Process Design Decisions and Project Economics
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Module - 7
Cost Diagrams and Quick Screening of Process Alternatives
Lecture -33
Lumped Cost Diagram and Cost Allocation Diagram
(Case Study of Hydrodealkylation Process)

Welcome we are starting the 7th module of this course that is cost diagram and quick screening of process alternatives. In the previous module, we got cost diagrams is an effective means of putting or summarizing the cost both operating as well as the capital cost of a particular flow sheet.

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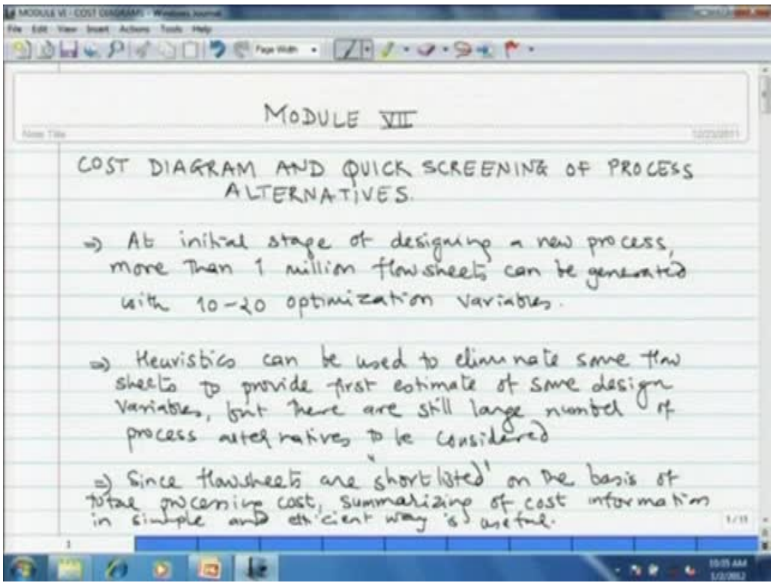

In this the cost is written directly on the flow sheet, the annualized capital cost of equipment is written inside the box indicate in the equipment. And the processing cost is attached to the stream for which the processing like heating, cooling, etcetera is carried out.

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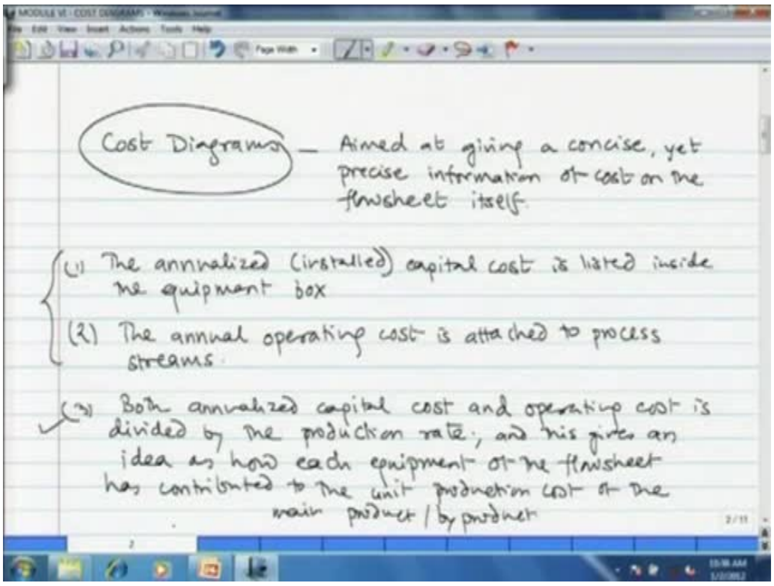

We saw as how what are the use of cost diagram.

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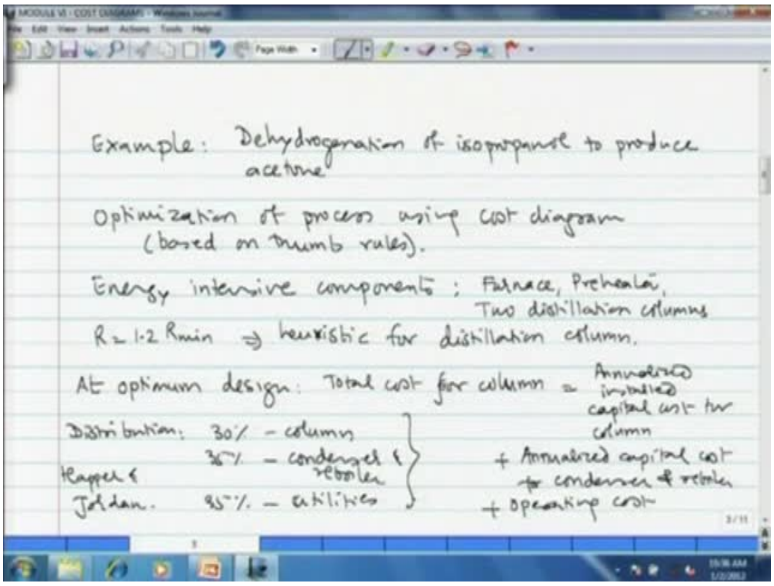

Cost diagrams are effective means of summarizing information, you can check the rules of thumb, using cost diagram and find out the areas of optimization of process in the flow sheet. We saw an example of acetone manufacture through iso propane, alcohol dehydrogenation. And we locate we found out that a 2 columns distillation columns in the flow sheet, where far from optimum operation based on the cost that was attributed to the column and column auxiliaries, the re boiler and condenser and then the cost of operation of re boiler and condenser. So, the operating cost and capital cost, so that gave us an indication of the area in which we have to optimize the process.

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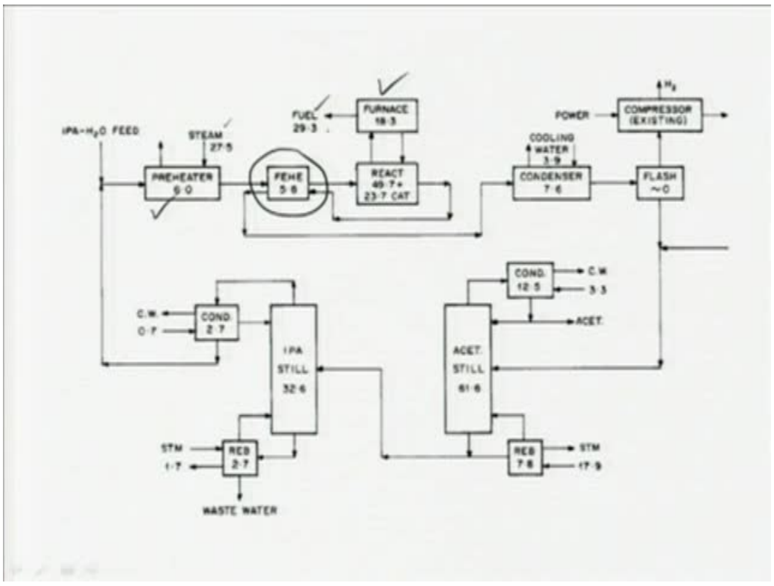

Similarly, we also saw the as how we can optimize the heat transfer in the process, for that flow sheet is now on the screen. Here you can see that the heat from the reactor effluent a stream emerging out of the reactor is recovered in the incoming stream. In the incoming stream through this f e h e feed to effluent heat exchanger and a feed to effluent heat exchanger is quite small as compared to the pre heater and the furnace, which supply heat to the feed that increases the cost of operation.

So, we recommended that based on the cost was given cost of the steam, cost of the fuel and then the cost of the annualized capital cost of the furnace and pre heater that we have to increase the size of the heat to effluent heat exchanger. So, as to have better heat recovery, and heat integration into the process that would bring down the operating cost.

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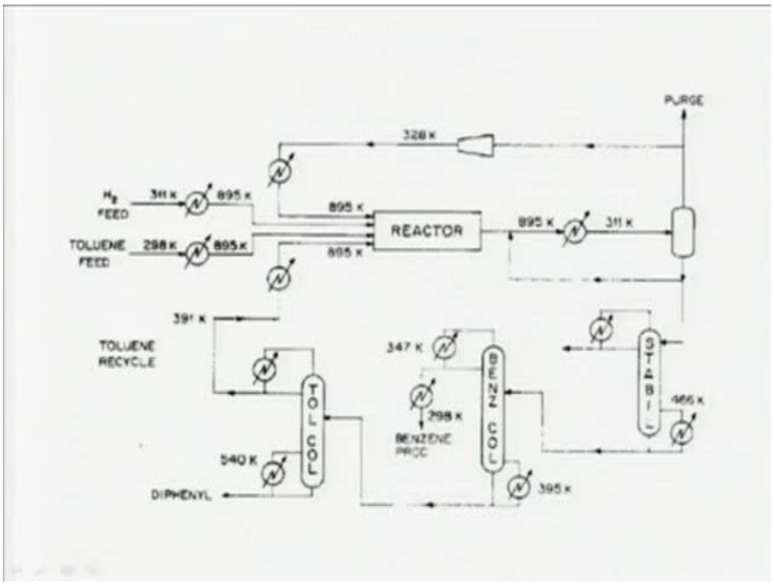

Next, we saw the our standard case study of hydro de alkylation, what you see now on the screen is the is the general flow sheet.

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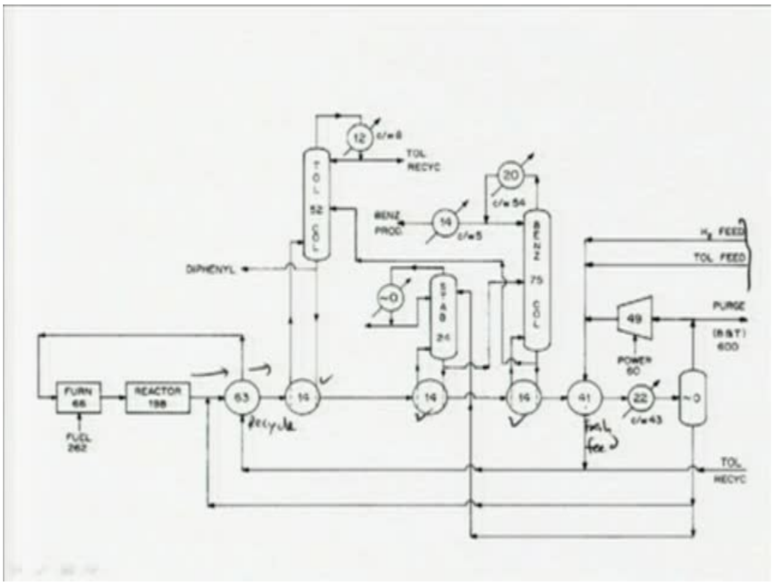

And then we saw the heat integrated flow sheet, but heat integrated flow sheet is rather complex, because of several exchangers that are there we saw that how the a reactor effluent was giving up it is heat to the feed. This is the recycle toluene then the re boiler of toluene column, re boiler of stabilizer column, re boiler of benzene column. Then it was also giving heat to the fresh feed that is coming in this hydrogen and toluene fresh feed.

And finally, whatever heat was remaining was removed through a condenser and then the react reactor effluent was flashed to bring down the temperature, so has to have the phase. Now if we have a heat, so if we have a cost diagram like this, then it is difficult to identify the areas of optimization therefore, somehow we have to simplify this particular cost diagram.

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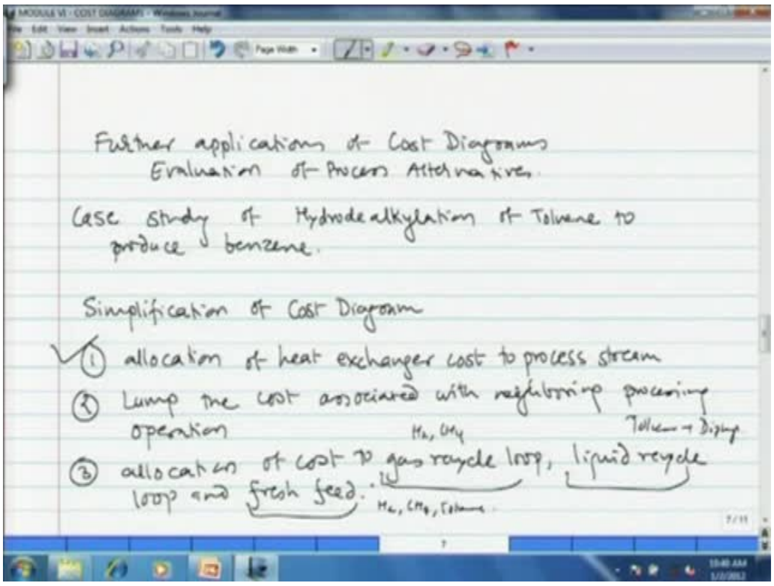

Now, how we can do that in that we introduced the concept of lumping of the cost, we have to we decided that we shall lump the cost. And then what we did we followed a 3 step strategy allocation of the heat exchanger cost to the process stream. Then lump the cost associated with the laboring process operation and allocation of the cost to 3 loops or 3 streams.

One is the gas recycle loop, second is the liquid recycle loop and third is the fresh feed. So, that these 3 are the like cost components, now each of the cost component has several sub component. For example, gas recycle loop cost component has hydrogen and methane as the elements on it. Then the liquid recycle loop has toluene and di phenyl as elements in it and the fresh feed has 3 elements in it hydrogen methane and toluene.

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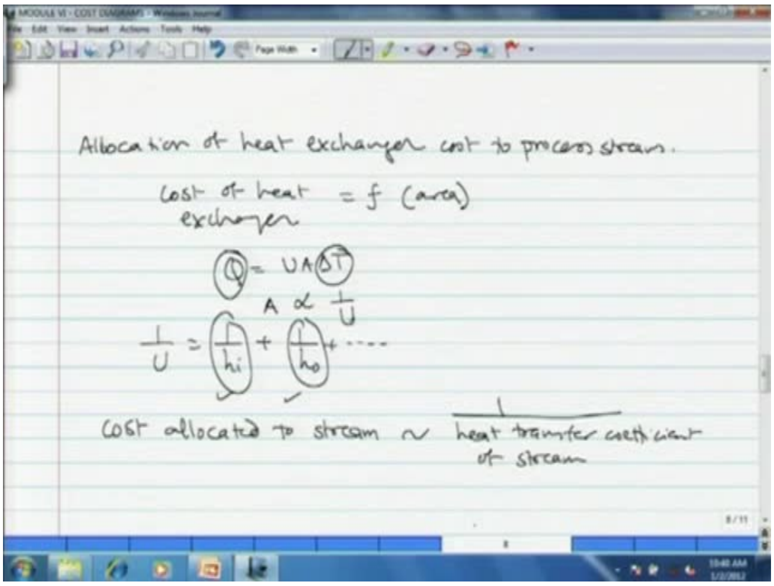

Now, next we adopted the strategy of allocation of the heat exchangers that are there in the process to the streams. Now how we can do that we used the thumb rule that heat exchanger area, sorry the heat exchanger cost is proportional to the heat exchanger area. And the area is inversely proportional to the overall heat transfer coefficient, overall heat transfer coefficient has contributions from both inside and outside film coefficients. So, if any exchanger is exchanging heat between 2 streams, then we allocate the cost of the heat exchanger the annualized capital cost of the heat exchanger with the 2 streams in the inverse proportion of their film coefficient. That is what cost allocated to the stream is inversely proportional to the heat transfer coefficient.

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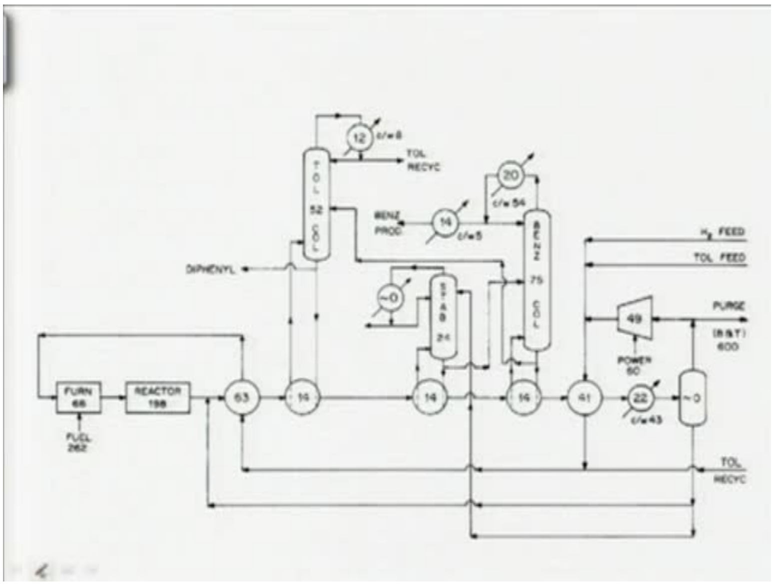

And then we identified 5 heat exchangers in the in the process that i just showed to you. The first heat exchanger that exchange a heat between reactor effluent and the recycle toluene. Then the toluene re boiler, then stabilizer re boiler, benzene re boiler then the fresh feed and reactor effluent heat exchanger and finally, the cooling the condenser.

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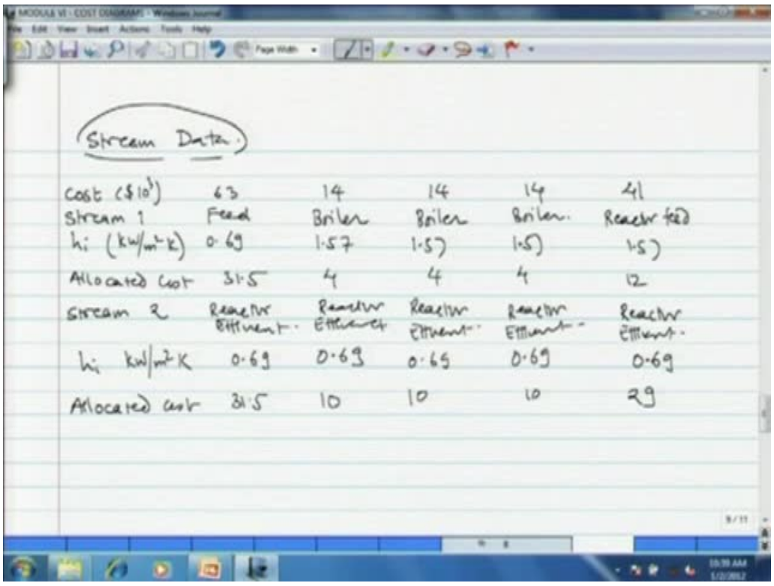

And based on this now we have to allocate the cost that we did in the previous lecture, we wrote the cost annualized capital cost of all these 5 exchangers 68 14 14 14 41, these are 1000 dollars. And then we wrote the streams that are treated in that particular exchanger like heat exchanger 1. The stream 1 is the feed that is, but remember it is recycle toluene feed and second stream is reactor effluent and the 2 coefficients were 0.69, 0.69 kilo watt per meter square per Kelvin.

And therefore, the total annualized cost of 63000 dollars is distributed equally, same thing for the re boiler, toluene re boiler. Now, in toluene re boiler one side there is vapor effluent or gas phase effluent and other side there is boiling liquid. So obviously, the inside heat transfer coefficient is likely to be higher, because it is boiling liquid. Then the outside heat transfer coefficient which is a vapor phase stream.

And then we distributed we assumed that the inside heat transfer coefficient was 1.57 kilo watt per meter square per Kelvin and outside coefficient was 0.69. And then the 14000 dollar cost was distributed in the inverse proportion as 4000 and 10000 to a stream that is inside the re boiler stream and the reactor effluent stream and so on and so forth. So, what you have on screen now is the allocation of the heat exchanger cost to the streams that are treated in the cost.

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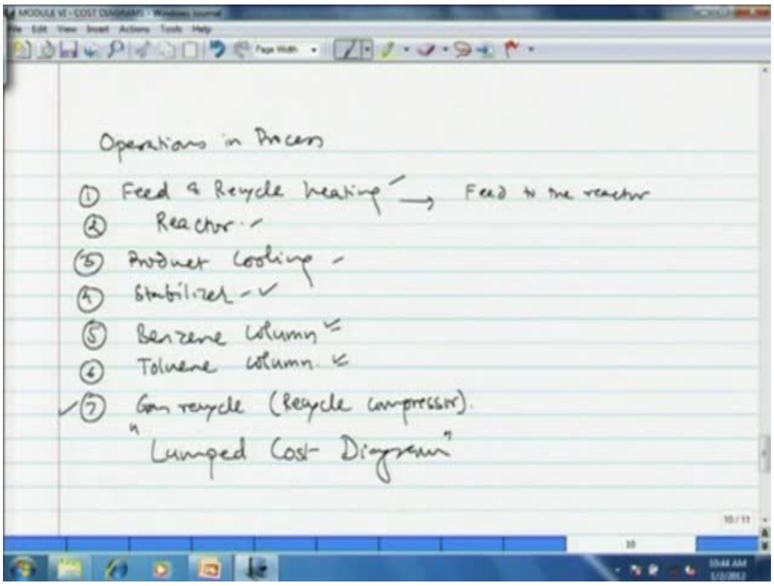

Now, what we decided is that we shall, now lump these cost in the neighboring operation, what are the operations in the process major operations in the process? The first operation is feed and recycle heating, then the next operation, that is the feed and recycle heating is essentially feed to the reactor. Then the next stage was the reactor itself, where reaction takes place, then the third operation was product cooling, then the 3 columns that follow stabilizer column, benzene column and toluene column.

And finally, after column we have a gas recycle loop, now here; obviously, we also have a liquid recycle loop as you saw that toluene recycle toluene heater was there, but toluene is the liquid element and therefore, cycling of toluene is not much cost intensive operation you can use a simple pump which you can buy in few 1000 dollars and then you can operate with it. So, liquid recycle is not a cost intensive operation, so we do not consider it in this particular process.

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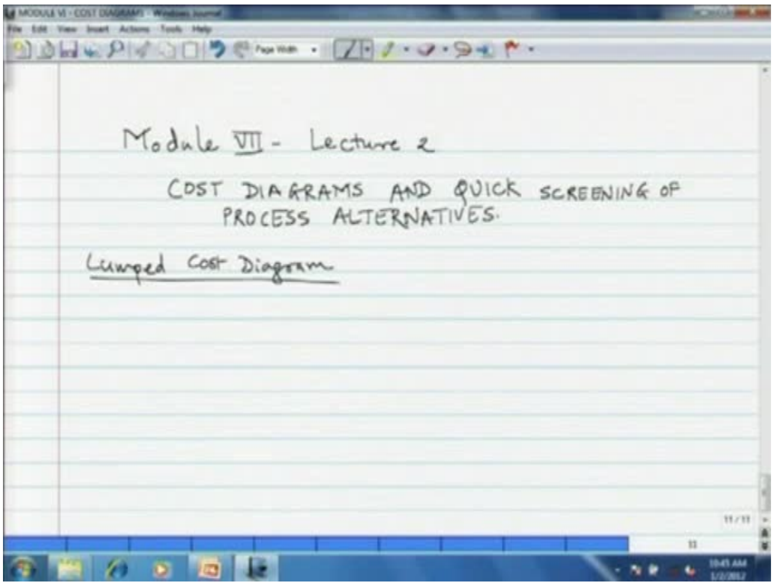

Let us see how we can develop a lumped cost diagram, that is today's exercise. Lumped development of lumped cost diagram, what we do now that we draw boxes that correspond to the to the operations that I just mentioned.

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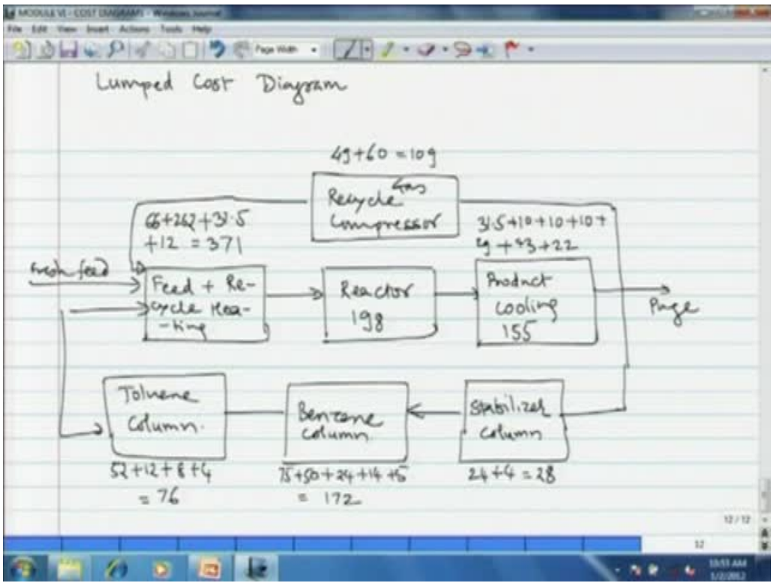

We have feed plus recycle heating, then the reactor then product cooling. Now from product cooling, we have the product as well as gas recycle purge streams emerging, the liquid is separated in 3 columns stabilizer benzene. Now this is our lumped cost diagram, where we have listed 7 major operations in the process. And we have connected them as how in the in the proper order, now let us gather the cost that is associated for each of these operations.

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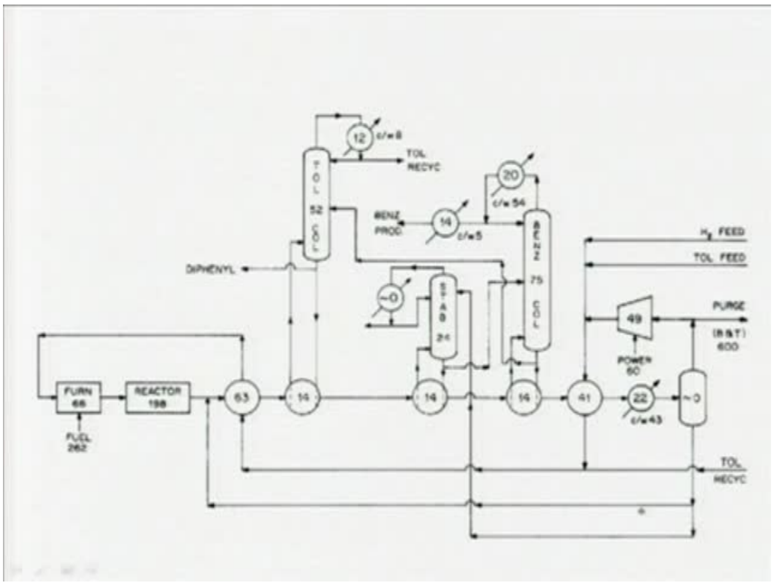

Now, reactor if you go to the main flow sheet, we see that a reactor annualized cost of the reactor is 198 1000 dollars. So, that we attached now here 198 1000 dollars. Now next the feed and recycle heating, let us go back to the flow sheet, we have here 2 heat exchangers that heat the feed fresh as well as recycle feed. And then we also have a furnace that does the job.

So, now, we lump all those cost gather the elements that are associated with feed and recycle heating and then we sum them together. Now what are the elements first, the furnace 66000 dollar plus fuel for it, 262. So, we write here 66 plus 262 plus we had here 1 heat exchanger that heated the recycle toluene 63000, but we have allocated the cost equally to the 2 streams.

So, 31.5 of that plus, we had another exchanger here that heated the fresh feed 41000 dollar heat exchanger annualized capital cost. And that cost, we had distributed as 29 and 12000 dollars to reactor effluent and fresh feed side. So, that cost we also add here plus 12. So, together these make 361 1000 dollars. Let us take product cooling, product is being cooled in 5 exchangers and one special condenser. So, these 5 exchangers plus condenser, we have already distributed the cost of the 4 5 exchangers that you have seen earlier. We just sum them together.

(Refer Slide Time: 09:16) So, 31.5 of the cost of toluene recycle heat, then 10000 dollars cost for the 3 columns re boiler column plus 29000 dollar cost for fresh feed heating and finally, 43000 dollars for the condenser that is cooling condenser plus 22000 dollars for the condenser cost. So, 43000 dollar is the cost of cooling water required for the condenser 22000 dollars is the annualized capital cost of the condenser. So, together these make out 155 1000 dollars. Now let us see the gas compressor, now gas compressor here the annualized capital cost is 49000 dollars and 60000 dollars is the power that is required for it annually.

So, that here we write 49 plus 60 that is 109 is the cost of gas recycle compressor operation and then the 3 columns stabilizer column, benzene column and toluene column. Now the first let us see the stabilizer column, stabilizer column cost is 20000 24000 dollars for the stabilizer plus 4000 dollars of the cost of operation of the re boiler. So, that is 28000 dollars, so 24 plus 4 is 28000 dollars.

Then benzene column benzene column has capital cost of 75000 plus 4000 of the re boiler plus 20000 of the condenser 54000 for the cooling water for it, then another 14000 for the sub cooling condenser and then cooling water for it is 5000 dollars. So, that cost we add, so 75 plus 50 plus 24 plus 14 plus 5, so together this makes out 172.

And then finally, the toluene column now toluene column has 52000 dollar as the annualized capital cost plus 12000 dollar cost of the condenser cooling water for it is 8000 dollars and then 4000 dollars for the re boiler. So, that cost we add together, so 52 plus 12 plus 8 plus 4. So, this together makes out 76000 dollars. So, what we have now is a lumped cost diagram that we have simplified a complicated flow sheet into a block diagram that gives that list the major operations in the particular flow sheet.

And then we have lumped together we have gathered together the cost of total cost of each of these operations. The next stage is to allocate these cost of each operations to the streams that are involved in that operation. And I just mentioned that we have identified 3 streams in the process, first stream is the net fresh feed n f f net fresh feed, then another feed is gas recycle and third is liquid recycle.

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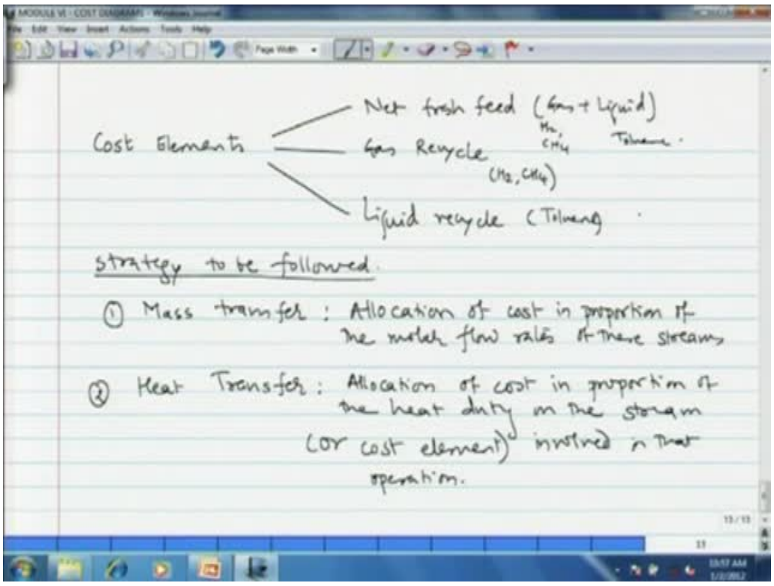

So, that point we note, cost elements are 3 first is net fresh feed. This includes gas feed plus liquid feed remember gas feed means H 2 C H 4 and liquid means toluene, the next is gas recycle that is H 2 and C H 4. And finally, the liquid recycle that is toluene plus di phenyl sorry I am sorry di phenyl is not recycled in the loop. So, only toluene, so what we will do is that whatever cost that we have lumped for a particular operation. We will allocate to the 3 streams that are involved in the operation and these are our cost elements net fresh feed, gas recycle, liquid recycle.

Now how what strategy we follow now to allocate these cost as far as mass transfer operations are concerned, such as distillation or reaction. We will allocate the cost to the 3 elements in proportion of the molar flow rates of these streams, and as far as the heat transfer operations are concerned. We shall allocate the cost in terms of the heat duty on the particular element that is involved in that operation. Now if we have to do this, we have first do the material and energy balance. So, as to find out the net distribution of sorry the net molar flow rates and the heat duties.

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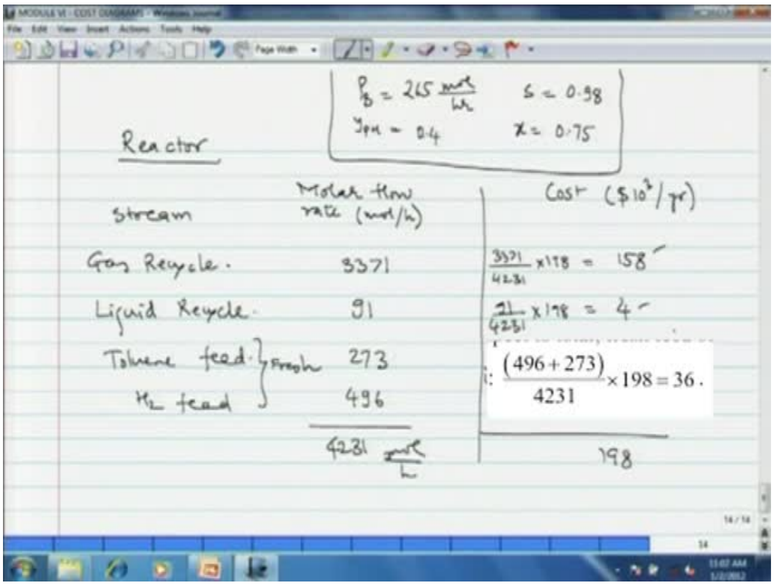

Now what I am giving now are the direct numbers, but we have seen these numbers. It is a H D A process, we have done the material and energy balance previously. So, these numbers you can very easily calculate. You refer to the lectures in module 2 that is flow sheet synthesis in which we have done, all these material and energy balances. We also have a tutorial in this module, in which we shall again see another variant of the H D A process.

And we shall in that tutorial, we shall revise our material and energy balance calculations, for the time being I am giving you the number and I request you to accept them. And if you have difficulty in how to these numbers as I just said you refer to module 2 and in the tutorial, we are again going to work out these material and energy balances in detail.

So, now, let us see the numbers the reactor, reactor receives stream in the form of gas recycle, liquid recycle, toluene feed and hydrogen feed. Now these both are what fresh, now these calculations are for following conditions, production rate of benzene to 65 mole per hour. Composition of hydrogen in the purge stream or mole fraction of hydrogen in the purge stream as 0.4 and selectivity 0.98, so conversion 75 percent. We have already seen the relation between conversion and selectivity. So, for conversion per pass conversion of 75 percent of toluene that is a limiting reactant selectivity is 0.98.

So, what numbers that the numbers that we are going to see now are for this particular set of operating conditions or the process parameters. Molar flow rate, mole per hour gas recycle is 3371 total moles, liquid recycle is 91, fresh toluene is 273 fresh gas is 496 the total 4231 moles per hour. So, the reactor treats total 4231 moles per hour. Now the total cost of reactor as we have seen in the lumped cost diagram is 198 1000 dollars.

We shall allocate that cost to the 3 elements cost elements in the proportion of their molar flow rates . So, what you see now is the numbers adjusted to nearest integer, 3371 divided by 4231 into 198. This is allocated cost in 1000 dollars per year, 158 for gas recycle, then toluene 91 divided 4231 into 198 that is 4000 dollars. Then net fresh gas feed 36000 dollars and then total is 198. So, we have allocated the cost of 198 1000 dollars to the 3 streams in proportion of their molar flow rates.

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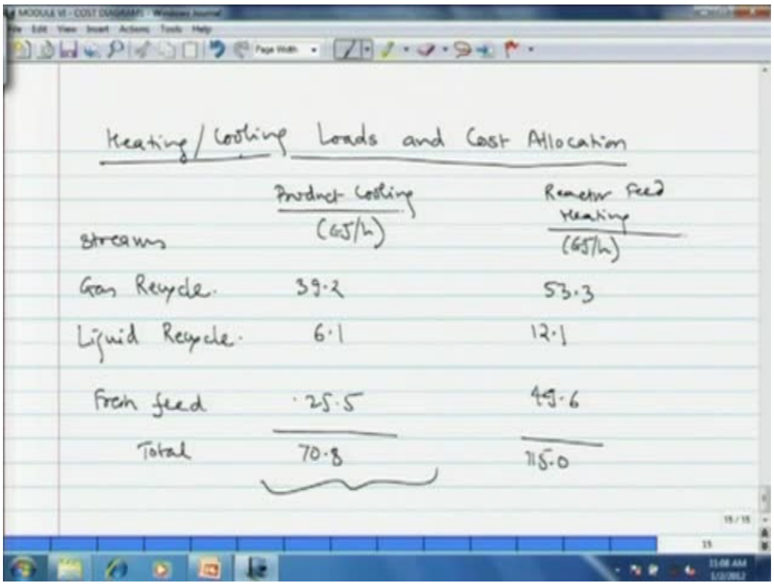

Now, let us see or heat or cooling load that we there are again 3 streams, gas recycle, liquid recycle and fresh feed. Gas recycle all these numbers are in giga joule per hour, 39.2 giga joule per hour. Liquid recycle 6.1, fresh feed 25.5. Similarly, reactor feed heating gas recycle 53.3, liquid recycle 12.1 and fresh feed 49.6. Now a question may arise in your mind as how we can allocate the cost of product cooling to the 3 streams that are there, gas recycle, liquid recycle and fresh feed. Because all the streams are coming, all the components are coming out together, now here we have used a logic that the product that is formed is from the reactants. Now see the production of benzene, now you have benzene is produced from toluene. So, toluene feed to the reactor is total 273 plus 91 that is 273 moles per hour fresh and 91 moles per hour recycle.

Now whatever is the heat that is released, by cooling of toluene sorry by cooling of benzene which is the product of toluene reacted that heat is allocated to the net fresh feed and the recycle feed in the ratio of 3 is to 1. Why because benzene is the product of toluene, toluene is fed into 2 parts. First is fresh another is recycle and fresh is 273 recycle is 91.

So, the net toluene feed is in the proportion 3 to 1 fresh and recycle. Therefore, whatever is the heat that is released from cooling of benzene, which is the product is allocated to the 2 streams recycle and the liquid recycle and fresh feed in the ratio 1 is to 3 or the other way round means, if you take the gas recycle to fresh is 1 is to 3 or fresh to recycle is 3 is to 1. So, that is the logic that we will also follow for allocation of the cost of the columns. For example, the stabilizer column is essentially for removal of the dissolved gas in the system.

So, the stabilizer column is treating all 3 elements, the stabilizer column is treating a liquid stream that contains both benzene, contains all 3 components benzene, toluene and di phenyl. Now how do you allocate the cost of that stabilizer column to the fresh feed and recycle feed, again that is in terms of is in the ratio 3 is to 1, because benzene and di phenyl are the products. However, these are being formed from toluene, which is fed in the ratio 3 is to 1 fresh and recycle.

Therefore, stabilizer column cost will be allocated in proportion 3 is to 1 to the 2 cost elements and the benzene will also be allocated in the proportion 3 is to 1. To the 2 cost elements net fresh feed and recycle stream as far as the toluene column is concerned. Now toluene column is treating 2 element, it is treating 1 stream that is the liquid recycle stream contain 2 elements that is di phenyl and toluene, but that cost we will allocate totally to the liquid recycle stream because there is no net fresh feed there.

And whatever is the product is either taken out as the fuel product the di phenyl or the toluene goes back to the reactor. So, the toluene column cost will be allocated totally to the liquid recycle stream. So, this is the logic that we are going to follow, please keep this in mind, I am going to repeat this in the tutorial. The total product cooling heat load is 70.8 giga joules per hour and total reactor feed heat load is 115 giga joules per hour. And now we allocate the cost the total cost of product cooling was as we found in the in the lumped cost diagram

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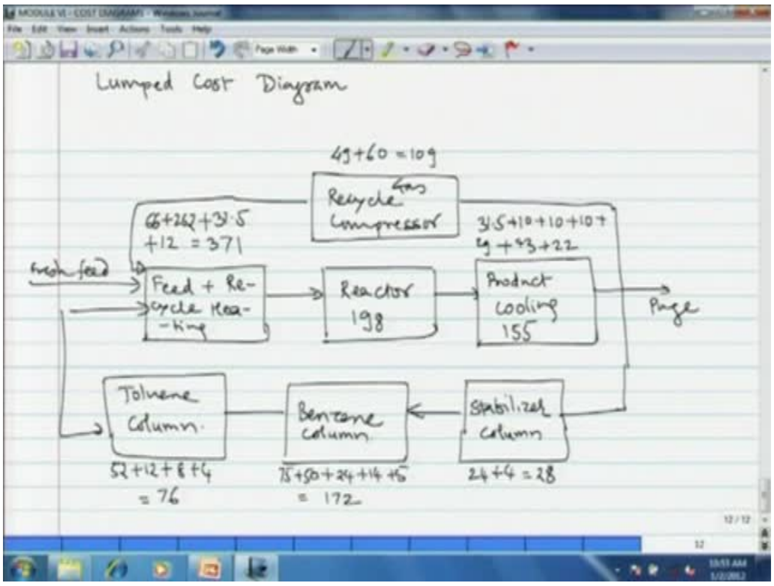

Here it was product cooling was 155 and feed and reactor heating was 71. So, that cost now we are going to distribute this is 355 total sorry product cooling 155 1000 dollars. So, 39.2 divided by 70.8 into 155, this comes out to be 866.1 divided by 70.8 into 155 that may comes out with 13 and 25.5 divided by 70.8 into 155 that comes out to be 56. Now similar distribution here of total cost of 371 1000 dollars, will be 172 39 and 160. And now we shall prepare what we term as the cost allocation diagram.

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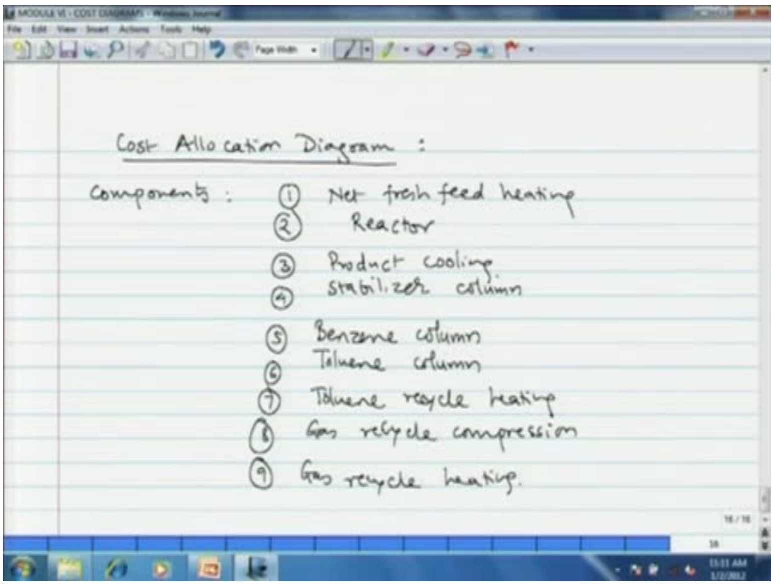

Now, cost allocation diagram has several other components that we will see now, components of cost allocation diagram are first the feed heating or the fresh feed heating net fresh feed heating, second will be the reactor, third will be the product cooling. Then fourth will be the stabilizer column, a flash drum is a simple equipment it is not, so cost intensive. So, that we do not include in this our analysis, then fifth is benzene column, then toluene column seventh the toluene recycle heating and finally, a 2 components that are associated with gas recycle stream first the gas recycle compression and the gas recycle heating.

So, our cost allocation diagram will have these 9 components, in addition to these in order to asses process alternatives. You also write the losses that occur in the system on this cost diagram, now what are these losses? The first loss is the loss of selectivity not all of the toluene gets converted to the desired product. So, some product is some toluene is lost as di phenyl, so that we put as the loss. So, the total cost of toluene that is lost to di phenyl that will be put also on the system also on that particular diagram. Then the second loss is that of the hydrogen some hydrogen leaves in the purge gas, so that loss we will write also on the cost diagram.

Now are we going to throw of these streams are we going to throw of di phenyl and also going to throw of the purge gas no, di phenyl can be used as a fuel in the process. So, you mix it with the diesel or oil that is being put in the furnace. So, that could be put to some use. So, we can recover some cost from this waste product. So, that cost we will also put the cost of di phenyl as fuel also we shall put on the cost diagram. Secondly, the purge gas it contains two combustible gasses hydrogen and methane. So, those also can be used in some gas engines in the process or similar thing. So, that cost the cost of fuel cost of these the purge gas we will also put on the cost diagram.

Now there is one more loss that we have not mentioned that is the loss of benzene and toluene through the purge gas, purge gas emerges from the flash drum where the phase split takes place. Now if the phase is phase split is not perfect, which is always the case because both benzene and toluene have finite vapor pressure. There will always be some loss of benzene and toluene through the purge gasses as in the form of vapor. So, that loss we will also put on the cost diagram. So, we will get an overall view of the cost that are involved in the process of hydro de alkylation

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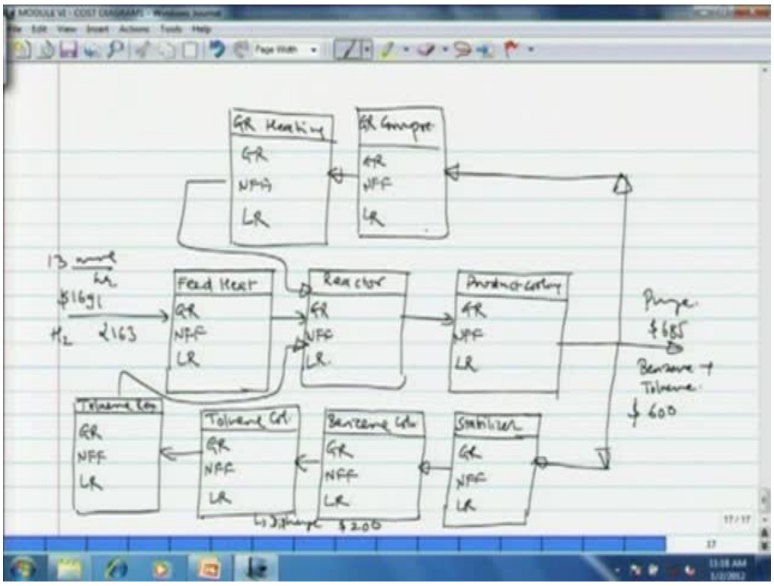

Now let us draw that cost diagram reactor, now each cost component and 3 cost elements gas recycle net fresh feed, liquid recycle. Then feed heating gas recycle, net fresh feed liquid recycle, then product cooling, stabilizer the 3 columns. Now we connect these elements and now we have to write the loss the total toluene loss is 13 mole per hours, 8 moles as in the form of di phenyl and 5 moles in the vapor. So, the total loss of toluene is 1691 1000 dollars, total loss of hydrogen is 2163 1000 dollars out of which di phenyl comes out from the toluene column.

And that is used in the process as fuel and that cost is 200 1000 dollars and purge gas is also used as feed the is also used as fuel. So, that cost is 685 1000 dollars and the loss of benzene plus toluene in the form of vapor, which is 5 moles per hour is together 600 1000 dollars annually. And now what we do is that we simply pickup the cost related to a particular operation and write inside the box.

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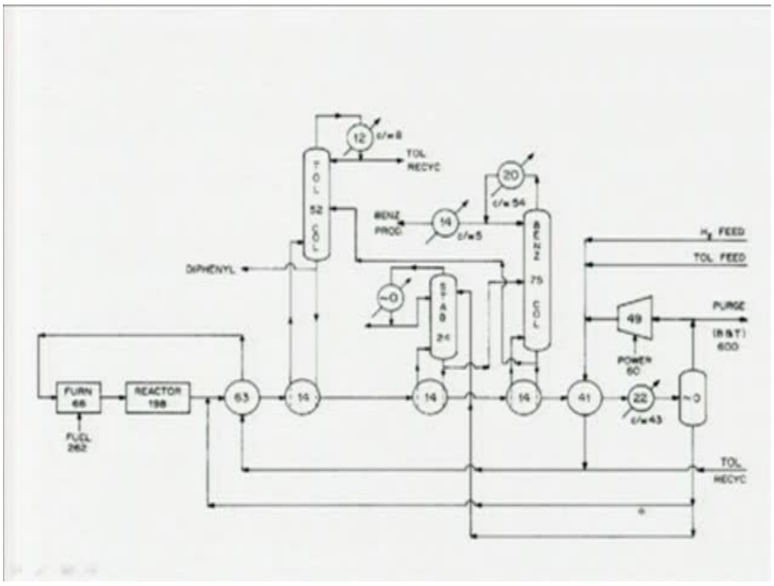

We start with the simple gas compression, gas compression as you will see in the flow sheet is the total cost is 109, because 49 1000 dollars for the compressor 60 1000 dollar for the power.

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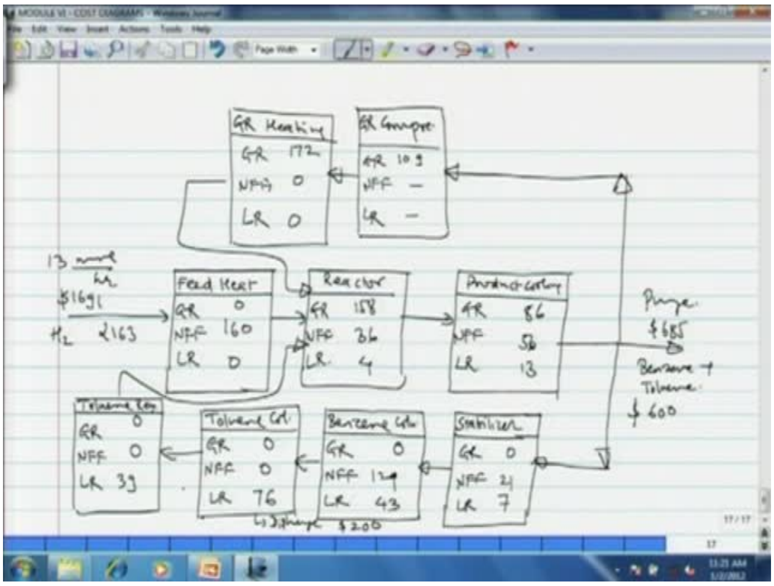

So, that we write 109 here, there is no net fresh feed neither liquid recycle. Now gas recycle heating, gas recycle heating if you go to the heating and cooling loads, you will find the gas recycle heating is 172 dollars here. So, that we put here the reactor is 198

1000 dollars, but we have to now as I said we have distribute in terms of the molar flow rates.

So that 158 4 and 36 for gas recycle, liquid recycle and fresh feed. So, that we write here 156 sorry 158 36 and 4, similarly product cooling total was 155 that we distributed 86 56 and 13, among the 3 streams. Now stabilizer column the total cost in the lumped cost diagram was 28 1000 dollars, but I just mentioned that we have to distribute to net fresh feed and liquid recycle in the ratio 3 is to 1.

So, 28 distributed to net fresh feed and recycle is 21 and 7, similarly 172 1000 dollars of benzene again distributed in the ratio 3 is to 1. So, there is no gas recycle in benzene column net fresh feed 129 liquid recycle 43. Then toluene column is the total cost that we saw in lumped cost diagram was 76 1000 dollars entire cost is allocated to liquid recycle. Toluene recycle heating, now this we have already found as 39 1000 dollar toluene recycle, liquid recycle heating.

So, that we put here liquid recycle 39 there is no gas recycle liquid recycle and now finally, the fresh feed heating. Fresh feed heating we have already seen here as 160 1000 dollars reactor fresh feed heating, so that 160. So, this completes our cost allocation diagram, what we have done now is that we have identified the cost elements of the process.

We have identified the streams that are involved and then accordingly we have allocated the cost to these. The cost elements net fresh feed, gas recycle and liquid recycle, then we identified the components of the cost allocation diagram total 9 components and 3 elements. We have made a cost allocation diagram out of it, now this cost allocation diagram is the very handy tool of assessing the process alternatives.

Now what is the process alternatives that we can see, the first process alternative is to recycle di phenyl, di phenyl is a reversible by product. So, you can see there is a tremendous loss of toluene in the form of di phenyl, if you see the annual loss it is over 1000 1 million dollars. So, if we have to cut down that cost, then we have recycle di phenyl to extinction which means that di phenyl being a reversible byproduct. It will get built up in the process, but at steady state the total amount of di phenyl will remain same.

So, the we will cut down the loss of toluene in the form of di phenyl, but the penalty that we pay for it is over sizing of the equipment in the process. So, as to accommodate the increased flow of di phenyl that is one process alternatives, second process alternative is to alter the hydrogen to aromatics ratio at the reactor inlet the molar ratio of hydrogen to toluene. Now this molar ratio that we have considered is 5 is to 1. So, there are 4 moles excess, suppose we reduce it to let us say 2 is to 1 or 1 is to 1. Then what happens what are the penalties that we pay.

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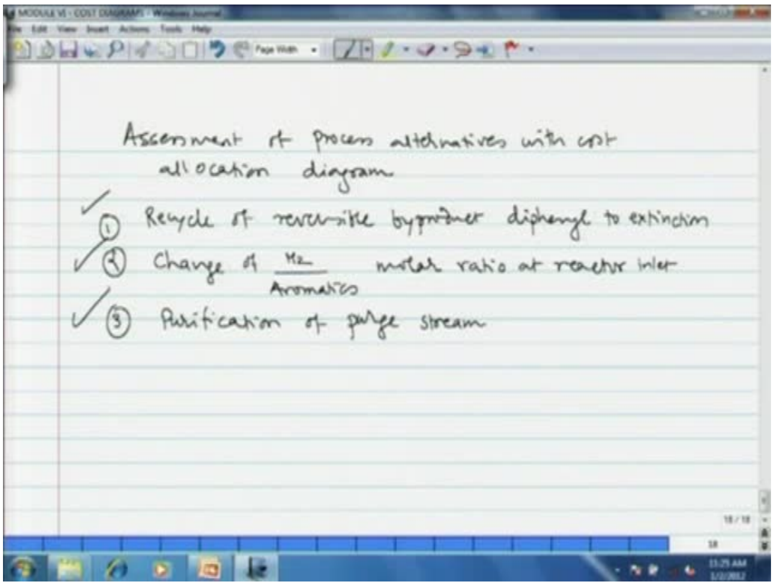

So, all of these process alternatives, we can asses in term using this cost allocation diagram that is the exercise in the next lecture, but I will just for your convenience. I list the process alternatives that variable process assessment of process alternatives with cost allocation diagram. First recycle of reversible by product di phenyl to extinction, second change of H 2 to aromatics molar ratio at reactor inlet.

Third alternative that we can think of is purification of purge stream, which means at the outlet of the flash drum, we will put a membrane module that will selectively filter hydrogen from methane. So, that we can purge only methane and recycle almost all hydrogen. So, let us asses these 3 process alternatives using the cost allocation diagram that we have developed in the next lecture.