much smaller than the concentration in the feed side. So many times we can neglect this term right?

So hence our equations become Jj equals to B x cjnot . So it follows from these above two equations that water flux is proportional to the applied pressure, but the salt flux is independent of the pressure. It is very important to note this. So, this means that the membrane becomes more selective as the pressure increases right? so water flux is obviously consequent to the applied pressure whatever we are applying the pressure. Okay, but salt flux has nothing to do with the pressure.

(Refer Slide Time: 11:52)

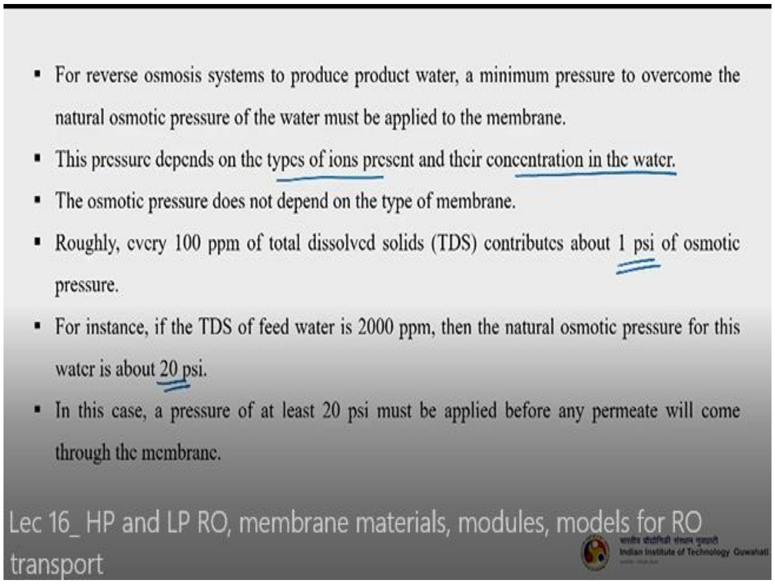


So the membrane rejection can be expressed by this particular equation so R equals to one minus rho i into P divided by A into delta p minus delta pi x 100%. 100% means in percentage actually will be expressed. So that is why 100% is being multiplied. So, the effect of feed pressure on membrane performance is shown in this particular figure. So you can see that at a pressure equal to the osmotic pressure of the feed that is 350 psi somewhere here.

Okay, the water flux equals to 0 right? There after it increasing linearly this is your water flux. Okay. And the pressure is increasing as we are increasing the pressure water flux linearly increasing the salt rejection, this is the profile of the salt rejection, you can see that the salt rejection also extrapoles at 0. It is also starting from 0 okay. at a feed pressure of 350 psi but increases very rapidly. Okay, with increased pressure to reach salt rejection of more than 99% this is about 99% you can see the salt rejection.

Okay so almost 99.5% at an applied pressure of 700 psi so here almost 700 psi so you can see at this result, it is almost reaching 99.5% salt rejection. So, this indicates that high salt rejection is happening at higher pressure, almost twice the feed solution osmotic pressure. okay so this particular figure, or this data was generated here at 25 degrees centigrade, with a 3.5% sodium chloride concentration.

(Refer Slide Time: 13:26)



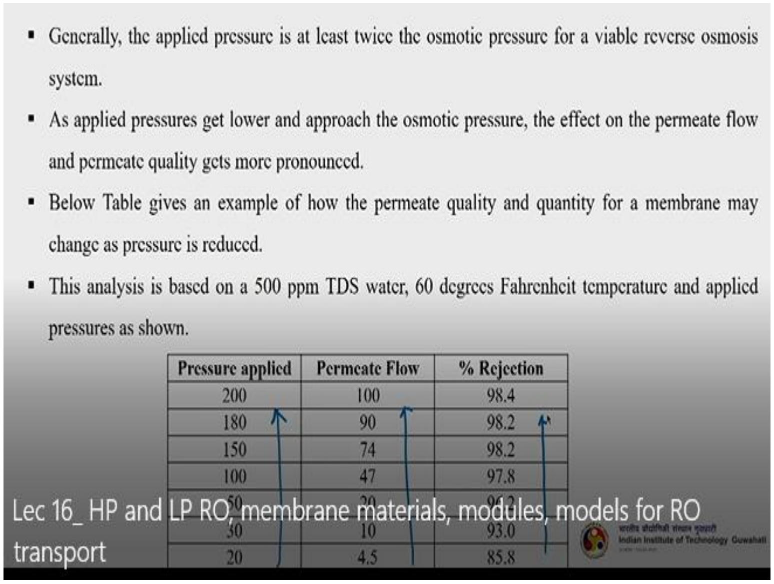
For RO systems to produce a product water a minimum pressure to overcome the natural osmotic pressure of the water must be applied to the membrane. This pressure depends on types of ions present, right, and their concentration in the water as I was just mentioning that. Please do not think that the whenever desalination of seawater or brackish water is happening, it is only sodium chloride, it is not that.

There are so many magnesium, calcium, so many things that there chlorine will be there, biophalims will be there. So, apart from that so many other ions of smaller and bigger size also present. So, the pressure whatever we are applying is obviously depends on the types of ion presents and their subsequent concentrations in the water. Osmotic pressure does not depend on the type of the membrane and this is also very important to understand, right?

Roughly every 100 ppm means parts per million milligrams per liter of total dissolved solids contributes about one psi of osmotic pressure. this is some sort of thumb rule you can say. So for instance, if the total dissolve solid of feed water is about almost 2000 ppm. Then the natural of osmotic pressure is about 20 PSI, so we can you can you can actually guess it from this particular understanding that for every 100 ppm of TDS the osmotic pressure corresponding is generated is almost 1 psi.

So in this case, a pressure of at least 20 psi must be applied before any permit that will come through the membrane.

(Refer Slide Time: 15:00)

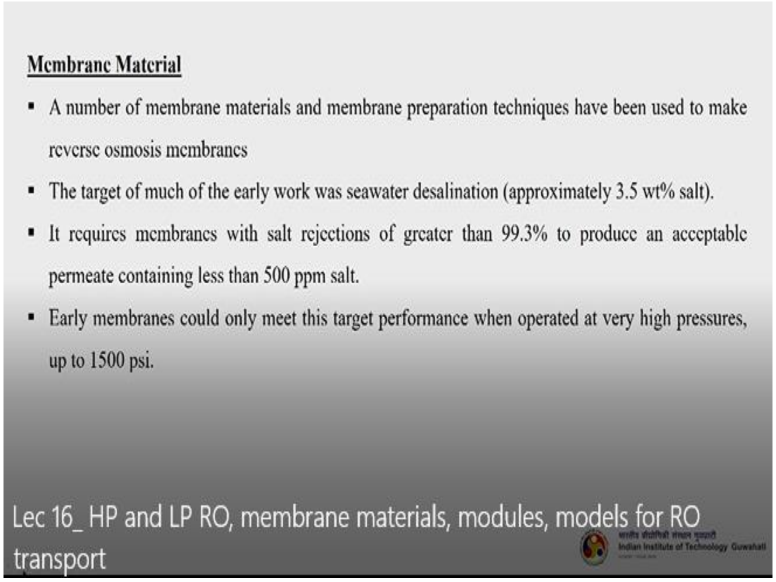


Generally, the applied pressure is at least twice the osmotic pressure for a viable RO system. Now, as applied pressure gets lower and approach the osmotic pressure, the effect on the permeate flow and permeate quality gets more pronounced. And that you can see this particular table below. So this gives an example of how permeate quality and quantity for a membrane may change as the pressure is reduced.

So this analysis of this table is generated. The data is generated based on 500 ppm TDS water, 60 degree Fahrenheit temperature and applied percent that is shown in here. You just have a look this particular table. You can see when the applied pressure is higher at 200. Okay Psi. Now, you can see this permeate flow is 100. Okay, and percentage rejection is 98.4, is the pressure actually decreased.

So you can see the permit flow as well is here the percentage rejection is decreasing. So you can say that, let us say we are starting from the below, we are we are moving from lower to higher side. Okay, pressure. So, your permeate flow increases as well as your percentage rejection also increases.

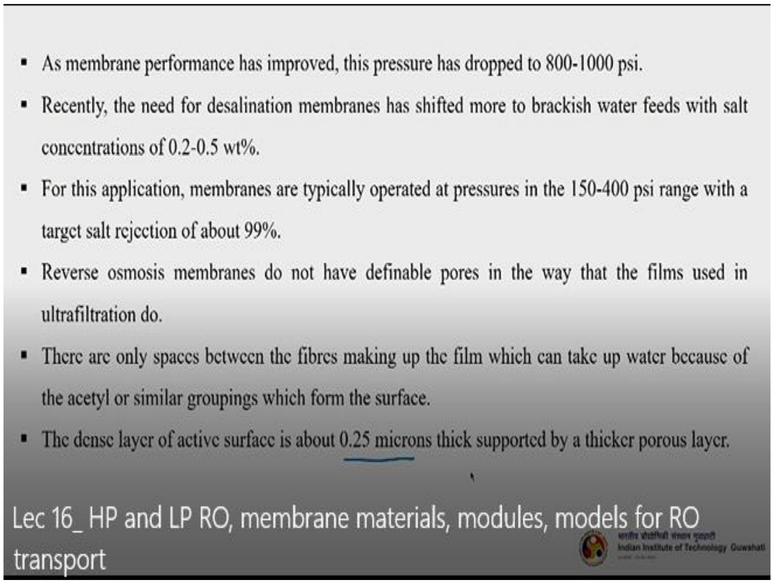
(Refer Slide Time: 16:15)



So now let us talk about the membrane materials. Membrane materials for RO. So a number of membrane materials and membrane preparation techniques have been used to make RO membranes. The target of much of the early work was seawater desalination about 3.5% weight percent of salt. So, RO was primarily developed for the desalination purposes. Now also RO is primarily used also desalination purposes.

Though, RO being used for other purposes also other applications also so it requires membranes with salt rejections of greater than 99.3% to produce an acceptable permeate containing less than 500 ppm salt. Now, early membranes could only meet this target performance when operated at very high pressures, Iet us say about 1100-1500 psi.

(Refer Slide Time: 17:00)

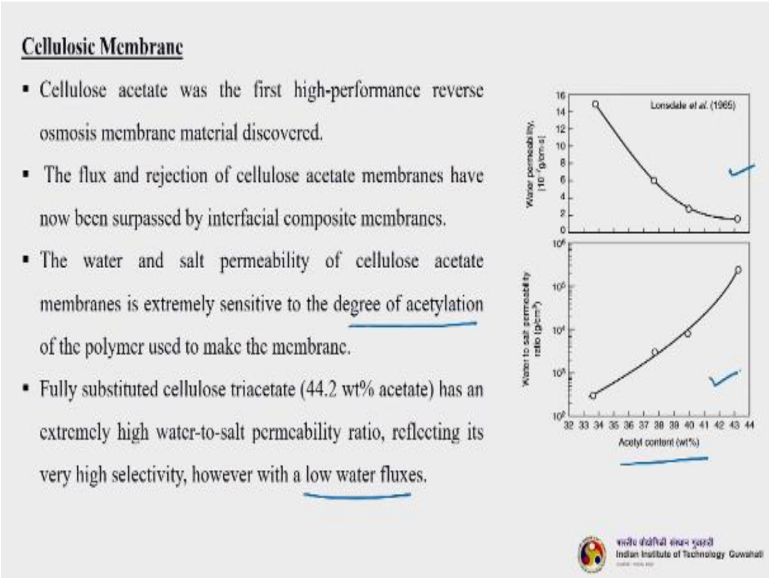


As membrane performances, improved this pressure has dropped 100-1000 PSI .Membrane performance has improved basically due to the breakthrough in membrane, manufacturing, right? So, recently the need for desalination membrane has shifted more to brackish water feeds with salt concentration of almost 0.2-0.5wt%. Now for this application membranes are typically operated at a presser of a range of 150 to 400 psi with a target salt rejection of about 99%.

RO membrane do not have definable pores in the way that the film is used in the ultrafiltration do. So you need to understand the difference between ultrafiltration membrane and RO membranes, they are all asymmetric membranes, have a ultrafiltration membranes even asymmetric membrane contains pores, however, RO membrane that do not have distinct, or definable pores..

So there are only spaces between fibers, making up the film, which can take up water because of the acetyl or similar groupings which form the surface. So the dense layer of the active surface is about 0.25 microns that is the thickness of the dense layer supported by a thicker porous layer.

(Refer Slide Time: 18:11)

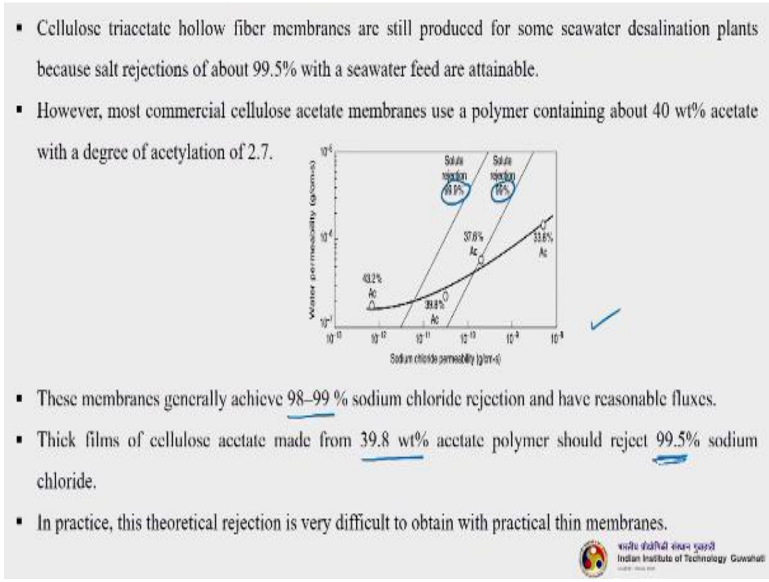


So let us see the cellulosic membrane. Cellulose acetate was the first high performance RO membrane material that was discovered and the flux and rejection of cellulose acetate membranes, have been now been surpassed by interfacial composite membrane, with the development of the interfacial composite membrane. Now, the water and salt permeability of cellulose acetate membrane is extremely sensitive to the degree of acetylation of the polymer used to make the membrane.

We have understood what is degree of acetylation? When we discuss cellulose, and its properties that fully substitute cellulose triacetate (CTA) almost 44.28% acetate has an extremely high water to salt permeability ratio, reflecting, its very high selectivity however with the lower water fluxes. So the selectivity is increased with the water flux has actually decreased.

So this is a Lonsdale study in 1965, you can see that water permeability is decreasing here. Okay. with acetyle content. However, water to salt permeability is increasing right?

(Refer Slide Time: 19:20)

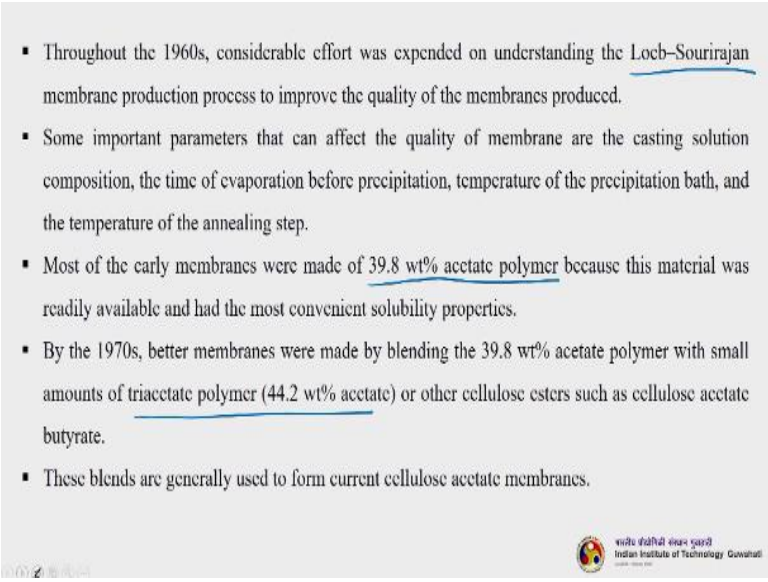


So CT hollow fiber membranes are still produced for some seawater desalination plants because salt rejection of about 99.5%, with the seawater feed are attainable.. However, most commercial cellulose acetate membranes, use a polymer containing about 40 wt% acetate with a degree of acetylation of 2.7. So you can see here, this particular figure, it’s a salt versus water permeability versus sodium chloride permeability. Water versus the salt the permeability actually.

So, membranes, these membranes generally 98 to 99% sodium chloride rejection. Okay, so you can see the solute rejection here, right 99%. he has solid rejection of 99.9%, okay with reasonably good fluxes. Thick films of cellulose acetate made from 39.8 wt% acetate polymer should reject 99.5% sodium chloride. So this has already been proved and commercially adapted also in practice this theoretical rejection is very difficult to obtain with practical thin membrane.

So,almost. It has been reduced to 98.5-close to 99, but not much rejections, so theoretical epics. This one commercial membrane and when it was prepared this thin membranes. Okay. The do not actually exactly matches the theoretical predictions of this 99.5%. Okay, however they're very close. That is why they have gained a lot of popularity nowadays, right.

(Refer Slide Time: 20:58)



So, throughout the 1960s considerable effort was expended on the understanding the Loeb-Sourirajan membrane. Okay, production process to improve the quality of the membranes produced ,right some important parameters that can affect the quality of membrane, are the casting solution composition. The time of evaporation before precipitation, temperature of the precipitation bath and the temperature of the annealing step.

Most of the early membrane were made up of this 39.8wt% acetate polymer, because this material was readily available and had the most convenient solubility properties. By 1970s better membrane are met by blending 39.8wt% acetate polymer with small amount of triacetate polymer. Okay, and other cellulose esters such as cellulose acetate butyrate. These blends are generally used to form current cellulose acetate membranes.

(Refer Slide Time: 21:54)

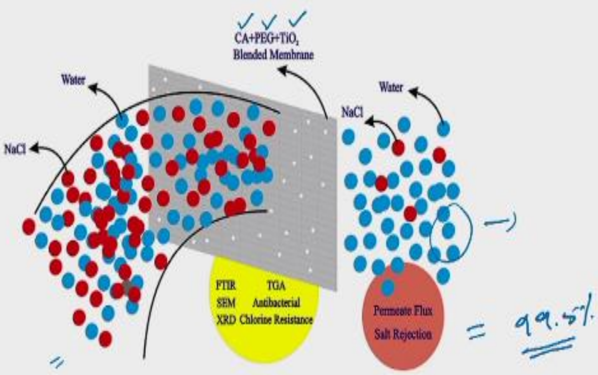


Fig. Cellulose acetate based thin film nanocomposite reverse osmosis membrane incorporated with TiO_2 nanoparticles

Courtesy: Muhammad Shafiq et al., Carbohydrate Polymers, 186, 2018, 367-376.

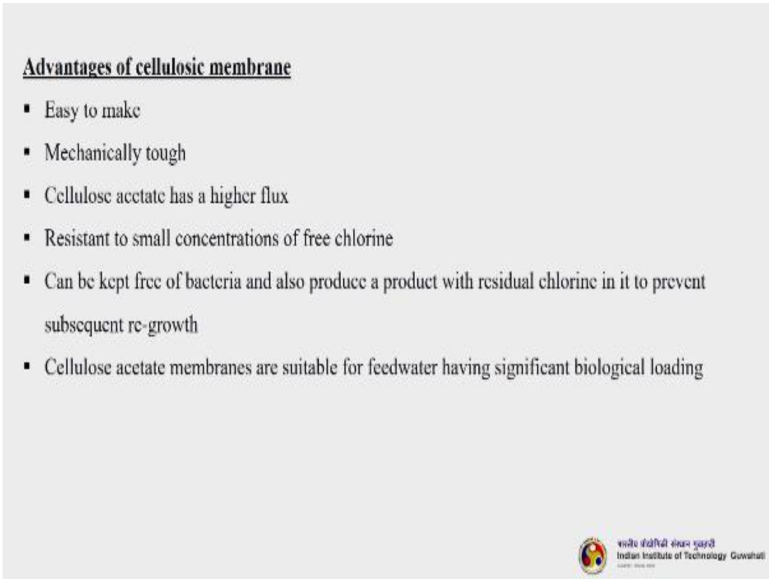
So, you can see this is a classic example, cellulose acetate based thin film nanocomposite RO membrane incorporated with the titanium dioxide nanoparticles. So, what is the composition here? This composition is cellulose acetate you can see here when PBG polyethylene glycol, then titanium dioxide nanoparticles are infused into this. What is the reason for this? The reason is that they are using the nanoparticles.

So, they disperse very quickly in a very homogeneous manner and their way this strengthen the membrane properties okay and the permeability also becomes better right? So, anyway, this is a research output by this particular people. Okay. They have characterized their membrane using a FTIR, SEM,XRD, TGA antibacterial resistance and chloride resistance also. So when we talk about RO membranes what should be their properties but it is very important to note few things.

Of course, the membrane material is very important Apart from that, how much is the solid permeability how much is how much are the salt permeability and how much is the water permeability because mostly with the membrane RO membrane job is that it will allow the water to pass through the other side thereby retaining the salt you can see here also that most of the salts are getting retented hear only the water okay is come on this side.

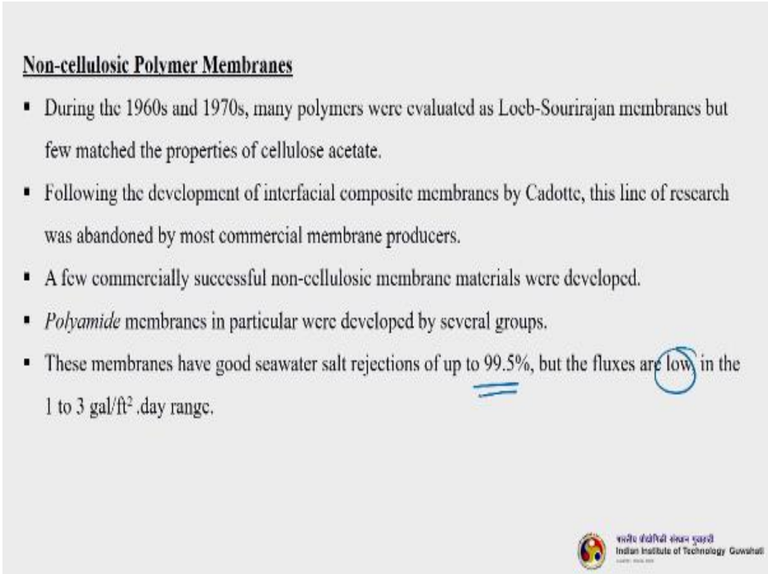
So, this is your permeate side and this the other side. a very small amount of salt will of course pass through because by nature all membranes are like that, okay. So, it will since they have very interspaces between the membrane material and the salt passes through, so, you get very less amount, but it is the amount is extremely less. So, you will just discuss that almost there are membranes we which can which will prepare almost 99.5%salt rejection and the will be more than that 99.9% right.

(Refer Slide Time: 23:56)



The advantages of cellulosic membrane is that it is easy to make their mechanically tough. Cellulose acetate has a higher flux ,resistant to small concentrations of free chlorine, can be kept free of bacteria and also produce a product with residual chlorine in it to prevent subsequent re-growth that is also very important, okay cellulose acetate membranes are suitable for feed water having significant biological loading.

(Refer Slide Time: 24:19)

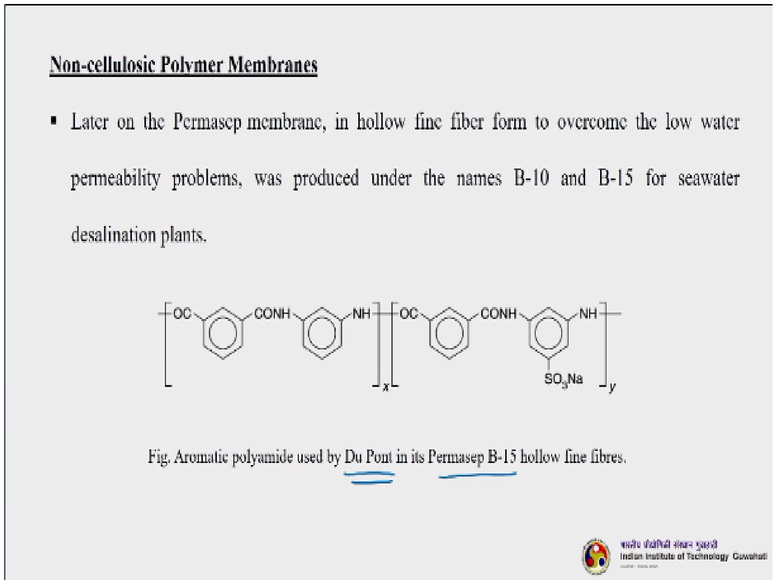


However, cellulosic materials are not the only materials that are being used right now, for commercial RO membranes, there are non cellulosic membranes also. So, let us understand and discuss a little about the non cellulosic polymer membranes. So, during 1960s and 70s many polymers are evaluated as Loeb- Sourirajan membranes, but few matched the properties of the cellulose acetate.

Following the development of the interfacial composite membrane by Cadotte this line of research was abandoned by most commercial membrane producers. because every membranes is shifted to the interfacial composite membrane, because of the better properties. And nevertheless a few commercially successful non cellulosic membrane materials were developed polyamide is such one of the material membrane material which is widely used and developed by several membranes manufacturers.

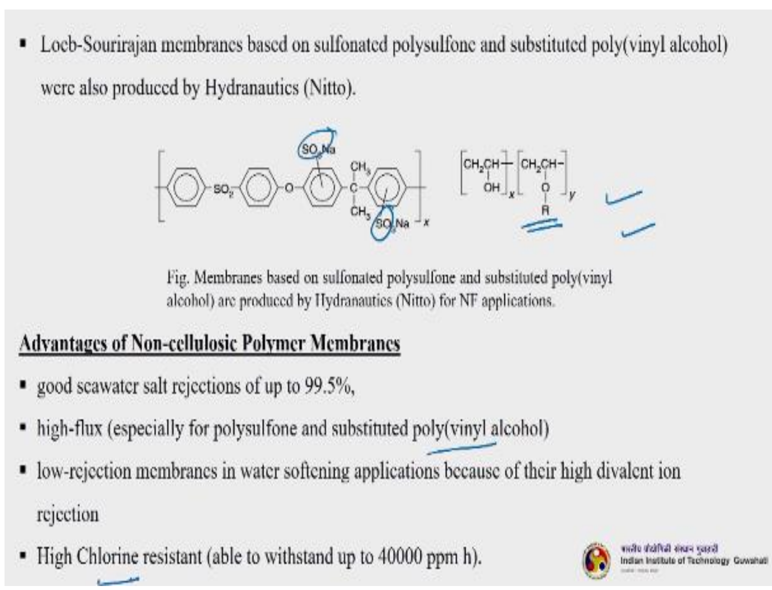
So, these membranes have good seawater salt rejection upto almost 99.5% but the fluxes are very low. So, in the range of 1-3 gallon per feet square per day range. So, due to the extremely low flux ranges actually this non cellulosic membrane materials and are not have not gained much importance to prepare RO membranes.

(Refer Slide Time: 25:31)



So, later on the permasep membrane in hollow fine fiber form for they have be used this aromatic polyamide visit the structure of a aromatic polyamide. So, dewpoint has prepared this membrane permasep B-15 is the brand name actually the trade name is a hollow fine fibers. So this was repaired for seawater desalination purposes.

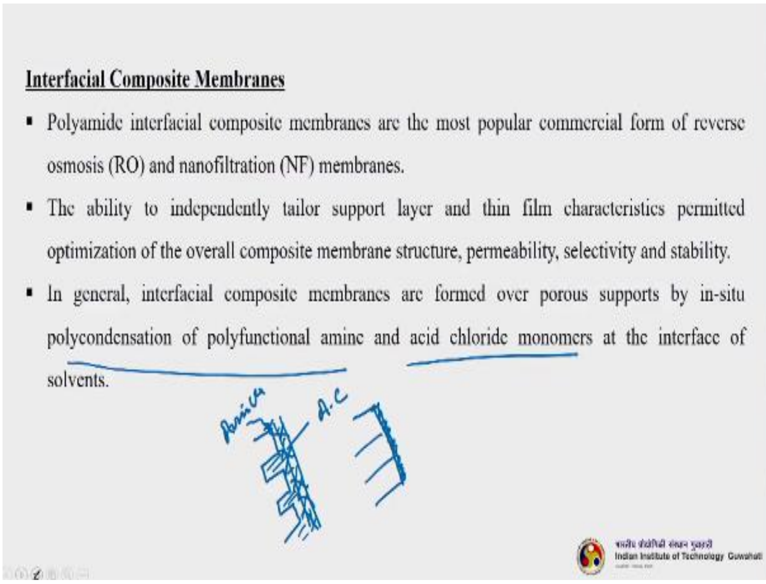
(Refer Slide Time: 25:54)



So Locb-Sourirajan membranes based on sulfonated polysulfone and substituted poly (vinyl alcohol) were produced by Hydranautics (nitto).okay that is the need to the brand name. So these are actually based membranes based on sulfonated polysulfone you can see this sulfonated groups here okay and substituted poly vinyl alcohol produced by the hydranautics but this is for the nano filtrationapplications.

So the advantages of non cellulosic polymer membrane is there right of course they are sea water salt rejection is upto 99.5% high flux especially for the polysulfone and substituted poly vinyl alcohol of these two membranes have given high flux. Low rejection membranes in water softening applications because of their high divalent ion rejection and high chlorine resistant able to withstand up to 40000 ppm/h.

(Refer Slide Time: 26:49)



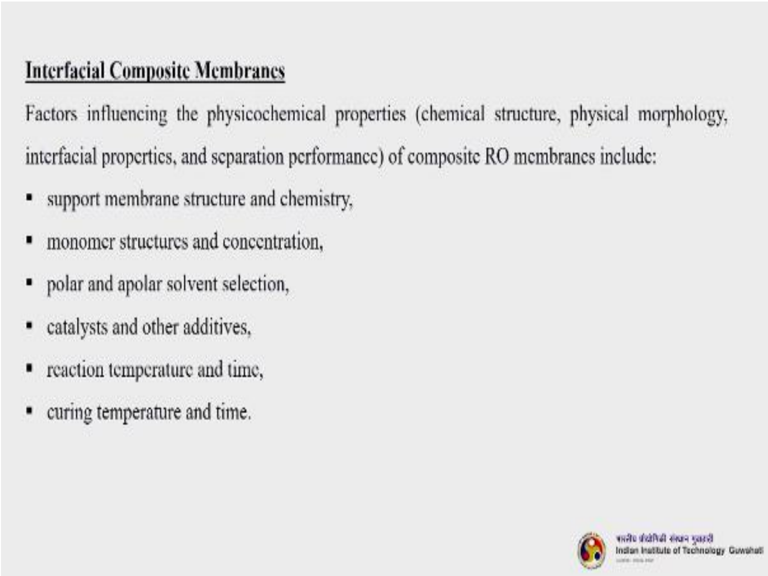
So next,classes of membranes for RO is that interfacial composite membranes. Now polyamide interfacial composite membranes are the most popular commercial form of RO as well as nanofiltration membranes. The ability to independently Tailor support layer and thin film characteristics permitted optimization of the overall composite membrane structure permeability selectivity as well as stability.

In gender interfacial composite membranes are formed over porous supports by in situ polycondensation system, okay, fully functional amine acid chloride monomers at the interface of solvent. But now students we have understood how the interpersonal polymerization actually works. So, I am not going to repeat this. We know how it actually works unit I mean, then you I am just quickly I am going I am going to take I am telling you, so a membrane okay.

So let us say, this is trying to let us say,this is a membrane have been some types of falls. So you impregnate this with some amine right okay. So, that goes into the porous and on the surface then you keep it in contact with acid chloride right. So, this is your amine and this is your acid chloride. Now, once it comes into contact with that here crosslinked or polymerisation begins, okay. So, what you will achieve actually something like this, right.

So, thin film was very thin film will come. So, very thin layer of film will come here on the surface, right. So, this is how its really we discuss this in detail in interfacial polymerization. So, it is very important to know this process because most of the commercial membranes are being prepared nowadays. And you can prepare it in the

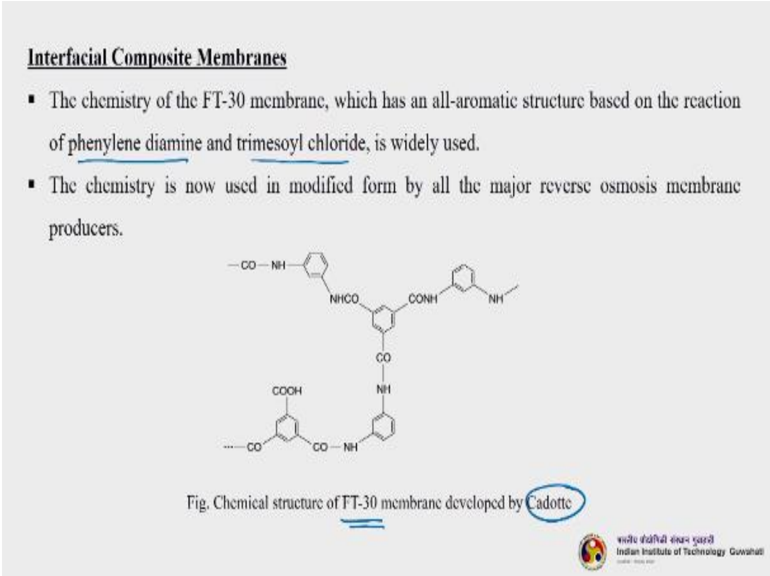
(Refer Slide Time: 28:47)



lab scale also. So,the factors influencing the physicochemical properties chemical structure physical morphology interfacial properties separation performance of the composite RO membranes. So, that included fully support membrane structure of chemistry those support membrane is giving the mechanical support However, its chemistry and structure is also plays a important role.

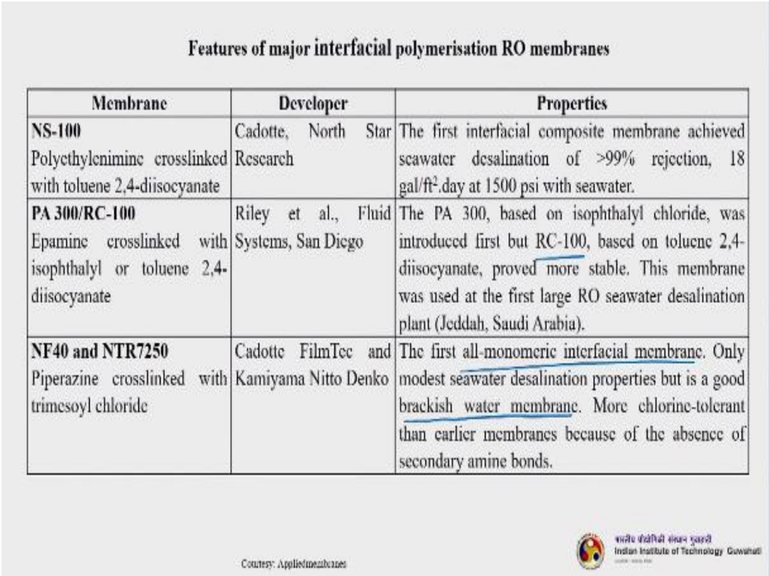
So, monomer structures and concentration polar and apolar solvent select some catalyst and other additives if at all it is there but it's not present always the extent temperature and time at curing temperature and time.

(Refer Slide Time: 29:21)



This is a structure of a FT 30 membrane that is developed by cadotte right which is an all aromatic structure based on the reaction of phenylene diamine and trimesoyl chloride okay. So, this is the phenylene diamine is the amine and trimesoyl chloride is the acid chloride Okay. So this chemistry is now used in modified form by all major RO membrane it produces most of the Membrane manufacturers adapted this material actually.

(Refer Slide Time: 29:53)



Features of major interfacial polymerisation RO membranes

Membrane	Developer	Properties
NS-100 Polyethylenimine crosslinked with toluene 2,4-diisocyanate	Cadotte, North Star Research	The first interfacial composite membrane achieved seawater desalination of >99% rejection, 18 gal/ft^2.day at 1500 psi with seawater.
PA 300/RC-100 Epamine crosslinked with isophthalyl or toluene 2,4-diisocyanate	Riley et al., Fluid Systems, San Diego	The PA 300, based on isophthalyl chloride, was introduced first but RC-100, based on toluene 2,4-diisocyanate, proved more stable. This membrane was used at the first large RO seawater desalination plant (Jeddah, Saudi Arabia).
NF40 and NTR7250 Piperazine crosslinked with trimesoyl chloride	Cadotte FilmTec and Kamiyama Nitto Denko	The first all-monomeric interfacial membrane. Only modest seawater desalination properties but is a good brackish water membrane. More chlorine-tolerant than earlier membranes because of the absence of secondary amine bonds.

Courtesy: Appliedmembranes

Indian Institute of Technology Guwahati

Now, let us understood in a nutshell the features of major interfacia polymerisation RO membranes which are commercially available, we discuss three or four out of this 4 actually. So, the first one you can see this NS-100 So, NS-100 is the brand name or the trade name. So, the membrane material is polyethylenimine crosslinked with toluene 2,4-diisocyanate .So, this is the membrane materials, right.

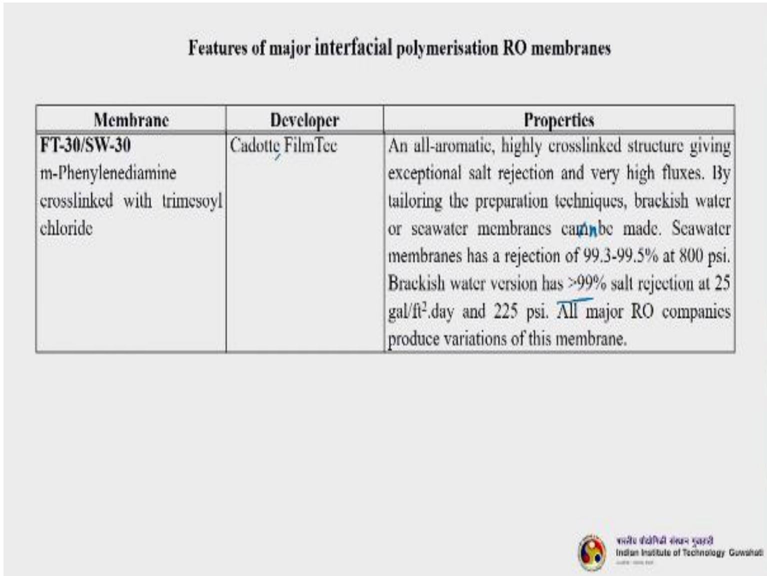
So, the developer is Cadotte North star research. So, what are his properties now, this is the first interfacial composite membrane that achieved a desalination of almost 99% that in the 99% of the rejection and 18 gallon feet square per day for flux,with 1500 PSI with seawater. Now the next is PA 300/RC-100 okay what are those are Epamine crosslinked with isophthalyl or toluene 2,4- diisocyanate.

So, Riley et al produced this membrane and developed this membrane at the fluid system San Diego. So, the PA 300 membrane based on isophthalyl chloride was introduced first but RC 100 based on toluene 2,4 diisocyanate proved more stable the stability is better for RC 100 membrane based compared to PA300 membrane this membrane is used as the first stage RO seawater desalination plant that in one of the slides I have told you about so this was used in Jeddah Saudi Arabia for desalination plant.

So, the next is NF40 and NTR7250. So,these are piperazine crosslinked with trimesoyl chloride So, trimesoyl chloride right so cadotte has prepared the develop this filmtec and Kamiyama nitto denko the first all monomeric interfacial membrane, this membrane okay So, only modest seawater desalination properties, but extremely good as a brackish water membrane, okay, because as you know the concentration of the ions are less in brakish water.

So, in this particular membrane prove to very good for the brackish water, and more chlorine tolerant than earlier membranes because of the absence of secondary amine bonds.

(Refer Slide Time: 32:57)

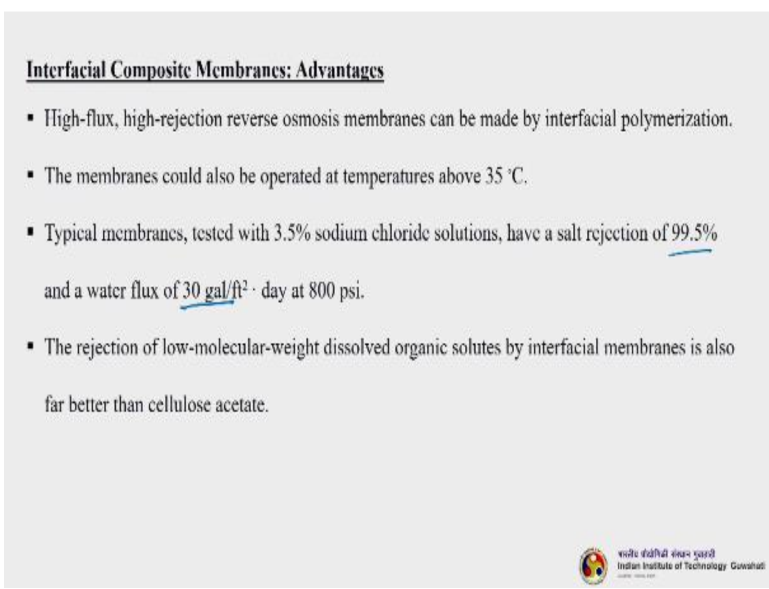

Features of major interfacial polymerisation RO membranes

Membrane	Developer	Properties
FT-30/SW-30 m-Phenylenediamine crosslinked with trimesoyl chloride	Cadotte FilmTec	An all-aromatic, highly crosslinked structure giving exceptional salt rejection and very high fluxes. By tailoring the preparation techniques, brackish water or seawater membranes can be made. Seawater membranes has a rejection of 99.3-99.5% at 800 psi. Brackish water version has >99% salt rejection at 25 gal/ft^2.day and 225 psi. All major RO companies produce variations of this membrane.

So, the next membrane is FT-30/SW-30 m-phenylenediamine crosslinked with Trimcsoyl chloride .So,Cadotte film Tec has developed this. So, this is an all aromatic highly crosslinked structure, giving exceptional salt rejection and very high fluxes. Now, by tailoring the preparation techniques, brackish water or seawater membranes can be made. Sea water membranes has a rejection of almost 99.3 to 99.5% at 800 psi.

Brackish water version has mandated the 99% salt rejection is at 25 gallon per feet square per day and 225 psi. So, all our major companies produce variations of this membrane.

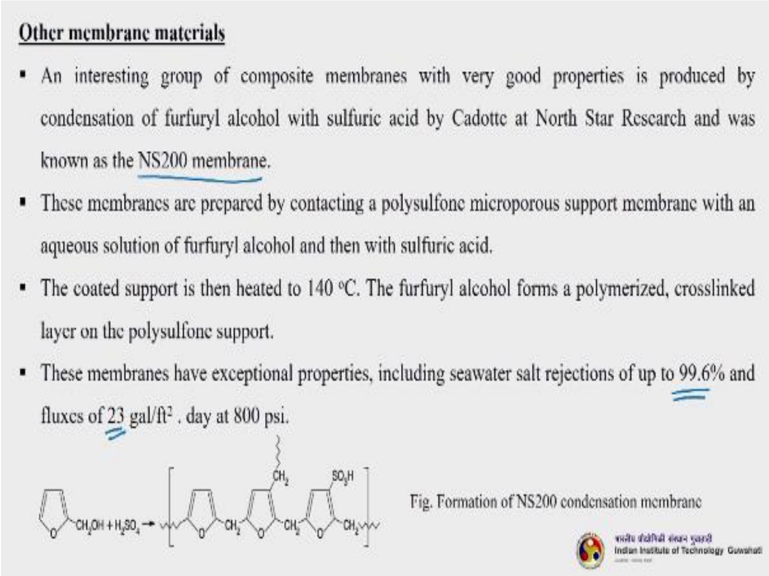
(Refer Slide Time: 32:57)



So, the advantages of interfacial composite membranes have that high flux high rejection that can be made using this particular technique, membrane could also be operated at a temperature above 35 degrees centigrade, this is one of the again measured advantage. So, typical membranes tested with 3.5% sodium chloride solutions have a salt rejection of 99.5% and the waterflux of 30 gallon per feet per square.

So, you can see this though with other membrane materials and other techniques also, we get a very good amount of rejection. However, the flux is not good about 1-5 or less than 10 feet gallon per feet square. So, you can see here it is higher 30. So, the rejection of low molecular weight dissolved organic solutes is also part better than that cellulose acetate membranes.

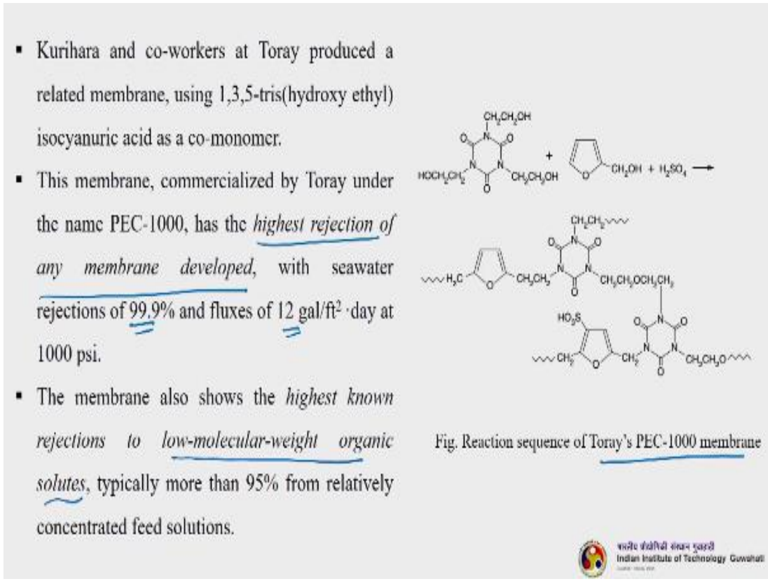
(Refer Slide Time: 33:49)



So, other membranes material says the interesting group of composite membranes with very good properties is produced by condensation of furfuryl alcohol with sulfuric acid by Cadotte at north star research and was known as NS 200 membrane in that trade name. These membranes have prepared by contacting a polysulfone microporous support with an acquisition of furfuryl alcohol and then with sulfuric acid.

The coated support is then heated to 140 degrees centigrade. The furfurly alcohol forms a polymerized crosslinked layer on the polysulfone support. These membranes have exceptional properties including seawater salt rejection of 99.6% and the fluxes of 23 gallon per day per square feet. So you can see the flux is also very good. In this this is the structure of the ns 200 Condensation membrane.

(Refer Slide Time: 34:39)



Then Kurihara and co-workers at Toray, one of the leading membrane and manufacturer produced a related membrane using 1,3,5-tris(hydroxy ethyl isocyanuric acid as a co-monomer

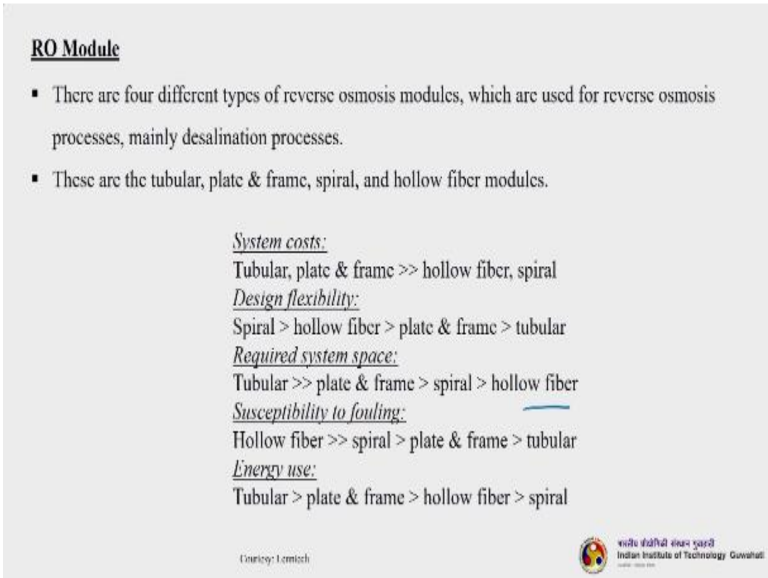
Okay. So, this is the reaction sequence of the torrents PC thousand membrane and you can see this membrane commercialized by Toria under the president Pc 1000 has the highest rejection of any membrane that is developed with seawater rejection of 99.9% and process of 12 gallon buckets carpenter, but you can see that the flesh is less.

So, in our lives we have seen that whether it is in interpersonal polymerization or when you have just report the membrane which we discussed on the previous slide, you can see that the rejection in 99.5% plus was good, but here the flux is little compromised. The membrane also source has non resistance to low molecular weight organic components solids. Now, please understand that as I was telling continuously in this lecture that seawater.

Even brackish water content so many other molecular weight organic solids So, so there is rejection is also equally important. Okay because we are one only one to survive. Flow that is the water to flow to the permeate side. So, this particular membrane is extremely good for rejecting the low molecular weight organic solids. So, you need to balance it things because what is the real intension?

Are you going to use the RO permeate as a portable water then you need to get devoid of all these things. So, for that maybe this particular membrane looks good of course, with a little compromise with the flux.

(Refer Slide Time: 36:20)

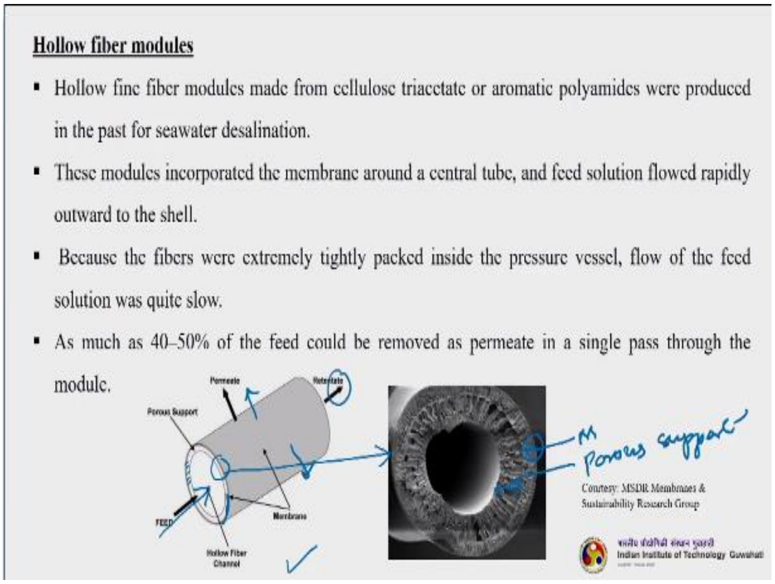


Now, let us quickly understood the different RO modules. So there are four different types of RO modules which are used for reverse osmosis processes mainly the desalination applications. So, these are tubular, plate and frame, spiral and hollow fiber. So all these we have discussed, but since I am telling you that under every membrane processes whether it is RO microfiltration ultrafiltration we will discuss this in a brief.

So that you need to understand that which particular membrane module is good for that, particular membrane applications. So if you look at system costs, cost is very important from any process industries. So in costs wise tubular or plate frame modules are higher than the hollow fiber and spiral. Design flexibility if you think then a spiral is better than hollow fiber and spiral is tougher than hollow fiber and Plate and frame and tubular.

Then required system space tubular is better followed by plate and frame, spiral and hollow fiber fiber and susceptibility fouling then hollow fiber is greater than spiral or higher than spiral plate and frame or tubular and energy used tubular is far far better than spiral.

(Refer Slide Time: 37:36)



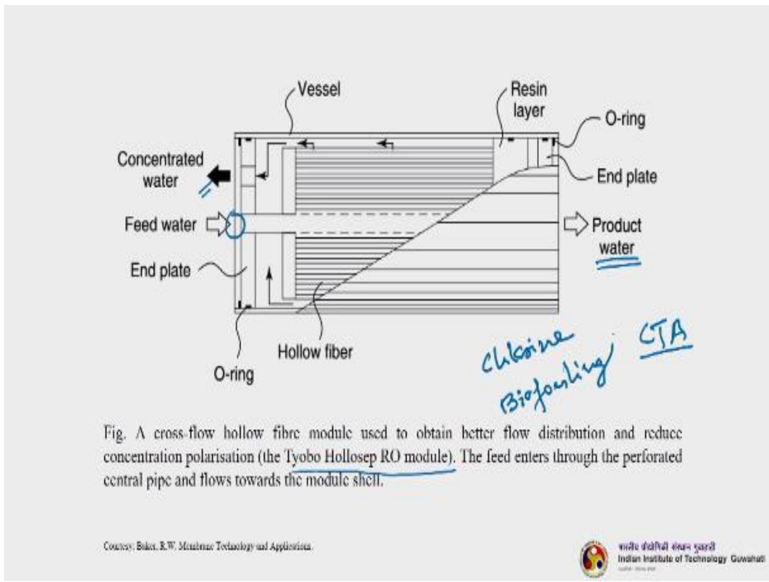
So, let us understand the hollow fiber module for RO. So hollow fine fiber modules made from cellulose triacetate or aromatic polyamides were produced in the past for seawater desalination. These modules incorporated the membranes around a central tube and the feed solution flowed rapidly outward to the shell. So you can see this is a single this, whatever I have shown here, so this is a single channel hollow fiber.

You can see the feed is flowing through the lumen okay or inside the hollow fiber okay and the permeate that is coming out here from the membrane and this is your membrane and this is your support okay. And you get a retentate here, because the fibers are extremely tightly packed inside the preservation flow of the feed solution is quite slow as much as 40 to 50% of the feed could be removed as permeate in a single pass through the module.

Now, as I was showing you this particular structure now, as usual, this one porous support along with a membrane. So, this is you can see how beautifully this scanning electron microscope is showing us. You can see, this is your poros layer, thickness of the porous layer, whereas this is your membrane. Okay, so this is your usual membrane, this is your poros support. So, this same image is telling us very nicely actually how.

There is a cross section a particular membrane. So, how actually two distinct layers that visible the porous support as well as the membrane layer.

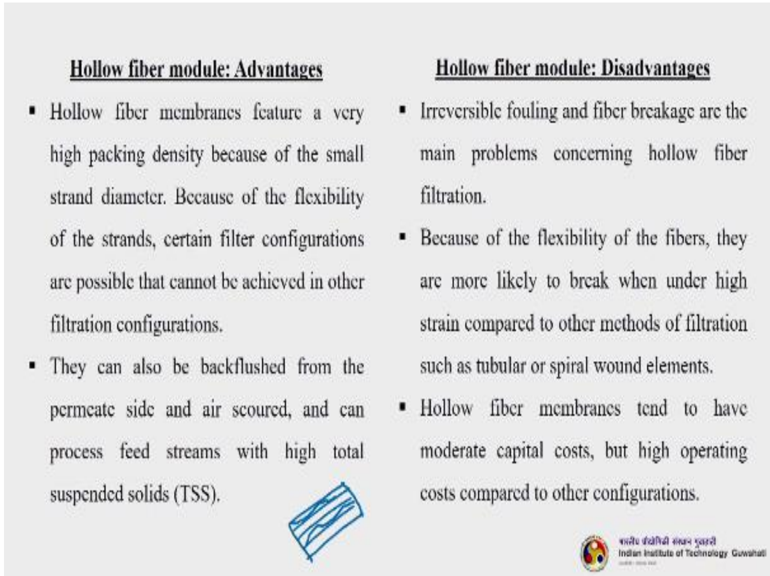
(Refer Slide Time: 39:18)



So, this is a cross-flow hollow fiber module, this is used to obtain better flow distribution and reduce concentration polarization. So, this is actually the Tyobo Hollosep RO module, the membrane material here is actually cellulose tri acetate and you can see that the feed enters here, okay. So, through a perforated central pipe, right, so, and the flow towards the module shell, okay. And you can get your product water here.

So that is actually the permit and the concentrator water here. Okay. And the feed. This particular Tyobo Hollosep RO module is very famous for two things. One is very good clotting resistance as well as extremely good bio fouling properties right.

(Refer Slide Time: 40:11)



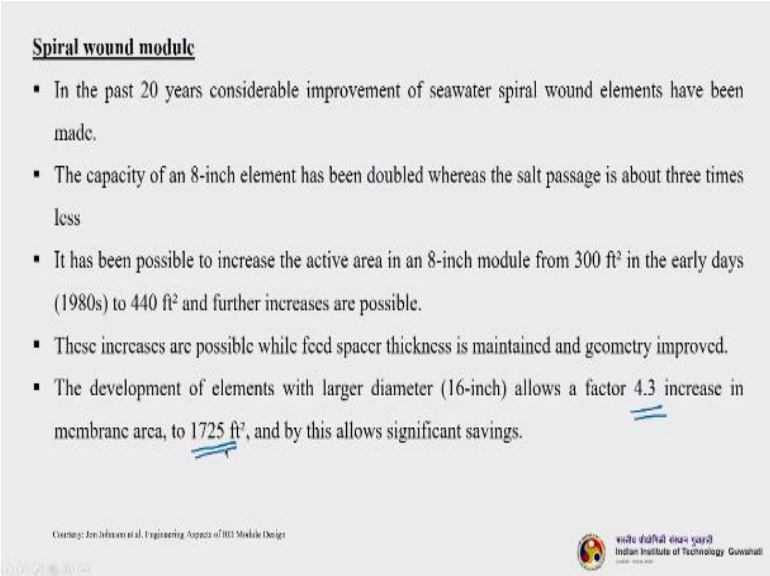
So, let us understand the advantages and disadvantages of the hollow fiber systems. So, hollow fiber membranes feature a very high packing density because of the small standard diameter. Now, because of the flexibility of the strands, that means, their individual tubes, certain filter configurations are possible that cannot achieve in other filter configurations. That is one of the very good things about this particular hollow fiber systems.

They can also be backflushed from the permeate side and air scoured and can process feed streams with extremely high TSS total suspended solids. However, the disadvantage is that irreversible fouling and fiber breakage are the main problem because of the flexibility of the fibers they are more likely to break when under high strain compared, let us consider these are small fibers, okay?

So single fibers, so they are fused together okay, right. So, they do not have any mechanical support inside. So, due to this whenever you are applying a very high pressure, so this fiber okay? They may become like this they may behave like this okay and they will get destructed due to the higher pressure So, that is why they will twist basically. So, that is why this will create flux problem as well as problem in separation.

And hollow fiber membranes tend to have moderate capital costs but high operating costs compared to other configurations. So, operating cost is actually a little higher.

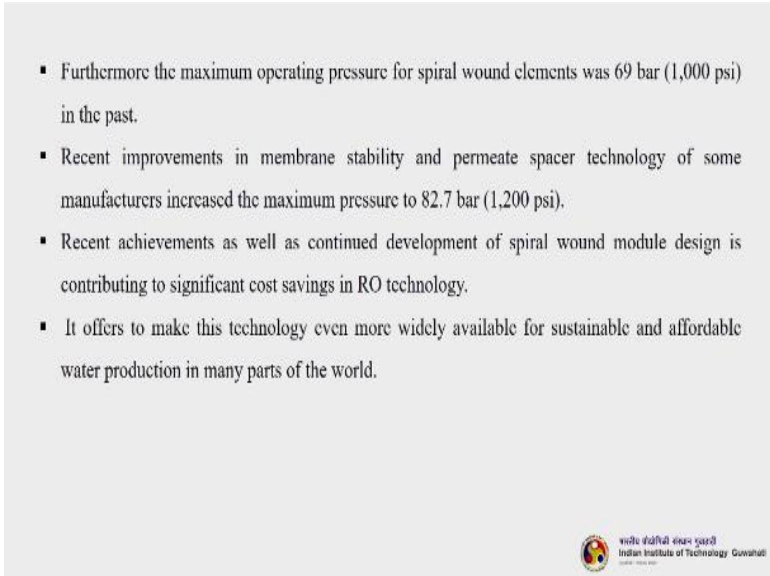
(Refer Slide Time: 41:41)



So, next category is spiral wound. So, in the past 20 was considerable improvement in sea water spiral wound elements have been made. And the capacity of an 8-inch element has been doubled whereas the salt passage is about three times less. It has been possible to increase the active area in an 8 inch module from 300 feet square in the early days to 440 feet square in 1980 and now further increases has also been possible.

Now these increases are possible while feed spacer thickness is maintained and geometry improved. Another development of elements with a larger diameter allows a factor 4.3 increase in membrane area to almost 1725 feet square, and by this allows significant savings.

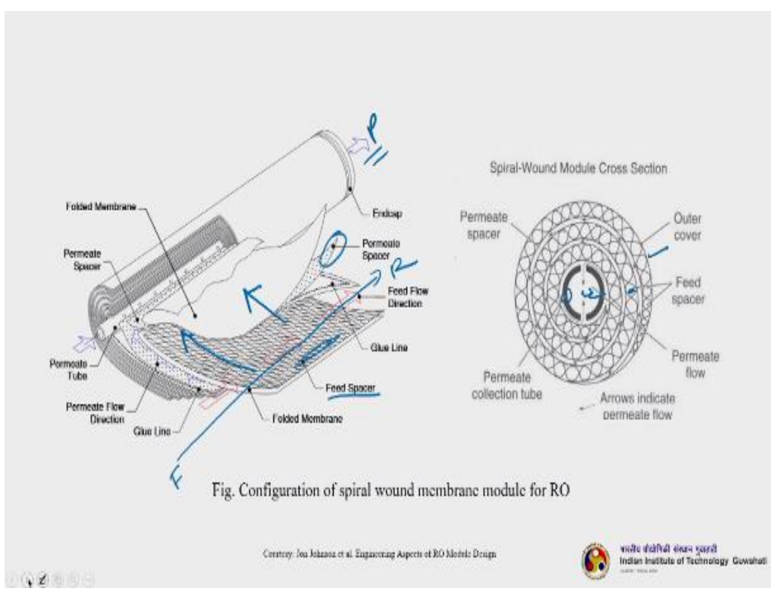
(Refer Slide Time: 42:24)



So furthermore the maximum operating pressure per spiral wound elements was 69 bar close to 1000 psi, in the past recent improvements in the membrane stability and permeate spacer technology of some manufacturers increased the maximum pressure to 82.7 bar to 1200 psi. Recent achievements as well as continued development of spiral wound module design is contributing to significant cost savings in the RO technology.

Now, it appears to make this technology even more widely available for sustainable and affordable water production in many parts of the world.

(Refer Slide Time: 43:01)



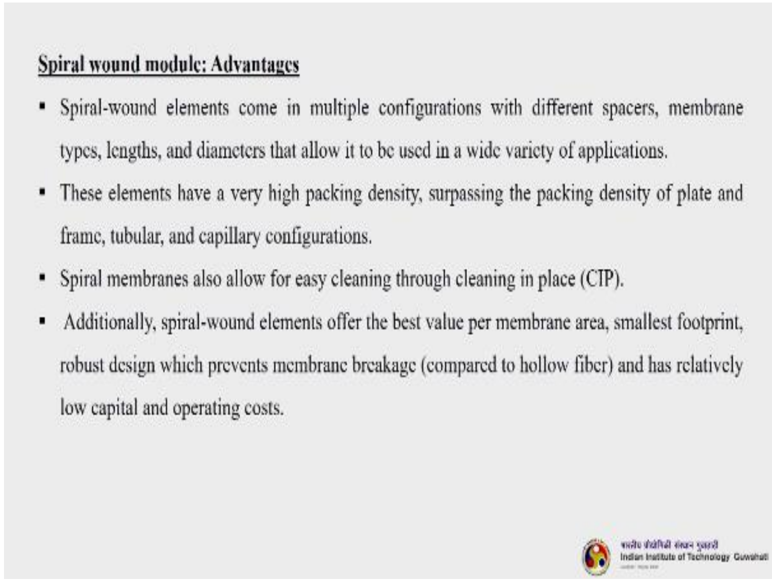
Let us understand and quickly go through have seen this earlier also. So when we discussed the modules, but again it is better to understand with respect to RO. You can understand that how the spiral wound is that, imagine that you are having the A4 size papers, which you are folding, we are just wrapping it like this, we are folding it okay? So within two membrane and two A4 size sheets, you have a fixed spacer okay?

So this you can see this channeling type of spacer is seeing here, so this is you have feed spacer usually they are made up of some very maybe stainless steel or some other metal alloys okay? then they are wrapped it right? So once it is done one that that is done that wrapping is done then you have to attach permeate spacer you can see this is a permeate Spacer here okay and this is a central permeate tube.

So there is a center tube like this over which you are wrapping, this one of holding the membranes as well as the feed spacer to that. So, the job of feed spacer is to distribute the feed across the entire membrane. So that there is no dead space available in the membrane of the entire area should be utilized okay? So the feed actually flows like this in this direction, okay? So you get retentate here, right?

So this is feed flow however permeate is flowing in this direction, okay? So you get our permit here. You can see this is the spiral wound module cross section. Okay, so this is the permeate tube, okay inside of the permeate tube, through is the permit is getting collected and you are getting here. Okay? And you can see how the cross section looks like this is the outer cover, and this is the feed spacer here and this is the permeate flow what is happening here and this is the permeate collection tube.

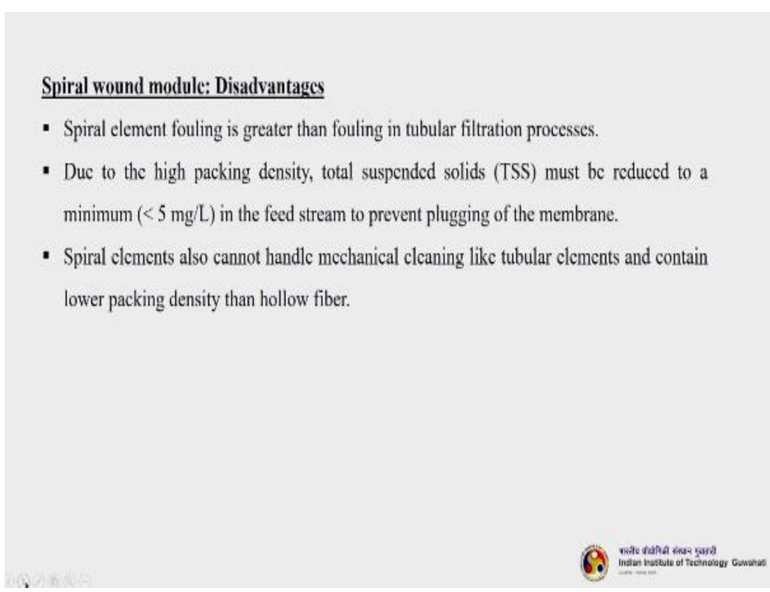
(Refer Slide Time: 45:00)



So spiral-wound elements come in multiple configurations with different spacers, membrane types, lengths and diameters that allow it to be used in a wide variety of applications. These elements have a very high packing density, surpassing the packing density of plate and frame, tubular, and capillary configurations. Now spiral membranes also allow for easy cleaning through the cleaning in place technology.

Additionally spiral-wound elements offer best value per membrane area smallest footprint, robust design, which prevents membrane breakages with respect to or if we compare it to the hollow fiber systems, and it has relatively low capital and operating cost.

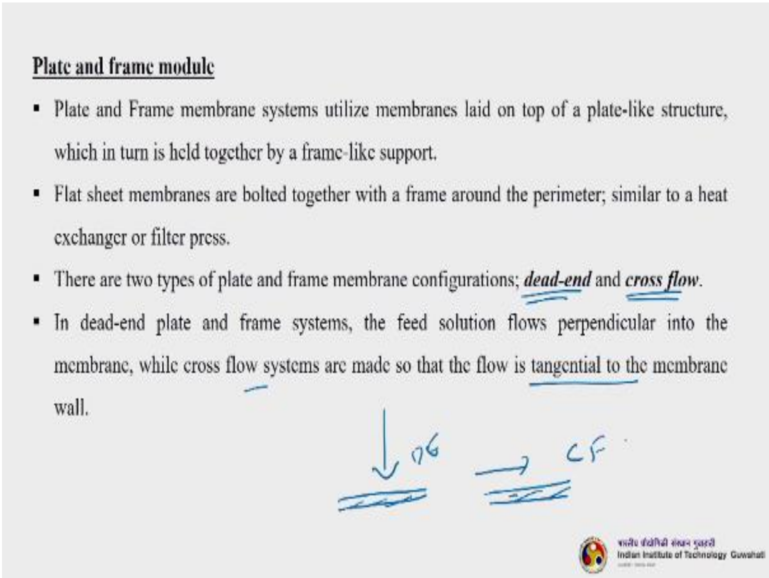
(Refer Slide Time: 45:35)



However, they have certain disadvantages also. So spiral element fouling is greater than the fouling in other tubular systems. So, due to the high packing density. The TSS that is the total suspended solids must be reduced to a minimum of less than 5 milligrams per liter in the stream to prevent plugging. Now we just discussed the TSS handling is far better in tubular systems. Okay, which is not so in spiral systems.

So spiral elements cannot handle mechanical cleaning like tubular elements and content lower packing density than hollow fibers.

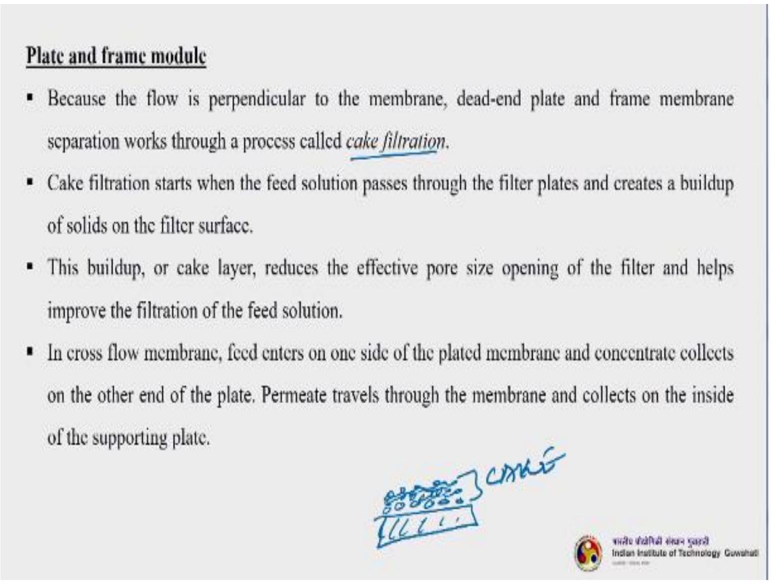
(Refer Slide Time: 46:08)



Now next category is plate and frame modules. Plate and frame module membrane systems utilize membranes laid on the top of a plate like structures which in turn is held together by a frame like support. Now, flat sheet membranes are bolted together with a frame around the perimeter, similar to a heat exchanger filter press. If you have seen the filter payment filter press in the labs.

Usually it is being shown in the mechanical operations lab. Okay. So, there are two types of plate and frame module possible one is dead end and another is cross flow. So in dead end plate and frame system, the feed solution flows perpendicular. Okay, whereas in cross flow systems, it is tangential, to this we know. So this is actually how the feed is flow in dead end. And this is how the plates, this is the membrane. Okay. And this is dead end that right. And this is how it happens in cross flow.

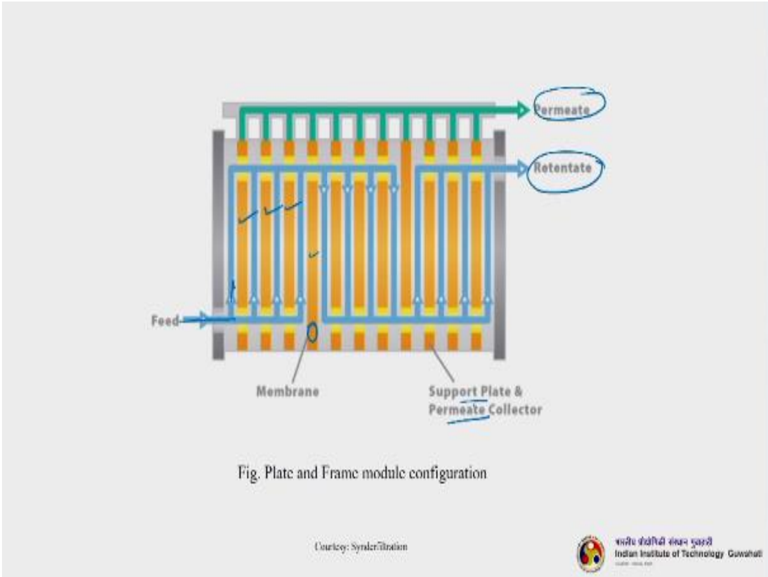
(Refer Slide Time: 47:08)



Because the flow is perpendicular to the membrane dead end plate and frame membrane separation works through a process called the cake filtration in the dead end system actually. So the cake filtration starts from the feed solution passes through the filter plates and creates a buildup of the solids on that surface so basically on the membrane. You have cake start to build up this some sort of concentration and polarization is happening. Okay.

Then when it grows the layer grows, so you will get a cake plate. This build up or a cake layer reduces the effective pore size opening of the filter and helps improve the filtration of the feed solution. Cross flow membranes, feed enters on one side of the plate and can call it a membrane and concentrate gets collected on the other side of the plate. Okay, so permeate travels through the membrane and collects the inside of the supporting plate.

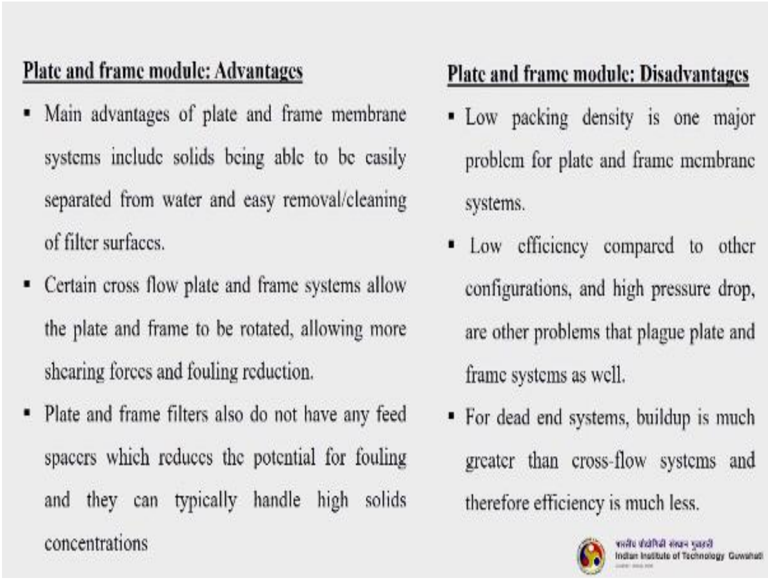
(Refer Slide Time: 47:59)



So this is how a plate and frame configuration looks like, so these colors. Actually, that is membrane material so this is membrane. Right. And feed is entering and it is generally you can see how it getting flow, the feed flow. Once it comes here across this three membrane system 1,2,3. Okay. Another membrane and then it goes and flow likes this, then again it goes so you get retentate here, and over all permeate here.

So then there are support plates and permeate collectors inside that, it is a very easy system, easy to manufacture also and easy to handle also.

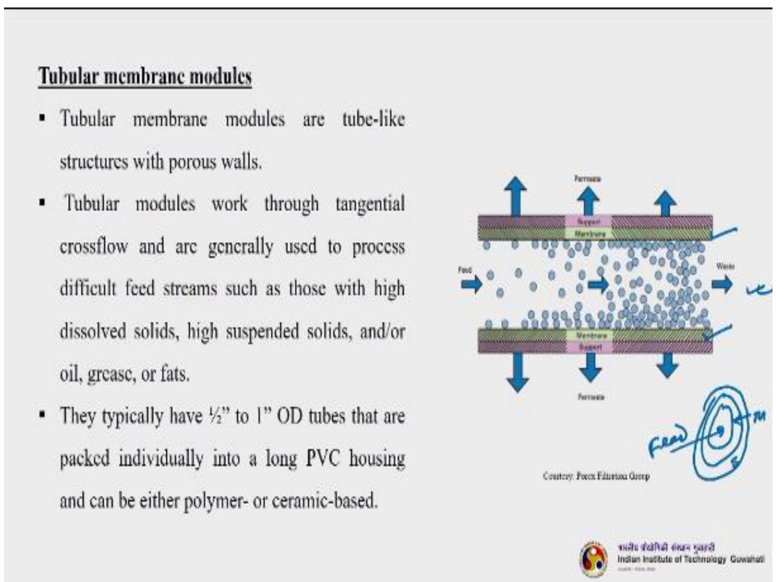
(Refer Slide Time: 48:37)



So, the main advantage is that it includes solids being able to solids being able to easily separated from water and easy removal and cleaning of filter surfaces. So mechanical cleaning is very easy. So certain cross flow plate and frame systems allow the plate and frame to be rotated, allowing more shearing forces and fouling reduction. Plate and frame filters also do not have any feed spacers, which reduce the potential for fouling, and they can typically handle high solids concentrations.

So the disadvantage is that low packing density is one of the major problem, and low efficiency compared to other configurations and high pressure drop other problems that plague and plate and frame system as well, and for dead end systems build up is much greater than the cross flow systems and therefore efficiency becomes lesser.

(Refer Slide Time: 49:27)

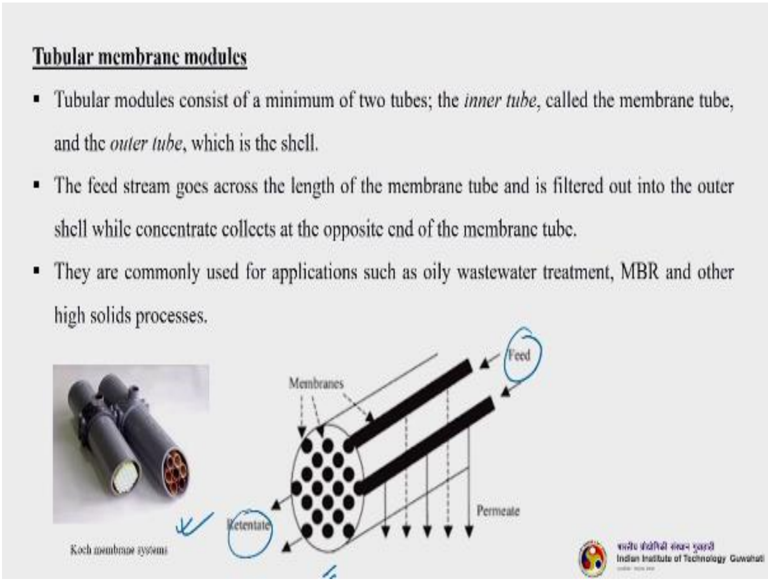


So next was the tubular membrane modules. So in the tubular system the membrane models are like tubular structures with porous one, so you can see how it happens, so this is single tube okay you can see this is actually the, this is your membrane. Okay. Right. And you can understand this, okay so the You can see this the call this area is this member. Okay, then above that, there will be support layer. So this is your support layer.

And this is Okay, the lumen through which your feed is flowing. Right, so the permeate is coming outside of the, this one support okay in both sides and the waste or reteneate are intended is being collected and the Fed end of the tubular systems. So, this is, this was the tangential cross flow, generally used to process difficult questions such as those with high dissolved solids, so high suspended solids and oil, grease or fats.

So that with cumulus systems are one of the superior systems, because they can handle high DPS high TSS and oil, grease beds, whatever it is, present they can handle it, but a spiral-wound cannot handle all systems. Even plate and frame also has difficulty because of the easy buildup of catalytes there. So that typically have 1/2 inch to 1 inch OD tubes that have been individually packed into a long PVC housing, and can either be polymer or ceramic-based.

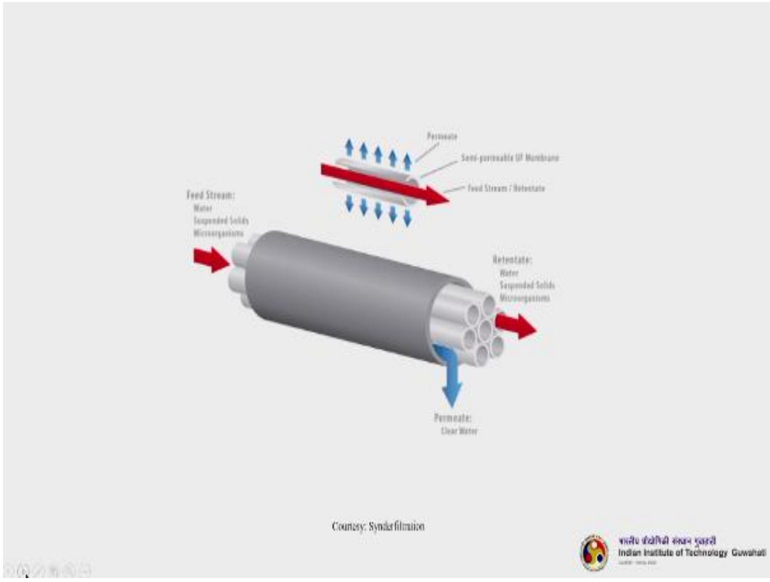
(Refer Slide Time: 50:57)



This is how it looks like you can see how the feed is entering here. This is a cross section. Okay. permeate is coming out of the porous this one, and retentate is coming this side. So feed entering one side of the tube retentate is getting collected, and other side of the tube. You can see this is these are developed by the courts membrane actually. So tubular modules consist two tubes one is the inner tube and another is outer tube, which is the sell side. Okay.

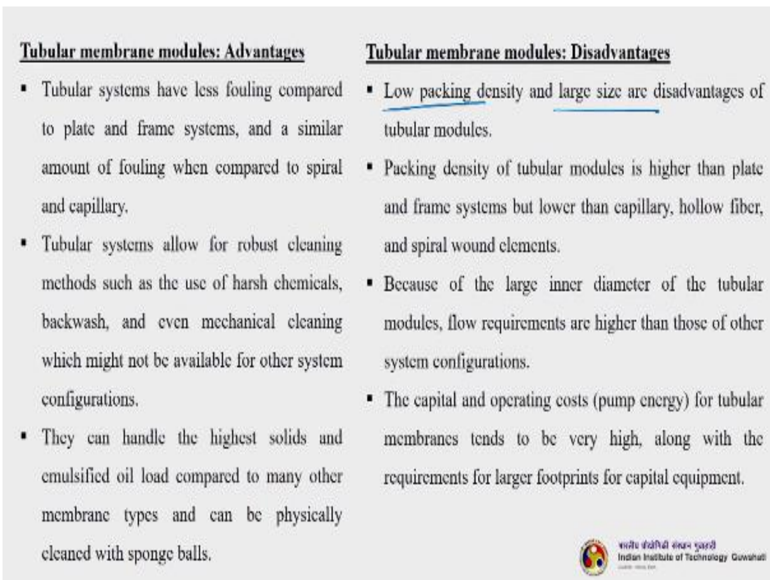
So the feed stream goes across the length of the membrane tube and is filtered out into the outer cell, while concentrate collects at the opposite end of the membrane tube. They are commonly used for applications such as oily waste water treatment membrane bioreactor and other high solid processes.

(Refer Slide Time: 51:42)



This is another just a little better understanding or view you can see this you can refer it later. So,

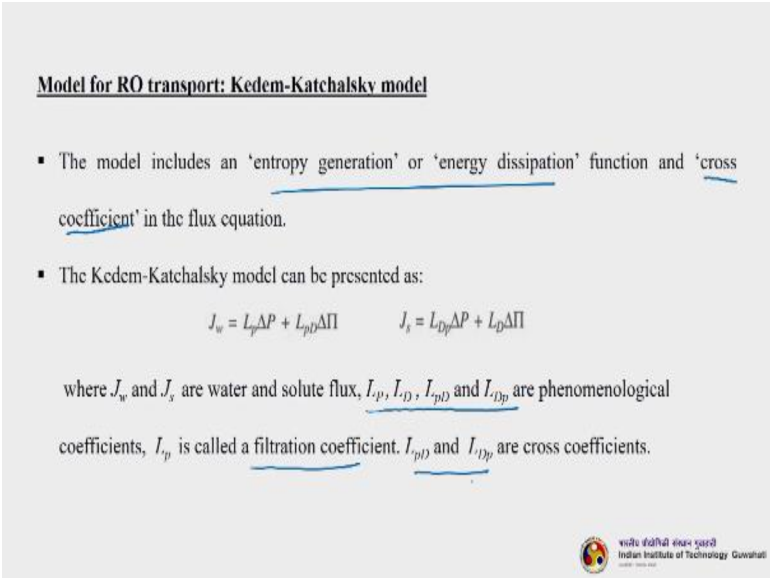
(Refer Slide Time: 51:50)



Let us go ahead and understand their advantages and disadvantages. So tubular systems have less fouling compared to plate and frame systems. Okay, develop systems allow robust cleaning methods, such as use of harsh chemicals backwash and even mechanical cleaning is also possible that can handle high solids, this we have already discussed, they can handle the highest TSS, TDS and emulsified oil also.

The disadvantage is low picking density in large size right? So, carrying and transportation also as a problem. Packing density of tubular membrane is higher. And because of the large inner diameter of the tubular models flow requirements are higher than those of the system configurations, the capital and operating cost for tubular membranes tends to be very high. Along with the requirement of the larger footprint capital equipment.

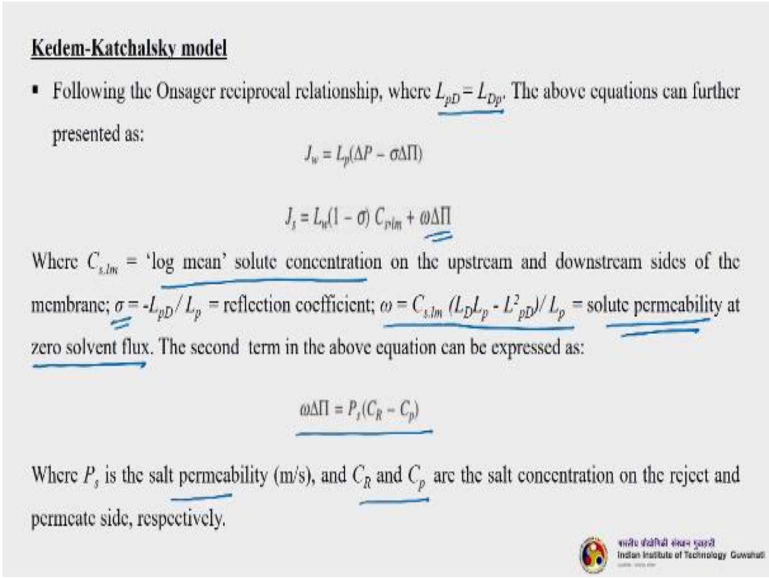
(Refer Slide Time: 52:40)



So let us quickly understand the different types of models for the RO transport. So the first one is the Kedem-Katchalsky model. So the model includes entropy generation, or energy dissipation function, and cross coefficient, we have discussed cross coefficient in our transport. Okay. Onsagar reciprocal that we have discussed, right? So, we can write the equation of the water flux as well as salt flux like this.

So Jw is the water flux is Lp delta P + L p D delta pi, and salt flux Js equal to a constant L d P delta p + LD delta pi. So Jw and Js of the water and salt flux L p, LD, L p D and L d P are phenomenological coefficients, LP is called the filtration coefficients L p D, L d P are the cross coefficients.

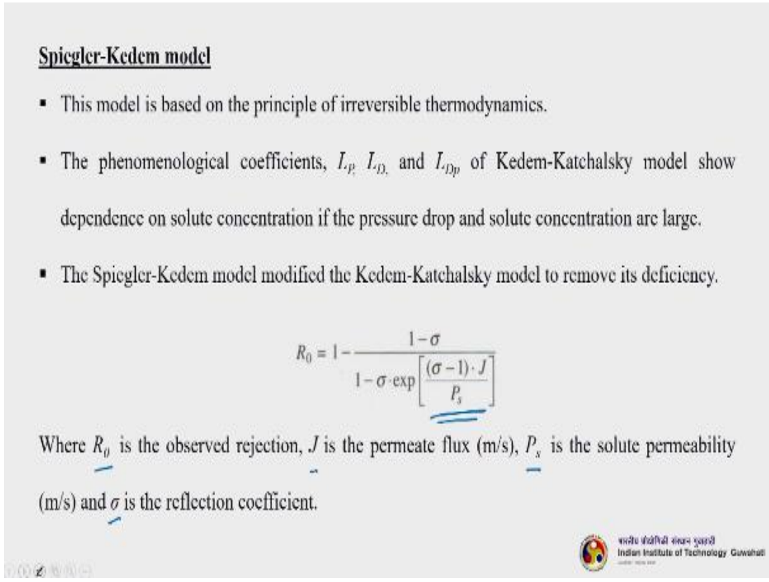
(Refer Slide Time: 53:28)



Now, as we know this Onsagar suggested that the cross coefficients are equal. So L p D equals two L d P. So we can rewrite the equation at water flux equals to L p delta pi - sigma delta, delta p - sigma delta Pi, and salt flux equals to Lw into 1 - sigma Cs,lm + omega delta Pi. Now, what are these terms? Now Cs,lm is the Log Mean solid concentration on the upstream and downstream sense of the membranes sigma. Okay,

Which is called also the reflection coefficient, is minus L p D by L p, and omega equals to Cs,lm, they buy into L d P, L p - L squared p d divided by L p, so this is actually solid permeability at 0 solvent flux right. So the second term in the above equation can be expressed as this, this actually omega Delta Pi, we can write as Ps to Cr-Cp, now Ps is the salt permeability Cr and Cp are the salt concentration on the reject and permeate sides respectively.

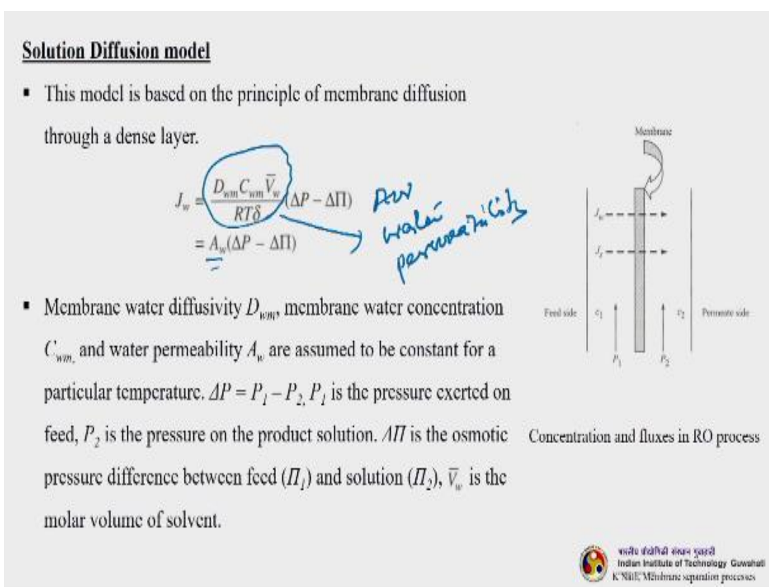
(Refer Slide Time: 54:32)



So the next model is Spiegler and Kedam model. Now this model is based on the principle of irreversible thermodynamics. The phenomenological coefficients Lp, Ld, Ldp of Kedem-Katchalsky model, so dependendence on solute concentration if the pressure drop and solid concentration are large. So this model modified the Kedem-Katchalsky model to remove its deficiency.

So you can write the rejection equals to 1-1- sigma divided by 1- sigma exponential of this particular term. Okay? R0 is the observed rejection J is the permeate flux Ps is the solute permeability and sigma is the reflection coefficient.

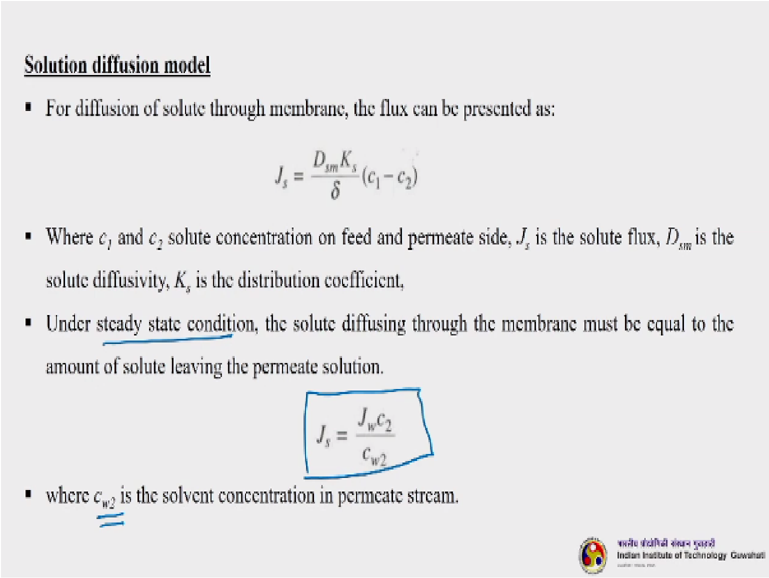
(Refer Slide Time: 55:09)



So the next one is a solution diffusion model. So this model is based on the principle of membrane diffusion through a dense layer so we have already discussed solution diffusion in detail so just quickly go through this, the equations Jw equals to D w m C w m divided by RT delta then delta P – delta pi, this can be written as Aw these are actually constants can be grouped together.

Now what is A w, so A w actually is the water permeability so A w is water permeability so that is actually all these parameters are constant so this is actually what we grouped as water permeability. So D w m is the membrane water differentiability and C w m is the membrane water concentration and delta p equals to P1-P2 delta Pi is the osmotic pressure difference between feed and solution, V w is the molar volume of the solvent.

(Refer Slide Time: 56:09)



So you can see that we can write the salt flux equals to D s m Ks by del into C1-C2, C1-C2 is a solute concentration on feed and permeate side , Js is the solid flux, D s m is the solute diffusivity, Ks is the distribution coefficient. So under steady state condition the solute diffusing through the membrane and must be equal to the amount of solute leaving the permeate solution.

So listen, so we can write, solid flux equals to Jw C 2 divided by c w 2, so C w 2 is the solvent the solvent concentration in the Permeate stream, so we understand, we have already discussed solution diffusion in general we have to learn the equations for that RO specific solution diffusion model. Okay?

(Refer Slide Time: 56:52)

So we came to the conclusion of today's lecture. So these are the text and references, mostly it was taken from this book today K Nath, and even this one, Richard Baker and Mulder okay so you can refer all this books for your reading purposes. So thank you very much so I wind up today and the next lecture will.

(Refer Slide Time : 57:15)

Focus on the advantages of the RO fouling things, the various applications of RO, and pressure retarded osmosis, one of the most beautiful modified RO systems, actually. Okay. And if you have any queries, do feel free to write to me at kmohanty@iitg.ac.in. So Thank you very much..