Process Design Decisions and Project Economics
Prof. Dr. V.S. Moholkar
Department of Chemical Engineering
Indian Institute of Technology, Guwahati

Module - 7
Cost Diagram and Quick Screening of Process Alternatives
Lecture - 32
General Concepts and Principles and Cost Allocation Procedure

Welcome we are starting the 7th module of our course, that is Cost Diagram and Quick Screening of Process Alternatives. In the previous modules, we have seen as how a flow sheet is synthesized, then we saw the aspects related to the reactor design, then the separation systems, then the heat exchanger network or heat integration of the system.

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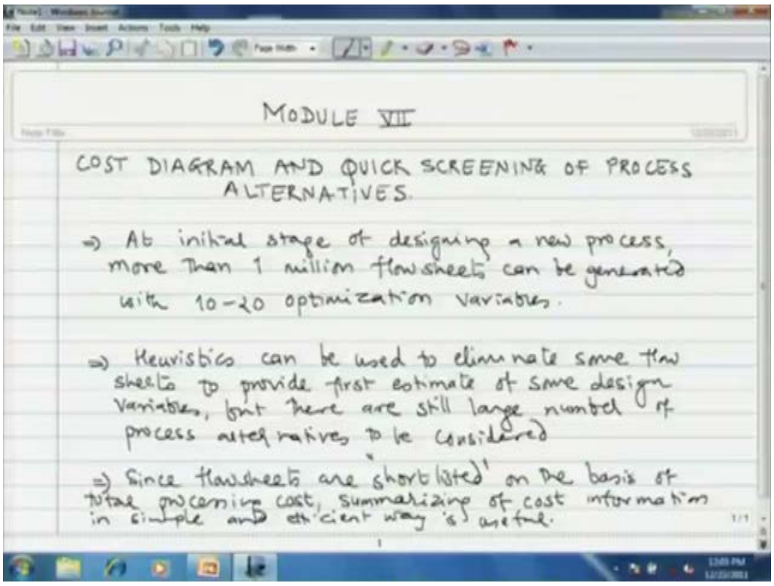

Now, having done this, when we are at initial stage of finalizing the new process, we may have more than one million flow sheets generated with about 10 to 20 optimization variables. Now, how to it is rather impossible to go for a detailed design and cost estimation of each of these flow sheet. Therefore, we have to somehow reduce the number of flow sheet or shortlist the best few best flow sheets. The heuristic that we have seen in previous modules can help us eliminate some of the flow sheets, and provide the first estimate of some design variables. For example in case of absorber we saw the thumb rule of l by m g equal to 1.4 in case of distillation columns we saw a thumb rule of reflux ratio r was equal to 1.2 time r minimum.

And therefore, you can eliminate some of these flow sheet alternatives using these kind of heuristics, but even with this we are left with very large number of process alternatives to be considered, may be few 1000 process flow sheets again estimation cost estimation profitability analysis of all these flow sheets in detail is impractical. So, we have to use some other criteria for short listing of these flow sheets.

The obvious criteria would be the total processing cost of the flow sheet and therefore, if we can find a means of summarizing the cost information in a simple and efficient way. It would be very useful tool for screening and short listing of process alternatives. What is the conventional way of representing cost information, conventionally, you have a flow sheet in which the equipment are different equipments are given certain numbers, and then there is a table that gives the installed cost of these equipment as per the numbers.

Then you have for that is as far as the capital cost is concerned for the operating cost, you have a flow sheet sorry a table of listing all the raw material requirement all the utilities and their annual cost and then it is summarized. However, bringing the 2 types of cost the capital fix, capital investment or the equipment cost and the operating cost or production cost on the same basis.

And then simultaneously analyzing the total processing cost is rather tedious job, because while taking into consideration all the tables and flow sheets, simultaneously you may lose the track of the cost data. And then the job of short listing and stirring of process alternatives becomes rather tedious. So, what we will see now in this module is an efficient way of representing the cost of a particular flow sheet. What is that way, it is essentially writing the annualized capital cost on the flow sheet itself the cost diagrams.

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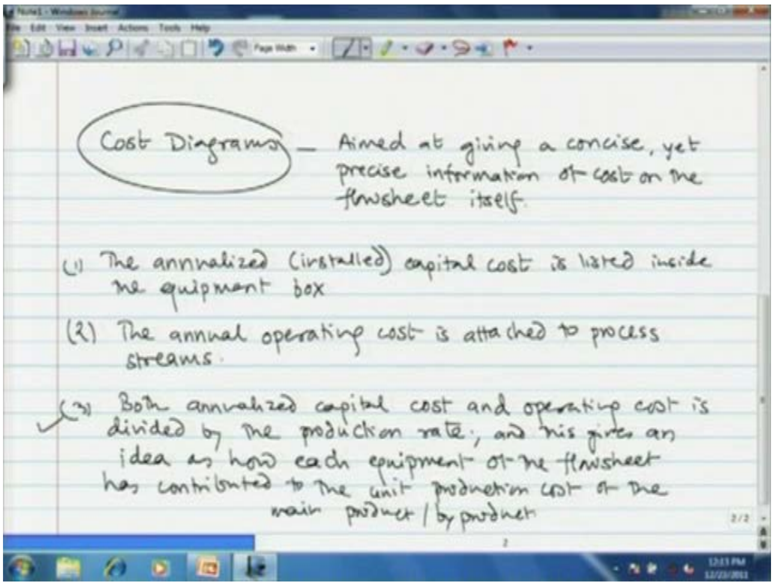

Cost diagrams are essentially aimed at giving concise, yet precise information of cost on the flow sheet itself. So, how a cost diagram is prepared the annualized capital cost, but of course, the installed capital cost is listed inside the equipment box. And the annual operating cost is attached to the streams different streams in the process, in some cases both annualized capital cost and operating cost is divided by the production rate.

And this gives an idea as how each equipment of the flow sheet has contributed to the unit production cost of the main product and by product. This is also method used sometimes, we shall basically see the first 2 methods for finding the out the cost diagram or establishing a cost diagram. Now what I will show, you is the cost diagram of the isopropanol de hydra hydrogenation process to produce acetone.

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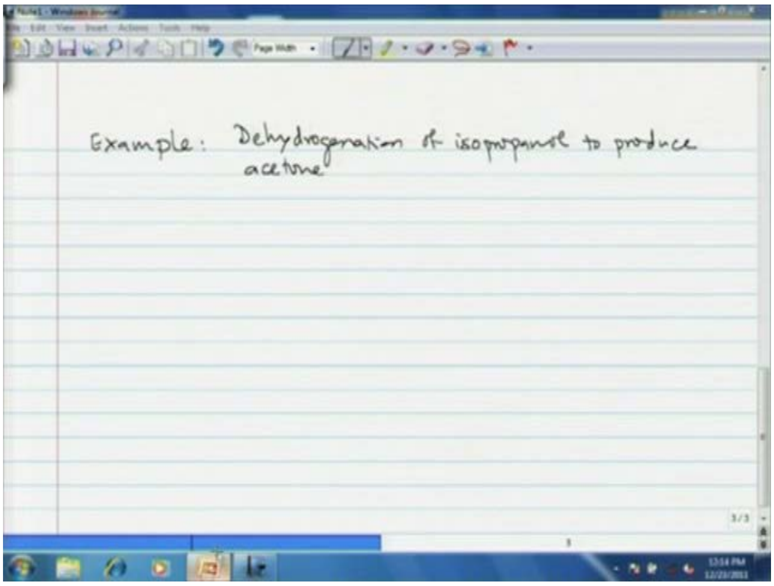

What you see we have seen this process before dehydrogenation of isopropanol to produce acetone.

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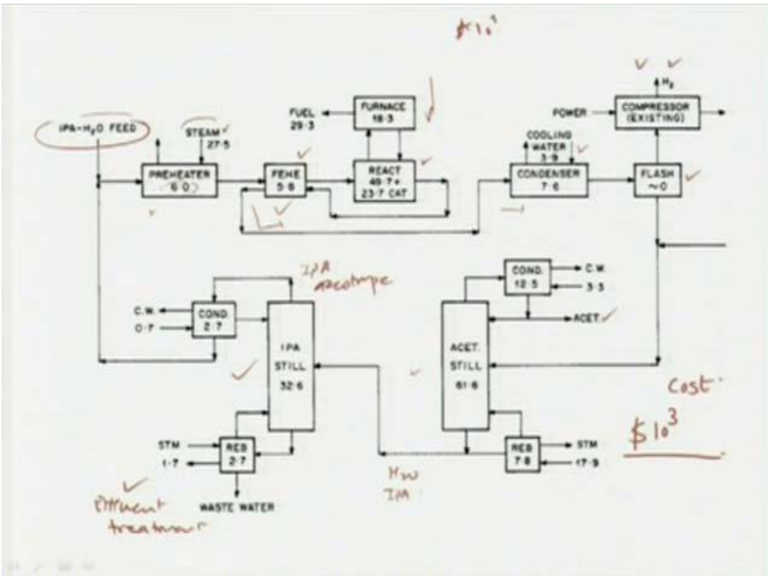

And now what you see on screen is the energy integrated flow sheet of this particular process. Now you can see that the feed to the process is an aseotrope of iso propyl alchohol, which is heated in a pre heater that you just steam as the utility, then the stream emerging from the pre heater enters, feed to effluent heat exchanger and finally, enters the reactor which is a catalytic reactor. Now since this is decomposition reaction, it is an endothermic reaction and the heat has to be supplied in a previous module, we have already done the heat and energy balance of this particular process.

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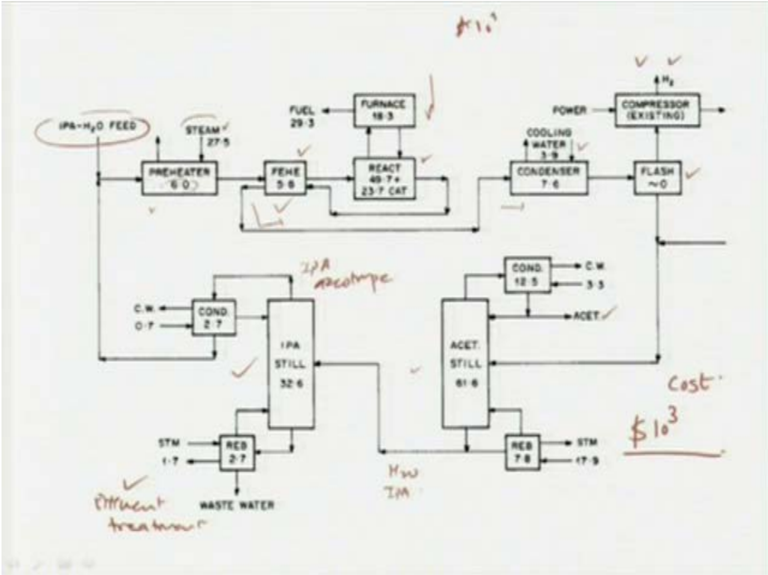

So, these things should not be much new to you, the stream emerging from the reactor first exchanges heat with the incoming stream in the heat to effluent heat exchanger. And then it enters a condenser where, cooling water is used as a utility, then the stream goes to a flash drum in which the liquid and gas products are separated the main gas product is hydrogen which comes out. It is compressed and later on used as fuel in somewhere or it can be also sold as a side product, the liquid that comes out which contains un reacted iso propyl alchohol and acetone and excess water is distilled in 2 columns the acetone column in which the acetone is removed as the main product.

And then water plus IPA goes into the second column in which the product the distillate product is IP azeotrope, which is recycled back to the reactor and excess water is sent out for effluent treatment. Now what you see here, is the cost diagram of this particular process. The numbers that you see inside the boxes are the annualized capital cost of that particular equipment and numbers that you see attached to the streams like for example, your steam 27.5 this is essentially 1000 dollars.

This all these numbers are in 1000 dollars. So, the pre heater the number 6 indicates that the annualized capital cost of pre heater is 6000 dollars the steam required for this particular pre heater are the annual requirement of steam cost 27.5 1000 dollars and so on. And. So, forth now what we can do is that using this particular cost diagram, we can see what are the areas or what are the locations, where we can go for the optimization of the process.

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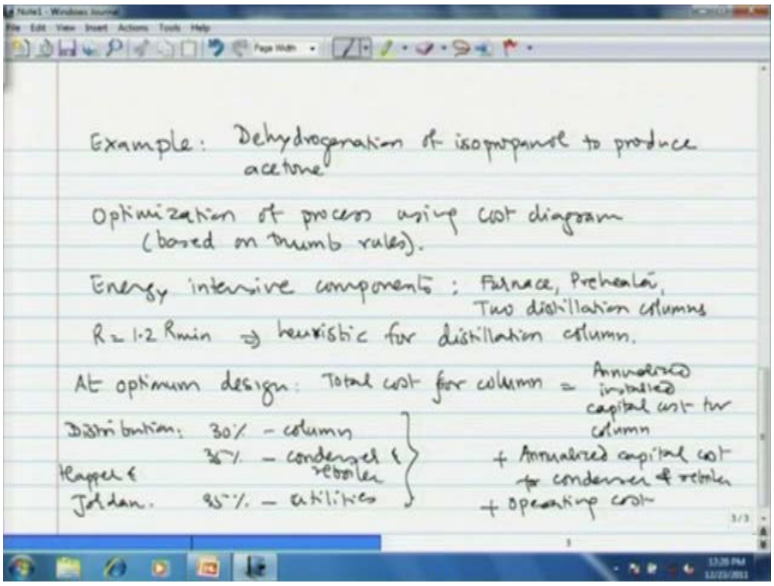

And that we will see now optimization of process using cost diagrams, now this optimization is based on thumb rules. The energy intensive components of this particular flow sheet are the furnace, the pre heater and the 2 distillation columns. Let us assume that the distillation column was designed with heuristic of 1 r reflux ratio equal to 1.2 times the r minimum, minimum reflux ratio heuristic for distillation columns.

However, the cost distribution that comes, for the distillation column may not be optimum, for example, at optimum design condition the total cost for the column which includes the annualized, installed capital cost for the column and the initial plus plates plus the annualized capital cost for the condenser and re boiler and the operating cost for utilities add condenser and re boiler.

The total cost for the column the distribution of this cost should be typically 30 percent for the column, 35 percent for the condenser and re boiler and rest 35 percent for the utilities at condenser and re boiler. This is given by happel and Jordan, in some cases like the cost analysis done by peters and timmer house

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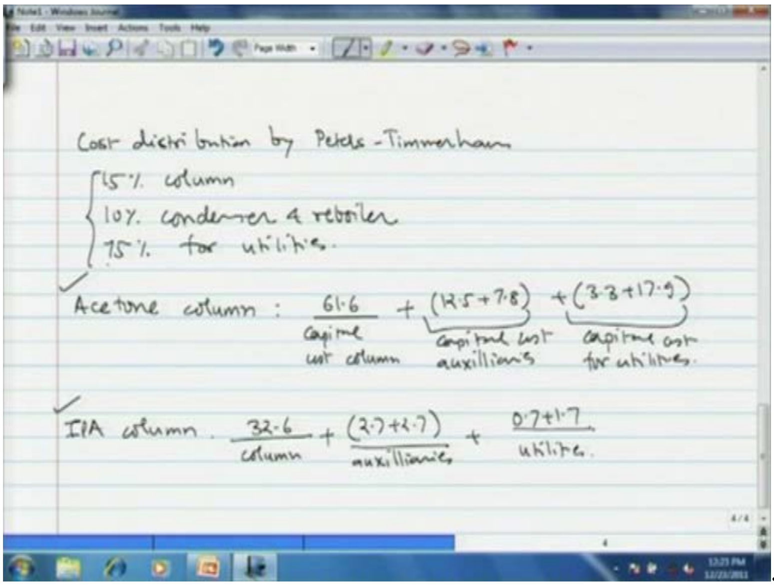

The cost distribution is typically 15 percent for the column, 10 percent for condenser and re boiler and 75 percent for utilities. So, 2 analysis of distillation columns, given by 2 separate team of engineers as given this distribution that the total annualized capital cost of the column should be distributed 15 percent for the column, 10 percent for condenser re boiler, and 75 percent for utilities.

Another analysis says that it should be 30 percent for column, 35 percent for condenser re boiler, and 35 percent for utilities. Now, if we see the total cost of the column in the flow sheet, like for example, column 1 the I the acetone column, what we see is that 61.6 1000 dollars is the capital cost of column, annualized capital cost plus 12.5 plus 7.8 is the capital cost for the auxiliaries or the condenser re boiler. And the total operating cost is 3.3 plus 17.9.

Take the second column the I P A column, here you will see 32.6 1000 dollars as the column cost plus 2.7 plus 2.7 that is 5.4 for the auxiliaries condenser re boilers and 0.7 plus 1.7 it is 2.4 for utilities. Now if you see the distribution of the cost among these three factors capital cost for column for auxiliaries and the utilities, now here we see a resemblance to the optimized distribution which means if you see the cost distribution among the 3 components of the distribution column, we do not see either distribution given by peters timmer house or Happel and Jordan; that means, these columns are far from their optimum operation. And this gives us or this helps us in identifying the areas of optimization; that means, both column need further optimization further design to reduce the total cost of operation.

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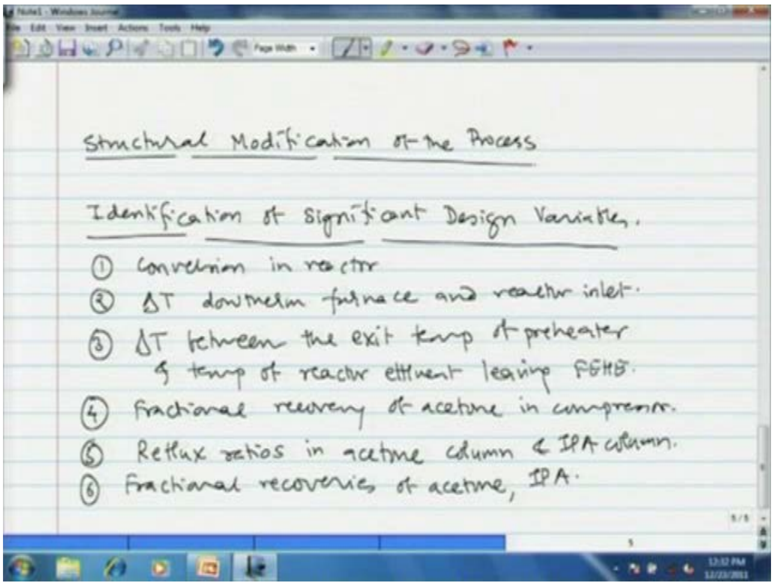

So, this is one thing cost diagram will also help us in determining the structural modification of the process, the process is energy intensive, because it is a dissociation decomposition endothermic reaction it is energy intensive. Therefore, we have to bring down the energy requirement as much as possible by doing energy integration of the flow sheet. Now let us try to evaluate that particular flow sheet on the grounds of the energy integration

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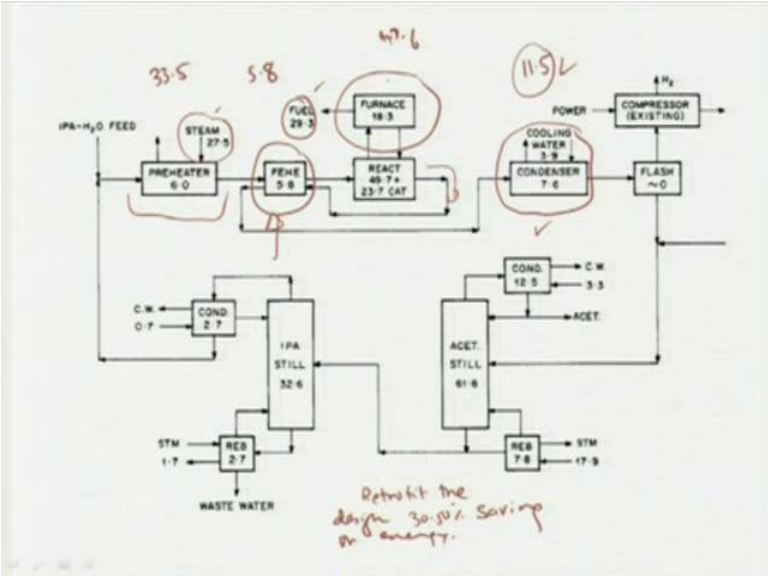

Now, if you see here again I am going back to the flow sheet, you will see that only 5800 dollars. The energy integration component is the feed to effluent heat exchanger and this exchanger is rather small with only 5800 dollars per year spent on it; however, if you see the cost of the pre heater. It is 6000 plus 6000 annualized capital cost plus 27.5 1000 for the pre heater, and similarly you see the furnace also consumes 29.3 1000 dollars of fuel and the annualized capital cost is 18,300.

You see here the cost of condensing the reaction mixture the condenser capital cost is 7 annualized capital cost is 7.6 1000 dollars, the cooling water takes 3 900 dollars. Therefore, if we see the cost distribution of the energy intensive components where, it is 33.5, 5.8 then 47.6 and here 11.5, the cost of the components that used external utilities is rather high. For example, steam load is high fuel load is high, how we can bring down these cost, that is by spending more on the feed to effluent heat exchanger we can make it larger.

So, that greater amount of energy of the stream that is emerging from the reactor can be recovered and then the load on the pre heater and the furnace reduces. Similarly, if greater energy of the reactor effluent is recovered, the load on the condenser also goes down. And therefore, we can have further saving in this 11.5 1000 dollars of for the condenser. Typically if you re profit a design with modifications of this particular components, then we can save up to 30 to 50 percent of the energy cost. So, this is another area for optimization of the process, what are the further application of cost diagram or utilities of cost diagrams.

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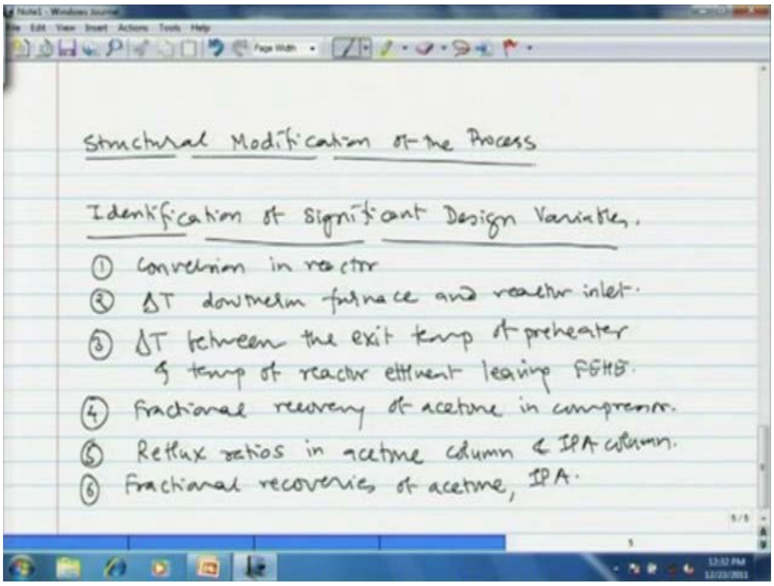

It is about the identification of the significant design variables, what are the design variables that we can identify from the flow sheet that we have seen. The first is the conversion in the reactor; the second is the delta T temperature difference between the dow therm furnace and the reactor inlet.

Then third is the temperature difference or approached temperature between pre heater exit temperature, and temperature of reactor producing the heat to effluent heat exchanger delta T between the exit temperature of pre heater, and the temperature of reactor effluent leaving the feed to effluent heat exchanger. Then fourth will be the fractional recovery of acetone in compressor the hydrogen stream that emerges from the flash drum contains mainly hydrogen that is the desired product of the process.

It may contain some impurities of methane or ethane, because it comes from reforming process. Now some acetone being rather volatile some acetone leaves with that stream not all of the acetone condenses in the flash drum. Now the recovery of that particular acetone is essential, because hydrogen is compressed before it is used for other purposes and during that compression acetone condenses which can be recovered, so that is another factor or another variable, design variable.

Then the reflux ratios in both columns the acetone column, and IPA column and then the fractional recovery of acetone in the column and fractional recovery of IPA in its column. So, these are some of the design variables that we can identify from the cost diagram. Now some of these design variables have local impact and some of these will have global impact, which means change of that variable will affect the entire flow sheet.

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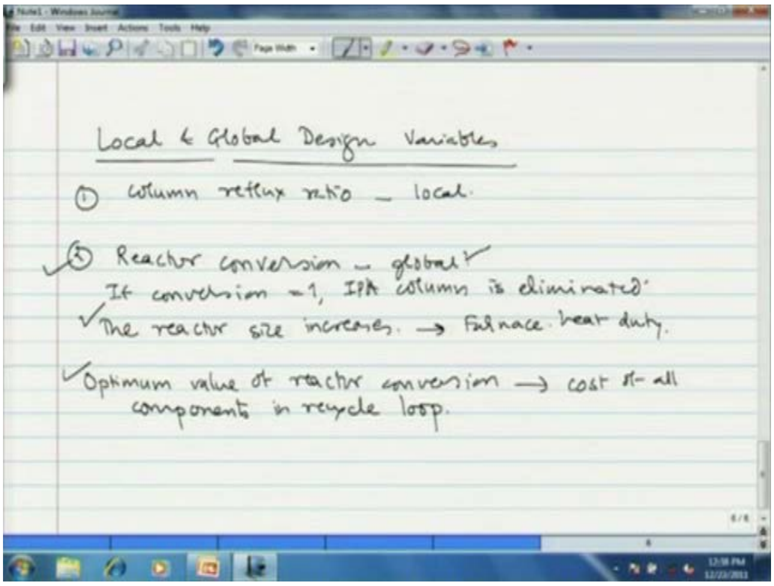

So, that view point we note local and global design variables, now the column reflux ratio is a design variable and if it is changed it will affect design of only that particular column. It is not going to affect a design of the reactor or the pre heaters. So, column reflux ratio could be designated as the local design variables, which affects only the particular column. However, the reactor conversion can affect the entire flow sheet, how if the conversion is unity.

Then we do not need any recovery and recycle of the reactants. So, the IPA column is eliminated, however, the reactor size increases and so does the furnace heat duty, so on and so forth. So, we can see that if we change the reactor conversion, it is likely to affect almost all components of the flow sheet. So, it is designated as the global variable. Now what is the optimum conversion?

Reactor conversion is thus a global variable, how we can obtain the optimum value of reactor conversion, because there is a trade of. If reactor conversion becomes 1, the IPA column is eliminated, the recycle loop is eliminated all the cost corresponding to recycle loops are eliminated; however, we will need an reactor of enormous size to approach conversion equal to 1 that will also increase the furnace heat duty. So, somehow we have to have a trade of and that trade of will give us the optimum value of the reactor conversion.

And this value will be based on the cost of all the components in the recycle loop and therefore, we have to make every effort to get the conversion close to the optimum value. So, this is the basic analysis or introduction of the cost diagram, now cost diagrams can be further utilized for determination of process alternatives the evaluation of process alternatives. And then finding the best possible flow sheet

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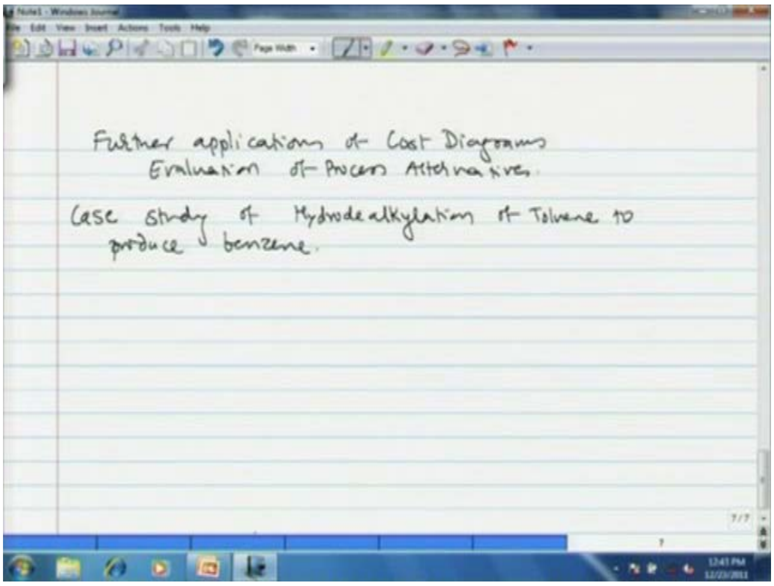

Now, let us see this analysis using the hydro dealkylation of toluene as the case study, which we have used in most of the analysis of this or lectures of this course. Further applications of cost diagrams evaluation of process alternatives and we do this using the case study of hydro dealkylation of toluene to produce benzene.

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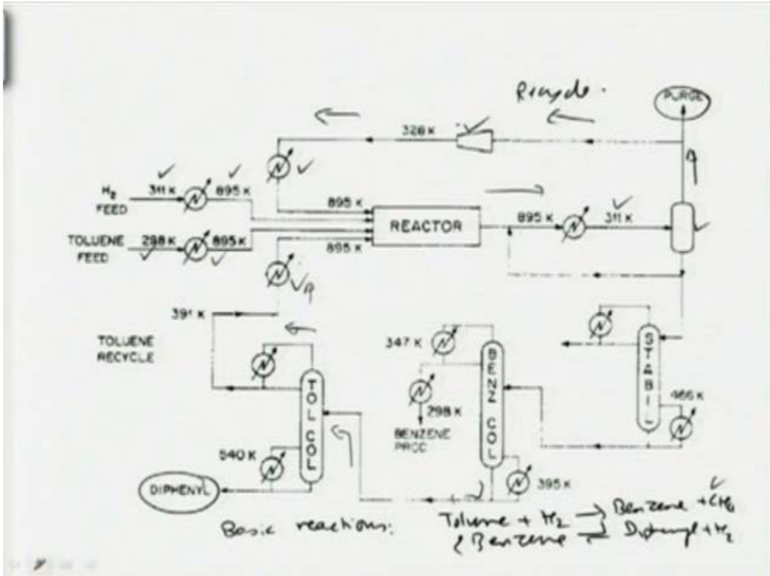

What you see on the screen now is the hydro dealkylation process the general flow sheet, we have seen this numerous times the basic reactions are toluene plus hydrogen giving benzene plus methane and 2 molecules of benzene combining reversibly to give diphenyl and hydrogen. We have done the material balance analysis, energy balance analysis of this particular process.

So, well I will just explain in brief the flow sheet that appears on your screen now. Hydrogen feed is heated from 311 Kelvin to 895 Kelvin before it to the admitted into the reactor toluene is at room temperature 298 Kelvin. It is heated and vaporized to 895 Kelvin before admitting into the reactor, then also admitted into the reactor of the 2 recycle streams the gas recycle, after compression and heating.

And then the recycle toluene after getting, after heating then the reactor effluent that comes out is cooled to 311 Kelvin nearly room temperature. And it then it is admitted into a flash drum, where the pressure is reduced, the pressure for the process as I mentioned is 500 p s i under optimum temperature is between 1100 to 1300 degrees feronhide or this 895 is optimum temperature 895 Kelvin. Some part of now in the flash drum face split occurs and benzene toluene and a diphenyl the 3 components condense and then hydrogen and methanol separated.

Now, that gas emerging from the flash drum also has some vapor of benzene and toluene diphenyl been having rather large boiling point. It does not have I significant vapor pressure. So, amount of diphenyl in the purge gas is negligible practically 0, you can take and then this gas is split in 2 parts. Some part is purged to heat the level of methane that is inert byproduct to particular level and remaining is recycled after compression and heating.

The liquid that comes out from the flash drum contains dissolved gasses, both methane and hydrogen that liquid is first heated hmm to remove the dissolved gasses in a stabilizer column. The liquid that comes out of the stabilizer column is admitted into the benzene column, where benzene is taken out as the main product as a distillate. And the bottoms contain the toluene and un reacted toluene and di phenyl.

And that stream is further admitted into the toluene column, where the un reacted reactant toluene is take out and di phenyl which is the reversible by product is removed as the bottoms. And then this toluene is recycled back to the reactor after heating. So, this is a very straight forward flow sheet that we can make from the basic reaction chemistry.

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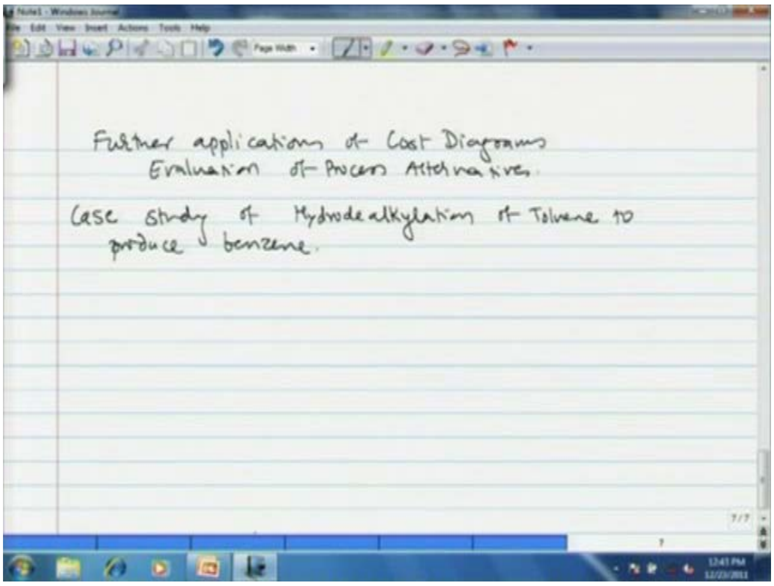

Now, the heat integration of the process since the reaction occurs at high temperature and high pressure it is energy intensive. So, to bring down the cost we have to have as much recovery of energy from the reactor effluent as possible.

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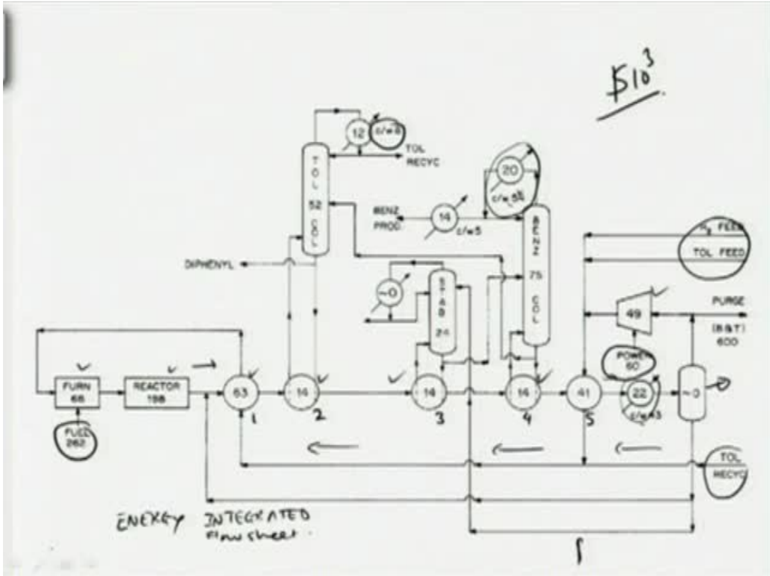

Now, what you see now on screen is the energy integrated flow sheet of this particular process, you can see that the reactor effluent that emerges from the reactor exchanges heat. In total 5 exchangers before getting condensed in the final exchanger condenser and then it goes to the flash drum. Now, what are the exchangers in which this reactor effluent gives out, it is heat the first react first exchanger is that f e h e feed to effluent heat exchanger.

You can see here that a recycled toluene is heated and vapor vaporized in this particular reactor, then the stream enters the re boiler column the re boiler of a toluene column. Then it enters the re boiler of stabilizer column, and finally it drives the re boiler of benzene column. And then it enters another f e h e feed to effluent heat exchanger in which the fresh hydrogen and toluene feed is heated using the remaining heat.

And finally, the reactor effluent goes into a condenser, where temperature is further reduced and in the flash drum the pressure is reduced, so as to cause the phase. And then the you can see here, the purge stream and recycle stream, the compressor of the recycle stream and then the liquid that emerges from the flash drum undergoes distillation in three columns. So, this particular energy integrated flow sheet looks complicated.

What you see inside the particular boxes or circles is the annualized capital cost of that particular equipment? And what you see attached to the different streams is the capital sorry the operating cost? For example, power required for the compressor the total operating cost over here is 60,000 dollars, again this is all in 1000 dollars all the cost. Similarly, this particular condenser it uses cooling water as the utility and 54000 dollars is the annual cost of that utility. Now using this cost diagram can we find out any means of evaluating process alternatives that is what we shall see now. This cost diagram is rather large and also complicated, so somehow we have to simplify this cost diagram.

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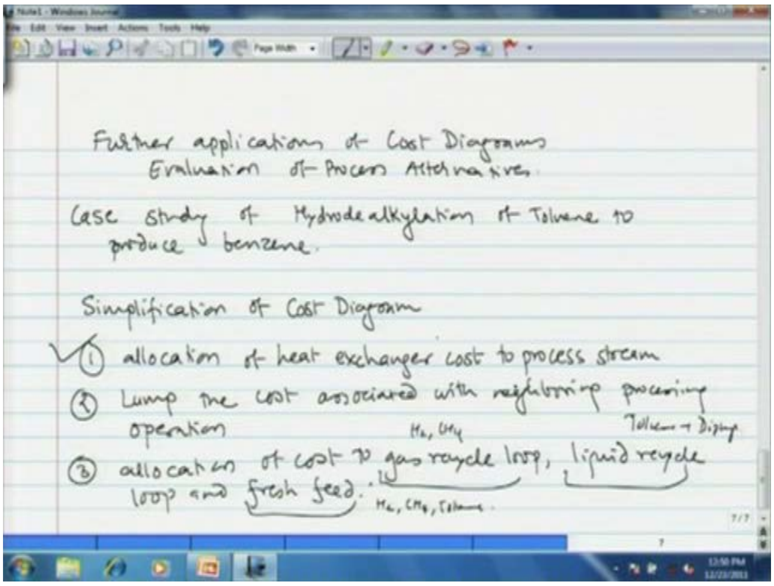

Now to simplify the cost diagram, we use 3 means first means is allocation of the heat exchanger cost to the process stream, then second is lump the cost associated with neighboring processing operation. For example, in case of a distillation column, we will add the cost of column annualized capital cost of column annualized capital cost of both auxiliaries re boiler and condenser as well as the operating cost of the utilities for these auxiliaries and lump that cost you know single figure.

And the third is allocation of cost to the gas recycle loop, then liquid recycle loop and fresh feed. So, all the 5 components of this particular process hydro dealkylation process benzene, toluene, di phenyl, hydrogen and methane are group together in 3 parts. first is gas recycle loop, liquid recycle loop and fresh feed. Now all of these components all of these elements will have a group of different elements, like for example, gas recycle would contain both hydrogen and methane. The liquid recycle will contain toluene plus di phenyl and the fresh feed will contain hydrogen methane and toluene. So, these are let us say the elements of that particular elements of out cost diagram

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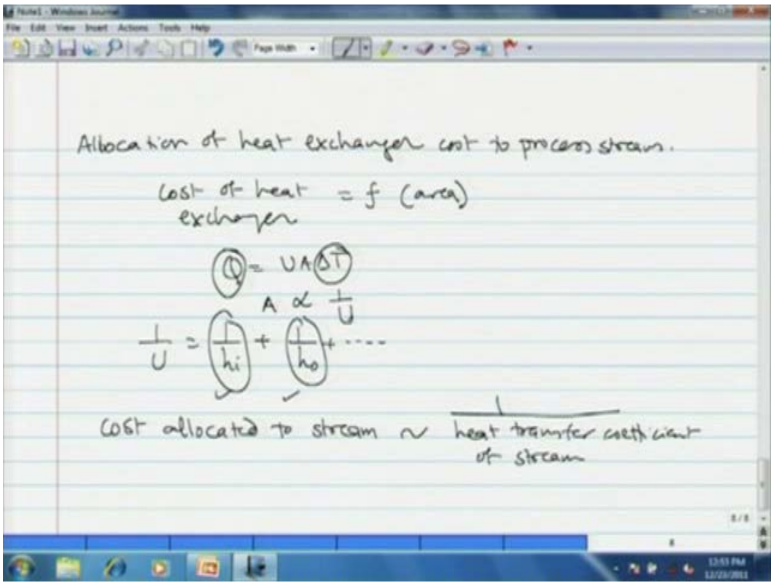

Now, let us see as how we can allocate the heat exchanger cost with the process stream, we know that the cost of heat exchanger is mainly a function of it is area heat exchanger area. And for a given heat duty we are very well aware of this relation Q is equal to U A delta T. So, for a given particular for a given delta T and Q the area is inversely proportional to U and then; obviously, the cost is inversely the cost is directly proportional to the area. So, the cost is inversely proportional to the overall heat transfer coefficient.

However, we know from our heat transfer principles that 1 by U the 1 by overall heat transfer coefficient is 1 by h i plus 1 by h o plus some other factors like the conductivity under factor. So, this means that the area of a particular exchanger is inversely proportional to the film coefficient of the 2 streams that are in that particular exchangers the inside and outside stream. Using this principle we now try to allocate the heat exchanger cost to the process streams. So, the cost allocated to the stream is inversely proportional to the heat transfer coefficient of that stream.

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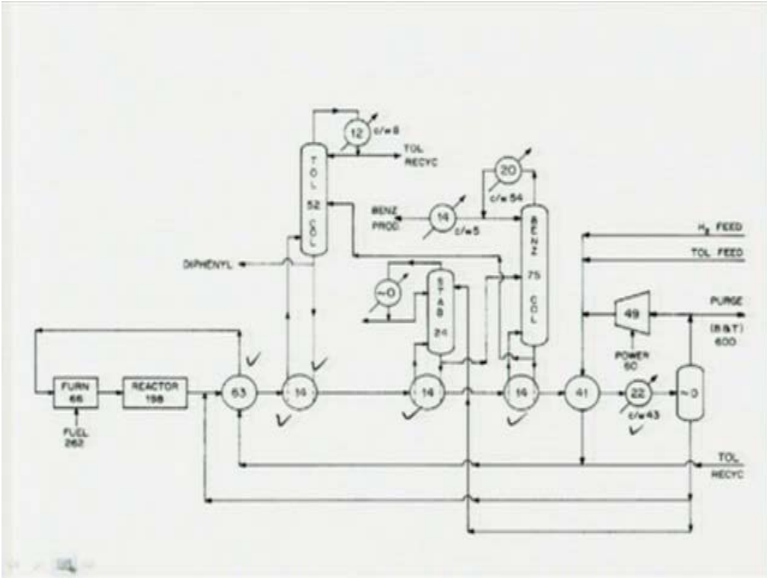

We have total of 5 exchangers in this each with annualized cost of 63000 14000, 14000, 14000 and 41 sorry 22000 dollars. So, there are 5 exchangers that treat the different streams.

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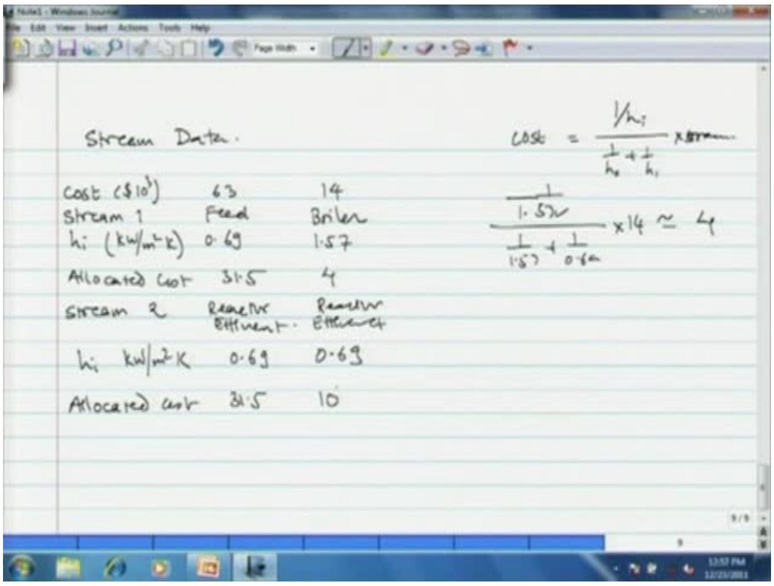

Now let us try to allocate the cost before that we before we do that we need to have idea of the heat transfer coefficients. So, now what I give you is the heat transfer the film coefficients of different streams in this 5 exchangers. So, stream data exchanger 1, which has cost of 63 1000 dollars annualized capital cost of 63000 dollars. Stream 1 is the reactor feed, it has a coefficient of 690 watt per meter square per Kelvin or 0.659 kilo watt per meter square per Kelvin. And the other stream is the reactor effluent, and let us say it has a coefficient film coefficient of also 0.69 kilo watt per meter square per Kelvin.

If we have to allocate the total cost of 63000 dollars to get 2 streams, we can simply divide it into half, because the 2 coefficients are same. Now the next exchanger that is a toluene re boiler, it has a total cost of 14000 dollars and now we have to assign it to the 2 streams that are there. Now the first stream is the boiler stream itself, since it is a boiling liquid it will have high coefficient let us say 1.57 kilo watt per meter square per Kelvin and a stream 2 is again reactor effluent.

Now reactor effluent since it is in vapor phase it has relatively low coefficient film coefficient 0.69. How we can allocate this? Here we have to use the that the cost allocated is 1 by h i plus 1 by h o plus 1 by h i is total cost. And therefore, we divide this using this particular form for stream 1, we have to we write 1 by 1.57 divided by 1 by 1.57 plus 1 by 0.69 into the total cost 14. And this comes out approximately 1000 dollars and then we do the same for the other stream replacing 1.57 by 0.69 comes out to be 4. And the other comes out to be 10. So, the 14000 dollars of the toluene re boiler are allocated 4 n time. If you do this for all exchangers, then you get the cost allocation I am giving the direct answer you can work it out.

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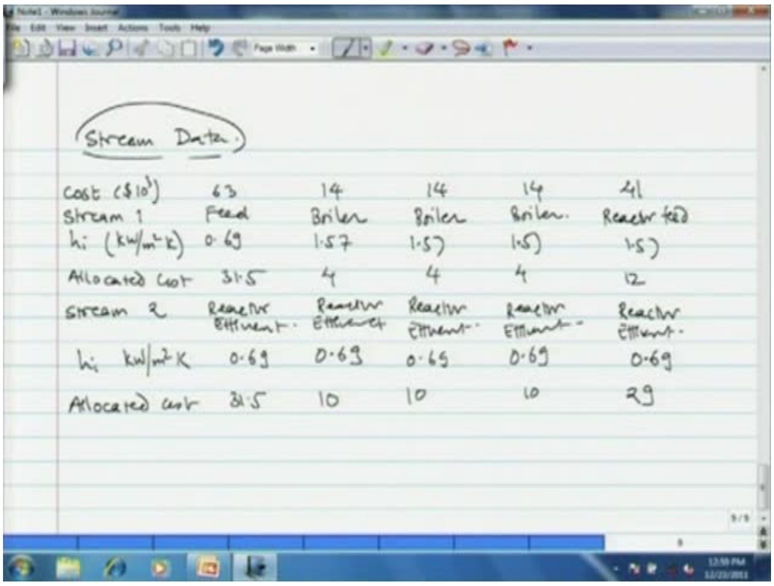

Stream Data

Cost ($10³)	63	14	14	14	41
Stream 1	Feed	Briler	Briler	Briler	Reactr feed
hi (kW/m²K)	0.69	1.57	1.57	1.57	1.57
Allocated Cost	31.5	4	4	4	12
Stream 2	Reactor Effluent	Reactor Effluent	Reactor Effluent	Reactor Effluent	Reactor Effluent
hi kW/m²K	0.69	0.69	0.69	0.69	0.69
Allocated cost	31.5	10	10	10	29

The third exchanger is stabilizer re boiler, it also has a annualized capital cost of 14000 dollars, then 1 stream is boiler stream, which will have high coefficient the other stream is reactor effluent. Since, it is vapor phase it will have low coefficient 0.69 and then exactly same distribution 10 in 4. The next column next exchanger is the benzene re boiler stream 1 is boiler stream.

It will have a high coefficient, other stream is reactor effluent and then exactly same distribution of price to cost. And finally, the exchanger that uses the fresh feed as 1 stream and reactor effluent is the other stream. This 41000 dollar exchanger here, the reactor feed is partially toluene and this liquid and gas. So, it may have higher coefficient, but the reactor effluent is still vapor phase.

So, it will have low coefficient 0.69 and then using the same methodology as we did earlier, we distribute 41000 dollars in numerous proportion of the film coefficient. So, the reactor feed which has a higher film coefficient has a lower contribution dollars and 29000 dollars for reactor. So, this is how we have allocated the cost of exchangers, which treat different process streams to the process stream.

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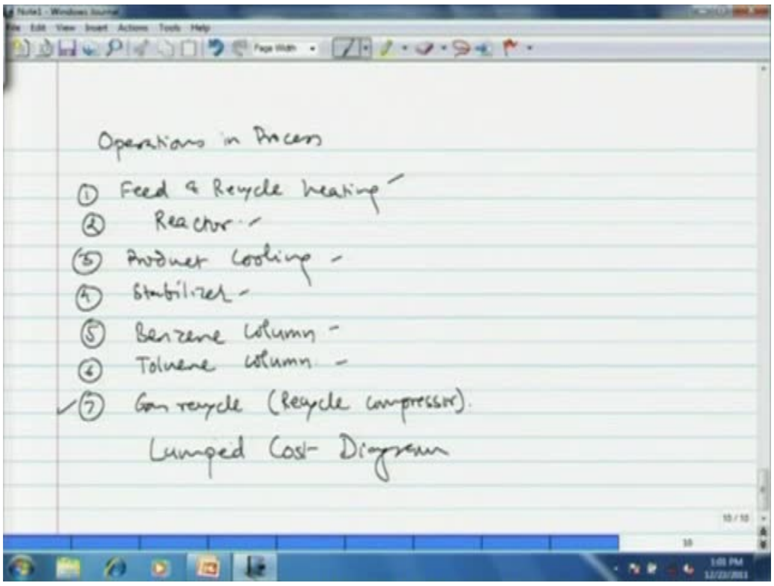

Itself the next task is to lump the cost associated with the particular operation that we shall see in the next lecture, but I just give you the introduction of it before we stop. we identify certain operations in the process, main operations in the process. What are these? First is the feed and recycle heating, second is the actual reaction or the reactor cost, the third is cooling of the product, fourth is the 3 columns stabilizer column, then benzene column and toluene column.

And then there is the operation of gas recycle or recycle compressor, we have not considered here the liquid recycle, because I mentioned to you in previous lectures that liquid recycle requires only a pump, which is an insignificant component. It does not have much cost, so that we do not consider, however gas recycle requires compressor, which has high capital as well as operating cost, so there that we identify as a distinct operation in the process. So, what we will do in the next lecture is that we will try to lump the cost that are associated with each of this operation and try to prepare what is known as a lumped cost diagram of the process.