Plantwide Control of Chemical Process
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Lecture - 38
Ethyl Benzene Process Case Study

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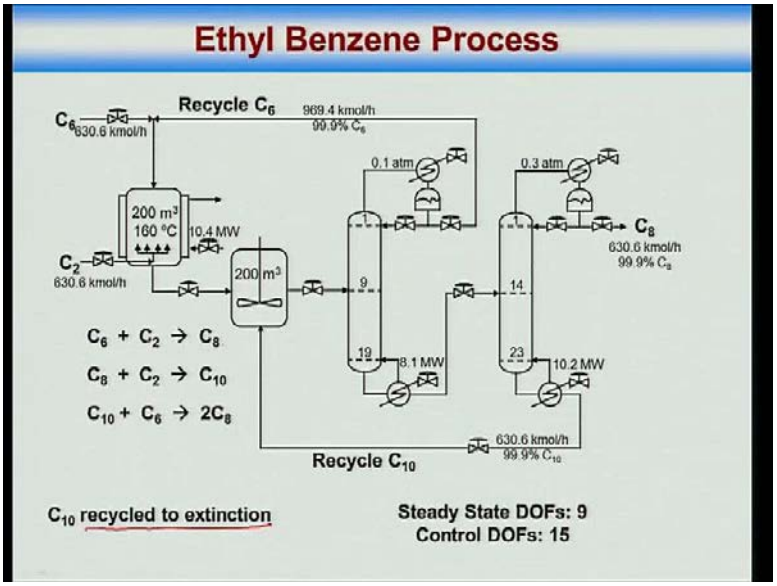

Two case studies, so here is benzene plus ethylene alkylation gives you ethyl benzene. Ethyl benzene is collaboration of ethyl benzene gives tiring, which is a which is polymer. The ethyl benzene further calculates with ethylene to give diethyl benzene C 10, and what you do is C 10 reacts with C 6 diethyl benzene reacts with benzene to give 2 moles of ethyl benzene.

So, the process is as follows you are putting in fresh benzene you are putting in fresh ethylene, reactor are sized to be large, so that all of the ethylene gets converted in the two reactors. Outlet from the reaction section is the diethyl benzene ethyl benzene ethylene is all converted. So, in the recycle column what you do is you recycle the benzene; benzene ethyl benzene diethyl benzene goes down.

The ethyl benzene and diethyl benzene are separated in a product column ethyl benzene is taken out the top diethyl benzene goes down the bottom. This diethyl benzene is recycled to reactor 2.

Now, if you look at the reaction, where the two reaction that are going at the two bottom reactions, there is the diethyl benzene formation reaction, and there is the diethyl benzene consumption reaction. Second reaction is diethyl benzene formation, third reaction is diethyl benzene consumption.

If you allow your diethyl benzene to build in the recycle loop in the bottom recycle loop in this bottom loop to a sufficient extend, such that it is concentration goes up then as it is concentration goes up, second reaction will consumption will go up, so second reaction rate will go up, and ultimately what you will have is consumption by the third reaction, sorry consumption by the last reaction will balance formation by the second reaction, yes or no.

And then you will have no net formation diethyl benzene in your process, yes or no. This is called now you are recycling diethyl benzene to extinction. Does that make sense, so diethyl benzene is recycled to extinction? Degrees of freedom Ah, the first reactor has got a cooling mechanism, the second reactor is adiabatic.

Now tell me what is the degree of freedom. Of course it is written there, but justify, 2 for reactor 1, 2 for reactor 1. How many for reactor 2, which is the level 1 for reactor 2, 2 each for the 2 columns, so that is 4. 4 plus 3 is 7 and 2 for the fresh feeds for the 2 fresh feeds for the 2 fresh feeds. So, that is 9 ethylene feed and benzene feed.

By the way note that since that you are recycling C 6, the reactors are operating in excess C 6 environment, yes or no. Excess benzene will make sure that ethylene is the limiting reactant that will suppress diethyl benzene formation, yes or no, so, that that makes sense. So, ethylene is consumed and diethyl benzene formation is suppressed by having excess benzene. Now, we do an optimization of course, this is the best case that I have taken from a paper.

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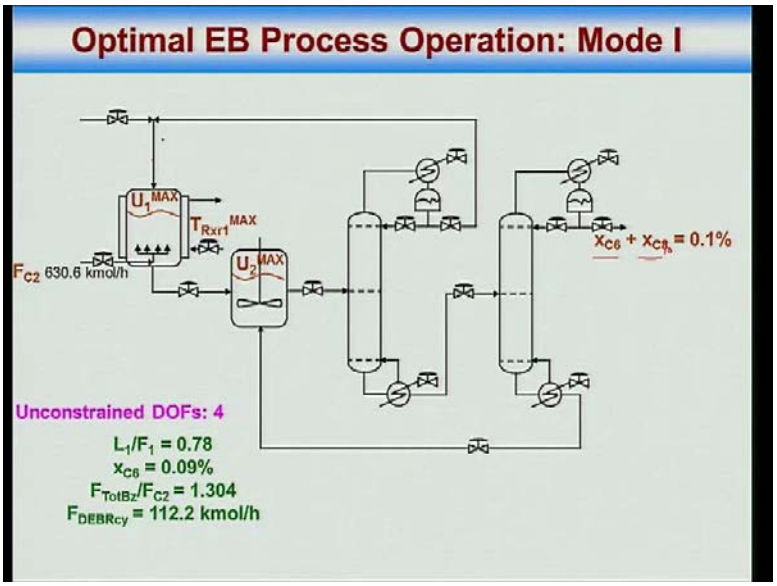

Mode 1, mode 1 is given throughput. So, let us just take the design throughput design throughput is ethylene feed rate is 630.6 kilo moles an hour. So, this is given to you. Then remaining 8 degrees of freedom you optimize, and the optimizer gives us what are the active constraint, if I look at the active constraints reactor one should be consume should be operated at maximum level, it should be operated at maximum temperature, the reactor two should be operated at maximum level also, the impurity in the product should be at its maximum allowable limit.

What is the impurity in the product any C 6, any benzene that leaks down here will guaranteed end up at any benzene that leaks down here, will guaranteed end up here plus, whatever is the split that is being done by the second column. So, it will have diethyl this should be C 10 I am sorry, so C 10 plus C 6, impurities are C 6 benzene leaking down and diethyl benzene leaking up. This should sum to 0.1 percent. So, that your product is 99.9 percent ethyl benzene.

Now, that we have this. How many degrees of freedom are left. How many things are specified.

Feed is specified 1, 2, 3, 4, 4 plus 1 5 things are specified.

How many m constraint degrees of freedom, 4, at the optimum it turns out that the reflux to feed ratio for column 1 should be whatever 0.78, it also turns out that you see these are

there are two impurities here, you could have maximum benzene, you know mostly benzene and very little diethyl benzene or you could have mostly diethyl benzene, and very little benzene of course, it depends on the separation, but what would you like.The question is how do you want to do the separation.

This way or that way. Sir, we have to see the relative (())

No. it is not a question of relative or utility it is related, but C 6 you see it turns out your you want 0.1 percent total impurity, at optimum what you finding is C 6 is 0.09 percent. So, you are basically what you are saying is mostly benzene impurity in the product.

Why? These need things to be thought through. Why? Why is t reactor one max active?

The second reactor is adiabatic. So, you will maximize the temperature in the second reactor and therefore, you will maximize the consump the Trans alkylation, the DEV consumption in the second reactor and therefore, DEV will not build up to that large in extend. Diethyl benzene will not build up to that large in extend. So, that makes sense or no.You see I want the reactor temperature of reactor one to be max because, that gives me the highest possible temperature in reactor 2, reactor 2 is adiabatic.

Now, that the temperature in reactor 2 is what is happening in reactor 2. Reactor 2 is basically Trans alkylation the last reaction. So, if the last reaction is fast what; that means, is I will not be having that much DEV accumulating in the recycle loop I do not I do not need to accumulate it to that large in extend to balance the consumption. For similar reason U 1 and U 2 max are also active, U 2 max is active for the same reason.

I do not want unnecessarily to re circulate too much diethyl benzene, if the my reactor level is maximum similarly U 1 max is active. Why is C 6.09 percent impurity? Why is the impurity in my product mostly benzene that is the question. So, because if you do not want to let out more C 10 since if we let out more C 10; that means, there is lesser amount in recycle.

No you have got nothing to do with the recycle. (()) C 10 how is C 10 make. C 10 is made from C 8 and C 2.

So, two molecules So, two molecules of C 2 and one molecule of benzene are there in C 10 by allowing benzene to be the impurity I am saving a two molecule of ethylene is expensive.

Yes or no. Of course I will. Then you will say I did not you put it at 0.1, because if you put it at 0.1 then what will happen is that the that the boil up in the second column I will have very little impurity C 10 in the product, and then what will happen is the boil up in the second column will blow up boil up, and reflux in the second column will blow up right.

But if you look at it common sensibly you know it is a it is a easily separable mixture, because two carbon numbers are different you know C 6, C 8, C 10. So, separation is not that bigger deal all my profit is will then come by how much raw material I am saving.

So, by allowing C 6 to be the primary impurity I am saving on I am consuming less ethylene. That gives me slightly higher profit it is not a big deal may be 0.1 0.2 percent greater profit, but nevertheless that is what is the justification.

Of course is the customer says that I want 0.05 percent benzene, and 0.05 diethyl benzene that it is not a degree of freedom then it is fixed its specified by the customer. But it is a degrees of freedom, this is how I would run it, because is separation is relatively easy in both the columns.

Yes or no. That makes sense. And of course, here excess ratio. So, two degrees of freedom, we talked about unconstrained L 1 by F 1 and the impurity benzene in the product.

The other two I have just chosen as total benzene to the reactor divided by fresh ethylene to the reactor, and that turns out to be 1.3, so there is a there is a 30 percent excess of benzene going to the reactor.

Here here, this is benzene total benzene going to the reactor. So, this is to this is 1.3 about. Similarly, it turns out that the recirculation rate of diethyl benzene is 112.2 kilo moles an hour; this is mode 1, agreed. So, this is what the optimizes gives me.

How to do the optimization I do not want to bother you because that, but how do to use the results from the optimization for control structure synthesis, that is what we are interested in.

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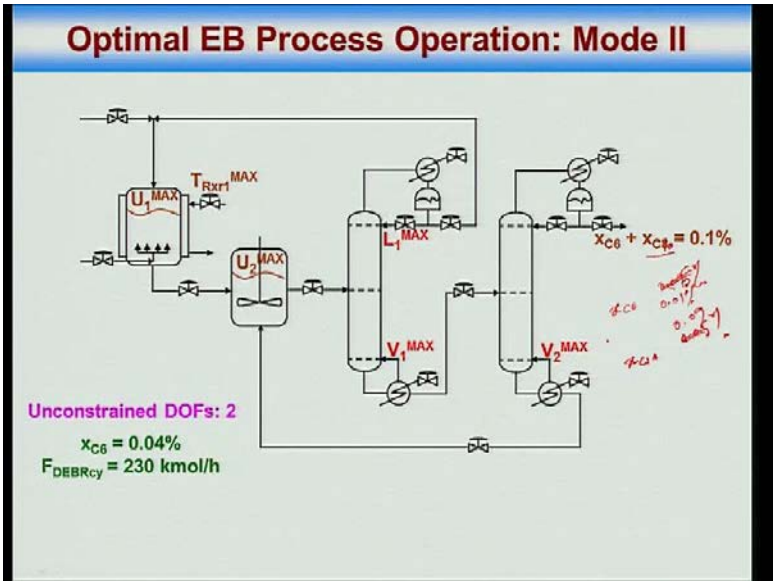

Now, mode one is design throughput I want to go to maximum throughput. So, at maximum throughput, well F C 2 is not specified, it is whatever it is.

It is a it is a dependent variable it is actually a design variable, the other four constraint are active, and what happens is these constraints become active at maximum throughput these constraints are active. Earlier throughput was given.

Now, F C 2 itself is a decision variable, earlier F C 2 was fixed the other 8 variables were optimized. (())

We do not know what that maximum is. You are maximizing F C 2, but F C 2, C 2 itself is a degree of freedom that used off because it is not specified, it is free to flow. (()) So, it is not dependent you have got 9 degrees of freedom and you are choosing all 9 degrees of freedom to maximize throughput. Earlier throughput was given you are left with 8 degrees of freedom.

So, two unconstrained degrees of freedom, it turns out that now you have X C 6 the impurity of benzene in the product going down to 0.04 percent, why is that well that is got to do with I do not know it is hard to explain, but once you look at the control system

it will become clear why that happened. If I do not explain it remind me I will explain it once you go through the control system.

Let us put it this way well see V 2 max is active, the boil up in the second column is active. So, as V 1 max. If I relax on the benzene, then I can allow more C 10 in the top. So, earlier benzene was 0.09 percent, if I reduce it to 0.07 percent, 0.06 percent I will be allowed 0.04 percent that, so my separation in the second column will become lose.

Earlier I was only allowing 0.01 percent diethyl in benzene at the top, now I am allow it to let 0.0 for percent ben diethyl benzene up the top not C 6 C 10.

0.0.

0.06 percent C 10 on up the top.

So, the separation is becoming less stringent, if the separation is becoming less stringent I need restless reflux, if I need less reflux boil up will reduce, but if I am keeping the boil up the same then I can sucking more feed, that gives me a rise and throughput, but then V 1 max is also active, why did the benzene impurity go down to 0.04 percent from 4.09 percent, that what we were discussing it turns out that V 2 max is active, because V 2 max is active, if I relax on the C 10 impurity there right, then I will have to tighten C 6 impurity.

So, if I relax on C 6 10 that mean X C 10 is increasing, which mean X C 6 must decrease. So, as I increase the X C 10 in the top reflux would decrease, if the boil up remains at V 2 max I will need to put more free to this column that mean my throughput goes up right, my F C 2 goes up I want to maximize F C 2.

But as I am doing that X C 6 is becoming more stringent is becoming smaller and smaller; that means, I am allowing lesser and lesser amount of benzene to leave down the recycle column the first column.

So, if X C 6 is becoming tighter V 1 max is fixed, there will come a stage when the freed to the recycle column will have to decrease in order to not let benzene leak out its contaminates your product right.

So, between these two extremes there is an optimum I cannot have 2 stringent C 6, and I cannot have 2 stringent C 10, somewhere in the middle and that middle turns out to be 0.04 percent something like that.

Wait I want to maximize F C 2, if I want o maximize F C 2, V 2 max is active if I keep X C 10 really tight at 0.01 percent then that is that will limit how much feed I can put to the second column.

If I relaxed this to let us say 0.05 percent, then what will happen is reflux will go down because, now I am allowing more diethyl benzene to leak up the top, then I can suck in more feed to this column.

Yes or no. So, by relaxing on C 10 I am sucking more feed to the second column.

However I am making the separation in the recycle column tighter, because now if earlier earlier X C 6 was 0.09 percent, but when you made C X 0.05, this must also go down to 0.05 percent, right.

Let us say I will say I will make X C 10 0.01 percent, 0.09 percent I will make it very loose, then this becomes very tight, if this becomes very tight in the first in the first column V 1 is at max I do not want to let any benzene leak out; that means, I am my the feet that I can suck in the first column will be only, so much right.

So, in this extreme in the extreme where the principal impurity is benzene the second column becomes limiting, in the extreme that the principal impurity is diethyl benzene the first column becomes limity, somewhere in the middle is the optimum that gives you maximum F C 2, that your objective right therefore, it goes down to 40.04 percent.

And of course, increasing throughput your DEV recycle increases to 230 kilo moles an hour. So, these are 2 unconstrained degrees of freedom.

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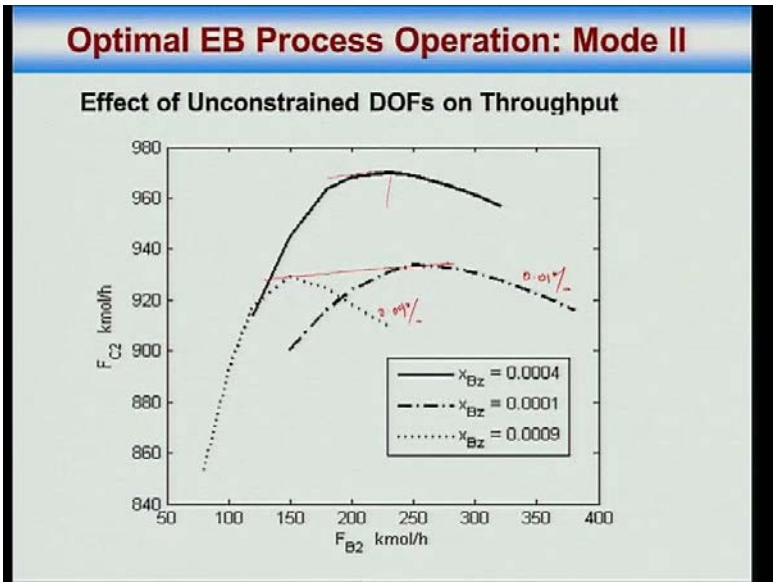

Now, let us synthesis the control system by the way, this is the variation in F C 2 with product impurity, and the DEV re circulation rate, you had two unconstrained degrees of freedom right DEV re circulation rate, and whatever was the product impurity X C 6 right.

So, X C 6 is X benzene the line that is in solid is the optimum 0.04 percent benzene, this line dash dot is 0.01 percent the this is 0.09 percent.

So, mostly benzene is the dotted line dash dotted line is mostly diethyl benzene, and the black solid line is a little bit of this and little bit of that comparable amount of the 2 impurities right. You can see that the throughput here is about 970 kilo moles an hour maximum achievable throughput is 970 kilo moles an hour and this is occurring at about 230 kilo you know somewhere around 230.

If you do not play with the product impurity the maximum achievable is I do not know this extreme or that extreme is about 930.

So, you are getting 40 kilo moles extra per hour, throughput and if you say 40, 40 is about 4 percent of 1000 970 is about 1000 right.

So, 4 percent extra production just by playing with the 2 unconstrained degrees of freedom 4 percent is a hack of a lot, 4 percent accumulated over year years of operation will turn out turn, out to be millions of dollars or crores of rupees in extra revenue.

Yes or no. So, even though it appears 0.09 percent 0.01 percent blah blah blah blah blah blah, but it makes a difference.

Of course, if the operator or if the if the customer is saying no you have to have, so much impurity this and, so much impurity that, then it is not a degree of freedom the it is fixed and then maximum, throughput is whatever the hell it is.

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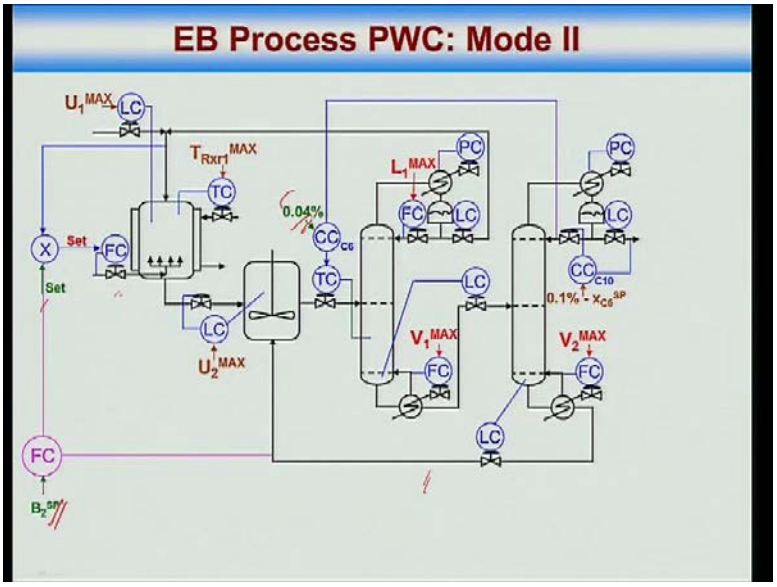

Now, let us synthesis move to max throughput what are my active input constraints, these are active. So, I keep them at max all right. I need to control my product impurity right. So, I do that. So, what am I doing I am controlling a tray temperature in the recycle column here, this tray temperature is control by adjusting the feed to the column.

Why am I using the feed because boil up is already max I am not allowed to change it reflux is also max I am not allow to change. So, this is what I am doing, and then this temperature set point is adjusted to maintain the benzene impurity in the product at 0.04 percent, which my optimizer gave me.

Why is it link to reflux (()) Who is linking to reflux? Reflux is a product [fl] you distillate and reflux is the same right. You just ease of drawing that is all. So, the product composition the product benzene impurity is setting the temperature set point. So, that takes care of benzene impurity.

Then I set the diethyl benzene impurity in the product as 0.1 percent minus whatever was the set point here that gives me how much diethyl benzene I am allowed to leak out.

So, independent is benzene dependent is diethyl benzene they way I have drawn it. So, well that is this and what I am doing is I have shown that I am adjusting the reflux, but usually what you will have is a temperature controller that adjusts the reflux, and that temperature set point is being adjusted by the composition controller, but for ease of drawing I have just drawn it like this.

What would you have is a temperature controller that does this, and this set point would come from the composition controller right, but then it becomes quite messy I just for the hake of showing I just showed it like this.

Then you see I am limited in my capacity to boil off V V 2 max is max I cannot boil up ethyl benzene. So, if I am getting more ethyl benzene then I can boil up to the column, where will that ethyl benzene going to drop down and build up in the DEV recycle loop.

Yes or no. I do not want to do that. So, what do I do I control a stripping tray temperature by adjusting the feed that will ensure the feed is only, so much no ethyl benzene drops down. Yes or no that makes sense. So, that is what this temperature.

Now, I have done this that is a stabilization issue, it is a stabilization issue what I mean what do I mean by stabilization issue, if I do not control this temperature I can have a situation where things will drop down and accumulate it is a you know dropping steam dropping down. If I am making more ethyl benzene in the reactors then I can boil up in the second column, where will that ethyl benzene go it will bloody drop down and keep circulating around and in the in that loop.

Yes or no. I do not want that that is a stabilization issue that is like the level is building up and up and up it is not a level, so I put a temperature controller that is a stabilization loop.

Now, that I have done this I had put in level controllers note that reactor 2 outlet valve is taken I have to control level of recycle column bottom the only valve available is here, so what I do is this because, this valve will be get will get used to control level of this valve right.

So, the only way to control level here is this way the only way to control level in the first reactor is this way, only way to control temperature of the first reactor is this way and of course, this set points must be max allowed there is because my optimization set, so and it makes physical sense actually.

Yes or no. Fair deal. Then I put level controllers on the column, pressure controller on the column. So, this level control controller work this way, this level controller works this way, this level controller works this way, pressure controller are standard using condense duty on both the columns, what about this level there are no valves to control these level the only valve that is available is this you see what I am saying, because I have two constraints active on the column. (()) And I am also wanting to control the benzene impurity, one of the level I do not know how to I do not have a local valve to control one of the levels, this is what is only left this is what is left, so I putting these level controller.

It sounds very odd, but if you think about it actually make sense, where is the ethyl benzene and the diethyl benzene accumulating inside the plants. (()) Its accumulating here, benzene is removed ethyl benzene and diethyl benzene drop and build here, so if this level is dropping what does that mean; that means, I am making two little product in the reactors, if the level is dropping; that means, I am making two little product in the reactor increased the ethylene.

If this level is increasing I am making too much product reduce the ethylene that is what this level controller is doing, it makes sense.

Only problem is if I make a change in the ethylene valve in the ethylene flow how long does it take for that effect to show up in the level, it turns out that because these two reactors are C S T R and they have been designed for complete conversion of ethylene, resistance times are very large 1 hour in reactor 1, 1 hour in reactor 2, reactor 2 at the designed condition.

So, if I do something here by the time it has not effect on the level you know. You know the time... Ethylene input a stream then we should benzene input (()) The level controller will take care of that. We have.

That's what I am trying to if I do it this way this is what this is the control structure that come. But the residence time problem if I had a pluck flow reactant. In fact, we had done stimulation and shown that if you have a pluck flow reactant there the distance time is not an issue you make a change here, right because the flow is compressival flow essentially.

So, but for the large residence time in the reactors the scheme would have worked. It turns out that for this process, it would not work because the reactors residence time total reactor residence time is of the order of 2 hours had it been of the order of 5, 10, 15 minutes, it would have worked all right.

So…(()) all need a very tight control. No, it is not a question of very tight control, you see what happen is if even for even for 1 percent change even for a 1 percent change in what is the throughput there is throughput manipulator here.

So, even if I even for a very small disturbance, let us say 1 percent change in throughput or one percent change in one of the set points either temperature or pressure or composition or whatever, even for a very small change in a set point, what happens is this bottom level in the recycle column either over flows or runs straight; that means, the level control is fragile.

(()) It is very fragile it is very fragile because I make a change in ethylene by the time effect comes to the bottom level, it may have run dry or it may have over flown, and that is what actually happens. So, it is fragile and it is fragile because of the large residence time in the reactor.

But in term of an attempt everything is tightly control, all the effect is being taken in the 2 levels 2, 3, 4 level 1, 2, 3, 4 in the column reflux, everything is tightly controlled and all the variability is being taken in the levels, and the and the utilities steam and cooling water and this and that.

Do you see what I am saying? However it turns out that it cannot work because of this. So, now I need to do something what do I do. So, well this level is fragile I need to make it more robust. So, what do I do I say well take the temperature controller off.

Now, I have a problem what is the and then I say I will maintain the ethylene in ratio with the total benzene. See what did I do. This was problematic. So, I took them. So, I took this temperature controller out and put a level con and put a level controller instead, now this valve is free how do I manage it I will say I ell keep the ethylene in ratio with the total benzene. So, now these are my 2 unconstrained degrees of freedom 1, 2.

Yes or no. Now, problem remains here in the sense that I am setting the ethylene independent of… there is problem in the control structure. What is the problem I have already described the problem. What did I take out I took out the temperature controller.

What was the temperature controller supposed to do? Ensure that, ethyl benzene you know if you are producing more ethyl benzene in the reactor, and you are limited by V 2 max you cannot boil it off, it I will accumulate in the DEV recycle loop. To prevent that I had put that temperature controller, now I have taken that temperature controller out, now this problem exist. So, what will we do will do this.

This or you can even control a temperature. If ethyl benzene drops down the flow will increase the bottom this flow will increase, if ethyl benzene is dropping down composition I do not want to make a composition, because composition only product purity you will get nothing else will get you still suppose to operate it without any composition temperature, pressure, flow that all that the variable composition very rarely only place, where people are willing to make a composition are product, because that is what they are suppose to sell they have to guaranteed to the customer. So, they will they will make some measurements, but rest is not available.

So, what I do is this. So, does this make sense? Does this make sense or no? (()) So, now, these are my 2 unconstrained degrees of freedom this and this. These two set point are operator can play with these are the same as I have told you earlier, product impurity, product benzene impurity and DEV re circulation rate.

All right. So, I have I have synthesis the control structure. Now, I want to reduce throughput what will I do.

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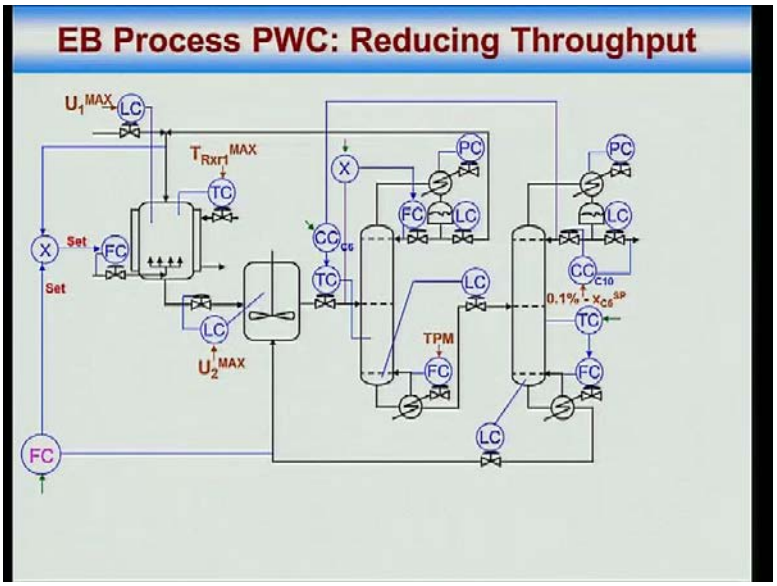

So, I have got my two unconstrained degrees of freedom I want to reduce throughput what will I do the first thing I will do is take you to 0.09 percent, throughput will reduce from 970 to about 940 something like that.

Once, I have done that what I will do is I will take this from 230 to whatever it was 112, right. So, let us get back. So, originally this is my throughput manipulator I want to reduce throughput I will change the product impurity mix from about the same impurities to mostly benzene that is what I do.

Once that is done I move the throughput manipulator here go from 230 to 112, when I do that my production will decrease for the by about 4 or 5 percent. Then if I want to reduce production it turns out that V 1 max is the last constraint to have become active. For this process it turns out that V 1 max last constraint to last input constraint to become active.

So, I use that as I use that as the throughput manipulator. Now, as I am reducing the throughput, if I keep V 2 max at V 2 max, and L 1 max at L 1 max what is the problem. If V 2 max is kept at V 2 max what; that means, is boil up is large that is what I am boiling it up do not allow the diethyl benzene to leak up the top I will have to reflux more.

Yes or no. So, I am I am unnecessarily re circulating things here in this way, and I am wasting steam. Yes or no. So, once the throughput has been reduced sufficiently I will take up temperature control whenever, I can of the stripping trick.

Same thing, here for L 1 max as I am reducing the throughput I will not you know again if L 1 is kept unnecessarily at max I will get extra re circulation. Yes or no. Yes or no. To prevent that what I am whenever, reflex can be maintain in ratio with the feed I will take up ratio control.

Now, let us go in reverse I am at low throughput I am increasing the steam here, as I am increasing the steam all flows are increasing, flow to this column is also increasing in ratio reflux is increasing, but then when reflux becomes max I cannot maintain it in ratio anymore, if I cannot maintain it in ratio anymore well that is it L 1 is at L 1 max.

I am increasing throughput I am increasing the steam to the recycle column further throughput is increasing, then what happens is the boil up in the second column reaches max, well if that reaches max I cannot control the temperature anymore, if I cannot control the temperature, that is what is given up.

Then I am increasing throughput further and then what happen is this becomes max. Then what I do is I change the DEV recycle rate from 112 to 100 and or 230 I keep increasing it, throughput increases.

Then what do I do I change this from 0.09 percent to 0.04 percent right. So, this is what will take me from low throughput to high throughput as I am going the other direction you see. So, as I am increasing throughput I give up control of thing that I was controlling as constraint become active as I am decreasing throughput, I take up control of things that make economic sense it does not make economic sense to unnecessarily re circulate too much in any of the columns.

Yes or no. In fact, instead of doing the ratio I could have also you know instead of. So, when this you know I take up temperature control, whenever I can and I will take up ratio control whenever I can.

I could have also control the tray temperature by adjusting the reflux in the in the in the rectifying section I could have done that too, it is just that this is simpler.

This is much simpler. Note this is something that I want you to notice that everything that you are doing, here comes from the constraint from the set of active constraints or throughput manipulator. Should I use boil up to control temperature, well if it is active no. Is it critical to control the benzene leaking down the second the first column, yes because I otherwise it will contaminate my product.

So, even though V 2 V 1 active V 1 max is active I still need to control it therefore, this loop has to be there right. It is all coming from what are my constraints set are active the structure is following from… Now, in this case what we have done is we have gotten robust control of the level in the second in the first column, which was not being control properly, because there was a very unconventional loop there.

What are we loosing what is it at the expense off. (()) It is at the expense of large swings here in this loop because, now the control of this guy is being done by ethylene, when I maintain this flow by changing ethylene it takes a long time to for its effect to come in the DEV, when I change ethylene it is effect on the… (())

Will be after a long time right, when I was doing this when I was doing, this it is effect was immeziate right. So, I have made a compromise, the compromise is what is the compromise? Sir, how exactly we decide which are the active constraints and… Optimizer.

This is see I told you this and this and that are the active constraints right. It came from the optimizer. Which one will be active first time. That comes from the optimizer. So, you do your optimization for various throughput at this throughput no constraints are active, then as I increase my throughput this constraints become active, then as I increase my throughput forward that constraint became active, then I have as I into my maximum throughput, this was the final constraint to become active right, you will have to do bunch of optimizations. I did not show you any of that I just gave you the result of the optimization, that was relevant to synthesizing the control system.

We cannot do it manually. You will have to apply lot of common sense to do it manually, you can talk to operator, then they will tell you when I try to jack up throughput this become active, and that become and then that becomes active and then that operators can also tell you that.

So, either from a module of the process which you optimized using an optimizer by playing with the degrees of freedom that are there with you, or by using some engineering common sense, which is actually quite there.

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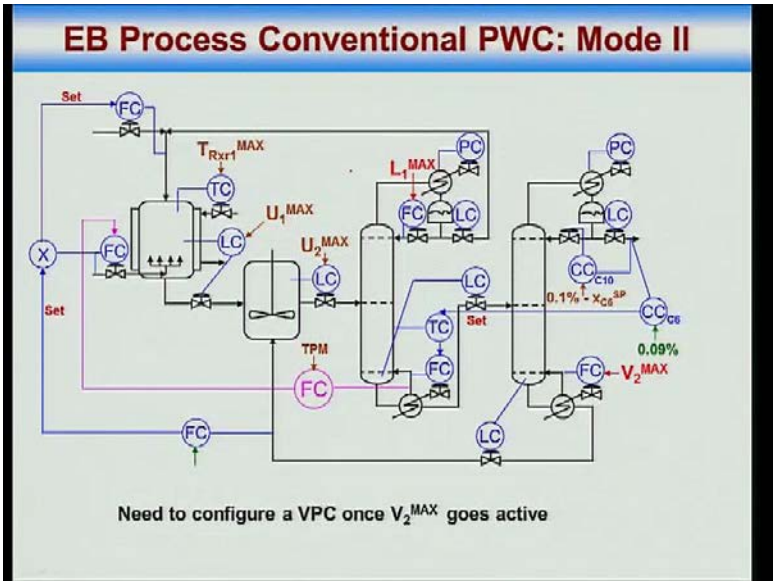

Now, convictional, convictionally what you would you do is you flow control the limiting reactant which is ethylene to the reactor, you will feed total benzene going in constant to prevents snow boiling and feed benzene as a make up steam all right.

Then the rest is you know level control, temperature control these are the level controllers on the column as well as on the reactor, pressure controller on the column, and then you are maintaining reflux to feed ratio in column 1, you are maintaining temperature of the stripping section by adjusting boil up in column 2, and then you are maintaining the product purities in this way.

This is make sense; this is a convectional control system. Obviously, you would like to keep these at max because that is optimum. Yes or no. What are your 4 unconstrained degrees of freedom those are shown I think in green, let us see, you maintain total benzene in ratio with the ethylene, and because you can get snow boiling in the DEV recycle loop what liabian is suggested is that you maintain the flow of the DEV recycle by adjusting the ratio set point. This is what has been suggested in that paper by him. So, I just took that structure.

Now, throughput manipulator is the fresh ethylene you jack the throughput up. These are you are the green arrows are your unconstrained degrees of freedom 4 unconstrained degrees of freedom, 4 green arrows total the DEV recycle rate 1, the reflux to feed ration in column 1, 2 the benzene impurity 3, and the temperature set point on the second column 4, 4 degrees of freedom. Yes or no. Mode 1 we had 4 unconstrained degree, these are the 4 unconstrained degrees of freedom.

Now, these are well what the hell am I doing. Now, I am going to increase the throughput and go to mode 2 go to maximum throughput. So, I start jacking up the ethylene this becomes maximum. So, I cannot maintain ratio that is fine I jack up the throughput further, this becomes maximum I cannot maintain the temperature. Same problem now occurs I can be putting more ethylene than I can boil off I can be I am putting more ethylene.

So, more ethyl benzene is getting formed, but I am limited in my capacity to boil it off, where will that ethyl benzene go that ethyl benzene will build in the DEV recycle loop. So, if DEV builds up here, if ethyl benzene drops in the in the in the DEV recycle loop, the flow rate of the DEV recycle will go up, if that flow rate goes up what the hell.

If that flow rate goes up I will adjust the ratio, and increase the total benzene if I am increasing the total benzene then the boil up in second in the first column will increase, then I have to send more step up now, so the boil up will have to increase.

So, what will happen is to maintain this flow rate constant I will start getting snow boiling in my boil up will start to increase in the first column. Yes or no. So, that increase in boil up is telling me what that I am producing more ethyl benzene then I can boil off in the product column, and it is essentially building up in the two recycle loops, all rights.

So, how do I prevent that. We I use a boil up controller that does this. Does that make sense or no. I use a boil up controller that does this. It appears that this is fine; because I am cont well let us see if I can pointer option pen. I am preventing snow boiling here by adjusting the ratio and I am keeping the total benzene constant right.

So, there is an impression that gets created that there will be no you know there will be no build up in the in both the recycle loops, but please note when I when you think about

it what is actually happening is I am just transforming, what is happening here to here you see, this loop is transforming here to here total benzene is increasing to increase total benzene you will actually get this to increase the boil up to increase.

Yes or no. So, the problem remains I get the impression I have maintain this also and I have maintain that also, but the moment V 2 max goes active that problem is there and I am just transferring it from here to there boil up will keep increasing in order to that.

Yes or no. So, therefore, to prevent that what is what we are doing is we will do this. So, if this boil up is going up; that means, that you are producing too much ethylene, you are producing too much ethyl benzene you cannot boil it off and its building up in the 2 recycle loops. Therefore reduce the amount of ethylene that you are putting in. So, this loops comes, in this is conventional.

But please not I need to configure this loop once V 2 max goes active in the previous control structure I did not configure anything, things are talking control up or giving control up there is no re configuration of loops here, I need to put in this magenta loops once V 2 max goes active, that is an additional complexities here.

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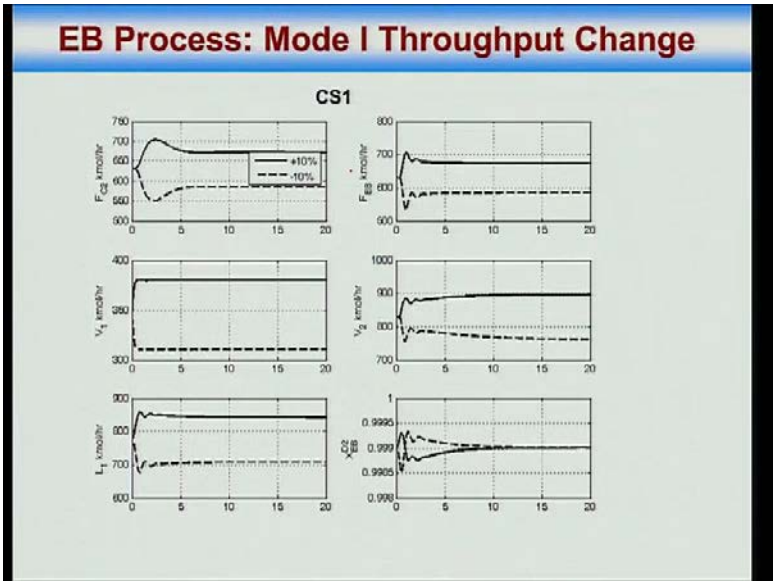

So, we have looked at two control structure now let us just compare the performance. Mode 1no constraints are active no input constraints are active and therefore, whether I

am using the convictional control structure or the control structure that we have proposed.

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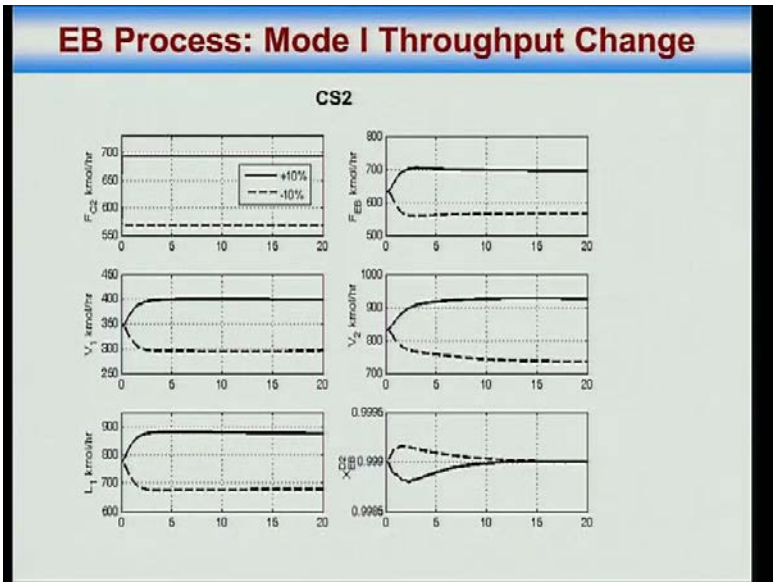

If you do a throughput change plus minus 10 percent throughput change everything is smooth CS 1 CS 2 does not really matter about 20 hours your response is complete product purity is tightly control smooth response.

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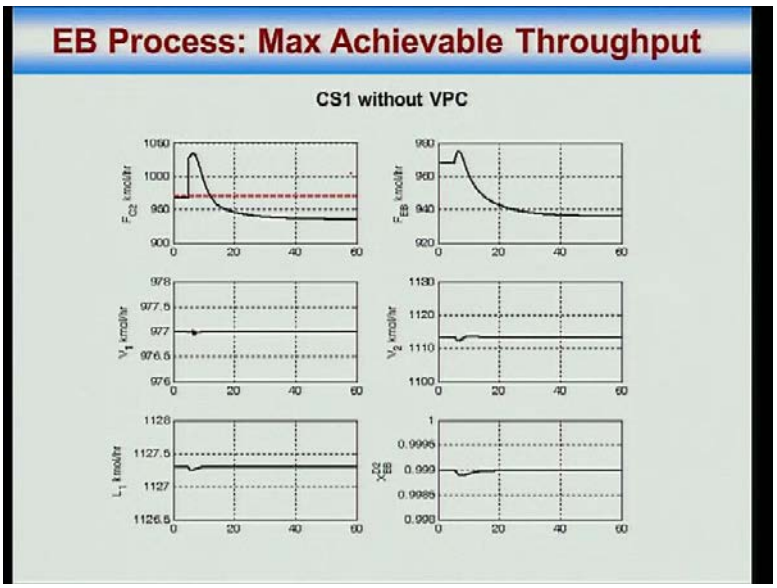

Now, if you go to max without VPC you know if I do not put that loop that adjust the ethylene in this structure and that structure, what happens in CS 1 the structure that we

synthesized what I am taking as the disturbance is a 5 percent noise a 5 percent bios in the fresh ethylene flows insert. So, the flows insert is saying flow is X suddenly, the flow goes from X to X plus delta X when the actual flow is remain X, sensor has got a 5 percent bias.

So, when that happens you know what this response is essentially showing is even if you get a 5 percent step bias you get a decent response throughput goes down a little bit, but that is.

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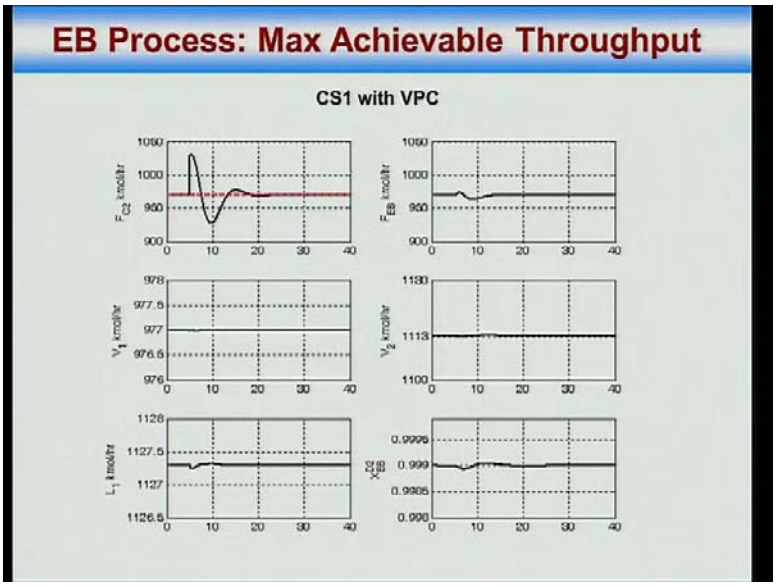

In CS 2 without that ethylene loop without that magenta loop. If you putting the VPC in CS 1 what you find is well the throughput comes back to wherever it was.

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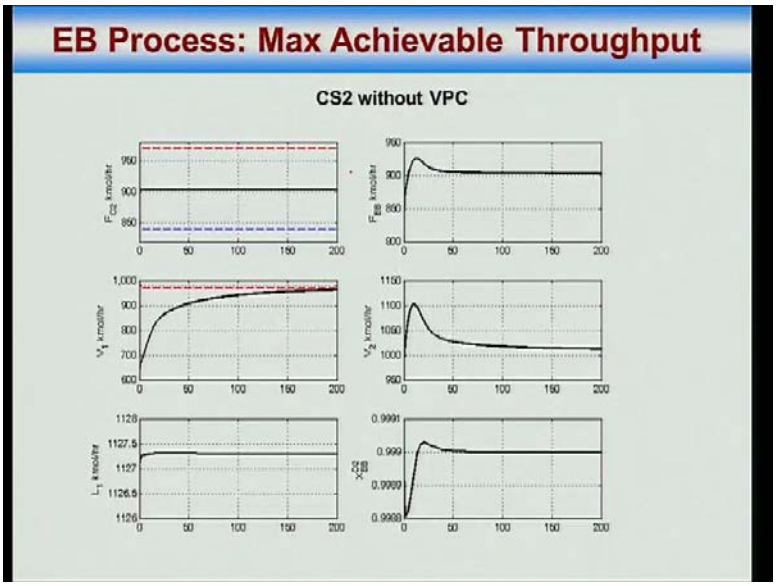

What is interesting is CS 2 the convictional control structure, if you do not put in that VPC I am at 840 kilo moles an hour of ethyl ethylene F C 2. When that 5 percent bias in the ethylene flow sensor comes, you find that V 1 keeps going, and it hits is maximum limit.

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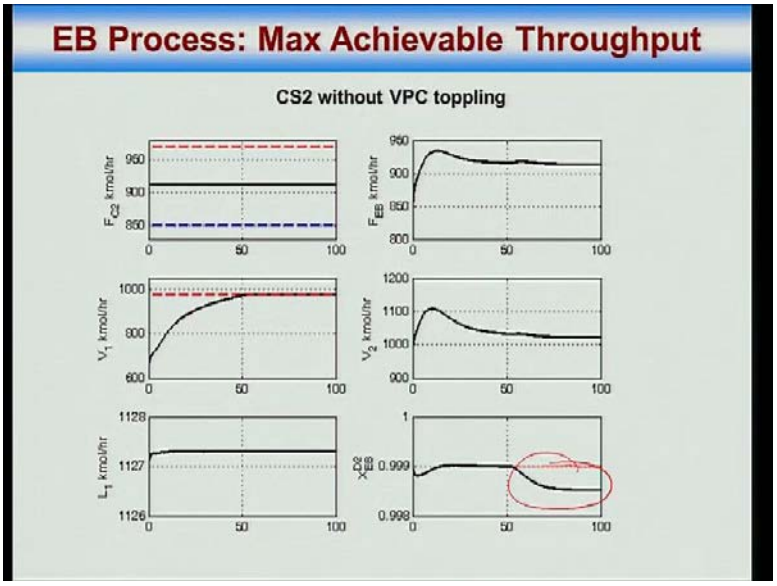

If I am at 850 kilo moles an hour what I find it find is when that disturbance comes, it hits it maximum limit, V 1 hits its maximum limit once V 1 hits it maximum limit I lose control of the product purity because, now benzene starts dropping down and you see

here. My product purity has gone down I wanted it here is not under control it has gone down.

It may have gone down by a very small amount, but it is gone down and gown down for good I cannot back it up, right. So, what would I what would an operator do he will say well I am producing junky product, we will never exceed 840 kilo moles an hour we knows, because the moment I go to 850 sensor keeps going here and there if it goes there, and I am having a cup of tea I will be producing junk.

Or I am not an attentive enough 15 hour later I will producing junk, and then the next operator would not know why that is happening, when the shift has changed. So, what you will do is let us forget about 970 kilo moles an hour will just operate it 800 and 820 830, but never exceeded 40.

So, without that VPC you are stuck at 840 what was the maximum capacity of the plant 970. (()) How much it is. 13 percent, that is a big amount of difference, and it all it is all got to do with the control system that you implemented.

Same process same everything this control system that accounts for what constraint are going to become active right that that is able to get you to whatever was the maximum achievable, this control system will fail.

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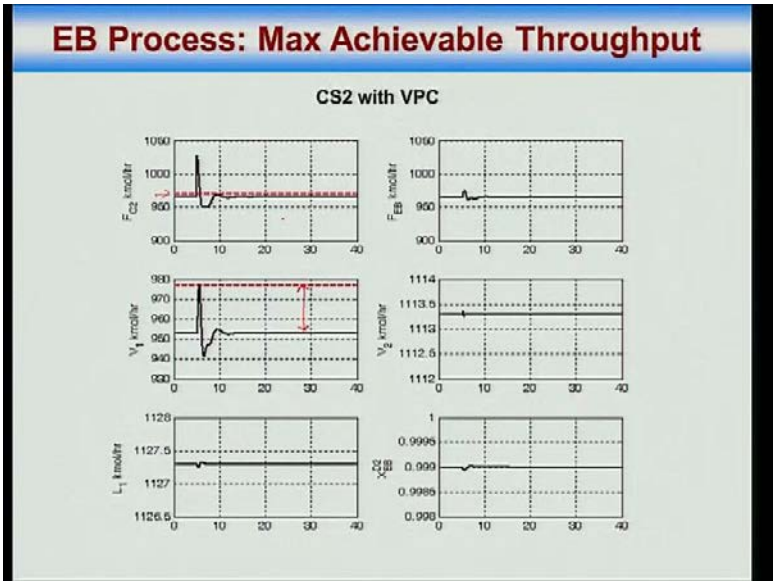

Then when you put in the VPC sure maximum achievable is 900 and I think 70 I believe, this is the maximum achievable, you are actually slightly below. Why you are slightly below, because there is a transient in the boil up in column 1, that transient can never exceed 977 or whatever is the limit on that whatever is the rate limit.

So, I am operating at I am operating at a about 20 25 kilo moles slower boil up in the first column that corresponds to a 5 kilo mole per hour loss in throughput. So, now the process is stable, but instead of getting 970 I get 965, this is only for one disturbance in the flow sensor ethylene, there are n numbers of disturbances operating at any given point in time not only the flow sensor here, that DEV recycle flow sensor the total benzene flow sensor, that temperature sensor on the column the heat loss in the column day and night etcetera etcetera all these things are operating in the same time.

So, each one of these disturbances will add an extra back off what seems like only 0.5 percent loss may actually turn out to be 1 or 2 percent when you take the effect of everything together. 1 or 2 percent throughput loss, because of back off in the boil up integrated over year an year of production will translate to millions of dollars right.

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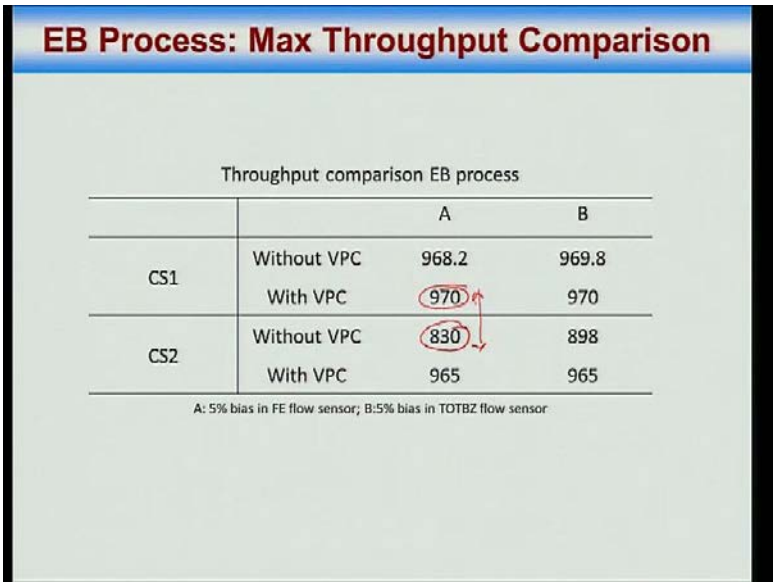

So, here is the comparison, basically what I wanted to draw your attention to was this versus this right, that is a hack of a lot of difference 12 percent, 14 percent I do not know how much greater than 10 percent, it is a big difference in throughput.

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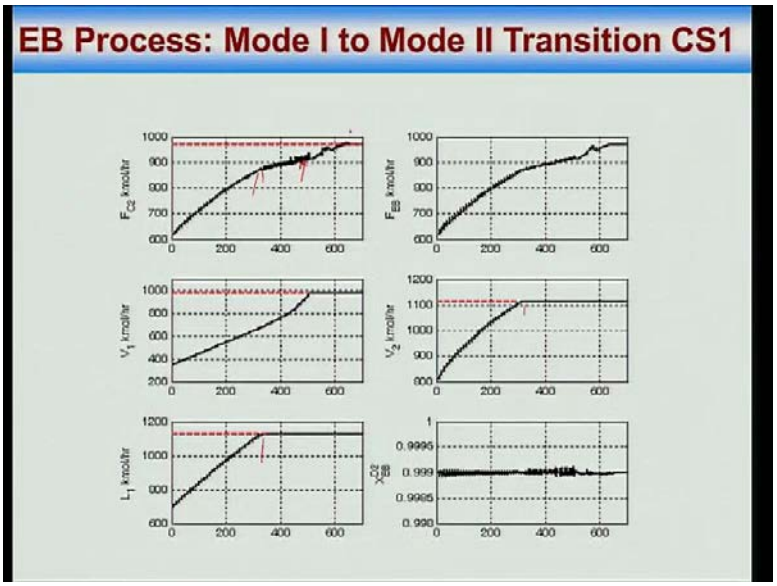

So, that is the point then I think last, but not least you got you keep changing the set point you want to increase the throughput. So, what we are doing is we are increasing the V 1 set point by 10 percent, and taking it to max and what you find is that the F C 2 keep increasing the rate of increase changes, because constraints are becoming active.

So, L 1 become active here, so somewhere L 1 becomes active somewhere here L 2 becomes V 2 becomes active and finally, finally, finally, finally, V 1 becomes active some place here. In spite of that I am still able to jack up the throughput by playing with those two unconstrained degrees of freedom 112 kilo moles an hour to 230 kilo moles an hour and benzene impurity from 0.04 percent to 0.09 percent or 0.09 percent to 0.04 percent.

That makes sense. So, I am getting an increase in throughput, and I am able to get to whatever was the maximum capacity 970 kilo moles an hour.

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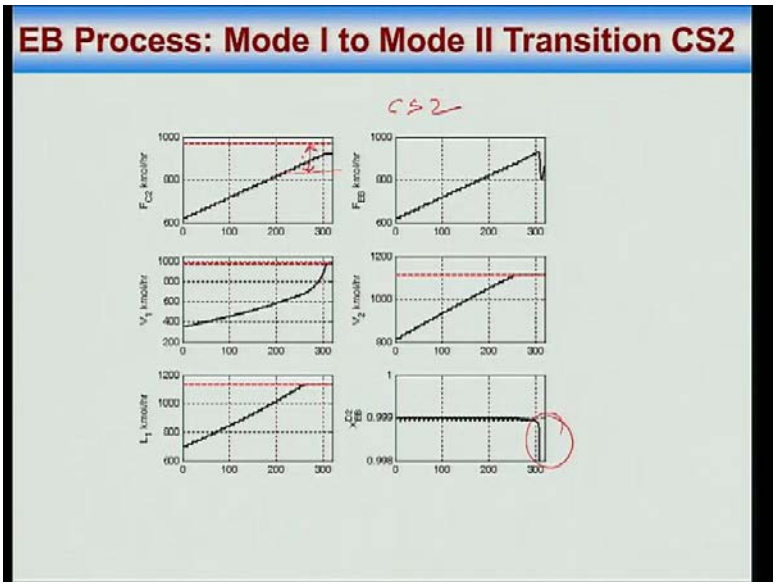

What happen in mode 1 to mode 2 transition without the VPC if I do not put the VPC in CS 2, this is CS 2 the convictional control system I am jacking up the fresh ethylene feed rate by 10 percent every 15 hour or 20 hours I do not know how much.

And then what happens is V 1 hits max and I lose product purity control.

So, an operator would say do not go beyond this right, and you are losing this much throughput ,even though the plant is capable your control system is basically screwed up it screwed up because you did not take it to consideration, what constraint are going to become active and what I am going to lose because of that.

It turns out here what I am losing is product purity control too much benzene contaminate my product that is because, V 1 max become an active constraint that is the problem.

Yes or no. I think that is that we will finish it here.

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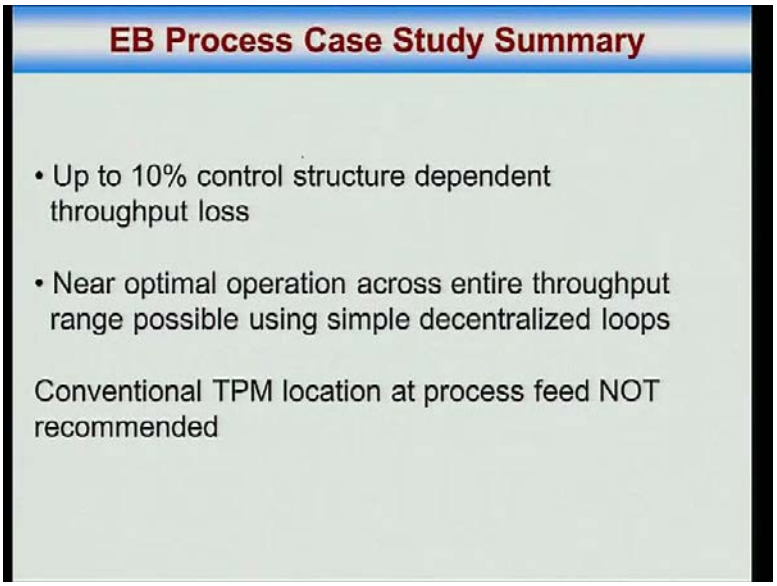

There is another case studies well, so summary more than 10 percent control structure dependent throughput loss. Near optimal operation across entire throughput range is possible using simple very simple control system and that simple control system does not require to configure additional loops when a constraint becomes active that is very important.

And conventional throughput manipulator location at the process feed is not recommended, throughput manipulator should be at the at the boil up, it was last constraint to become active.

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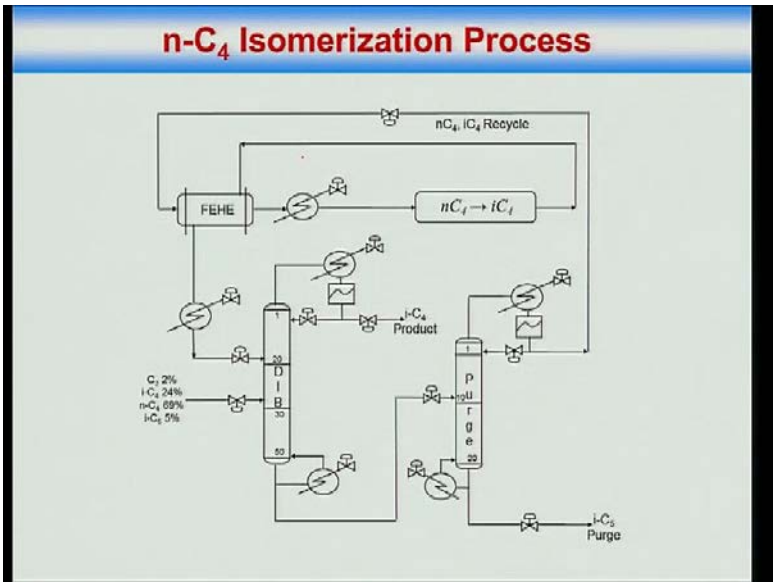

In these case studies actually there are 7 or 8 degrees of freedom all degrees of freedom are lost at maximum throughput 8 active constraints.