

One Multivariable Controller Increased Capacity of an Oleflex™/MTBE Complex

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Abstract

Capacity increased by more than 4.6% when one dynamic matrix controller began operating in Valero Refining Company's MTBE production complex in Corpus Christi, Texas. This was on a plant that was already running well above design capacity due to process changes previously made on the plant. A single controller was developed to cover an Oleflex™ isobutane dehydrogenation unit and an MTBE reaction and fractionation plant with the intermediate isobutylene surge drum. The overall benefit is realized by a comprehensive constrained multivariable predictive controller, which properly handles all sets of limits experienced by the complex, whether limited by the front-end Oleflex™ or back-end MTBE unit.

The controller has 20 manipulated, 6 disturbance and 44 controlled variables, and covers widely varying dynamics with settling times ranging from twenty minutes to six hours. The controller executes each minute with a six-hour time horizon. A unique achievement is intelligent handling of the surge drum level by the controller for higher average daily capacity of the complex as a whole. The Oleflex™ often operates at simultaneous limits on reactor effluent compressor capacity, cold box temperature and hydrogen/hydrocarbon ratio and the MTBE at impurity in butene column overhead as well as impurity in MTBE product.

The Oleflex™ and MTBE Processes

Background to Ether Production

The reduction in use of tetra-ethyl lead (TEL) in gasoline during the 1970's caused petroleum refiners to begin to use alternative high octane additives in their gasoline blends. Alcohols were generally used because they were easily available and their blending characteristics were understood. Over time, alcohols lost favor to ethers, which have better blending and combustion properties, in particular having lower blending vapor pressures. The ethers used were methyl tertiary butyl ether (MTBE), ethyl tertiary butyl ether (ETBE) and tertiary amyl methyl ether (TAME).

During the 1990's environmental regulatory bodies in the United States began to require minimum quantities of oxygen in gasoline. The objectives of these requirements were to reduce carbon monoxide emissions and to reduce atmospheric ozone through reduced reactivity of volatile emissions. As a result of these requirements, most refiners now blend MTBE and/or TAME into gasoline. While small refineries typically purchase ether blending components, large refineries make MTBE and TAME by reacting isobutylene and isoamylene with purchased methanol.

In a refinery, isobutylene and isoamylene are obtained from FCCU light ends and light naphtha products or from refinery coking units. Isobutylene can also be sourced from steam crackers as a by-product of ethylene and propylene production or from the catalytic dehydrogenation of isobutane.

The Oleflex™ Process

Catalytic cracking and coking in a refinery do not produce enough isobutylene to achieve a two weight percent oxygen content in the gasoline pool. The additional isobutylene required can be supplied through dehydrogenation of isobutane. Catalytic processes are preferred to thermal dehydrogenation because of their much higher selectivities. High temperatures and low pressures favor the reaction and are necessary to achieve a reasonable conversion level. The reaction is endothermic and therefore the heat of reaction must be provided by the process. The three processes in use in North America are Houdry's "CATOFIN", Phillips Petroleum's "STAR" and UOP's "Oleflex™".

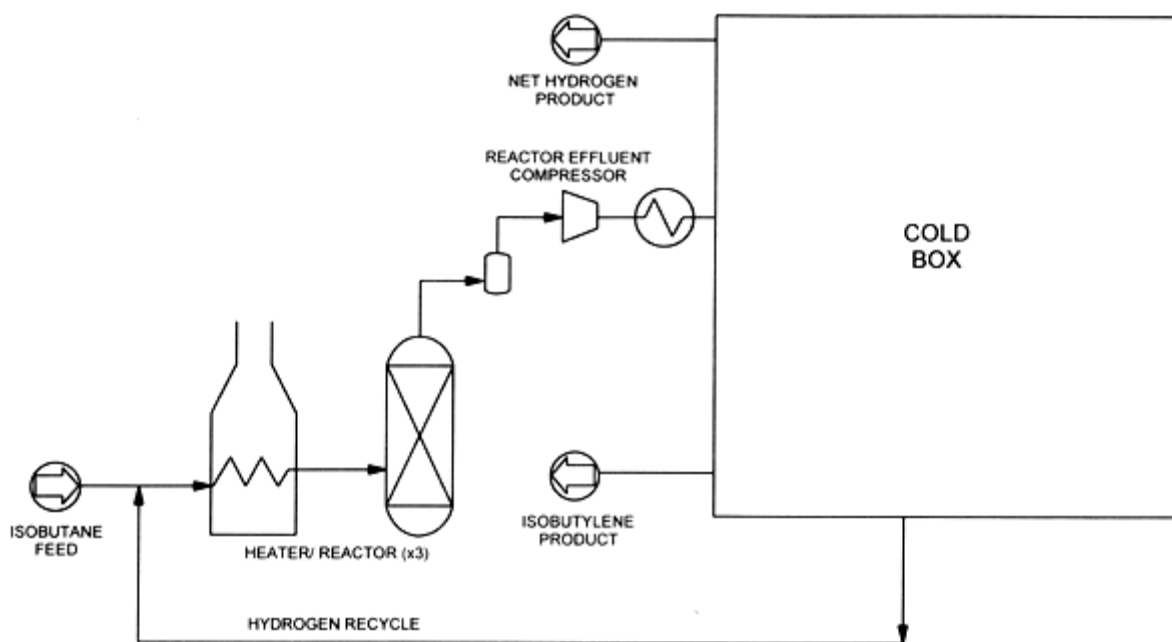


Figure 1 – Oleflex™ Simplified Flow Diagram

A heavily simplified flow diagram of the Oleflex™ process is presented in Figure 1. The diagram shows the most significant flows and equipment although a number of flows and intermediate drums have been excluded. The isobutane feed to the Oleflex™ is preheated and mixed with recycle hydrogen before being charged to a series of three heater and reactor pairs. Each heater heats the reactants to the desired temperature. The mixture is then charged to the reactor and flows radially outward through a slowly moving bed of catalyst. The effluent from the third reactor is cooled before passing to the reactor effluent compressor (REC), which boosts the pressure of the gases for separation. The REC provides the power that drives the remainder of the process and is critical to Oleflex™ operation. The compressed gas is cooled further before discharging into the cold box section of the process where the liquid product is separated from evolved and recycle hydrogen.

The cold box contains a series of vessels at different pressures and temperatures. Liquid product is removed from the bottom of each of these separators, while hydrogen is either recycled to the reactors or compressed in the “net gas” system. The liquid product containing isobutylene, unreacted isobutane and small quantities of side products flows to the isobutylene surge drum from which the MTBE unit is supplied.

The MTBE Process

There are a number of available commercial processes for ether production. All of the processes use an acidic ion exchange resin catalyst under controlled temperature and pressure conditions. The reaction is exothermic, and temperature control is important to maximize conversion and minimize side reactions and catalyst deactivation. Usually, the reaction is performed in two stages with a slight excess of alcohol.

Valero Refining Company’s MTBE unit is a UOP-HuelsTM design with two fixed-bed, adiabatic reactors, downflow liquid phase and a cooled external recycle flow. A heavily simplified flow diagram of the relevant section of the unit is presented in Figure 2. Isobutylene rich feed from the OleflexTM unit is drawn from the intermediate surge drum and mixed with methanol and effluent recycle before being cooled and charged to the top of the primary reactor. The resin catalyst is a fixed bed of small beads. The flow then passes to the secondary reactor where the reaction progresses essentially to equilibrium. The secondary reactor effluent contains MTBE, isobutane, excess methanol and small quantities of side reaction products such as dimethyl ether (DME).

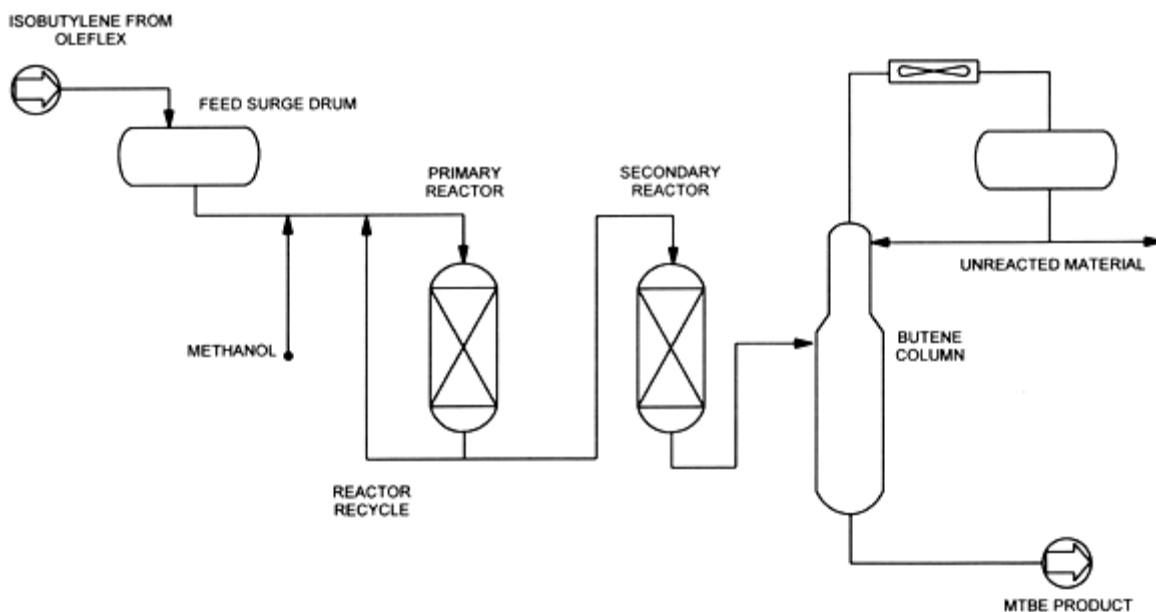


Figure 2 – MTBE Simplified Flow Diagram

The effluent from the secondary reactor flows to the butene column where MTBE is separated as bottoms product and the other components pass overhead for further processing. Impurities are removed from the unreacted isobutane, which is then recycled back to the OleflexTM feed. This remaining section of the unit is not relevant to the multivariable control design and is not discussed further in this paper.

The Challenge of Maximizing Production

The OleflexTM/MTBE complex is operated to maximize production of MTBE. Operation of any modern process unit at maximum throughput is a very challenging objective. In Valero’s case, production had already been increased well above nameplate capacity and operators were constantly reviewing process operation and active constraints in order to try and “squeeze” additional capacity. This section discusses

the nature of the true maximum throughput conditions and the prohibitive difficulty of achieving them for any human operator.

Each unit has a large number of constraints that must be honored for reasons of safety, product quality or equipment capacity. In addition, each of the constraint variables is affected by a number of process variables other than feedrate. This means that it is often possible to relieve an active constraint by making other adjustments and therefore creating more room for additional feed. These constraint relief adjustments will ultimately result in other process limits becoming active. In this way, the true maximum throughput is achieved when the unit is operating at multiple constraints simultaneously. In fact, barring significant non-linearities, the optimum will occur at as many simultaneous limits as there are "handles" on the process.

Achieving this truly maximized operation is virtually impossible for any human operator since even small disturbances require continuous multiple adjustments to prevent violation of any of the constraints. It is therefore more common for an operator to concentrate on pushing one or two key constraints, while maintaining a safe distance from others. This approach makes the response to disturbances manageable.

Maximizing Oleflex™ Throughput

At Valero, where capacity had already been pushed well over design rates, the key process limits for the Oleflex™ unit with respect to feedrate are reactor effluent compressor (REC) capacity, cold box temperature and hydrogen to hydrocarbon ratio. The REC capacity is measured by feedback of the compressor turbine governor output. The cold box temperature is an indication of the effectiveness of separation of heavier materials from the recycle and net hydrogen. The hydrogen to hydrocarbon ratio is calculated from the unit feedrate and recycle hydrogen flow and purity.

These three primary constraints are affected by a number of other variables, creating the opportunity for the constraint relief discussed above. Figure 4 presents the qualitative response of these three constraint variables to four selected process setpoints. In this table, the manipulated variables are arranged in rows with the constraint variables in the columns. A plus sign in the table indicates that an increase in the manipulated variable will move the process towards the constraint, while a minus sign indicates that an increase in that variable will move the process away from the constraint. A zero indicates no response in the constraint variable. Each of the three constraints has both positive and negative responses to the manipulated setpoints, and three of the manipulated variables also have opposing responses to various constraints. Feedrate can be seen to exacerbate all three of the constraints, while other variables relieve some and worsen others.

The table allows us to visualize the problem facing the console operator. Asked to push throughput, feedrate could be raised until the REC capacity constraint is reached. At this point, recycle hydrogen flow could be reduced to relieve this constraint and thus allow feed to be increased further. This will reduce the hydrogen to hydrocarbon ratio, however, and when the minimum target is reached, no further reduction in hydrogen flow is possible. At the same time, it is possible to reduce the cold box inlet pressure, thus offloading the compressor. This has the effect of moving towards the cold box temperature constraint and therefore a limit to this response will be found. The effect of the recycle hydrogen flow on the cold box temperature also has to be accounted for in selecting the operating point. The best solution, with the highest feedrate, will have all three example constraints active along with two others found by adjusting the remainder of the four setpoints.

It is already clear, even using this simplified example, that the problem of achieving true maximum throughput while honoring all the constraints is not easy to solve mentally. The system is highly interactive and is subject to a number of constraints. To achieve the true maximum throughput, we have to solve a multivariable constrained optimization problem. Even without external disturbances to deal with, this problem is too difficult to expect any human operator to solve unaided.

	REACTOR EFFLUENT COMPRESSOR CAPACITY	COLD BOX TEMPERATURE	HYDROGEN TO HYDROCARBON RATIO
OLEFLEX FEED RATE	+	+	+
HYDROGEN RECYCLE	+	-	-
REACTOR PRESSURE	-	○	○
COLD BOX INLET PRESSURE	+	-	○

Figure 4 – Constraint Response Table

The Oleflex™ operation is of course subject to other constraints in addition to the three used in the example. The REC discharge pressure must be maintained below some safe limit, and the compressor operation must be kept away from the surge control line. Other cold box parameters have to be maintained in a range and therefore have both high and low limits. There are also more manipulated variables available in the process than the four examples chosen. Thus, the dimension of the real life optimization problem is higher than our example, making the complexity greater.

Maximizing MTBE Throughput

Although not quite as multivariable in nature as the Oleflex™ Unit, the MTBE is similarly subject to multiple constraints and multiple responses to the manipulated setpoints. The primary constraint to MTBE feedrate is the butene column capacity. This constraint is experienced as a reduced capability to fractionate as feedrate is increased, resulting in higher levels of MTBE in the butene column overhead product. The main constraint relief response available is to reduce the column bottoms temperature, thus allowing higher concentrations of butane and methanol in the MTBE. This response is of course limited by the product specification. Column reflux can also be maximized up to the flooding limit as measured by differential pressure across the trays.

The true maximum throughput on the MTBE unit is again achieved at multiple simultaneous process limits. Again, barring significant non-linearities, the best solution will have as many active constraints as manipulated variables. The Effect of Disturbances

Establishing the operating point for true maximum throughput is a challenging objective. The task is complicated by a number of process disturbances. Both the Oleflex™ and MTBE Units have intermittent processes that use isobutane as a regnerant. The functioning of these processes temporarily changes throughput in either half of the plant or causes a temporary change in the MTBE feed surge drum level and/or composition. The surge drum is sized large enough to handle the effect of these disturbances.

Less sudden but equally as important are changes in ambient conditions, which affect the cooling capacity available to the process. This disturbance is typically a twenty-four hour cycle between day and night operation, although rainstorms or cold fronts have a more immediate effect. High ambient temperatures affect the Oleflex™ unit's cold box in particular, restricting capacity. Again, it is possible to limit the necessary reduction in throughput as ambient temperature rises by adjusting other process conditions to

re-establish the constrained optimum.

Because of these disturbances, the optimal conditions for maximum throughput are constantly changing. The effect on the process from all sources of disturbance are also more pronounced at higher feedrates, thus discouraging operators from trying to squeeze the last amount of capacity out of the unit. The net effect is a small, moving target for maximum throughput that is harder to reach the closer you approach.

Balancing the Units as Process Limits Shift

The capacities of the Oleflex™ Unit and the MTBE Unit are closely matched and therefore either can represent the throughput limit. The feedrates of the two units are tied together through the isobutylene surge drum. The control room is organized such that the two units are run by different board operators and therefore communication between the two is very important for good operation.

Either unit may need to be artificially restricted when the other unit is limited. As ambient temperature rises, the relative capacities may shift in favor of the MTBE and therefore this unit would have to cut back to balance the restricted Oleflex™ capacity. The opposite scenario may be true for other changes in conditions. When the disturbance is known to be an intermittent process step, it may be more attractive to allow the surge drum level to rise or fall temporarily.

The coupling of these two problems in throughput maximization represents the final complication facing the console operator. Despite being almost intractable to the human operator, this problem is very well suited to multivariable control techniques with an incorporated optimization method such as a linear program. The following sections describe the single multivariable controller implemented and the benefits obtained through its use.

The Controller Design

The multivariable controller applied to the complex is a [DMC] controller, which contains an embedded linear program to calculate the control targets, thus allowing an economic objective to be pursued.

Understanding the Operation

The objective of advanced process control is to increase the profitability of the plant to which it is applied. To achieve the best result, the design process must therefore begin with an understanding of the plant and its economics. The design process should be aimed at identifying the absolute best-case operation for the plant in question and then to set about creating a controller to achieve all of the benefits that are on the table. Every technical decision made during the course of the project must be guided by this objective to achieve the maximum dollar benefit.

The first task in the design process is therefore learning everything possible about the plant operation. The drawings must be reviewed to gain an understanding of the base layout of the plant. Significant time must be spent at the console with the operators to understand the way the plant is operated in practice and the interplay of the plant's constraints. Economic objectives must be discussed with plant management. Maintaining a global view of the objectives of the process ensures that these are what guides the design and function of the multivariable controller.

Every process handle should be viewed as a potential opportunity for constraint relief and therefore more benefit. A detailed understanding of the underlying process allows the engineer to see the potential for juggling constraints and furthering the plant's overall economic objective.

Setting the Controller Scope

The selection of the controller scope is the defining decision in the design of a multivariable controller. This decision, to include or exclude sections of the process in the controller, will determine its ability to achieve the economic objectives of the plant.

The scope of the Oleflex™/MTBE controller was determined based upon the economics and constraints of the complex. There are no constraints to throughput downstream of the butene column, which was therefore chosen as the boundary of the scope that encompasses all of the Oleflex™ unit and the MTBE

feed, reactors and butene column. A smaller scope than this would be unable to address the objectives and trade-offs relevant to the overall problem.

The resultant multivariable controller design has 20 manipulated variables, 6 disturbance variables and 44 controlled variables. The model matrix is shown in Figure 5. The diagram gives a good impression of the size of the control problem. Each row in this matrix represents a manipulated or disturbance variable, with each column a controlled variable. Each cell contains the model response between the relevant two variables, a blank indicating no effect. This model matrix was derived using plant data from a controlled test which involved making multiple step moves in each of the manipulated variables. The plant data is regressed using a least squares algorithm to fit a convolution model form.

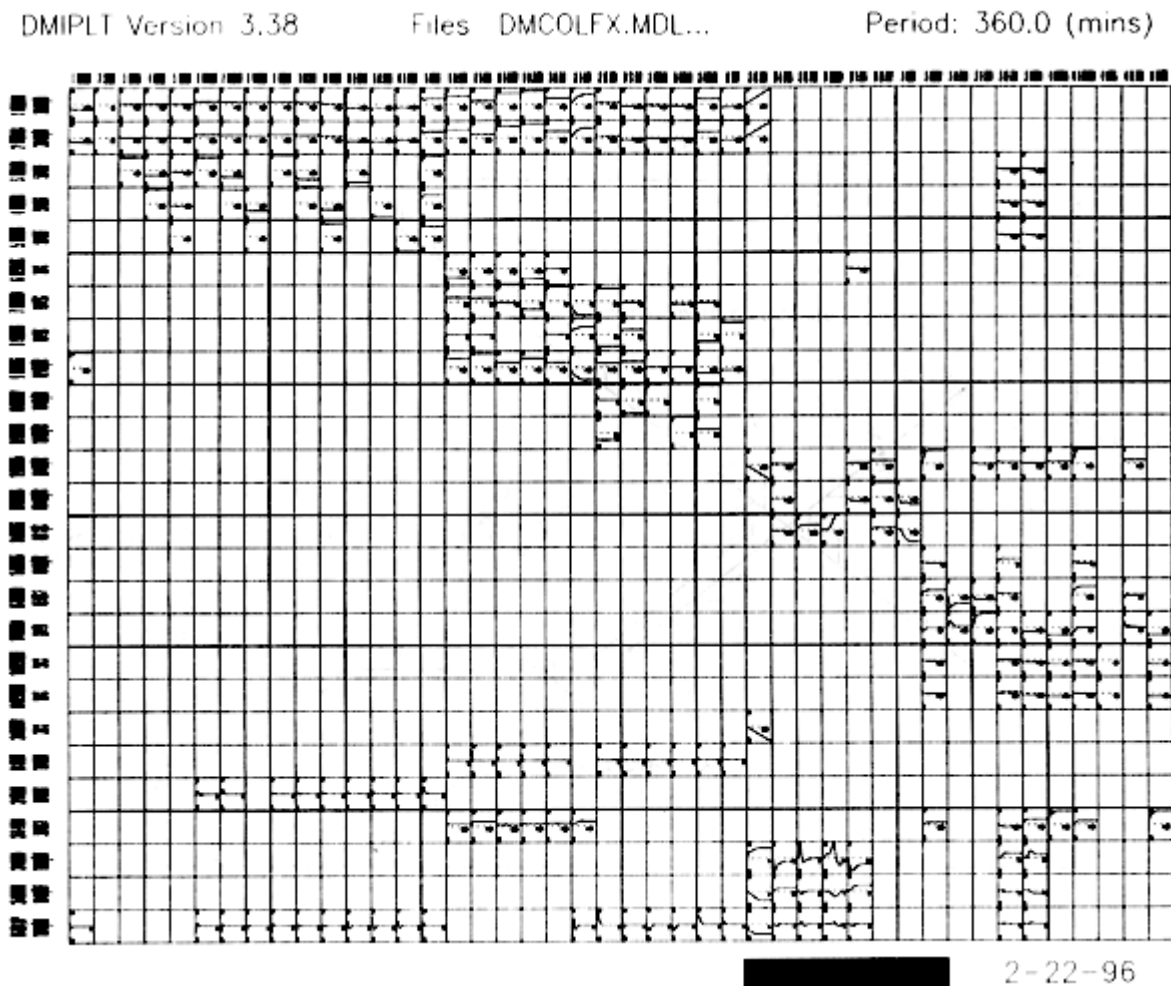


Figure 5 – [DMC] Model Matrix

The broad scope results in the controller having to handle a wide range of dynamic characteristics ranging from 20 minute settling times in the Oleflex™ expander system to 6 hour time horizons in the MTBE's large liquid filled reactor system. The overall time horizon for the controller prediction is therefore 6 hours and the execution frequency is once per minute. The matrix inversion calculations required for the controller's move calculations are made more difficult by this wide ranging dynamic behavior. This makes a robust numerical engine essential for the application to avoid problems with the calculation "blowing up."

The controller uses the most important intermittent processes as disturbance variables, allowing it to predict their impact and take correcting action before the effects reach the process. This pre-emptive action significantly reduces the negative effect of these events. Ambient temperature is also used as a disturbance variable to take advance action as weather conditions change.

Setting the Economic Drives

The controller's economic objective is applied as a cost coefficient on each of the manipulated variables. These define the objective function for the linear program, which drives the operating targets in the multivariable controller. The LP uses the process model from Figure 5, high and low limits set by the operators for each variable, and this objective function to find the constrained optimum operating point for the process.

In order to translate the plant's economic objective into these cost coefficients, a simple spreadsheet is constructed. The objective for the OleflexTM/MTBE controller is to maximize MTBE production so the spreadsheet is set up to tabulate the effect of each manipulated variable on this production rate. These relationships are established using plant data in the same way as the controller model matrix. The gains between the manipulated variables and product rate are used directly as the objective function coefficients.

If the plant's economics were more subtle and subject to change, a dollar objective function would be constructed in the spreadsheet to take account of all the feed, product and utility streams. Some variables may not affect the production rate, and in these cases, small bias costs can be added to cause the variable to be moved preferentially in one direction or another. The use of a spreadsheet to calculate the costs makes updating the objectives for new economic drives a simple matter.

The Performance of the Controller

Pursuit of the Economic Objective

When operating, the multivariable controller single-mindedly pursues the objective function assigned to it. The LP explicitly identifies all of the constraint trade-offs available using the plant model and calculates the operating targets to achieve the true maximum throughput. It finds as many constraints as it has degrees of freedom, a condition for a linear optimization. This optimization calculation is carried out once per minute, with the plant continuously being driven to the targets identified.

The results are presented in Figure 7, a plot of just over 37 weeks of OleflexTM daily average feedrate. The controller was commissioned around day 154 on this plot, April 7, 1995. The average feedrate after the controller was commissioned is 4.6% higher than before. This is considered to be a low limit on the benefit obtained, since the post-commissioning period analyzed covered the first half of summer while the pre-commissioning period was mostly winter. In fact, the feedrate after commissioning shows a distinct downward trend as daily ambient temperatures climbed toward the peak of summer. Some abnormal operating days have been removed from the data to make it representative of normal full rate operation. Rates below 120 were excluded since these typically indicate process problems or shutdowns. All of the data removed was from the period before the controller was commissioned. OleflexTM feedrate has been used as a measure of performance since the MTBE feedrate can include other streams, and the MTBE product rate is a function of many process variables. The OleflexTM feedrate is therefore the cleanest variable for benefit analysis.

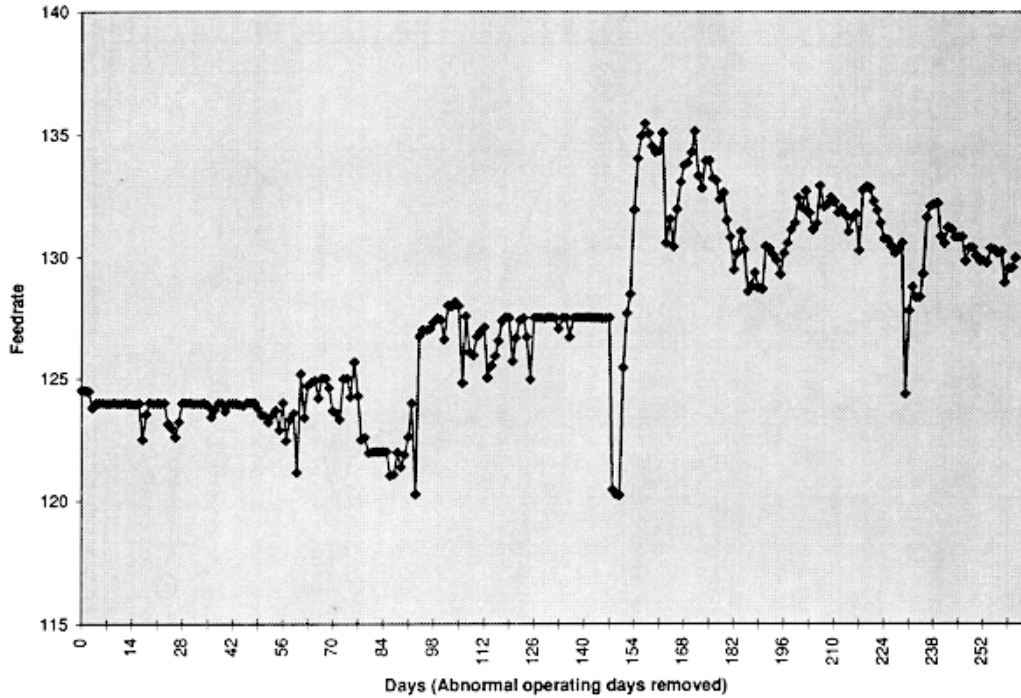


Figure 7 – Oleflex™ Daily Average Feedrate

Operation at Multiple Constraints

As discussed earlier, the true maximum throughput is achieved by using all the process handles available to relieve constraints until the process is operating at multiple simultaneous constraints. The linear program in the multivariable controller performs this function, realizing as many constraints as there are degrees of freedom. Figure 6 illustrates this principle by a simple two variable example.

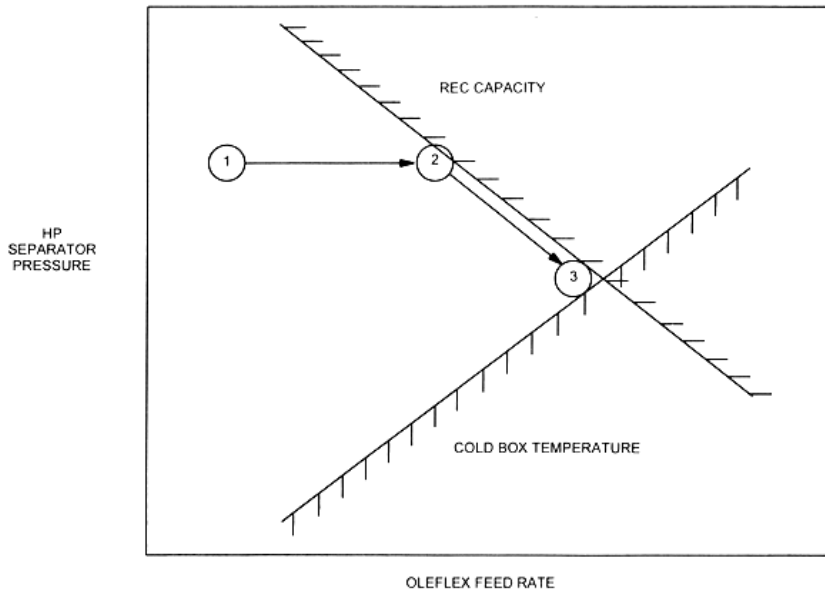


Figure 6 – Linear Program Operates at Multiple Constraints

The plot in Figure 6 represents the selection of two manipulated variable values: the Oleflex™ feedrate and the cold box inlet pressure. Two constraints are considered: the REC capacity and the cold box temperature. The two manipulated variables are represented on the axes, with the constraint limits shown as lines on the plot. The shaded sides of the lines represent operating regions where the constraints would be violated.

Consider the maximization of Oleflex™ feedrate from starting point (1) on the plot. If the separator pressure is maintained constant, the feedrate can be increased to point (2) at which the REC capacity constraint has been reached. We have reached one constraint by manipulating one variable. If the cold box inlet pressure is used to relieve the constraint, the pressure is reduced and feedrate increased to point (3) where simultaneous limits have been reached on the REC and the cold box temperature. Two constraints have been found using two manipulated variables, and the feedrate is of course higher than was possible using one variable. The controller's LP solves this problem using all 20 manipulated variables in the pursuit of more product rate.

Balancing the Units Using the Surge Drum

As discussed above, the Oleflex™ and MTBE units are closely matched in capacity, with the limit shifting between them depending on ambient conditions or temporary disturbances. The original process design allowed the level to float in response to these disturbances. The controller goes one step further in fully utilizing available surge capacity by forcing the drum level to build or deplete for periods of time when the units are out of balance. The controller is able to maintain each unit at maximum throughput for as long as the level remains within the operator defined limits.

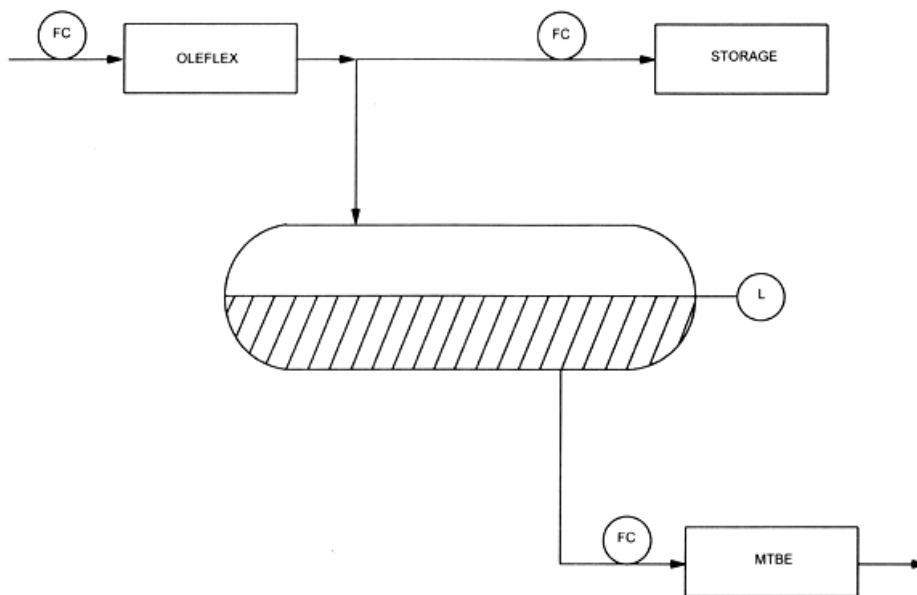


Figure 3 – Intermediate Surge Drum

Figure 3 is a simple flow diagram showing the configuration of the surge drum. The level can be controlled by varying the Oleflex™ or the MTBE feedrates. Additionally, there is a flow to storage, which ultimately feeds another unit elsewhere in the refinery. The economics dictate that MTBE production is the first priority, but excess isobutylene is still economic and should be taken to storage. The controller achieves the plant's objectives as follows:

- If the units are balanced, both will be maintained at maximum rates and the level will hold constant.
- If the Oleflex™ is limited, the surge drum will be allowed to drain to keep the MTBE at full rate. Only when the surge drum level gets to the low limit will the MTBE rate be cut.

- If the MTBE is limited, the surge drum level will be built by holding the Oleflex™ at maximum rate. Only when the level reaches the maximum limit will the excess be sent to storage to control it.

This intelligent use of the surge drum level has contributed tangibly to the controller's benefits.

Figure 8 is a plot of the isobutylene surge drum level over a one-day period with the multivariable controller running. The time axis is labeled in minutes with the level axis in engineering units. At point (1) on the trend the process experienced a temporary drop in Oleflex™ product rate due to one of the intermittent processes. The multivariable controller allows the drum level to fall rather than cut the MTBE feedrate. After the temporary reduction is complete, the drum level builds for a while as the Oleflex™ capacity outstrips the MTBE. Then, at point (2) another temporary reduction step begins, reducing the Oleflex™ capacity for a number of hours. The MTBE feedrate is maintained at maximum and the drum level is allowed to fall until point (3) when the step completes. The Oleflex™ is then restored to full capacity and the level is built up again. The MTBE production rate is maintained at maximum during this entire time period despite the temporary reductions in Oleflex™ capacity.

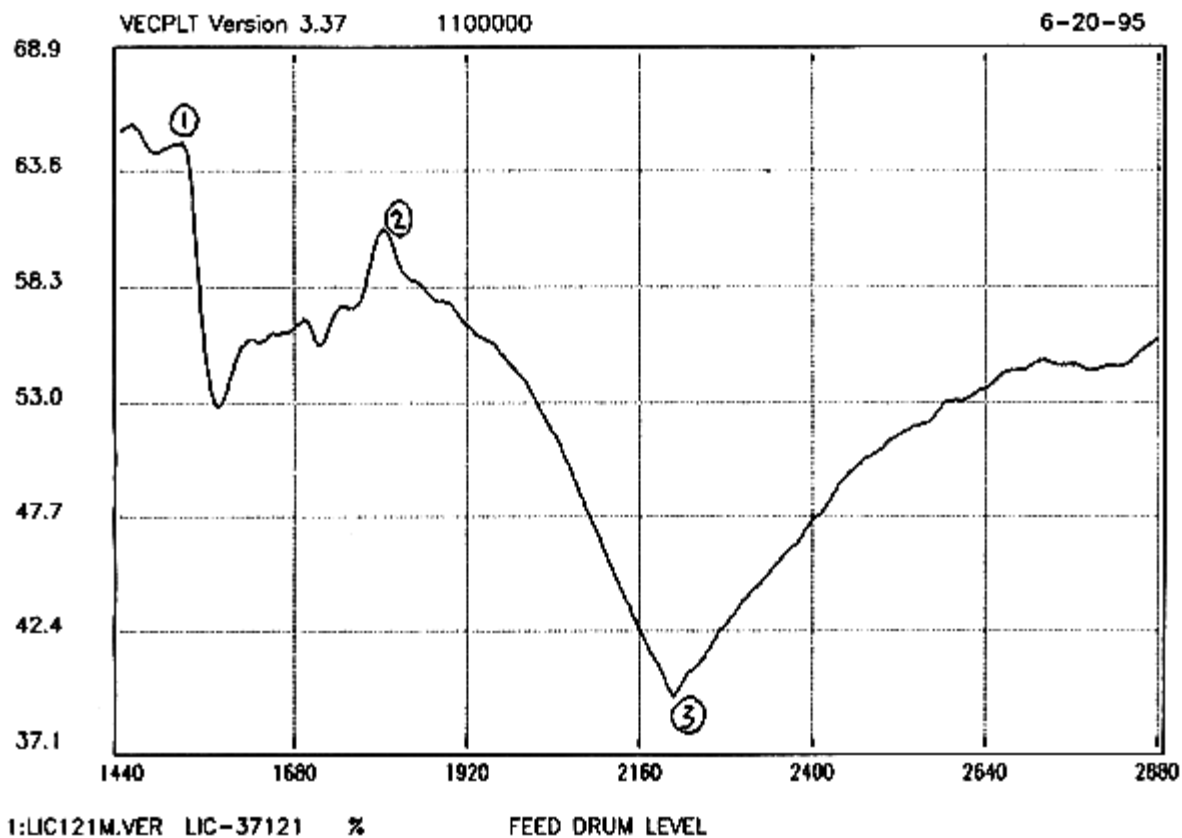


Figure 8 – Surge Drum Level Plot

Conclusions

A single, large-scale controller has been implemented on an Oleflex™/MTBE complex owned by Valero Refining Company in Corpus Christi, Texas. The complex was already running over design capacity when the project began. Commissioning of the controller resulted in at least 4.6% additional throughput.

The controller pushes capacity by simultaneously looking at all possible constraints in both the Oleflex™ and MTBE sections of the plant. It also takes advantage of available intermediate surge capacity to forcibly build or deplete surge drum level when there is an imbalance in production capacity between sections of the complex. This allows additional production capability when capacity limits regularly flip-flop between the front and back-ends of the plant.

Appendices

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