INSTALL PRODUCTION RATE MAXIMIZERS IN CHEMICAL PLANTS IN TWO WEEKS USING MODERN ADVANCED CONTROL TECHNIQUES

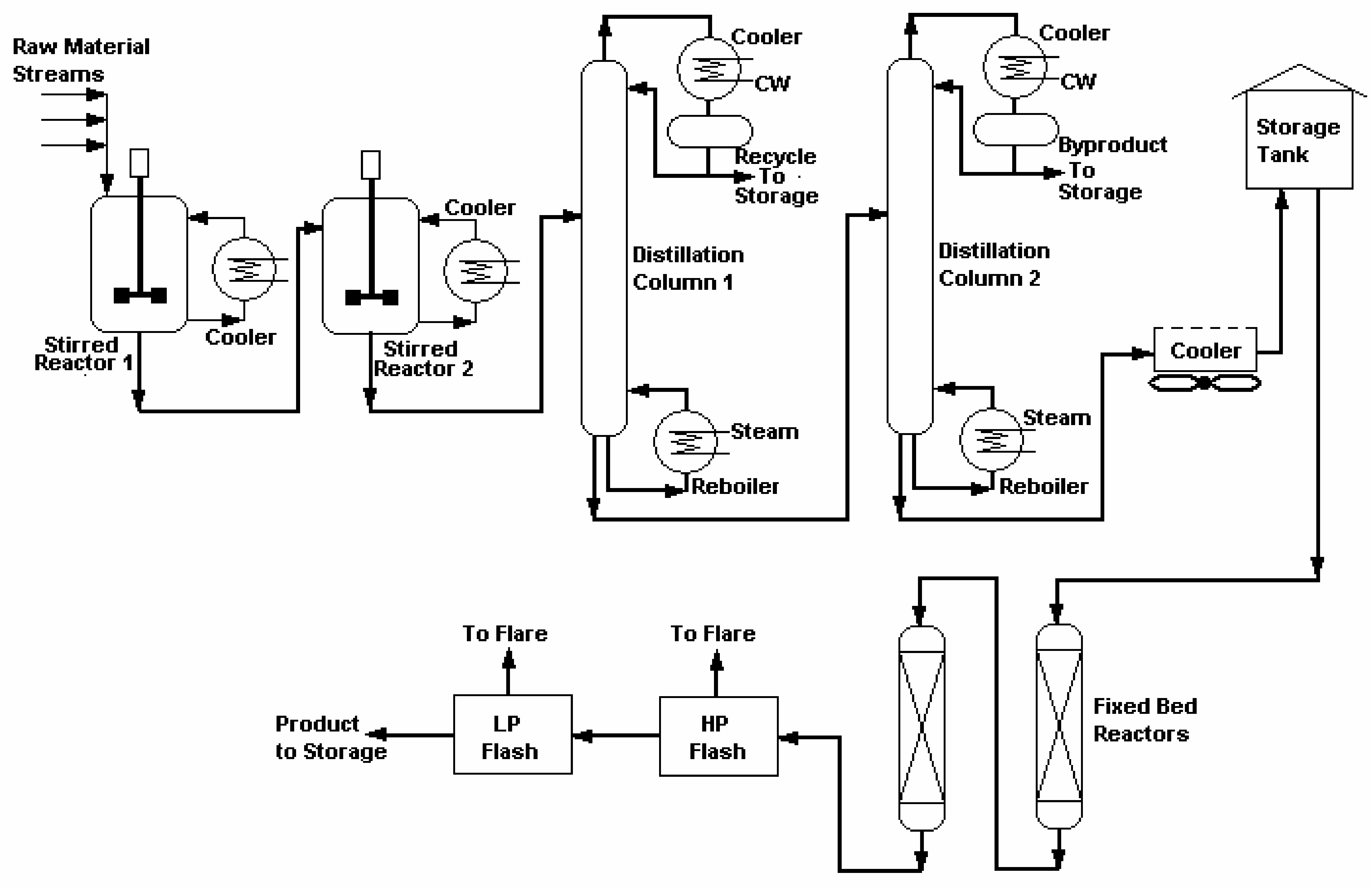
Maximizing production rates and minimizing utilities is a common goal in most chemical plants. This paper shows how to implement a DCS-resident production rate maximizer with minimal effort and in a remarkably short time. Several novel advanced control techniques required to design such a control strategy are explained.

A typical industrial chemical process schematic has been shown in Figure 1 for illustrating the production maximizer implementation. Raw materials are mixed in a liquid phase stirred reactor. Effluent from the first reactor is allowed more residence time in a second reactor. Both reactors are equipped with coolers to remove the exothermic heat of reaction. The effluent from the second reactor is then separated in two distillation columns before being cooled and sent to storage as intermediate product. The intermediate product is fed to fixed bed reactors and the lights are flashed in two separator drums before cooling and final product storage.

You are a team member in the production/controls group at your plant. Management is tight on budget and production is pressure to maximize production rate at the plant. If you can design an effective production rate maximizer with little or no cost in a short time frame, you can become a hero. Here is your action plan:

Day #1: Examine the process flow diagrams (PFDs) and process-instrumentation diagrams (P&IDs) and pencil-sketch a schematic of the process, similar to what is shown in Figure 1 below. Leave unimportant details (e.g., filters, tiny flows to flare- any non-money-making equipment, instrumentation or piping) out of the schematic and thinking.

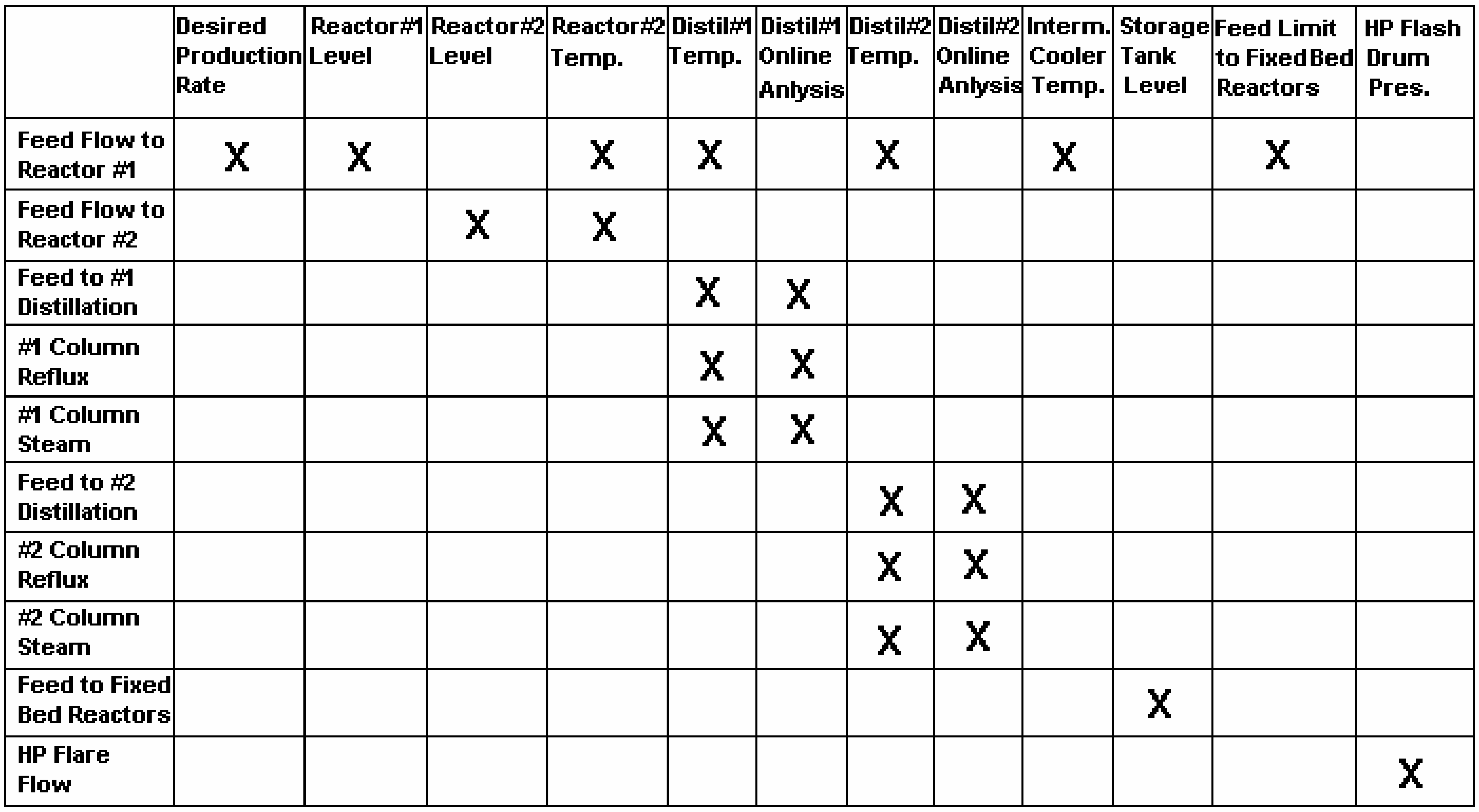
Figure 1. Typical Industrial Chemical Process Schematic



Go to the control room and ask the operator about all important process and equipment constraints. When he tries to increase production rate, what process variables need to be looked at, and when to back off on rates in case those constraints are approached. Ask these questions to at least four of the best operators in order to gather a complete picture.

Day #2: Draw the control matrix for the whole process. An illustrative control matrix for the above process schematic is shown below in Figure 2. The "X" shows a relationship between a given pair of variables. The variables in the left vertical column are the manipulated variables (MVs) and the variables in the upper horizontal row are the controlled variables (CVs). The MVs can be manipulated by the new advanced control strategy that you are about to design and implement. The CVs are variables that the new strategy will strive to maintain at the desired limits specified by the production team. Continue to ask questions from day #1 to additional operators that you may have missed earlier.

Figure 2. Control Matrix



	Desired Production Rate	Reactor#1 Level	Reactor#2 Level	Reactor#2 Temp.	Distil#1 Temp.	Distil#1 Online Anlysis	Distil#2 Temp.	Distil#2 Online Anlysis	Interm. Cooler Temp.	Storage Tank Level	Feed Limit to Fixed Bed Reactors	HP Flash Drum Pres.
Feed Flow to Reactor #1	X	X		X	X		X		X		X	
Feed Flow to Reactor #2			X	X								
Feed to #1 Distillation					X	X						
#1 Column Reflux					X	X						
#1 Column Steam					X	X						
Feed to #2 Distillation							X	X				
#2 Column Reflux							X	X				
#2 Column Steam							X	X				
Feed to Fixed Bed Reactors										X		
HP Flare Flow												X

For every box checked with an "X" you need to identify, calculate or estimate the dynamic relationship (transfer function) between the pair of variables. The transfer function consists of the dead time, process gain and one or two time constants. In almost all industrial applications, the use of one or two time constants (first or second order transfer function) adequately characterizes the dynamic relationship.

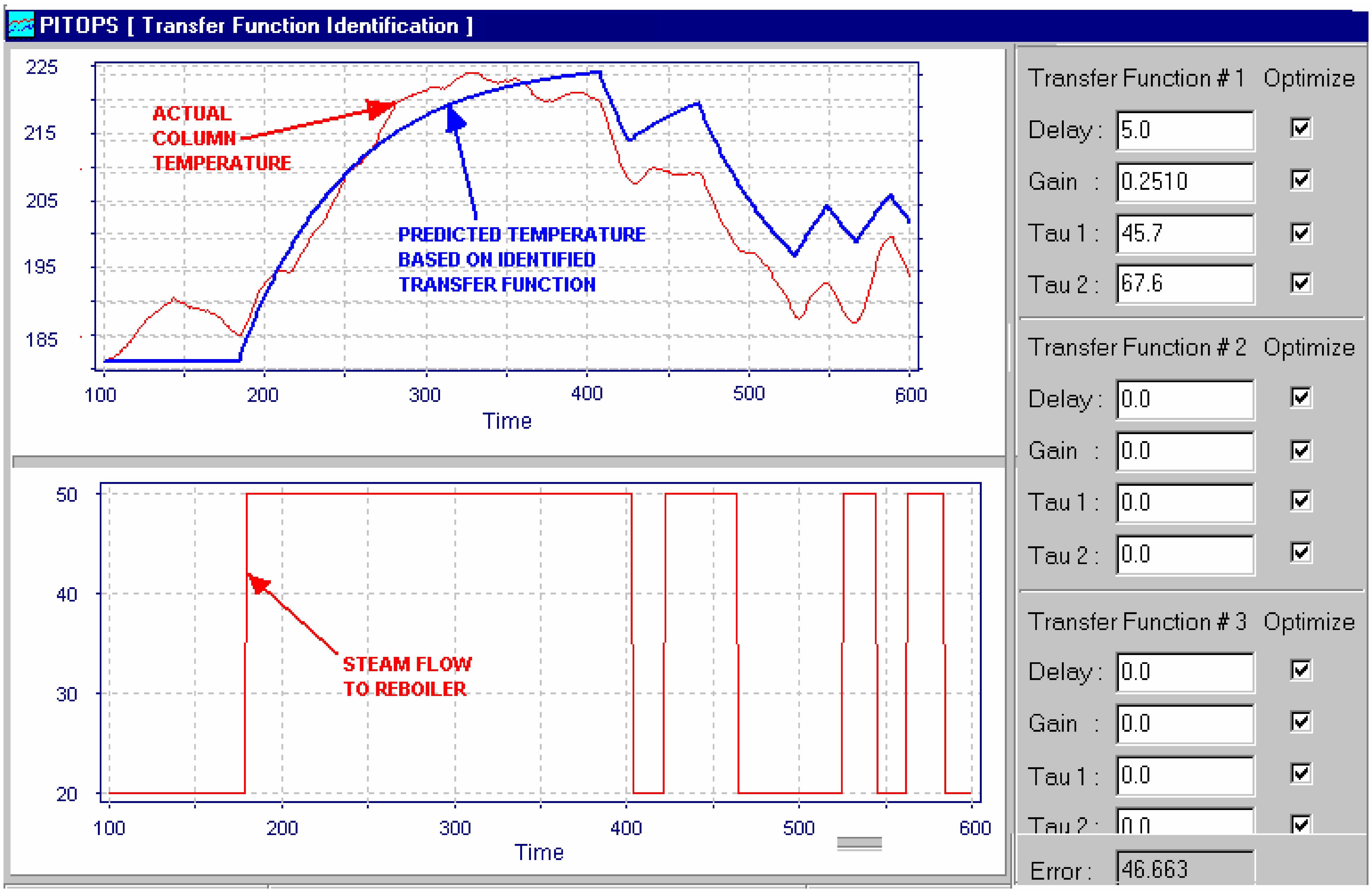
Day #3 and #4: Determine the transfer function parameters using one or more of the following techniques:

Operator Experience and Knowledge: Ask the operator- "If a given MV is changed by a specific amount, what is its impact of the temperature? How much time elapses before any change is seen and how long does it take for the CV to reach a new steady state? Note down all the information and specify the transfer function parameters- dead time, process gain and first order time constant.

Visual Inspection of Historical Data: Examine several months of historical data. Operators might have made several changes to various primary PID setpoints or valve positions. In many cases it is possible to determine transfer function parameters based on visual inspection of historical data.

<u>Open-Loop Tests</u>: A third method to determine transfer functions is by conducting open loop tests. An illustrative example is shown in Figure 3. The bottom trend shows open-loop step tests on a column reboiler. The actual temperature is shown in the upper trend- as reboiler flow is increased, the temperature rises. Using the steam flow and temperature data, we can use process control software techniques to identify the transfer function between the steam and temperature. The transfer function parameters are shown on the right in Figure 3. The accuracy of the transfer function is confirmed by the prediction of the temperature also shown in Figure 3.

Figure 3. Transfer Function Identification using Open-Loop Test Data



Transfer Function # 1 Optimize
Delay : 5.0 ☑
Gain : 0.2510 ☑
Tau 1 : 45.7 ☑
Tau 2 : 67.6 ☑

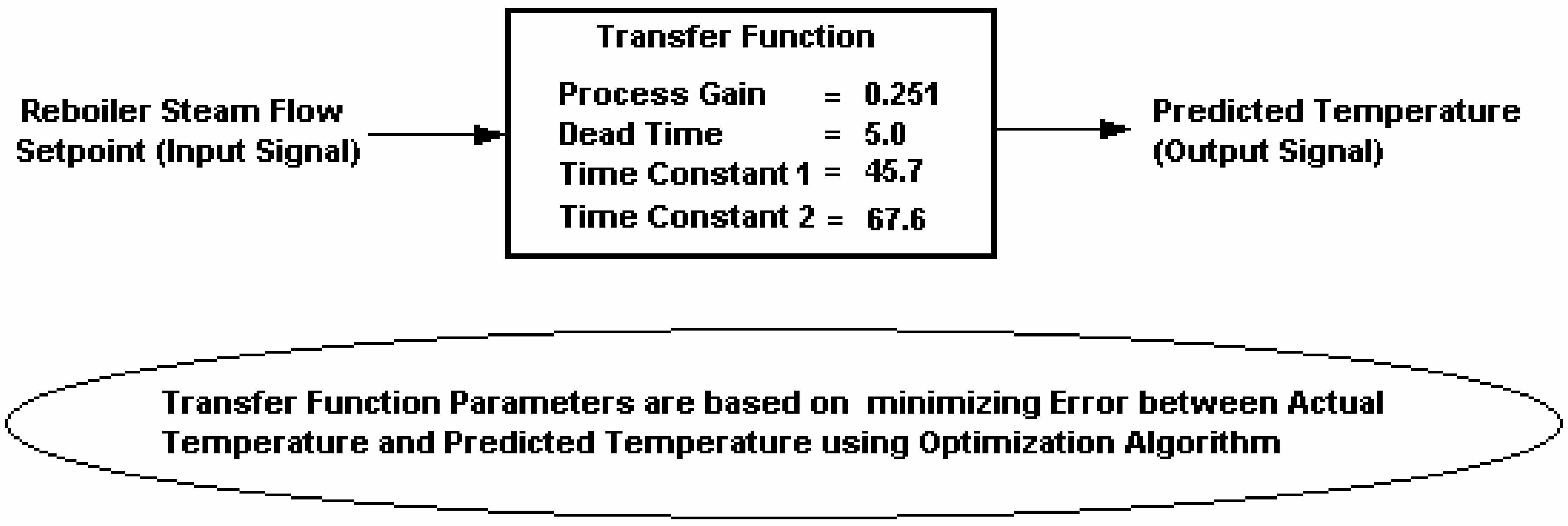
Transfer Function # 2 Optimize
Delay : 0.0 ☑
Gain : 0.0 ☑
Tau 1 : 0.0 ☑
Tau 2 : 0.0 ☑

Transfer Function # 3 Optimize
Delay : 0.0 ☑
Gain : 0.0 ☑
Tau 1 : 0.0 ☑
Tau 2 : 0.0 ☑

Error : 46.663

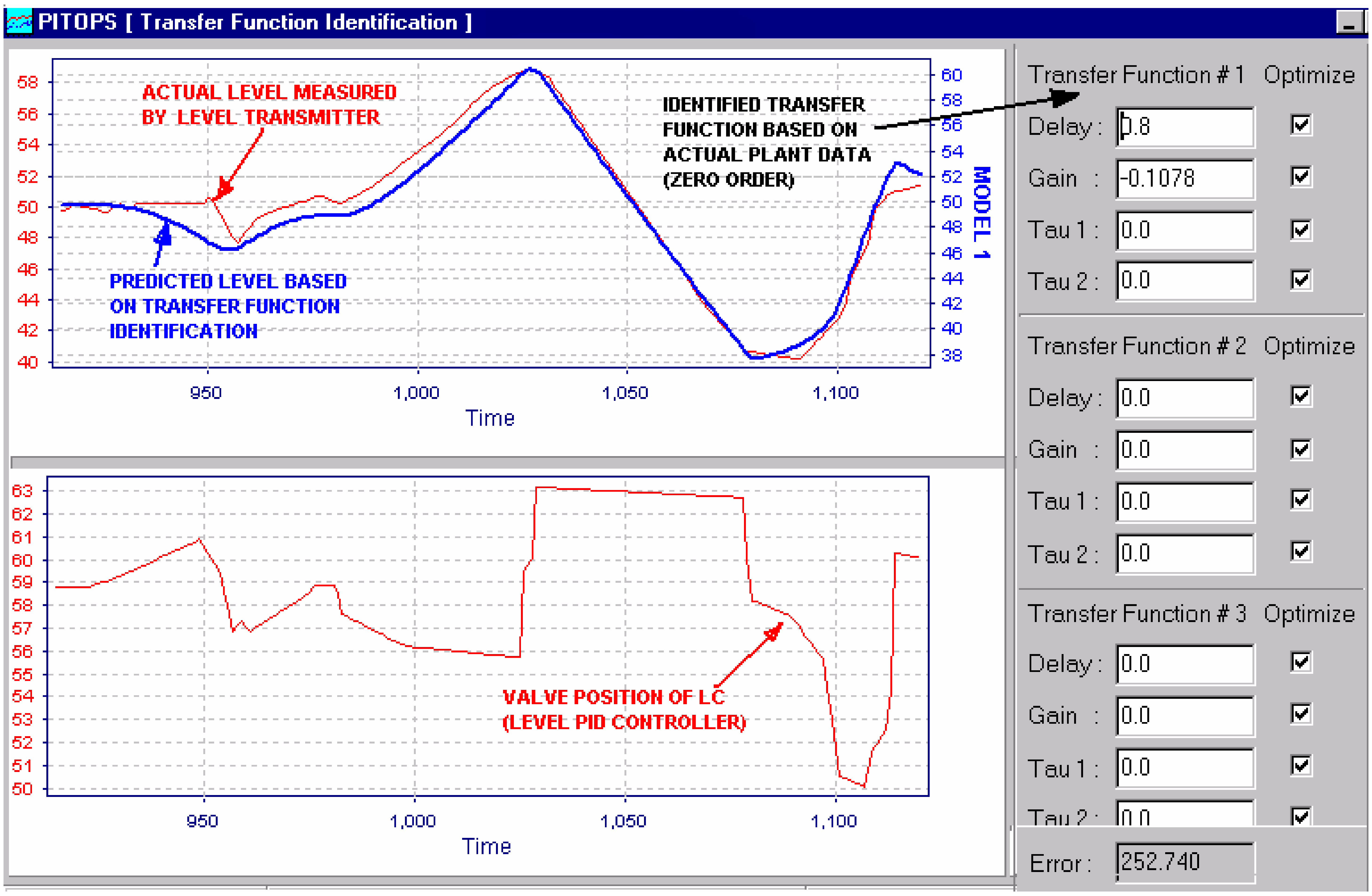
The method for transfer function identification is shown in Figure 4. An optimization algorithm searches the best transfer function parameter set by minimizing the error between the actual temperature and predicted temperature.

Figure 4. Summary of Transfer Function Identification Procedure



Data containing setpoint changes on a given controller can be also used to identify the transfer function. Figure 5 shows trends of a level controller (LC). The LC's setpoint was moved up and down causing its output (valve position) to change as seen in the bottom trend in Figure 5. The LC dynamics are described by a ramp (zero order dynamics) which are identified by the optimizer algorithm using the data on valve position (bottom trend) and the actual level (upper trend). The optimum identified parameters are shown on the right in Figure 5. Since this is a zero order transfer function, there are no time constants- dynamics are fully defined by the dead time and the process gain (ramp rate).

Figure 5. Semi-Open-Loop Test Transfer Function Identification (with Setpoint Changes on Controller in Auto Mode)



PITOPS [Transfer Function Identification]

Transfer Function # 1 Optimize
Delay : 0.8 ☑
Gain : -0.1078 ☑
Tau 1 : 0.0 ☑
Tau 2 : 0.0 ☑

Transfer Function # 2 Optimize
Delay : 0.0 ☑
Gain : 0.0 ☑
Tau 1 : 0.0 ☑
Tau 2 : 0.0 ☑

Transfer Function # 3 Optimize
Delay : 0.0 ☑
Gain : 0.0 ☑
Tau 1 : 0.0 ☑
Tau 2 : 0.0 ☑

Error : 252.740

Closed-Loop Data: Closed-loop data can also be used to determine transfer functions. This is relatively a complex and advanced technique. A three-input multivariable transfer function identification is illustrated in Figures 6 and 7. All three inputs (reboil flow, reflux flow and feed flow) are changing with their respective controllers in closed-loop (auto) mode. All three inputs relate to the column temperature through three transfer functions, as shown in Figure 7. Using the optimization techniques described earlier, three transfer functions can be identified using the closed-loop data shown in Figure 6.

Figure 6. Three-Input Transfer Function Schematic

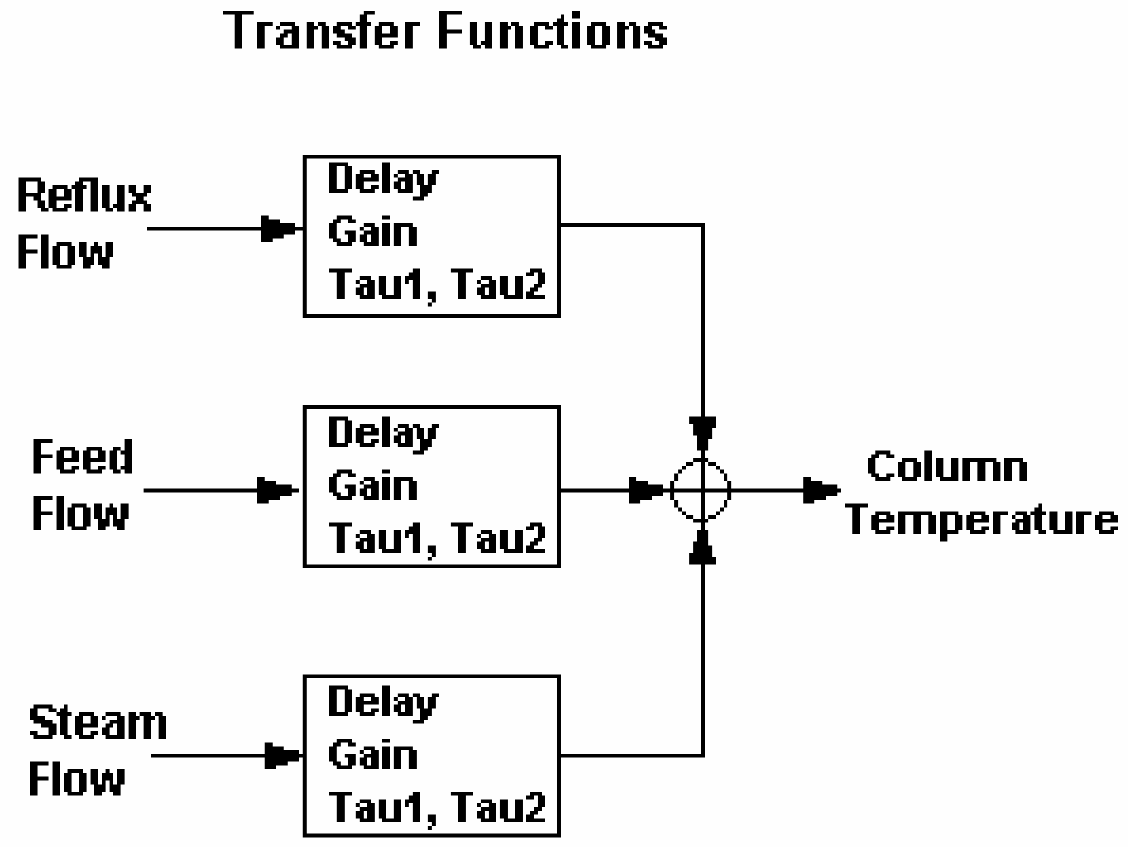
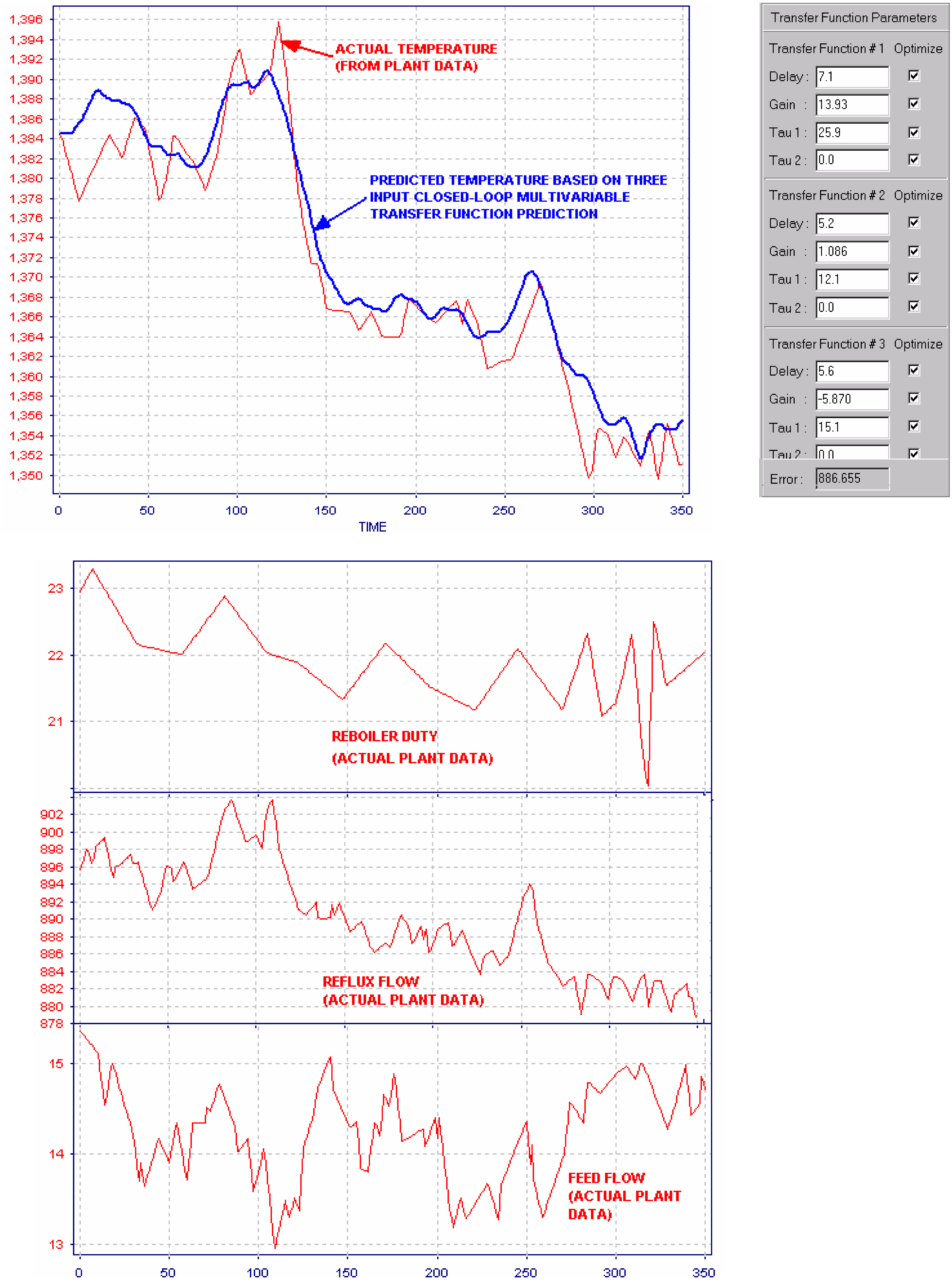


Figure 7. Simultaneous Multivariable Identification using Closed-Loop Data



Transfer Function Parameters

Transfer Function # 1		Optimize
Delay :	7.1	☑
Gain :	13.93	☑
Tau 1 :	25.9	☑
Tau 2 :	0.0	☑

Transfer Function # 2		Optimize
Delay :	5.2	☑
Gain :	1.086	☑
Tau 1 :	12.1	☑
Tau 2 :	0.0	☑

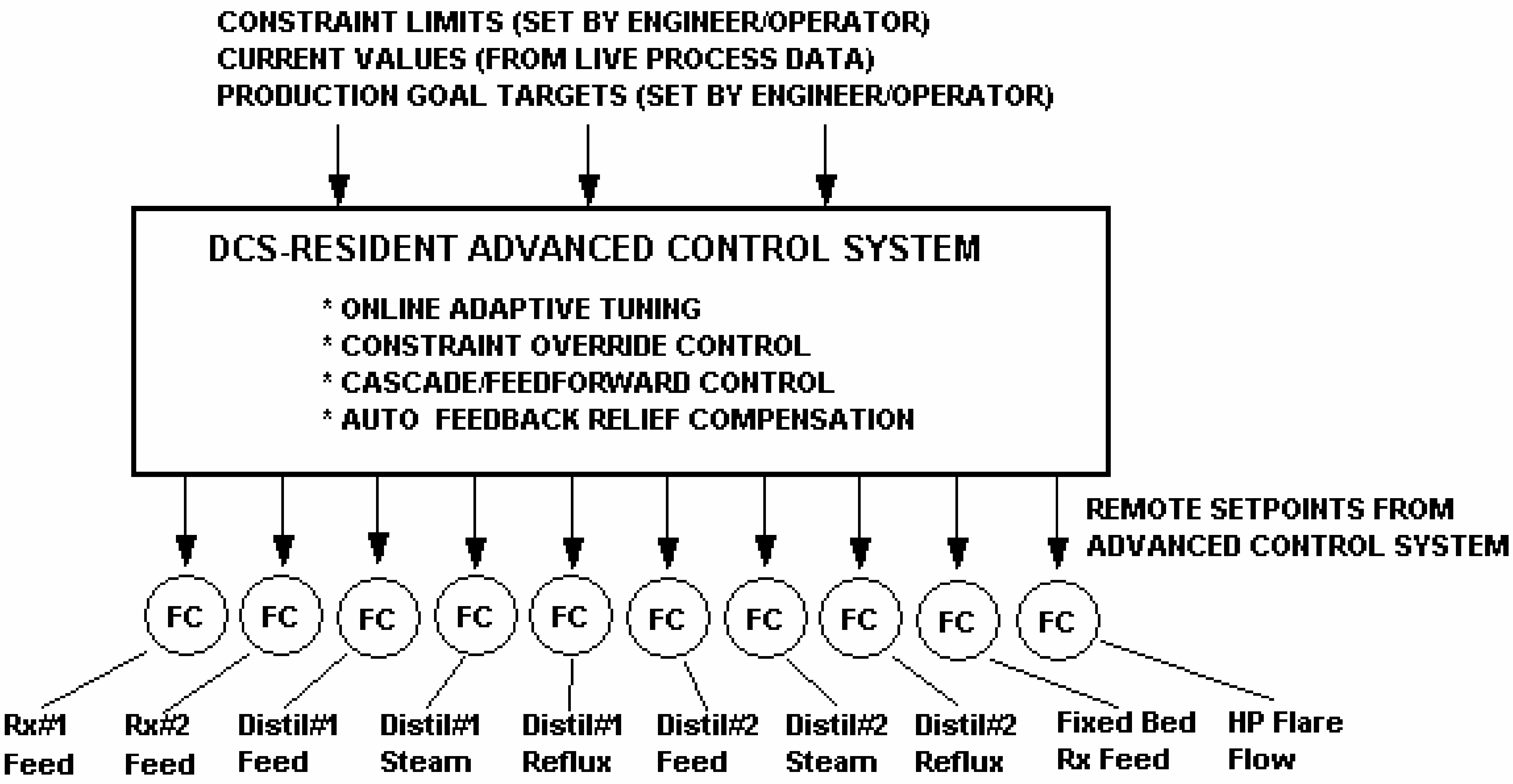
Transfer Function # 3		Optimize
Delay :	5.6	☑
Gain :	-5.870	☑
Tau 1 :	15.1	☑
Tau 2 :	0.0	☑

Error : 886.655

<u>Day #5 and #6</u>: The next step is to build DCS configuration. Use standard DCS blocks in the design of the new advanced control strategies. Commonly needed blocks are: Control Summation, Ratios, Cascade PID blocks, PID blocks with special features, Selectors, Dynamic Compensators (for specifying Lead, Lag and Time Delay), Discrete On/Off Switches, Ramp and Soak blocks. Write custom code for auto-adaptive tuning for loops known to be nonlinear. Nonlinear dynamics can be identified using the same identification techniques described earlier. An illustrative advanced control system overview is shown in Figure 8.

Auto Feedback Relief Compensation automatically disconnects weak inputs in certain situations thereby increasing the overall stability and robustness of the control action. In many multivariable control applications, often one MV-CV pair is dominant; other MVs may have process gains that are 1/5th or 1/10th of the dominant MV. In certain operating regimes, it is desirable for the dominant MV only to control a given CV, otherwise, too many MVs move needlessly causing the process to move erratically. Auto Feedback Relief Compensation consists of special custom logic that monitors various process conditions and then systematically adjusts or activates/deactivates controller gains. This provides nonlinear and adaptive control functionality.

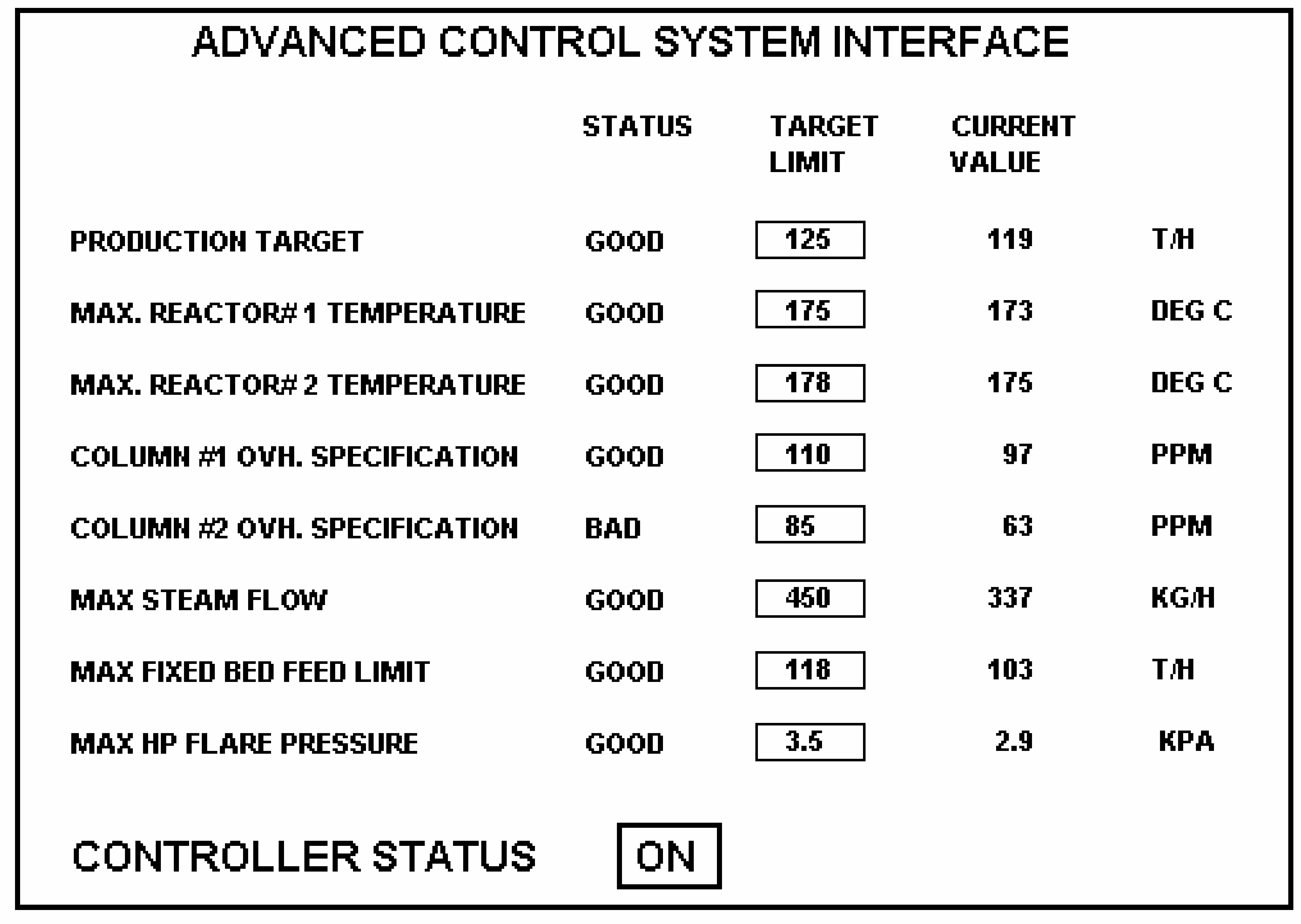
Figure 8. DCS-Resident Advanced Control System Architecture



<u>Day #7 and #8</u>: After completion of the DCS configuration, the next step is to build one or more DCS screens for operator interface. Depending on the number and complexity of loops there may be several screens. A sample illustrative DCS screen is shown in Figure 9. This screen allows the operator or production engineer to specify production goals (targets) and important process and equipment constraints monitored and controlled by the advanced control system. A single On/Off click-able button is used to activate or deactivate the advanced control system. The operator is expected to specify production targets and some critical process constraints that might need to be changed based on different product grades or other reasons. Constraint limits that do not require to be changed often are not displayed on this screen. The screen should be kept as simple as possible to make the operators job convenient and easy to understand. All advanced control parameters that are not required to be seen or changed by operators ought to be displayed on special screens accessible by control engineers only.

The advanced control system can be activated or deactivated easily with a single click of a button. The DCS logic and configuration provides smooth and bump-less transfer. If a problem arises in the plant and the operator needs to take over manual control, he turns the system off and makes appropriate adjustments in manual mode. Once he is ready to turn the system on, he clicks on the On/Off button.

Figure 9. DCS Screen for Operator Interface to Advanced Control System



ADVANCED CONTROL SYSTEM INTERFACE

	STATUS	TARGET LIMIT	CURRENT VALUE	
PRODUCTION TARGET	GOOD	125	119	T/H
MAX. REACTOR# 1 TEMPERATURE	GOOD	175	173	DEG C
MAX. REACTOR# 2 TEMPERATURE	GOOD	178	175	DEG C
COLUMN #1 OVH. SPECIFICATION	GOOD	110	97	PPM
COLUMN #2 OVH. SPECIFICATION	BAD	85	63	PPM
MAX STEAM FLOW	GOOD	450	337	KG/H
MAX FIXED BED FEED LIMIT	GOOD	118	103	T/H
MAX HP FLARE PRESSURE	GOOD	3.5	2.9	KPA

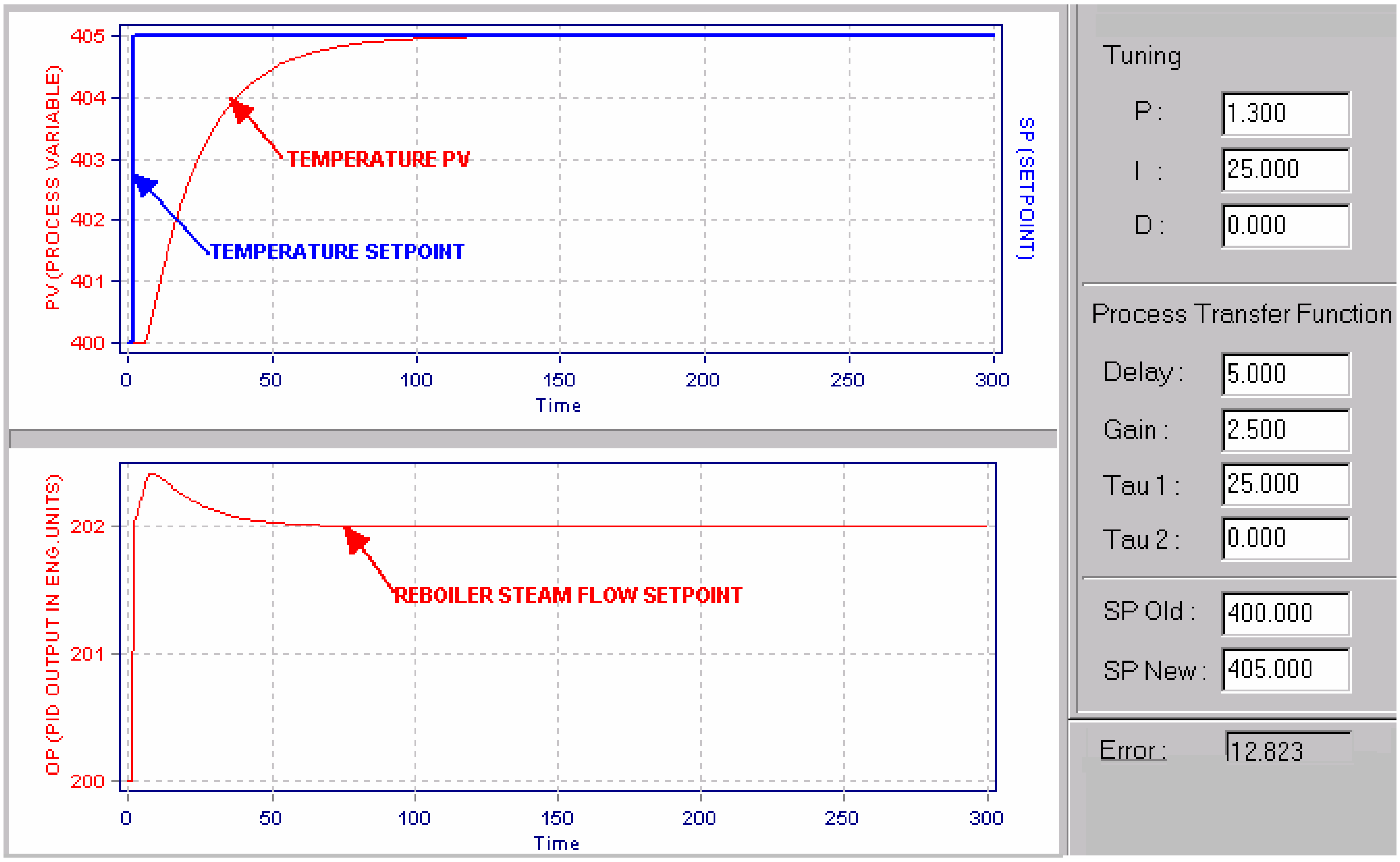
CONTROLLER STATUS ON

Day #9 and #10: Now it's time to calculate and set initial tuning parameters for the various control blocks in the DCS. Several helpful tips listed here will expedite the tuning calculations with high accuracy and ease. Look at the process flow diagrams and the location of major equipment. For some of the important constraint variables, you may not have enough information to be able to estimate or calculate the transfer function parameters. Some variables, though important may not have been close to their constraint limits because of changes in operating goals during the most recent months. Nevertheless, these constraints are known to be important and you need to calculate some reasonably meaningful initial tuning parameters. In case of such variables, estimate the process time constant by examining some historical data. Search periods of production change or change in temperatures or other parameters reflective of the dynamics. Watch for peak-to-peak lags between the feeds and the variable under study. Discuss with operators for their feel for the dynamics. In most cases, you can estimate the transfer function parameters with a fair degree of accuracy.

Consider an example where if the reboiler steam flow is changed from 200 to 202 kg/h, the column temperature changes from 400 degC to 405 degC. The time delay is about 5 minutes and the new temperature settles down fully after about 100 minutes. The process settling time is typically considered to be about 4-5 times the time constant. In this case, the time constant is approximately 20-25 minutes, lets set our best guess of time constant to be 25 minutes. The range of the temperature indicator (TI) is 0-1000 degC and the range of the reboiler steam flow FC is 0-300 kg/h.

You can simulate a setpoint change for the above control loop as shown in Figure 10. The temperature setpoint is change from 400 to 405 degC, seen in the upper trend. The actual change in temperature is also shown in the upper trend. The bottom trend shows the change in the reboiler steam flow- this is the setpoint to the steam flow (FC) and is the same as the output (OP) from the TC. The process control simulation software also identifies the optimum tuning parameters for this loop. You can conduct several "what-if" studies to make sure that the tuning parameters are not overly aggressive. During the simulation stage, ask an experienced operator to inspect the simulation and make sure that he is satisfied with the control action.

Figure 10. Process Control Simulation to Determine Optimal Tuning Parameters



Tuning

P : 1.300

I : 25.000

D : 0.000

Process Transfer Function

Delay : 5.000

Gain : 2.500

Tau 1 : 25.000

Tau 2 : 0.000

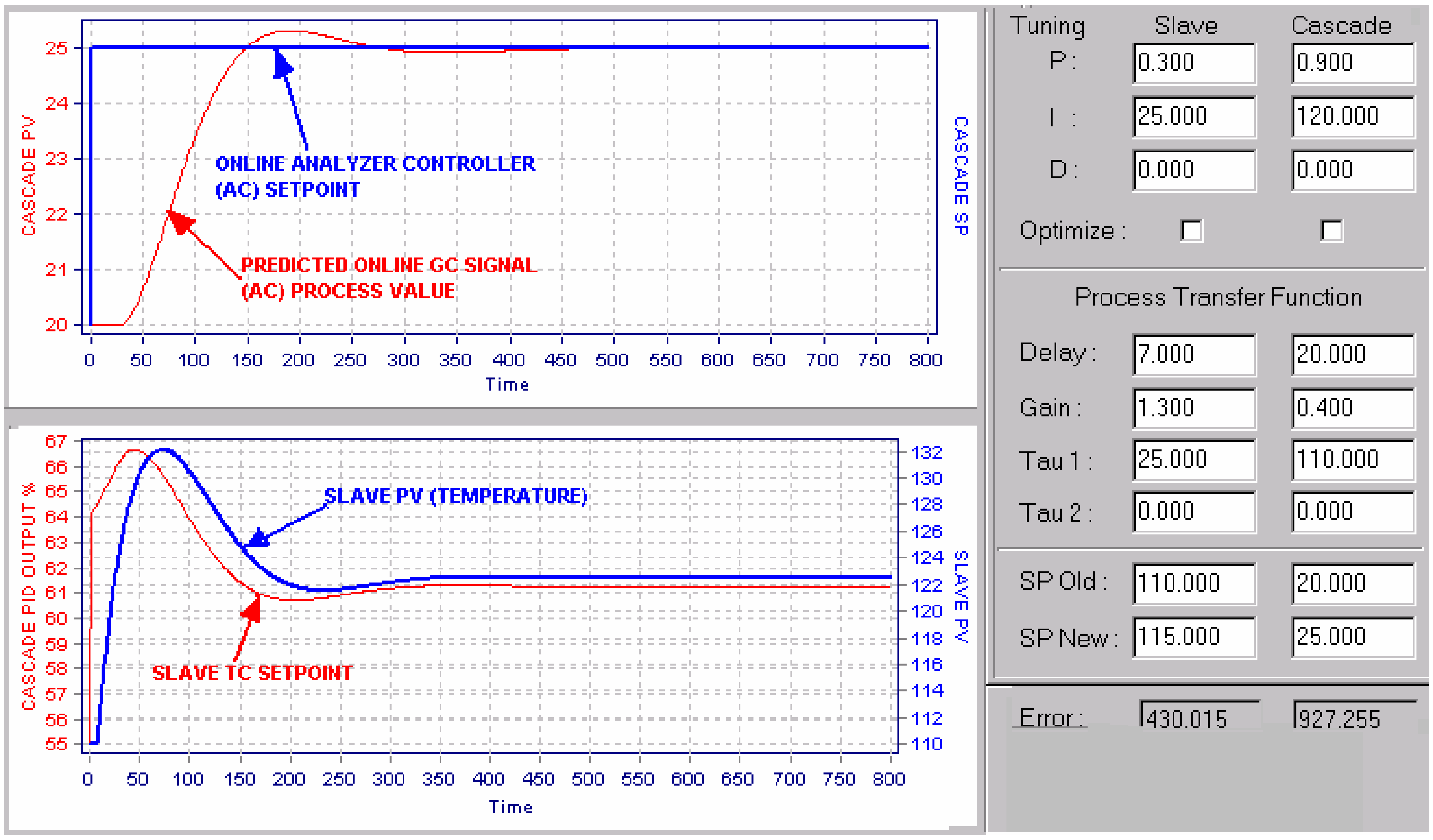
SP Old : 400.000

SP New : 405.000

Error : 12.823

Modern tools as illustrated in Figure 10 can be used to simulate any type of cascade, constraint override, feedforward and other forms of control strategies. A triple cascade simulation is illustrated in Figure 11.

Figure 11. Triple Cascade Simulation showing an AC-TC-FC cascade

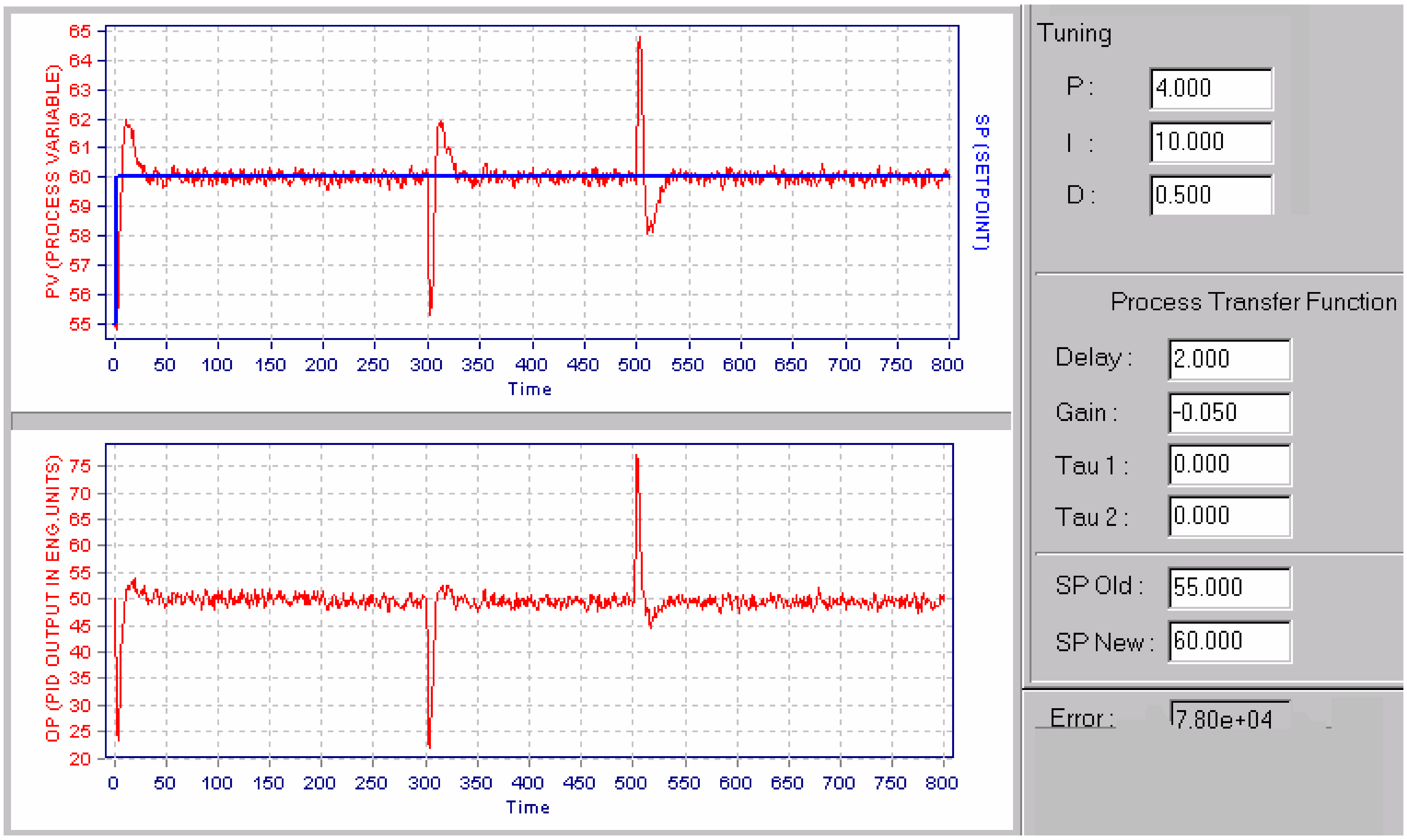


Tuning	Slave	Cascade
P :	0.300	0.900
I :	25.000	120.000
D :	0.000	0.000
Optimize :	☐	☐
Process Transfer Function		
Delay :	7.000	20.000
Gain :	1.300	0.400
Tau 1 :	25.000	110.000
Tau 2 :	0.000	0.000
SP Old :	110.000	20.000
SP New :	115.000	25.000
Error :	430.015	927.255

The triple cascade loops consists of an AC-TC-FC cascade. The AC receives a signal from an online gas chromatograph (GC). The process transfer function for the two loops (AC-TC) and (TC-FC) were identified using the identification techniques described earlier. Knowing the two transfer functions (shown on the right side of Figure 11), you can build a simulation and identify optimal tuning parameters for all the loops. The tuning parameters can be set for the loops in the DCS. If the process transfer function reasonably matches with the real plant dynamics, then the control simulation projections will very closely match reality.

Typical measured or unmeasured disturbances, random (electronic) or white noise can also be superimposed on any simulation to match the real plant behavior. The nature of disturbances is important in the design and selection of tuning of the control schemes.

Figure 12. Superimposed Noise and Unmeasured Disturbances to check Optimality of Controller Performance



Tuning

P: 4.000

I: 10.000

D: 0.500

Process Transfer Function

Delay: 2.000

Gain: -0.050

Tau 1: 0.000

Tau 2: 0.000

SP Old: 55.000

SP New: 60.000

Error: 7.80e+04

The complete repertoire of process control simulation blocks is shown in Figure 13. With these function blocks, a complete advanced control system can be quickly and conveniently tuned.

<u>Day #11- #14</u>: Now you are ready to activate and commission the advanced control system. During the first few days after activating the controller, set some tight limits on the setpoints or outputs to protect against possible errors in data analysis or process misunderstandings. With the methodical and structured procedure explained in this paper, there will be little room for error. However, it is always better to be extra-cautious during the initial commissioning period. Some additional fine-tuning may be necessary as you observe the action of this controller.

In most chemical and petrochemical plants, typically, 1-10% increase in production rates can be achieved by a well-designed advanced control system. About 1-4% reduction in utilities can be achieved if maximizing rates is not attractive based on market and economic conditions.

The proposed design can be successfully implemented and commissioned in a remarkable short time frame of about two weeks with minimal cost. No new hardware or software is required except for an inexpensive PC-based process control simulation and dynamics identification package. Commercial packages are available at about US $ 3000-5000 for a site license. Given the low-cost of this approach and the high monetary benefits, this type of an advanced control project will be attractive in most chemical and petrochemical complexes.

Figure 13. Process Control Simulation Blocks for Design of a DCS-Resident Advanced Process Control System