Downstream Processing
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Lecture - 5
Problems in Mass Balance, Flow Sheet

Today we are going to do only problems. Doing problems related to mass balance heat balance and separations help you to understand the various concepts in downstream processing. Downstream processing as I explained in the previous class is design of the cycle time, design of the dimensions of the vessels, deciding on the operating conditions like temperature, pressure, ph, flow rates and so on. So, you need to do problems, then only you will be able to understand the concepts.

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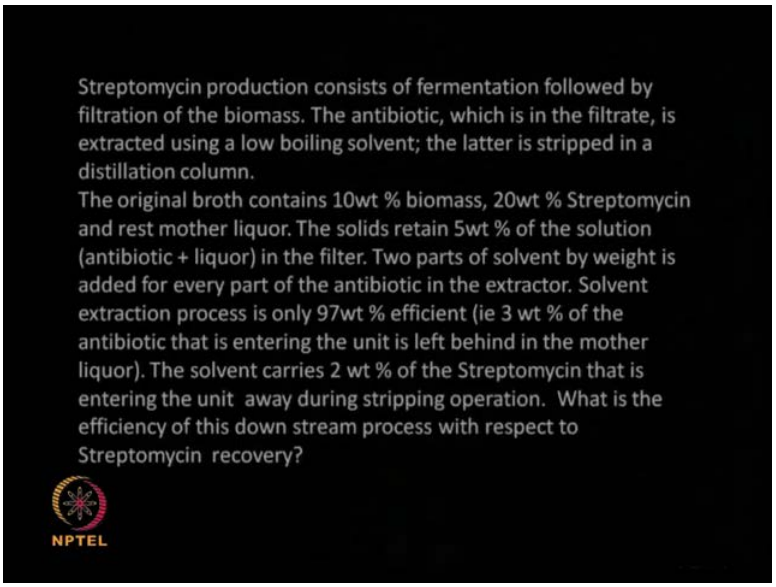

Let us look at the first problem. So, you have an antibiotic produced in a fermentor and then you are recovering and purifying the antibiotic. So, the very first step in downstream generally after the fermentation is to remove the biomass because you will find lot of cell debris, biomass salts and so on. That needs to be removed first before you actually go into extraction or purification. So, the very first step after the fermentation is the filtration.

After the filtration, what they do is they are adding a low boiling solvent to extract your antibiotic streptomycin. Then, you can use a distillation column to remove the solvent.

So, the streptomycin will be left in the bound and the solvent can be again recycled. It can be fed into the extractor to once again remove the streptomycin. So, this is the entire process.

So, you have a filtration, you have an extraction, you have a distillation. So, each step, it is going to have some efficiencies. It is definitely not going to be 100 percent, but it will have very good efficiencies. So, the idea is to determine what is the total efficiency of the entire process, the downstream process? So, the original broth contains 10 weight percent biomass, 20 weight percent streptomycin and rest mother liquor that is the liquid. So, we are interested in this particular product.

So, once you filter, the solids are going to be held in the filtration unit and the liquid passes through it, but the solids are not going to be totally dry. So, obviously it will retain some solution, 5 percent of solution here. That solution contains both antibiotics and liquor. So, some antibiotics are going to be lost in the solids. Then, it goes to the extractor where you are adding some solvent and extracting your antibiotic.

The extraction is not very efficient because 3 weight percent of the antibiotic that is entering the unit is left behind in the mother liquor. That means only 97 weight percent of the antibiotic entering the extractor is taken up by the solvent and 3 weight percent of the antibiotic that is entering the extractor is left behind by the mother liquor.

So, we have lost here 3 percent. Now, the solvent is taken to a distillation column. There is something called stripping taking place in the solvent generally because it is a low boiling solvent comes at the top of the distillation column and the bottom will have your product streptomycin.

Now, when the solvent is getting evaporated, it carries little bit of streptomycin that is about 2 weight percent of streptomycin that is entering the stripper is taken away by the solvent. So, again you are losing some streptomycin. So, you have lost streptomycin in three stages. One is in the filtration. So, the filtrate liquid is lost in the biomass, 5 weight percent of the liquid is lost in the biomass, which will contain some antibiotic.

Then, during the extraction process, 3 weight percent of the antibiotic is taken away by the mother liquor. Only 97 weight percent is coming out in the solvent extraction. Then, when you do the solvent stripping, 2 weight percent of the streptomycin is taken away by

the solvent which you are distilling off. So, the goal is to find out what is the efficiency of this entire downstream operation.

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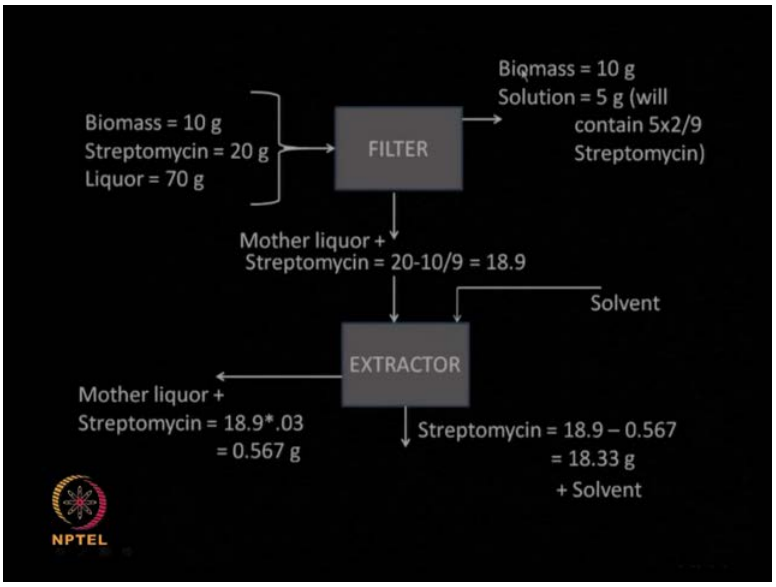

So, let us draw flow charts of each of the downstream operation. So, you assume a filter because it is 10 weight percent, you have 10. Suppose you take 100 grams of the total mother liquor will have 10 grams of biomass, 20 grams of streptomycin and remaining is the liquid that is 70 grams. Now, when you do the filtration, the biomass is completely removed, 10 grams, but it is retaining 5 weight percent.

As it is shown here, it is retaining 5 weight percent. So, what happens? 5 weight percent of the solution is lost in the biomass. Now, these 5 grams will contain both streptomycin and liquid. So, two by ninth of this 5 grams will be streptomycin. Understand? 7 by 9 grams will be the liquid. So, the amount of streptomycin lost here is 5 into 2 by 9.

So, what is coming down after the filtration, will be 20 minus 5 into 2 by 9 that is 10 by 9. So, that comes to 18.9 grams. So, in the filtration process, we have lost some streptomycin and we are getting only 18.9 grams. Now, this goes to the extractor and in the extractor, you are adding a solvent. There is a liquid, liquid separation the mother liquor goes away here. The streptomycin with the solvent comes out here. Depending upon whether it is a low boiling I mean low molecular weight solvent or a high density solvent, the solvent layer may be either at the top or at the bottom.

So, according to the problem, we are saying that 3 weight percent of the antibiotic is taken away by the mother liquor. That means the efficiency of the extraction is only 97 percent, 97 weight percent. So, the 18.9 and 3 percent that is 0.03, when you multiply, you get 0.567 grams. So, 0.567 grams goes away with the mother liquor and you are not able to extract that. So, whatever is coming in the solvent will be 18.9 minus 0.567 that is 18.33 grams. So, after the extraction, you are getting 18.33 grams of the antibiotic in the solvent layer. So, you notice, you start with 20 grams. Then, after the filtration, you end up with 18.9 grams and after the extraction; you are left with the 18.33 grams.

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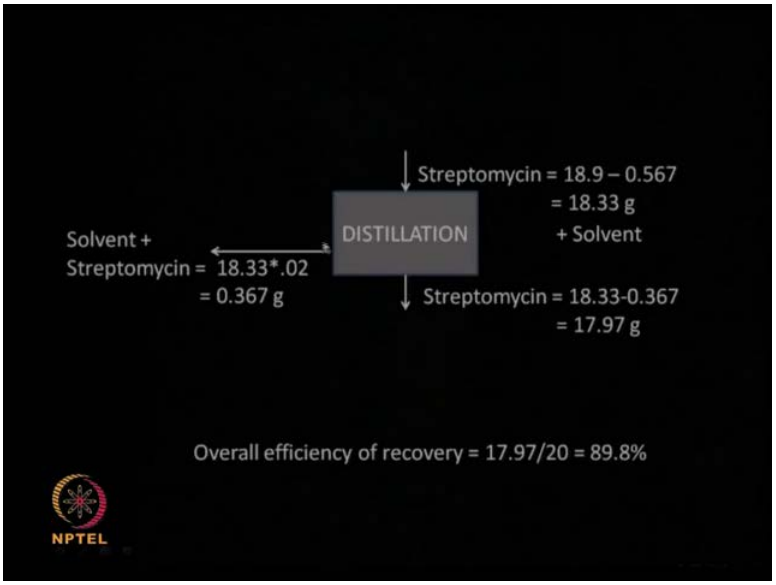

Now, this enters a distillation column, where the solvent is distilled out and the remaining is this streptomycin. Now, according to the problem, if you remember 2 weight percent of the streptomycin that is entering the unit is taken away by the solvent. So, the solvent when it is getting distilled takes away 2 weight percent of the streptomycin that is entering the distillation column. So, what happens? I will take 18.33 into 2 percent that comes to 0.367. So, whatever is left behind is 18.33 minus this 0.367. So, that comes to 17.97 grams. Understand?

So, you started with 20 grams of streptomycin in the mother liquor after fermentation. Then, you have a filtration where some liquid is lost with the biomass. So, some streptomycin is lost. Then, you have an extraction where the solvent is able to remove only 97 percent of the streptomycin. So, remaining 3 percent is lost. Then, after that

when you do the distillation, 2 percent of the streptomycin is taken away by the distillation process. So, only 17.97 grams of streptomycin you are able to recover in hand.

So, you started with 20 grams and you are ending up with 17.97 grams. So, the overall efficiency is 17.97 divided by 20, so approximately 90 percent. So, you see three steps, you have the filtration, you have the extraction. Then, you have the distillation. So, you are ending up with 90 percent efficiency. That means 10 percent of the streptomycin is lost during this process. So, this is a very useful problem to look at.

So, it tells you the efficiencies of downstream and whatever is the value, you do not end up with what you generate in your fermentor, but you end up with much less then what you generate in fermentor because each step has certain efficiencies. That means in each step, you are going to lose some product. The more you lose; your profit margin goes down more. The more you recover; your profit margin goes up. So, you need to keep that point in mind, if you want to improve your profit margin, your efficiency of each one of the downstream steps has to be extremely good. Now, let us look at another problem.

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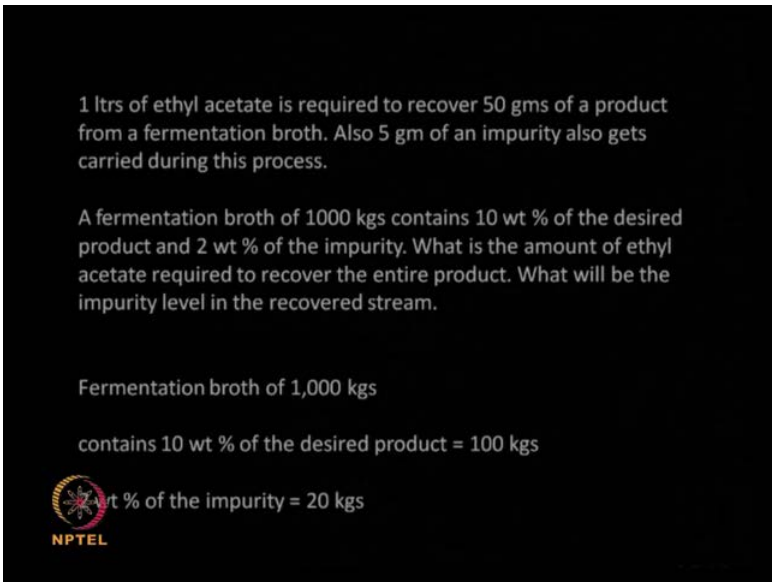

You have 1 liter of ethyl acetate and it can recover 50 grams of a product. So, it is something like a partition coefficient that means 50 grams of a product can be taken up

by 1 liter of ethyl acetate in a fermentation broth. But, ethyl acetate can also take 5 grams of an impurity that also can get carried away. So, if you have 1 liter ethyl acetate and you try to recover 50 grams, you will end up recovering 5 grams of impurity also. You cannot help it. Now, you have a fermentation broth 1,000 kilograms, which contains 10 weight percent of the desired product and tw2o weight percent of the same impurity.

So, what is the amount of ethyl acetate I will require to recover the entire product? What will be the amount of impurity that will also be coming into my extraction? So, suppose I take 1000 kilogram of the fermentation broth, so 10 weight percent that means I have 100 kilogram product 10 divided by 100 into multiplied by 1000 obvious. So, you have 100 kilogram of the product in 1000 kilogram of the fermentation broth. Now, 2 weight percent impurity that means I have 20 kilogram of impurity. So, this fermentation broth, 1000 kilogram fermentation broth contains 100 kilogram desired product, 20 kilogram impurity.

Now, I need to find out how much of ethyl acetate I require to recover all the 100 kilogram. Now, this is given in this first line. 1 liter of ethyl acetate is required to recover 50 grams of product. So, for 100 kilogram of product to be recovered, how much ethyl acetate I need? It is straight forward.

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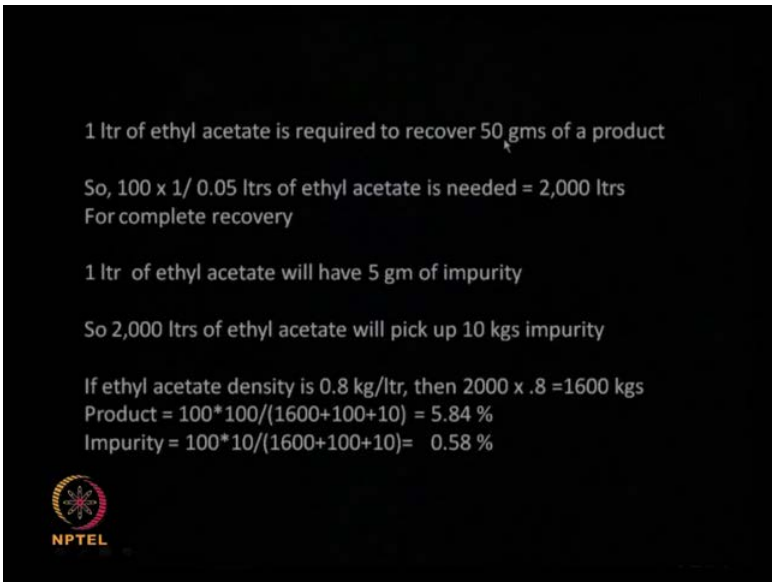

So, we look at the next slide. 1 liter of ethyl acetate is required to recover 50 grams of the product. So, I need to recover 100 kilogram of ethyl acetate, 100 multiplied by 1 and 50

grams when you convert into kilogram, 0.05. Agreed? So, you need 2,000 liters of ethyl acetate to recover this 100 kilogram of the product from the fermentation broth. This is a theoretical value actually. This is an ideal condition. Generally, there is always efficiency.

You might not be able to, even if you add 2,000 liters; you might not be able to recover all the 100 kilograms because of real partitioning, because of miscibility problem, because you do not give enough time for the solvent to really come in complete contact with the product. Generally, if your contact time is very little, all the solute or the product is not extracted. So, you might not get it, but this is a theoretical ideal situation. So, you need 2,000 liters of ethyl acetate to recover all the 100 kilogram of the product.

Now, if you remember, the problem says 1 liter of ethyl acetate will also have 5 grams of impurity, 5 grams of impurity. So, when I take 2,000 liters of ethyl acetate, what will happen? I will end up with 2,000 liters into that will be, so 10 kilograms of impurity will get carried away by the ethyl acetate. Understand? This is because 1 liter of ethyl acetate will have, will be able to pick up 5 grams of impurity. So, if I have 2,000 liters of ethyl acetate, I will end up having 10 kilograms of impurity. So, my 2,000 liters of ethyl acetate will have 100 kilogram of the product and 10 kilogram of the impurity.

So, what is the percentage if I calculate, product 100 divided by 1000, ethyl acetate density if you take 0.8 kilogram per liter, then 2,000 liter will give me 2,000 into 0.8 that gives 1,600 kilogram. So, 100 divided by 1,600 plus 100 kilogram is the amount of product plus 10 kilogram is the impurity. If you multiply by 100, you get 5.84 percent and then. Similarly, for the impurity, 10 divided by 1,600 plus 100 plus 10 multiplied by 100, you get 0.58 percent. So, my ethyl acetate solvent will have 5.84 percent of the product and 0.58 percent of the impurity.

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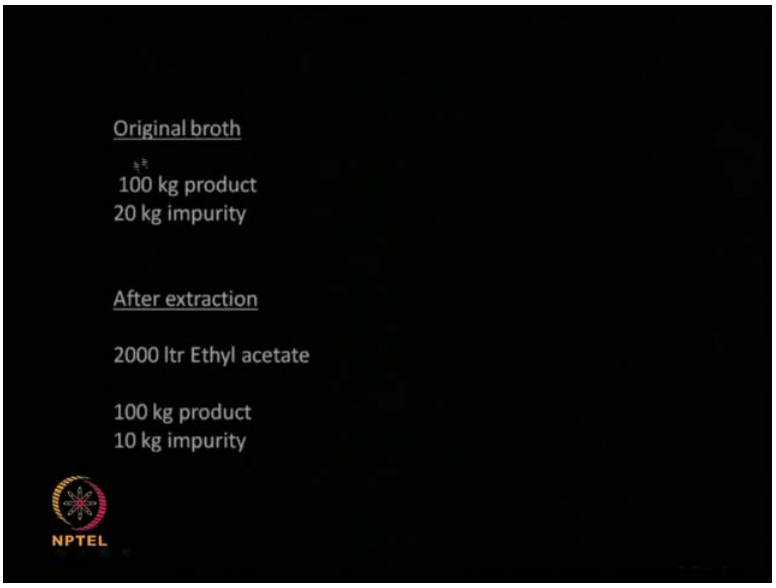

So, originally, my original broth had 100 kilogram product and 20 kilogram impurity. Now, after extraction, when I put 2,000 liters of ethyl acetate, it will have 100 kilogram product and it will have only 10 kilogram impurity. So, you see that I am able to reduce the amount of impurity that is present that is in contact with my real product. So, I can do this type of extraction and bring down the quantity of the impurity further and further down. So, that is the whole idea of concept of extraction and that determines based on the partition coefficient.

So, the product has higher partition coefficient, whereas the impurity has lower partition coefficient. That is why; I am able to start with 100 kilogram product, 20 kilogram impurity to 100 kilogram product, 10 kilogram impurity. Understand? So, this is a problem very typical of extraction systems where I need to calculate what should be the quantity of solvent I will require to extract my product of interest. What will happen to the impurities present in my fermentation broth because impurities are also going to get extracted? It is not that only my product will get extracted, impurities also will come depending upon the partition coefficient.

So, there is always going to be some impurity present in my final extraction. So, you need to select the best solvent so that there is a large difference in the partition coefficient between the product and the impurity present, but in real life, you may have many impurities present. So, in this particular problem, we talked about only one

impurity, but in real life, you may have many several impurities present and that is much more challenging. Some impurities may have partition coefficient almost close to your desired product. Then, extraction might not be the best way to do the downstream or purification.

You may have to resort to some other technique. If the partition coefficients are largely different, then extraction is a good method in this particular problem. If you see, you had 50 grams of product taken in by 1 liter ethyl acetate, 5 grams of impurity taken in by 1 liter ethyl acetate that means there is a difference in the partition coefficient by an order of magnitude, ten times difference.

So, extraction is a good method, but if this impurity solubility is higher, then you will get lot of impurity also taken in with the product. Then, we may have to go to some other way of a purifying the product and removing the impurity from the product. So, it is not that extraction is the only way of a purifying the product. You may have to try different techniques and different methods.

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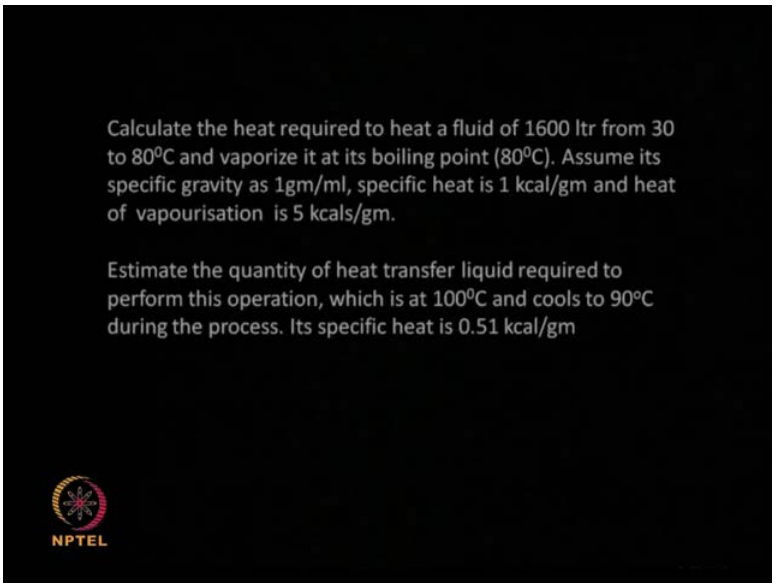

Now, having looked at two different mass balance type of problems, let us look at a heat balance problem. This is also very relevant when you are using a heating of a fluid, when you are vaporizing a fluid, when you are performing a fermentation type of a process where the reactions are carried out at a higher temperature. Then, you need to calculate that what is the amount of heat required to heat a fluid, amount of heat required to

vaporize a fluid? Then, also calculate what should be the quantity of the heating fluid required? If you are using hot oil, then I would like to know what should be the hot oil quantity.

So, this problem deals in that fashion actually. So, imagine we have 1,600 liters of a fluid. You want to heat this fluid from 30 to 80 degree centigrade. Then, we would like to vaporize it because the boiling point is 80 degree. So, two things are happening. We are raising the temperature of the fluid from 30 to 80 and then we are vaporizing this fluid at 80 degrees. So, there are two types of heats there. One is the sensible heat. The other is the heat of vaporization.

Now, certain physical properties of this fluid are given. Specific gravity is 1 gram per ml or 1 gram per cc, specific heat is 1 kilo cal per gram and the heat of vaporization is 5 kilo cals per gram. So, estimate the quantity of heat transfer liquid required to perform this operation. Now, the heat transfer liquid is at 100 degree centigrade and when it is heating this and vaporizing this fluid, it is cooling down to 90 degree centigrade; may be it is being performed in a vaporizer. The specific heat of this particular heat transfer fluid is 0.51 kilo cals per gram.

So, our goal is to find out how much heat is required, if I want to heat a fluid of quantity 1,600 liters from 30 degrees to 80 degrees and vaporize it. Then, calculate how much heat transfer fluid is required, whose property is given here, 0.51 kilo cals per gram. When it is heating the fluid, it is getting cooled from 100 degrees to 90 degree centigrade. So, this is losing heat and this is gaining heat. So, we need to do a heat balance in this particular case. Understand?

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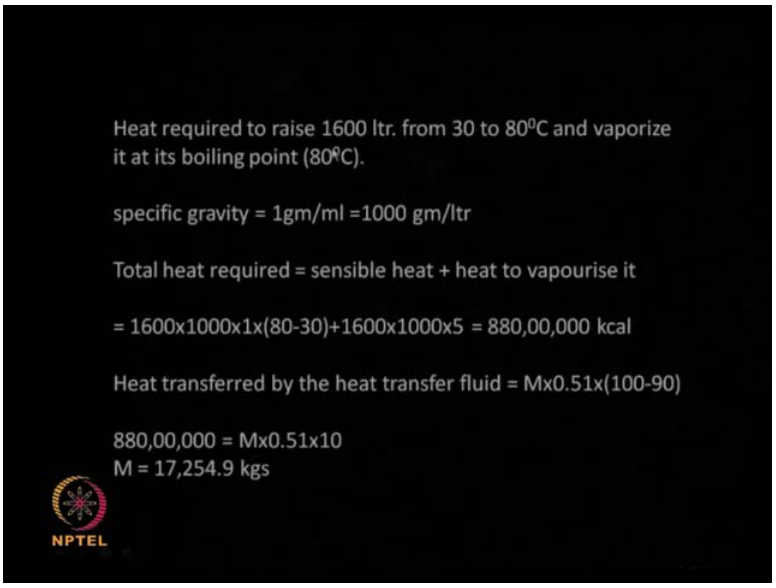

Now, heat required to raise 1,600 liters from 30 to 80 degrees and vaporize it at its boiling point, which is at 80 degrees. Now, specific gravity is 1 gram per ml. That means it is 1000 grams per liter because 1000 cc is equal to 1 liter. Now, total heat required is made up of two terms. One is called the sensible heat. The other is called the heat to vaporize it. Now, the sensible heat is nothing, but mass into specific heat into delta t that means the rise in temperature, 30 to 80 degrees.

So, mass 1,600 liter into specific gravity 100 grams per liter that gives your mass specific heat is 1 kilo cal per gram. So, 1 multiplied by 80 minus 30, so this is the sensible heat part of it, this is the heat of vaporization. So, again 1,600 into 1000 into heat of vaporization; heat of vaporization is 5 kilo cals per gram. So, 1,600 into 1000 into 5, so that is come to a big number like this 880, 00,000 kilo cals. This is the amount of heat required to heat 1,600 liter fluid from 30 degrees to 80 degrees and then vaporize it at 80 degrees.

Now, we need to calculate how much of heat transfer fluid is required. Now, the property of the heat transfer fluid is it has got a specific heat of 0.51 kilo cals per gram. During the process, it is getting cooled from 100 degrees to 90 degrees. So, what do I do? I do same mass balance, mass into specific heat into delta t. Specific heat is 0.51, delta t is 100 minus 90, mass will be in so many grams. So, I equate this with this. So, here we are

neglecting heat lost to the surroundings and so on actually. So, there could be some heat lost. Generally, we take about 10 percent heat lost, but we will neglect in this problem.

So, you are equating this term with this term. After that, you calculate M. So, M will become, you divide by 10, you divide by 0.51, you will end up with this particular number. If you convert that into kilogram, you will get 17, 255 kilograms of heat transfer fluid is required to heat a fluid of quantity 1,600 liter from 30 degrees to 80 degrees and then raise it into its vapor.

So, this is a typical heat balance problem, where you are balancing the heat lost by the heat transfer fluid to the heat gained by the process fluid. So, you can have two, three fluids entering and you can have two, three fluids leaving. So, we can perform similar heat balance calculations and then we can calculate what is the amount of heat transfer fluid required.

Similar problem can be looked at when you are talking about a cooling in a condenser; we can again calculate what the amount of cooling water required is so that particular fluid can be cooled down from one temperature to another temperature. So, just like heating a fluid, we can also look at cooling a fluid, using cooling water, same approach. You put in the heat balance for the heat lost by the hot fluid and then equate it to the heat gained by the cold fluid. So, it is a typical heat balance calculation. Let us look at another problem.

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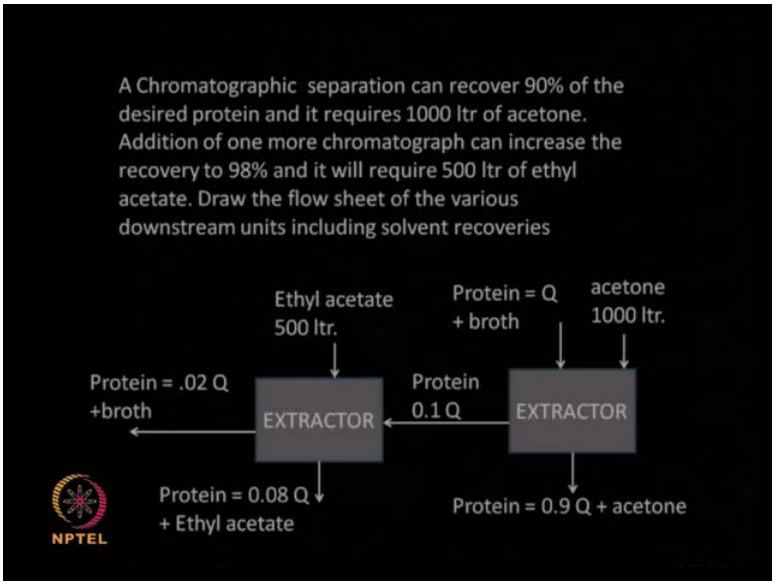

Again, this is an extraction problem. Generally, extraction is never done in one stage. You may do multiple stages. You may also resort to different extracting solvents. So, that is what this problem is about actually. So, imagine that you are using a extractor using acetone here and then you use another extractor where you are using ethyl acetate. So, 1000 liters of acetone is added here and the extraction efficiency is only 90 percent. That means it is only 0.9 Q.

If you start with the Q that is the amount of protein that is present, only 0.9 Q comes out with acetone. Agreed? So, that means 0.1 Q is lost. Now, what you do? You put in another extractor and now you are using ethyl acetate and you are using 500 liters of ethyl acetate to recover. Now, the extraction efficiency becomes 98 percent. That means only 2 percent is lost; whatever you started with, only 2 percent is lost here. So, you have 8 percent coming out with ethyl acetate fraction. Understand? So, you have 90 percent coming out with acetone fraction and you have 8 percent coming out with the ethyl acetate fraction.

So, the problem is to draw the flow sheet of the various downstream units including solvent recoveries. So, obviously it is going to have two extractors. First extractor is going to work using acetone as your solvent and the second extractor is going to use ethyl acetate as your solvent. So, generally it is called, these extractors are called mixed mixer settlers. So, what you do is you add a solvent; you mix it thoroughly with the mother liquor and then stop the mixing. Let it settle down, let it separate into two layers. So, you will have two layers.

If the solvent is heavy, solvent goes down at the bottom with your product and the mother liquor remains at the top. If the solvent is lighter, then it remains at the top with the solute and your mother liquor goes down. Then, after the layer separation takes place, you can separate both the layers. So, they are called mixer settlers. So, you mix the solvent and then you let it settle and separate the two layers. That is how the mixer settlers work. So, you have two extractors.

Now, how do you separate this protein from solvent? How you separate this protein from the solvent? So, obviously we cannot directly do a distillation because protein is not very stable at higher temperature. So, what do we do? May be there are so many different ways may be, we may try to use, may be salting out.

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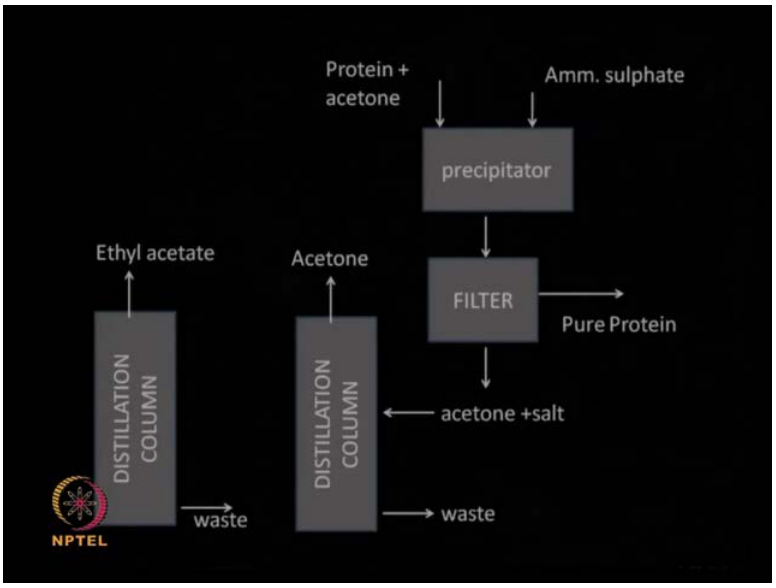

We can try think of precipitating the protein, but this is not the only solution. You may think of precipitation. You may think of using a membrane type of filtration. You may think of chromatography. You may think of so many different methods depending upon the physicochemical properties of the protein and the solvent. So, keep in mind. I am just showing a precipitation as a possible option by adding some salt, but that is not the only option.

You may go into a membrane depending upon the size of the protein or you may go into a chromatography depending upon the physicochemical properties of the protein. If the protein is hydrophobic, you may go into hydrophobic chromatography. If the protein has got certain specific sizes, you may go into size exclusion chromatography and so on actually. So, what you do is you here in this particular case, you may add a salt so that there is a difference in solubilities. So, your protein may precipitate out. So, if the protein precipitates out, what did you do? You can go to a filter. So, you can filter the protein. So, the liquid will contain the solvents salts and everything.

So, we can take out the pure protein. So, here I am talking about a possible suggestion of a using a salt to precipitate my protein. Then, I need to go for a filter so that my protein is removed. Then, the liquid will contain my solvent and the salt. So, if I want to purify the solvent, I may have to go for a distillation column, so distillation column. My solvent is a low boiler. So, it will come at the top and all the waste will go here. Now, I can take

this solvent. Again, I can go into the extractor and again I can extract my protein from the mother liquor.

So, here I may have to go for two distillation columns because I have used two different solvents for extraction. Keep that in mind. I have used acetone, I have used ethyl acetate. So, I cannot mix both the solvents into one distillation column. Then, there will be a problem of separation. So, I may have to go into two distillation columns. So, if you look at this flow sheet, we have extractors, two extractors, and two mixer settlers. Then, I may have to go for some way of separating the protein from the solvent, either using a precipitation type of technique or using a membrane or using a chromatography. Then, the solvent will contain other products, unwanted products.

So, you need to recover the solvent in distillation column and the waste goes at the bottom. This solvent can again go back to my extractor and again it can start extracting this protein. So, this is a typical downstream flow sheet. This is how it will look like. But, please remember that just because I have drawn one set of flow sheet does not mean this is how it needs to be done. You can always think in something different way and you may be able to come up with a different flow sheet. You may have different sets of unit operations that are being formed.

So, one can think about different ways of recovering the protein using different techniques. That depends upon the physicochemical properties of the protein, which you are recovering; the stability of the protein, presence of impurities or presence of other toxins or inhibitors presents and so on actually, viscosity density of the proteins and so on. So, depending upon all these properties, you may select different methods. Then, and when you have two or three different methods, you may look at the overall efficiency. You may look at the overall cost of the process and then make a final decision. So, you can always have two, three flow sheets.

Then, once you perform a complete a mass balance, heat balance, yield calculation, then you perform a cost calculation. Then, you may like to decide on which flow sheet to follow. So, that is left to you at the end of the entire study period. So, any flow sheet design, it is not that you will always have one approach for recovery and purification of the product. You may have two, three different approaches. Each approach has its own

advantages, disadvantages. Each approach will have certain amount of cost factor involved in it. Each approach will have different yields of the product and purity.

So, you can make your decision at the end of the complete study and that is left to you based on several factors, which we discussed in the past previous two or three classes. Depending upon the ease of operations, depending upon the amount of waste generated, depending upon the amount of solvents you are going to use, depending upon the operating cost, depending upon the capital cost, depending upon the profit you, are going to make and so on actually. Now, let us look at another problem.

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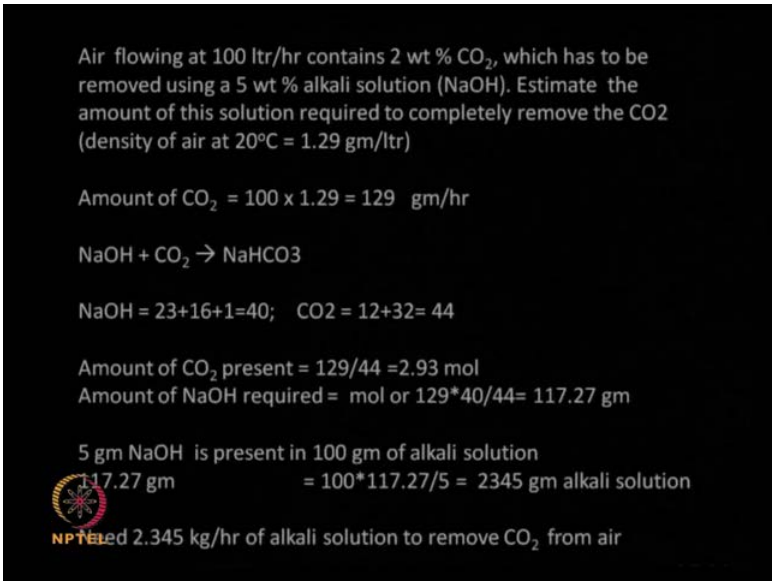

This problem is typical absorption type of problem. I have gas carbon dioxide present in air. Carbon dioxide is formed quite a lot in fermentors, especially if I am doing an aerobic fermentation; I am going to produce lot of a CO2. Sometimes, I might not like to leave all the CO2 in the atmosphere. So, I may like to collect it using some alkali. I have put in sodium hydroxide, but sodium hydroxide is slightly expensive.

People may go into things like calcium hydroxide, which is much cheaper, but just for the sake of the problem, I have done sodium hydroxide because sodium hydroxide is slightly more expensive than calcium hydroxide; calcium hydroxide, lime. So, you all know what is lime and it is very cheap. So, what you have is you have air coming out at 100 liter per hour. It contains 2 weight percent of carbon dioxide. This has to be removed using an alkali solution that means sodium hydroxide dissolved in water that is aqueous

alkali solution. Now, it contains 5 weight percent of sodium hydroxide, 8 weight percent in water.

Now, the goal is to estimate the amount of solution required to completely remove the CO2 that is coming out. So, this is all always done in something called an absorber. So, any gas removal from a mixture is done in an absorption column. So, how much carbon dioxide is there weight percent wise? So, we can take 100 liter and then we can calculate approximately how much of carbon dioxide is present in this. Now, this particular problem is related to absorption.

Absorption is used if you want to remove a certain gas; maybe it is a toxic gas or may be it is a gas, which is of interest to you. So, you use a solution that is the absorbent to remove a particular gas. So, there are different types of solutions that can be used to remove different gases.

So, in this particular problem, what we are talking about is we have carbon dioxide present in air and we want to remove the carbon dioxide. We do not want to let the carbon dioxide into the atmosphere. We all know about the global warming and presence of global warming gases is leading to increase in the temperature of the earth and so on. So, we do not want to let CO2 escape into the atmosphere. So, here we are trying to use alkali solution that is sodium hydroxide present in water, the solution containing sodium hydroxide in water for absorbing carbon dioxide that is present in air.

Generally, we do not use sodium hydroxide because it is a bit expensive. We go into calcium because calcium hydroxide, lime is much cheaper for removal of a carbon dioxide, but this is just an example. I just want to show you how to attack a problem related to absorption systems. So, we have some carbon dioxide present in air and you want to add sodium hydroxide solution and remove the carbon dioxide. We want to calculate how much of sodium hydroxide solution is required to do this operation. So, air is flowing at 100 liter per hour and it contains 2 weight percent of carbon dioxide.

Now, the density of air is given here at certain temperature at 20 degree centigrade. So, density of air changes depending upon temperature. You all know that because it is a compressible gas. Now, so amount of air we can calculate 100 into 1.29 that gives you 129 grams. Now, this contains 2 weight percent carbon dioxide, so 129 into 2 that gives you about 2.58 grams. Now, carbon dioxide will react with sodium hydroxide to give this

sodium by carbonate. So, 1 mole of sodium hydroxide is required for 1 mole of carbon dioxide.

Now, if you look at the molecular weight of sodium hydroxide, we all know sodium is 23, oxygen is 16, hydrogen is 1, so that comes to 40. Carbon dioxide is, carbon is 12, oxygen is 16, so that is 32, 44. So, the molecular weight of a sodium hydroxide is 40, molecular weight of carbon dioxide is 44. Now, the amount of carbon dioxide we calculated from the previous is 2.58 grams.

So, we can convert that into mole, 2.58 divided by 44 that gives you so many moles. Now, amount of sodium hydroxide required is we can multiply by 40 because 1 mole of sodium hydroxide absorbs 1 mole of carbon dioxide. So, if you multiply by 40, you will get about 2.34 grams. So, this is the amount of sodium hydroxide required.

Now, your solution contains 5 weight percent of sodium hydroxide in water. So, that means 5 grams of sodium hydroxide is present in 100 grams of the solution. Now, to remove 2.34 grams, how much of the solution I will require? It is simple, 2.34 divided by 5 into 100, so that will give you 46.88 grams of alkali solution. Now, air is flowing at 100 liter per hour. So, you will require 46.8grams per hour of alkali solution per hour because continuously air is flowing. That means continuously carbon dioxide is also flowing and continuously you have to supply the alkali solution so that you can capture all the carbon dioxide that is present.

So, you will require 46.8 grams per hour of alkali solution to absorb all the carbon dioxide. Again, this is a very ideal situation because when a gas bubbles into a liquid, it is not that all the gas will get absorbed immediately. It will take time because gas has to dissolve and get converted into the liquid form. Then, that liquid carbon dioxide, which is dissolved, goes and reacts with the sodium hydroxide. So, there are two processes taking place. One is the solubilization of the gas from the gas phase to the liquid phase and the next is the reaction.

So, if the solubilization of carbon dioxide into the gas phase is very slow when compared to the reaction taking place between the carbon dioxide and sodium hydroxide, so what will happen? The gas will be bubbling inside the alkali, but it may not get absorbed into the solution phase. The reaction may be fast, but still the gas is not getting absorbed. So, you are not going to get a complete removal of the carbon dioxide. Do you understand?

But, if the reaction is slow, but the solubilization is very fast, then what will happen? Carbon dioxide will go into solution, but it not going to react very fast. Then, there will be a buildup of carbon dioxide concentration in the solution phase. Understand?

Two different situations can happen. One is the carbon dioxide dissolution into the liquid phase is slow, whereas the reaction between carbon dioxide and sodium hydroxide is fast. So, the reaction, the whole process is controlled by the solubilization of the carbon dioxide into liquid phase. The second alternate could be the reaction is slow, but the solubilization of carbon dioxide into the solution is fast. So, what will happen? Carbon dioxide will quickly go into solution, but it will not react. So, there is going to be a buildup of carbon dioxide inside the liquid phase.

So, both the situations can happen that is in a non ideal condition, but here we are assuming an ideal situation. In an ideal situation, we assume as soon as the carbon dioxide is coming in contact with the alkali, it quickly reacts and it forms the sodium bicarbonate. So, this is a typical process that is taking place in an absorber or absorption tower. So, you have an absorption tower where the air may be entering from the bottom of the absorption tower and it may be rising. Air will contain carbon dioxide. Your alkali solution will be flowing from the top, flowing down slowly. As it flows down slowly, it will absorb all the carbon dioxide.

So, you need to build up a very good mixing or very good interaction between the gas and the liquid. So, when you bring in a very good gas liquid contact that is the term that is used in chemical engineering, the gas liquid contact. If you bring in a very good gas liquid contact, all the carbon dioxide will a completely get dissolved into the solution phase and then they start immediately getting converted into sodium bicarbonate. So, how do you bring in a very good gas liquid contact? You can increase the contact area. That is why; in a tall absorption column, you pack it with inert material. So, as the liquid flows down, it is expanding into the packing and the gas and the liquid come in contact.

So, the area of contact is increased, number one. Number two, you can create a very good mixing situation by creating turbulence. Again, that will also improve the gas liquid contact. So, these are two ways by which you can improve the contact between the gas and the liquid so that all the gas of interest can be completely absorbed by the liquid.

So, otherwise although we assume that it is completely getting removed, in real situation, it might not be happening so because of a non ideal mixing, non ideal gas liquid contact or short circuiting and so on actually or effects like, which I talked about sometime back, whether the solubility of the gas into the liquid is controlling or whether the reaction is controlling.

So, if the reaction is controlling, you are going to have a buildup of a carbon dioxide and you are not going to get all the carbon dioxide absorbed. If the solubilization or dissolution of the gas is controlling, the gas will escape the absorption column and leave the absorption column and not get completely removed.

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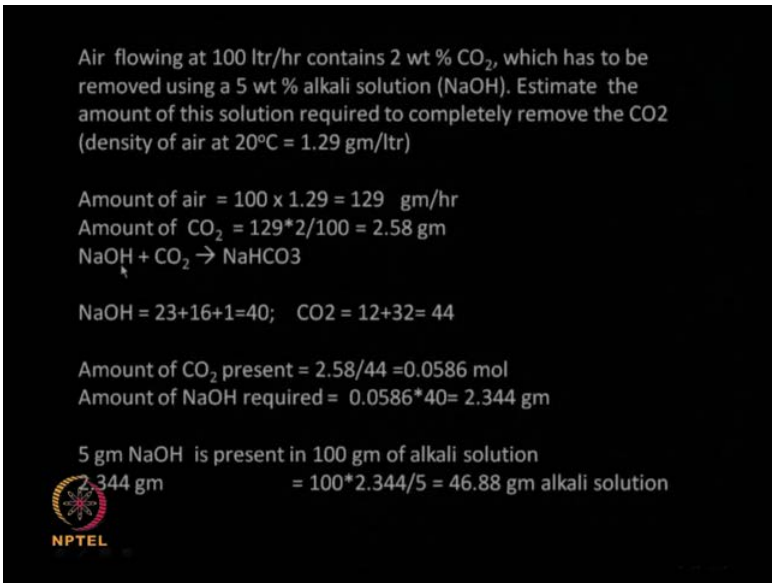

So, generally when we select the type of absorption material, we try to select so that the reaction is very fast. As soon as it gets, the gas gets absorbed, reaction will take place very fast and there is no buildup of the gas in the solution phase. So, there are different types. Sometimes we use mono ethanol, I mean as absorption for carbon dioxide. For chlorine, we use a sodium salt based material and so an actually. For different types of gases, we have different types of reactants so that the reaction is always very fast, so that you do not have any problem about the buildup of the gases inside the solution phase. So, this is a typical absorption type of a situation.

So, so far we have looked at five different problems related to downstream, flow sheeting, related to mass balance, related to heat balance as well as related to absorption

of a gas from a gas phase into the liquid phase. So, in all these cases, we performed mass balance of various streams. We assumed whatever is coming in is equal to whatever is going out, whether it is a single stream or whether it is a multiple stream. The same thing we did for the heat balance also.

So, we calculated the amount of heat required to heat a fluid and we equated it to amount of heat lost by a hot fluid. By equating these two heats, we are able to calculate the amount of a hot fluid required to heat up some other cold fluid. The main assumption was there were no heat losses to the surroundings. So, that is part of the assumption, which we mean we need to resort to get a heat balance going.

Then, we looked at problems on how to generate a flow sheet like if I want to recover a protein using two different solvents, how do I generate a flow sheet. So, in that situation, we found out that we have an extraction, two extraction systems with two solvents. Then, we resorted to something called salting out or precipitation of the protein. Then, you need to go into filtration of the protein, and then finally, distillation of the solvent to recover the complete solvent in a pure form so that the solvent can be again put back into the extraction unit.

If you are using two different solvents, the problem is twofold because you need two different extractors because you cannot mix the solvent. You need two different crystallizers or precipitators because again you are handling two different solvents and you will require two different distillation columns because you have two solvents. So, you see that by having two solvents, you have to double the number of downstream. So, it is always advantageous to use one single solvent. Then, you can always mix the contents from each of the extractor because you are handling only one solvent.

If I used only ethyl acetate, I will be using one distillation column because I will require recovering and purifying only ethyl acetate, whereas here I had ethanol, sorry methanol and ethyl acetate. I required two distillation columns. Similarly, if I am having only one solvent, I will require only one precipitator. I will not require two precipitators. So, you see the disadvantages of having two different solvents for extraction.

So, always minimize the types of solvents, the types of chemicals, the types of a consumables you use so that you will not have two different sets of downstream minutes,

whereas if you have one single solvent, you can mix up all the streams together and purify. So, we will have only one distillation column.

Finally, we looked at an absorption system and where you would like to absorb a gas instead of letting it go into the atmosphere. This is a typical absorption system, which is always found in fermentor downstream or a bio reactor. You may be able to recover carbon mono oxide, carbon dioxide, chlorine, so many other toxic gases or toxic vapors using an absorption system. This particular last problem tells you how to go about doing this type of calculating the amount of a solvent required for absorbing the entire minute operation.

Thank you. Yeah, stop.