INTERACTIVE CONTROL ENGINEERING
Principles and Applications

Volume 11 Control in Petroleum Refining

CHAPTER 10

Three Clocks Behind One Octane in a Sulfuric Acid Alkylation Unit

Pages 233–261

Edited by John D. Hedengren

How to cite this chapter. "Three Clocks Behind One Octane in a Sulfuric Acid Alkylation Unit," in *Control in Petroleum Refining*, John D. Hedengren, Ed., vol. 11 of *Interactive Control Engineering: Principles and Applications*. Advanced Process Solutions, LLC, 2026, ch. 10, pp. 233–261.

The page numbers in this file are those of the printed volume.

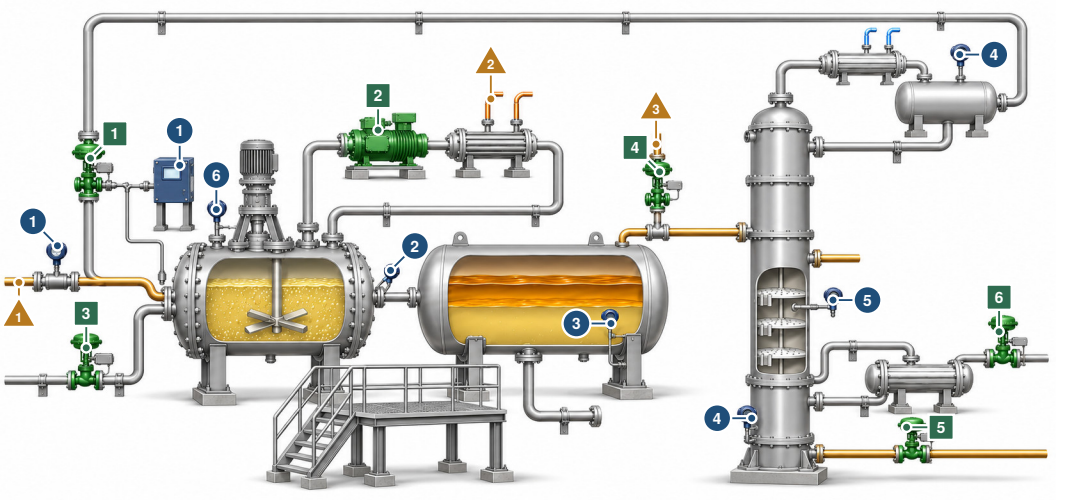
The app for this chapter
https://apmonitor.com/apps/alkylation-unit/

The volume online: contents, other chapters and citation records
https://apmonitor.com/apps/books/v11-refining/#alkylation-unit

Copyright © 2026 Advanced Process Solutions, LLC. All rights reserved. Produced by Advanced Process Solutions, LLC.

CHAPTER 10

Three Clocks Behind One Octane in a Sulfuric Acid Alkylation Unit



The controller moves 1 valve on the isobutane recycle 2 refrigeration compressor 3 fresh acid valve 4 isobutane makeup valve 5 alkylate valve at the column bottom 6 steam valve of the reboiler

The controller reads 1 olefin flow, isobutane in the recycle 2 contactor temperature 3 acid density 4 receiver and column-bottom levels 5 column tray temperature 6 compressor suction pressure

What disturbs it ▲1 more olefin, propylene or water in the feed ▲2 warm cooling water ▲3 a lost isobutane makeup

Notice the three stocks side by side: the cold made by the compressor loop above the stirred contactor, the isobutane that the column's receiver sends back from the right, and the acid lying under the hydrocarbon in the settler. Illustration, not to scale.

IN PLAIN TERMS Three Clocks Behind One Octane

The main idea. An alkylation unit joins two light liquids into a clean gasoline that resists engine knock, a quality called octane. A strong acid makes them join, and the unit must stay cold, rich in one of the two liquids and strong in its acid.

The challenge. The cold changes in minutes, the mix of liquids in hours and the acid in more than a day. The acid is tested by a lab only every four hours, and a weak acid spoils itself faster and faster.

Why it matters. The acid is the largest running cost, and the same waste that weakens it also lowers the octane.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	This page, the History boxes in Sections 10.1 and 10.2, the Did you know? boxes in Sections 10.1 and 10.6, the Try it boxes in Sections 10.3 and 10.4, and Key points in Section 10.9. No equations.
Study	65 min	The whole chapter in order, stopping at the three pause points, then Exercises 1 to 12.
Practice	25 min	This page, Section 10.6 with Figure 10.5, Section 10.7 and Section 10.8 with its Open challenge box.

The control question The octane of a sulfuric acid alkylation unit rests on three stocks that answer on three clocks, the contactor's cold in minutes, the recycle's isobutane in hours and the acid's strength in more than a day, while the acid is titrated only every four hours. Which loops, sensors and supervisors hold the octane and the acid bill through a day of upsets, and where does each of them lose?

Learning objectives

- Compute the fresh acid that holds a strength from the acid balance, and the acid-soluble oil the activity law adds as the strength falls.
- Explain why a ratio loop on the flows reads on setpoint while the true isobutane-to-olefin ratio drifts with the recycle's purity.
- Compare a strength loop on a four-hourly titration with one on a density soft sensor, and state what the soft sensor cannot see.
- Run the acid to its runaway floor and the graded day, and read each outcome from the app's verdict and exported log.
- Judge whether a predictive controller's lead comes from its model or its plan, and test it on a plant whose acid law has changed.

Prerequisites Sections 1.4.6, 1.4.7, 1.6.2 and 1.6.3, with Section 1.4.3 for the column. Chapter 8 for a late analyzer in this volume.

The app https://apmonitor.com/apps/alkylation-unit/

See also Volume 5, Chapter 10 for a soft sensor corrected by a delayed laboratory and Volume 5, Chapter 3 for a loop on a slow analyzer. Volume 9, Chapter 4 for an offset-free predictive controller with a bias in its estimator and Volume 9, Chapter 8 for a supervisor whose optimum sits on a moving constraint.

10.1 Introduction

Nine moles of isobutane pass the contactor of an alkylation unit for every mole of olefin that reacts there. In the generic unit simulated here, 530 kmol/h of butenes meet that excess at 7 °C over 80 t of acid at 92 wt% and become 60.0 t/h of alkylate with a research octane number (RON) of 95.00, while 251 kg/h of the olefin turns into acid-soluble oil (ASO) that dilutes the acid. A fresh acid flow of 3831 kg/h, 63.8 kg per tonne of alkylate, keeps the strength, and a compressor that boils 2321 kmol/h of light ends off the contactor, at 85 % of its capacity, keeps the cold. Each of the three stocks moves at its own speed. A cut of 0.05 bar in the compressor's suction pressure takes the contactor 63 % of the way to its new temperature in 2.1 min, 15 % more olefin drifts the recycle's isobutane purity 63 % of the way in 7 h 00 min, and 20 % less fresh acid needs 36.3 h to move the strength as far.

Alkylate is valued because it carries octane without aromatics or olefins, and Chapter 15 blends it with reformate and cracked gasoline toward a tank-average octane. Sulfuric acid is one of the two acids on which the commercial process is run [1–3]. The acid is also its largest running cost. A process patent puts sulfuric acid consumption at approximately 30 % of the overall process costs and calls an improvement of half an octane number significant [4], and feedstock consumption, acid usage and alkylate quality have been compared across the processes in use [5]. Every operating decision therefore trades octane against acid, and the acid is consumed by the same side reaction that lowers the octane.

+ DID YOU KNOW? Seven Percent of the Crude Capacity

On January 1, 2003 the refineries of the United States could alkylate 1,170,019 barrels per calendar day, 7.0 % of their crude distillation capacity [6]. The process shrinks what it is fed. Two light feedstocks become a denser product, and the volume falls by about 30 % at the same weight [7]. The unit of this chapter makes 60.0 t/h of alkylate.

Two beliefs are corrected by this simulator. The first is that a ratio loop reading on setpoint holds the ratio. In case 2 the loop counts the recycle as 89.3 % isobutane and reads an isobutane-to-olefin

ratio (I/O) of 9.0 throughout, while the true ratio is 8.88 at 4 h and 8.75 at 12 h, because the recycle's composition belongs to a distillation column and its n-butane can leave only through a side draw. The second is that the acid strength is a fast variable to be held by a fast loop. It is an inventory renewed at 4.79 % an hour, it is measured four-hourly, and below about 89 wt% it accelerates its own decline. With the fresh acid withheld from 90 wt%, the strength falls 0.35 wt% in the first hour and 0.52 in the last, and reaches the declared floor of 87 wt% after 7 h 30 min.

The class of problem is general. A quality that depends on a recycle through a separation column inherits the column's inventories, the setting in which snowball effects in reactor and separator processes with recycle were analyzed [8]. A quality measured too rarely to close a loop on is inferred from secondary measurements, which inferential control [9] and the soft sensors of the process industry [10] have addressed for decades. Section 1.4.6 sets out the analyzer delay, the soft sensor and the laboratory bias update that this unit combines. Setpoints chosen by a steady-state economic optimization above the loops are the real-time optimization of current practice [11]. A catalytic reactor whose catalyst is a slowly renewed inventory, assayed in a laboratory, with a recycle through a column and refrigeration that runs out on a hot day, has all three at once. Between the loops and the optimizer, industry places model predictive control [12], and minimum-time constrained control of the acid strength has been published for a sulfuric acid alkylation unit [13].

> ⧖ HISTORY **1997: A Controller Takes Over the Fresh Acid**
>
> In 1996 a refinery in France decided to install a controller to limit the acid consumption of its alkylation unit [13]. Extra acid lowers the risk and raises the cost, so the operators tried to hold the unit just above a minimum strength, below which undesired reactions cause serious malfunctions. The unit was too slow to steer by hand, since a change of the fresh acid flow was fully felt only after about a week. The controller estimated the strength in the second settler from an analysis made downstream and late, and it solved a minimum-time problem as successive linear programs every 15 min. It entered full service in January 1997, ran more than 98 % of the time and saved about 5 % of the cost of the acid. It surprised the operators at first by moving the fresh acid before the measured strength had changed.

However, the alkylation literature treats the chemistry, the kinetics and the process apart [14–16], and the control literature treats ratio loops, soft sensors and optimizers as separate structures [9–11]. This chapter puts numbers on how ratio, temperature and strength loops, a laboratory-corrected soft sensor, a moisture feedforward and an economic supervisor hold the octane and the acid bill through a day of olefin, water and heat upsets, using a browser simulator of a sulfuric acid alkylation unit that logs the true ratio, strength and octane beside every instrument. The selectivity law, the activity law and the octane correlation are declared teaching relations of published direction, and the controllers are standard ones. One finding is that neither the soft sensor nor the moisture feedforward can be made necessary by a target on a single day, because the soft sensor's blindness to water trims back the feedforward's acid. A model predictive controller added as a fifth structure gives a second finding, that its lead on a four-hourly titration belongs to its acid balance reading the feed more than to its plan, and that the lead is lost once the plant's acid law departs from that balance.

Section 10.2 traces the process and the evidence behind its octane and acid laws. Section 10.3 builds the unit, a 108-state model whose hydrocarbon and acid balances close to 7.4×10^{-8} over a day, with a 24-tray deisobutanizer on the column module the apps share and a boundary that keeps every controller to the instruments. Section 10.4 measures its three clocks, its floor and its trip. Section 10.5 adds the loops, the soft sensor, the supervisor and the predictive controller. Section 10.6 runs the nine cases and the graded day, each of which credits an action only when the unit responds to it. Section 10.7 sets the hardware of a real unit beside the model, Section 10.8 states the limitations, Section 10.9 concludes, and the exercises of Section 10.10 work through the cases.

10.2 Isoparaffin Alkylation, Acid Strength and Octane

The process dates from 1939, and its acid strength was an economic question from the start, as the History box below tells. A thesis of 1969 reproduces Putney's pilot-plant curves of F-2 (motor) clear octane against acid strength, which reach a maximum between 95 and 96 wt% titratable acidity [17]. Read from those four curves, the octane falls by 0.33 to 0.39 numbers per point of strength between 94 and 90 wt%. Its review also records that one gallon of butadiene depletes 58 lb of fresh acid from 98 to 90 wt%, that water in the feed reduces the acidity, and that a reactor temperature between 40 and 50 °F was then recommended, because warmer raised the acid consumption and colder thickened the acid [17].

> ⧖ HISTORY **1939 to 1969: A Wartime Fuel and the Cost of Its Acid**
>
> The addition of olefins to isoparaffins to make high-octane isoparaffinic fuels was described in 1939 [18]. A federal manual of refining dates the process to the early 1940s, when it produced more high-octane aviation gasoline [19]. By 1949 the alkylation of isobutane with propylene over sulfuric acid was reported as a commercial production [20]. Acid strength was an economic question from the start. A study of lower acidity sulfuric acid alkylation appeared in 1951 [21]. A thesis of 1969 reports from it that the alkylate yield could be held at lower acidity by raising the reactor temperature, and concludes that some optimum strength based on minimum cost must exist [17].

Kinetics followed. A 17-reaction mechanism for isobutane and propylene, measured in a continuous stirred tank over 95 wt% acid, held from 81 to 135 °F and departed from it at 65 °F, with a change of selectivity reported when the acid was lowered to 90 wt% [15]. The chemistry, catalysts and processes were reviewed in 1993 [1], the physicochemical sequence of events in the sulfuric acid process in 2003 [14], and a kinetic model of olefin and isobutane alkylation over sulfuric acid was published in 2022 [16]. A process patent of 1992 moved the contactor colder, to −6 to 0 °C over 92 to 95 wt% acid. Its examples report about half an octane number more at 28 °F than at 49 °F, acid consumption of 0.197 against 0.323 lb per gallon of alkylate, and maximum octane at 93 to 94 wt% with 0.5 to 1 wt% water [4].

The textbooks describe the unit this simulator is drawn from: a refrigerated contactor, an acid settler, a compressor on the flashed light ends and a deisobutanizer that returns the isobutane [3]. No commercial unit's control configuration was found in the literature consulted here, so the loops below follow the structure the process implies and are not offered as any plant's practice.

10.3 The Unit as Modeled

The unit is generic, sized without any licensor's data, as shown in Figure 10.1. A cracked C_4 cut of 963.6 kmol/h (55 % butenes, 30 % isobutane, 15 % n-butane) and the isobutane recycle enter a stirred contactor over acid. The cut comes from a catalytic cracker such as that of Chapter 6. The hydrocarbon boils at the pressure a compressor leaves it, the vapor is condensed against cooling water and returns at once. The settler sends the net hydrocarbon to a deisobutanizer (DIB), whose receiver supplies both the reflux and the recycle, whose vapor side draw takes the n-butane and whose bottoms is the alkylate. Fresh acid at 98.5 wt% enters the contactor and spent acid leaves over the settler's weir. The engine's clock is the minute, hydrocarbon flows are in kmol/h, acid flows in kg/h and heat in megawatts.

The variables are classified in Table 10.1. The integrated state holds the contactor's isobutane and n-butane fractions, its temperature, the compressor's vapor flow, the acid's three masses, the product octane, 78 column states (a holdup and two fractions on each of the receiver, 24 trays and the sump) and eight flow-loop lags, 94 physical states, and 14 ledgers that integrate what enters, leaves and reacts so that each balance can be checked.

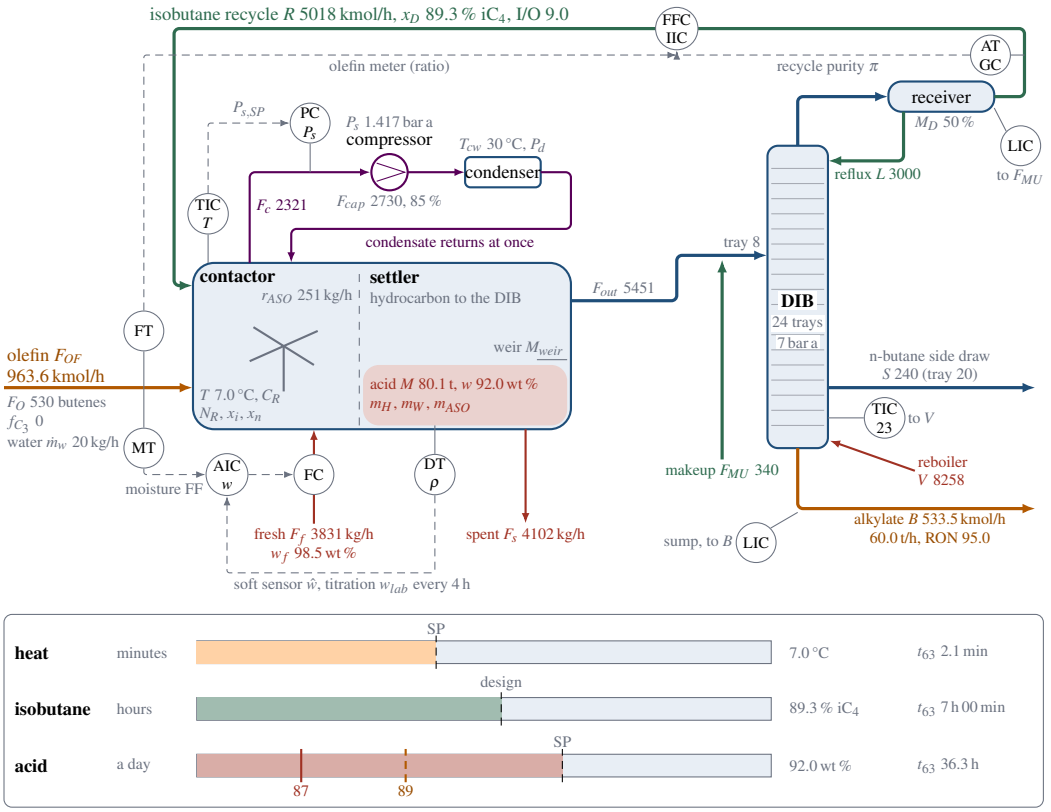


Figure 10.1 The sulfuric acid alkylation unit as modeled, case 1 at $t = 0$, after the app's Unit view, at the design values. The olefin feed F_{OF} (olefin F_O, propylene share f_{C_3}, water $\dot{m}_w$) and the recycle R of purity x_D meet in the contactor (N_R, C_R, T, x_i, x_n), the compressor holds the suction pressure P_s that the TIC asks for up to its capacity F_{cap}, which falls as the condenser's water T_{cw} warms, and the settler's acid (M, m_H, m_W, m_{ASO}, strength w) is renewed by F_f at w_f and leaves over the weir as F_s. The net hydrocarbon F_{out} and the makeup F_{MU} feed tray 8 of the DIB, the side draw S leaves from tray 20, the receiver M_D supplies the reflux L and R, and the reboiler's boilup V is set on tray 23. The IIC sets R in ratio to the olefin meter with the recycle chromatograph, the AIC sets F_f on the density soft sensor or the titration with the moisture feedforward, and two LICs hold the receiver and the sump. The strip below shows the three inventories, each against its setpoint or design mark, with their 63 % times. The drawing shows the model, not the piping or a safety layout, and is not to scale.

10.3.1 How the Olefin Splits

The olefin reacts within seconds and is not stored. It splits between alkylation, isobutane plus olefin to alkylate, and conjunct polymerization to ASO, in the ratio of two declared rates, as shown in Equation (10.1).

$$\rho = \frac{r_{ASO}}{r_{alk}} = \kappa_0 \, \mathrm{e}^{\theta(T-7)} \left(\frac{9}{I}\right)^n \frac{1 + c_3 f_{C_3}}{a(w)}$$

$$r_{alk} = \frac{F_O}{1+\rho}, \qquad r_{ASO} = F_O - r_{alk} \tag{10.1}$$

$$I = \frac{R\,x_{D,i} + z_I F_{OF}}{F_O}$$

Table 10.1 Variables, Their Roles and Design Values (Case 1 at $t = 0$)

Variable	Role	Design	Range
I	CV, isobutane to olefin	9.00	SP 6–14
R	MV, recycle	5017.5 kmol/h	0–9000
T	CV, contactor	7.00 °C	SP 2–14
$P_{s,SP}$	MV, suction pressure	1.417 bar a	0.6–2.5
w	CV, acid strength	92.00 wt%	SP 88–96
F_f	MV, fresh acid	3831 kg/h	0–12 000
M_D, M_B	CV, receiver, sump	50 %, 50 %	SP 20–80
F_{MU}, B	MV, makeup, bottoms	339.9, 533.5 kmol/h	0–1200, 0–1500
T_{23}	CV, DIB tray 23	87.26 °C	SP 70–110
V	MV, boilup	8257.5 kmol/h	0–10 500
F_{OF}	DV, olefin feed	100 %	40–130
$\dot{m}_w$	DV, feed water	20 kg/h	0–1000
T_{cw}	DV, cooling water	30 °C	20–42
f_{C_3}	DV, propylene in olefin	0 %	0–60
—	DV, makeup supply	100 %	0–100
x_D	state, recycle iC_4	89.31 %	—
F_c, F_{cap}	state, output: compressor	2321, 2730 kmol/h	—
M	output, acid held	80.05 t	—
RON	state, product	95.00	—

where $F_O = z_O F_{OF}$ is the olefin, $z_O = 0.55$ and $z_I = 0.30$ are the feed's olefin and isobutane shares, $x_{D,i}$ is the recycle's isobutane fraction, $\kappa_0 = 0.0085$, $\theta = 0.06\,\mathrm{K}^{-1}$, $n = 1.5$, $c_3 = 1.5$ and I is floored at 0.5 inside the law. Alkylation runs in proportion to the acid's activity, which is the declared law of Equation (10.2).

$$a(w) = \frac{\mathrm{e}^{-\beta(92-w)}}{1 + A\,\mathrm{e}^{(w_r - w)/s}} \tag{10.2}$$

with w in wt%, $\beta = 0.06$ per point, $A = 0.5$, $w_r = 87$ and $s = 0.6$. Near design the ASO rises 6.25 % per point of strength lost, and $1/a$ is 1.063, 1.131, 1.219, 1.391 and 2.025 at 91, 90, 89, 88 and 87 wt%. At design $a = 0.99988$, $\rho = 0.008501$, 525.53 kmol/h is alkylated and 4.468 kmol/h of olefin becomes 250.7 kg/h of ASO. The alkylate leaves at $r_{alk}(M_i + M_O)$, 60.032 t/h, with $M_i = 58.12$ and M_O the olefin's molar mass, 56.11 kg/kmol for butenes and 42.08 for propylene. The collapse replaces a linear activity law, which made the design point unstable at a fixed fresh acid.

10.3.2 Contactor, Settler and Autorefrigeration

The contactor and settler are one stirred hydrocarbon holdup N_R at fixed moles, so the olefin consumed leaves the outflow, as shown in Equation (10.3).

$$\begin{aligned} N_R \frac{\mathrm{d}x_i}{\mathrm{d}t} &= R\,x_{D,i} + z_I F_{OF} - r_{alk} - F_{out}\,x_i \\ N_R \frac{\mathrm{d}x_n}{\mathrm{d}t} &= R\,x_{D,n} + z_N F_{OF} - F_{out}\,x_n \\ F_{out} &= R + F_{OF} - F_O \end{aligned} \tag{10.3}$$

where $z_N = 0.15$, the alkylate fraction is $1 - x_i - x_n$, flows are divided by 60 in the balances because the clock is the minute, and $N_R = 1500\,\mathrm{kmol}$. The temperature follows an energy balance in which

the vapor the compressor takes carries the heat away, as shown in Equation (10.4).

$$\begin{aligned} C_R \frac{\mathrm{d}T}{\mathrm{d}t} &= Q_{rx} + Q_{mix} + (R + F_{OF}) c_p (T_f - T) \\ &\quad - \lambda F_c \\ Q_{rx} &= r_{alk}(-\Delta H_a) + r_{ASO}(-\Delta H_s) \\ P_s &= P_{bub}(T, x) - F_c / k_v \\ \tau_c \frac{\mathrm{d}F_c}{\mathrm{d}t} &= \min\!\left(k_v (P_{bub} - P_{s,SP}),\ F_{cap}\right) - F_c \end{aligned} \tag{10.4}$$

where the contactor's heat capacity is $C_R = 300\,\mathrm{MJ/K}$, the heats of alkylation and polymerization are $-\Delta H_a = 80$ and $-\Delta H_s = 90\,\mathrm{MJ/kmol}$, the mixers add $Q_{mix} = 1.5\,\mathrm{MW}$, the hydrocarbon's molar heat capacity is $c_p = 0.13\,\mathrm{MJ/(kmol\,K)}$ and the feed enters at $T_f = 10\,^{\circ}\mathrm{C}$. The coefficient $k_v = 28\,000\,\mathrm{kmol/(h\,bar)}$ is the vapor leaving the boiling liquid per bar over the suction pressure, and the compressor's speed governor, equipment rather than a loop, follows with $\tau_c = 0.5\,\mathrm{min}$. The latent heat is $\lambda = R_g B = 21.618\,\mathrm{MJ/kmol}$ for every component. At design $Q_{rx} = 11.790\,\mathrm{MW}$, the mixers and the feed add 1.5 and 0.648 MW, and the compressor carries 2321.1 kmol/h. The bubble pressure uses the deisobutanizer's own constant-volatility law, as shown in Equation (10.5).

$$P_{bub} = \sum_j x_j P_0 \,\mathrm{e}^{B(1/T_{b,j} - 1/T)}, \qquad \frac{1}{T_{b,j}} = \frac{1}{T_{b,n}} + \frac{\ln \alpha_j}{B} \tag{10.5}$$

with $P_0 = 1.013\,25\,\mathrm{bar}$, $B = 2600\,\mathrm{K}$, $T_{b,n} = 272.65\,\mathrm{K}$ and $\alpha = (1.3, 1, 0.1)$ for isobutane, n-butane and alkylate, so isobutane boils at −7.80 °C and the alkylate at 86.3 °C. At 7 °C the contactor's liquid has a bubble pressure of 1.5000 bar, the suction is 1.4171 bar a, and the contactor runs 5.39 K above isobutane's own saturation temperature at that pressure because its liquid also holds n-butane and alkylate.

10.3.3 The Compressor and Its Condenser

A fixed-volume machine moves fewer moles at a lower suction pressure, and fewer again as a warmer condenser raises its pressure ratio, as shown in Equation (10.6).

$$\begin{aligned} F_{cap} &= F_{c,0} \frac{P_s}{P_{s,0}} \left(1 - \kappa_c (r - r_0)\right) \\ r &= \frac{P_{sat,i}(T_{cw} + \Delta T_{cd})}{P_s} \\ W &= \frac{F_c}{3600} \frac{\gamma}{\gamma - 1} \frac{R_g T}{\eta_c} \left(r^{(\gamma-1)/\gamma} - 1\right) \end{aligned} \tag{10.6}$$

where $F_{c,0} = 2730\,\mathrm{kmol/h}$ at the design suction $P_{s,0}$ and ratio $r_0 = 3.276$, $\kappa_c = 0.15$, the condenser approach $\Delta T_{cd} = 11\,\mathrm{K}$ puts its pressure at 4.643 bar with 30 °C water, $\gamma = 1.1$, $\eta_c = 0.75$, and $W = 2.509\,\mathrm{MW}$ at design. With 38 °C water the same suction pressure leaves a capacity of 2424 kmol/h. The capacity is proportional to the suction pressure because, without that term, power alone never bound and the supervisor ran the contactor to its coldest box at every price.

> **TRY IT IN THE APP 3 · Temperature by suction pressure, and a hot afternoon**
>
> Load the case and press Run. Before 2 h lower the Contactor temperature setpoint from 7 to 6.0 °C. The suction pressure falls from 1.409 to 1.362 bar a and the temperature follows within 11 min. From 2 h the cooling water warms. The compressor reaches its capacity at 2 h 17 min, and the contactor peaks at 7.10 °C at 5 h 26 min.

10.3.4 The Acid as an Inventory

The acid is three masses, sulfuric acid m_H, water m_W and ASO m_{ASO}, renewed by fresh acid and spilled over a weir, as shown in Equation (10.7).

$$\begin{aligned}
\frac{\mathrm{d}m_H}{\mathrm{d}t} &= w_f F_f - \frac{m_H}{M} F_s \\
\frac{\mathrm{d}m_{ASO}}{\mathrm{d}t} &= M_O r_{ASO} - \frac{m_{ASO}}{M} F_s \\
\frac{\mathrm{d}m_W}{\mathrm{d}t} &= (1 - w_f) F_f + \dot{m}_w - \frac{m_W}{M} F_s \\
F_s &= \max\left(0,\ \frac{M - M_{weir}}{\tau_w}\right), \qquad w = 100\,\frac{m_H}{M}
\end{aligned} \tag{10.7}$$

where $M = m_H + m_W + m_{ASO}$, $w_f = 0.985$, $M_{weir} = 78\,\mathrm{t}$ and $\tau_w = 30\,\mathrm{min}$. Both diluents lower the strength. At steady state the fresh acid must balance the dilution $D = M_O r_{ASO} + \dot{m}_w$, as shown in Equation (10.8).

$$F_f^* = \frac{w D}{w_f - w}, \qquad F_s^* = F_f^* + D \tag{10.8}$$

with w as a fraction. At design $D = 270.7\,\mathrm{kg/h}$, $F_f^* = 3831.1\,\mathrm{kg/h}$ and $F_s^* = 4101.8\,\mathrm{kg/h}$, the acid held is 80 051 kg, sulfuric acid enters and leaves at 3773.6 kg/h, and each kilogram of water costs 14.15 kg of fresh acid at 92 wt%. The fresh acid renews 4.79 % of the inventory an hour. At the design point an extra 100 kg/h of water lowers the strength 0.115 wt% an hour, a contactor 2 K warmer 0.036 and an I/O cut from 9 to 7.65 0.079, so every diluent pulls the same way.

10.3.5 Octane, the Deisobutanizer and the Instruments

The octane of the alkylate formed is a declared teaching correlation, mixed through the alkylate holdup, as shown in Equation (10.9).

$$\begin{aligned}
\mathrm{RON} &= R_0 + 3a \tanh\frac{I - 9}{3} - b(T - 7) \\
&\quad + 3c \tanh\frac{w - 92}{3} - 100\,d\,f_{C_3} \\
\tau_R \frac{\mathrm{dRON}_p}{\mathrm{d}t} &= \mathrm{RON} - \mathrm{RON}_p
\end{aligned} \tag{10.9}$$

with $R_0 = 95.0$, $a = 0.45$, $b = 0.12\,\mathrm{K^{-1}}$, $c = 0.35$, $d = 0.06$ per percent of propylene and $\tau_R = 30\,\mathrm{min}$, stated for I/O 6 to 14, 2 to 16 °C, 86 to 96 wt% and up to 60 % propylene. The directions follow the literature. The strength term, 0.35 per point near 92 wt%, lies on the 0.33 to 0.39 read from Putney's curves between 94 and 90 wt% [17], although those curves peak near 95 to 96 wt% where the tanh only saturates. The temperature term is 0.12 per kelvin against the patent's half octane number over the 11.7 K from 49 to 28 °F, 0.043 $\mathrm{K^{-1}}$ [4], about three times as steep, and the sources read give the I/O term only its sign. The coefficients were raised from 0.30, 0.10 and 0.25 because a smaller octane response let the shipped challenge pass.

The deisobutanizer is the column module the apps share, a total condenser and receiver, 24 equilibrium trays and a partial reboiler and sump at 7 bar a, with constant relative volatility, constant molar overflow, 30 kmol on each tray and a linearized weir of time constant 0.1 min. Vapor and liquid flows follow $V_i = V_{i+1} - W_i^V$ and $L_i = \bar{L}_i + (M_i - \bar{M}_i)/\tau_L$, the vapor is $y_{ij} = \alpha_j x_{ij} / \sum_k \alpha_k x_{ik}$, and each stage's temperature is its closed-form bubble point $T = B / \ln\left((P_0/P)\sum_j x_j \mathrm{e}^{B/T_{b,j}}\right)$. The net hydrocarbon and the makeup, 95 % isobutane, feed tray 8, the n-butane leaves as a 240 kmol/h vapor side draw from tray 20, the reflux is 3000 kmol/h, and the receiver holds 2000 kmol at full. At design the recycle is 5017.5 kmol/h at 89.305 % isobutane, the makeup 339.9 kmol/h, the boilup

8257.5 kmol/h (89.3 t/h of steam at 2000 MJ/t) and the bottoms 533.5 kmol/h with 1.79 % butanes. Isobutane closes over the unit as 289.09 fed plus 322.90 of makeup isobutane against 525.53 alkylated, 85.46 in the side draw and 1.00 in the bottoms. A pump draws a reduced share once its vessel holds less than 2 % of its capacity, and every flow station follows its setpoint with a lag of 0.2 min, the boilup 0.4 min.

The instruments are flow meters with noise of 0.5 to 12 kmol/h or 8 kg/h, a contactor thermometer with a 0.2 min lag, the suction pressure, the compressor's flow and its governor's limit signal, a feed moisture analyzer with a 3 min lag, a vibrating-tube acid density meter with a 1 min lag, the two DIB levels and the tray 23 temperature (0.3 min). A recycle chromatograph samples every 10 min and reports 5 min later with $\sigma = 0.001$, and the laboratory titrates a sample every 4 h and reports it 30 min later with $\sigma = 0.1$ wt%, both on the framework's analyzer module, whose delay and sampling combine as in Equation (1.12). The density, the soft sensor's input, is a teaching law, as shown in Equation (10.10).

$$\rho = \left(\frac{1 - x_{ASO}}{1814 + 4(w_{HW} - 90)} + \frac{x_{ASO}}{900} \right)^{-1} \tag{10.10}$$

with ρ in kg/m^3, x_{ASO} the ASO mass fraction and w_{HW} the strength on an ASO-free basis. At design $\rho = 1734.54\,\mathrm{kg/m^3}$ with 1.889 wt% water and 6.111 wt% ASO. Per kilogram ASO lowers the density 6.6 times as much as water does.

10.3.6 Lining Out, Integration and Balances

Table 10.2 gives each parameter and whether a learner may change it. Every case lines out at its own setpoints before $t = 0$. A pass runs from a recycle composition through the contactor to the column's Newton steady state and back to the receiver, and Newton's method on the receiver's two fractions closes the loop, because the plain fixed point contracts only by 0.87 a pass while the side draw purges the n-butane. An independent solver of the contactor and the 24-tray column reproduces the recycle, makeup, compressor flow, suction and fresh acid to four decimals. The largest relative derivative at the design point is 2.9×10^{-15}. A fixed 2 s step of fourth-order Runge–Kutta integrates the state, the controllers execute each 6 s, and the historian keeps one row per 30 s, on the engine of Section 1.6.1. Over the challenge's day the isobutane, n-butane, alkylate and olefin ledgers (kmol) and the sulfuric acid, water and ASO ledgers (kg) close to 7.4×10^{-8}, and halving the step moves the strength, temperature, I/O and octane after 8 h by 1.2×10^{-8}.

10.3.7 Assumptions

The olefin reacts completely within seconds, and only its split between two products is modeled, by a declared ratio of rates. A real contactor runs an emulsion whose interfacial area, set by the mixers and the acid-to-hydrocarbon ratio, governs both rates, and its byproducts other than ASO, light ends, heavy alkylate and esters, are left out. The contactor and settler are one hydrocarbon holdup and one acid holdup, where real units run several contactors with their own temperatures and strengths. The refrigerant returns condensed at once, with no economizer, receiver or depropanizer, and the vapor pressures follow the column's constant-volatility law, so isobutane boils at −7.80 °C at one atmosphere instead of −11.7 °C. The column is 24 theoretical trays at a fixed pressure, its condenser and reboiler duties are not modeled beyond the boilup and its steam limit, and its tray count is a design choice that sets how far the recycle drifts. The strength is the sulfuric acid mass fraction, where a titration counts total acidity. The selectivity, activity, octane and density laws, the floor at 87 wt%, the STRENGTH LOW alarm at 89 wt% and the low-I/O trip at an I/O of 5 for 2 min are teaching values. A real minimum strength comes from the licensor's operating guidelines and the refiner's procedures, and a low-isobutane interlock and its settings from the unit's safety review.

Table 10.2 Parameters. A: Adjustable in the Model Dialog. H: Hidden and Fixed

Symbol	Meaning	Value	
$F_{O,0}$	design olefin	530 kmol/h	A
z_O, z_I	olefin, isobutane shares	0.55, 0.30	H
μ_I, $F_{MU,max}$	makeup purity, capacity	0.95, 700 kmol/h	H, A
N_R, C_R	contactor holdup, heat capacity	1500 kmol, 300 MJ/K	A
$-\Delta H_a$, $-\Delta H_s$	alkylation, polymerization heat	80, 90 MJ/kmol	A, H
Q_{mix}, T_f, c_p	mixers, feed, heat capacity	1.5 MW, 10 °C, 0.13	H
k_v	boiling coefficient	28 000 kmol/(h bar)	A
κ_0, θ, n, c_3	selectivity law	0.0085, 0.06, 1.5, 1.5	A
β, A, w_r, s	activity law	0.06, 0.5, 87, 0.6	A
R_0, a, b, c, d	octane law	95.0, 0.45, 0.12, 0.35, 0.06	A
τ_R	alkylate holdup	30 min	H
τ_c, $F_{c,0}$, κ_c	governor, capacity, loss	0.5 min, 2730, 0.15	A
ΔT_{cd}, η_c	condenser approach, efficiency	11 K, 0.75	H
M_{weir}, τ_w	acid to the weir, weir lag	78 t, 30 min	A, H
w_f	fresh acid	98.5 wt%	A
w_{floor}, w_{low}	runaway floor, STRENGTH LOW	87, 89 wt%	A
$\dot{m}_{w,0}$	design feed water	20 kg/h	H
P_{DIB}, α_I, α_A	pressure, volatilities	7 bar, 1.3, 0.1	H, A, H
B, $T_{b,n}$	latent heat over R_g, n-C_4	2600 K, 272.65 K	H
M_t, τ_L	tray holdup, hydraulic lag	30 kmol, 0.1 min	A, H
$M_{D,cap}$, $M_{B,cap}$	receiver, sump capacity	2000, 400 kmol	A, H
V_{max}	reboiler (steam) limit	10 500 kmol/h	A
$\bar{L}$, $\bar{S}$, B_l	design reflux, side draw, butanes	3000, 240, 8 kmol/h	H
τ_Q	flow loop lag	0.2 min	H

10.4 Three Clocks, a Floor and a Trip

10.4.1 Minutes, Hours and More Than a Day

The three clocks were measured in the app, loops and instruments included, as shown in Figure 10.2. With the temperature loop in Manual, a cut of 0.05 bar in the suction pressure takes the contactor from 6.984 to 5.994 °C, 63 % of the way in 2.07 min. A linearization of Equation (10.4) with $\mathrm{d}P_{bub}/\mathrm{d}T = 0.0497\,\mathrm{bar/K}$ gives 0.86 min, and the measured response is slower because the step asks the compressor for more than its capacity during the first minute. In case 2, with the ratio held on the meters and the design purity, 15 % more olefin drifts the recycle's purity from 89.305 to 86.094 % a day later, 63 % of the way in 7 h 00 min. The extra n-butane leaves the loop only through the fixed side draw, and the column, receiver and sump hold about 1900 kmol beside the contactor's 1500 kmol, which turn over in about 35 min at 5800 kmol/h. The purity is the column's to set, not the loop's.

> **TRY IT IN THE APP** **2 · A ratio on flows and the recycle's purity**
>
> Load the case and press Run. Touch nothing. At 30 min the olefin rises 15 %. Watch the I/O trend. The loop's value stays at 9.0 while the analyzer's value, the dashed line, sinks below 8.9 at 2 h 56 min. Set Recycle purity from to Analyzer. The loop raises the recycle from 5770 to 5842 kmol/h and the analyzer's I/O returns to within 0.1 of 9.

On Fixed flows, 20 % less fresh acid takes the strength from 92.000 to 89.608 wt% over four days, 63 % of the way in 36.3 h. A linearization of Equation (10.7) at fixed fresh acid gives 29.4 h, with the ASO rising 14.96 kg/h per point lost. The measured response is slower because the activity's slope steepens as the strength falls, so each point lost adds more ASO and weakens the restoring rate. A loop on the acid therefore acts on a plant whose time constant is longer than a day, through a measurement that arrives every four hours.

Pause. Try Exercise 10.3 before reading on.

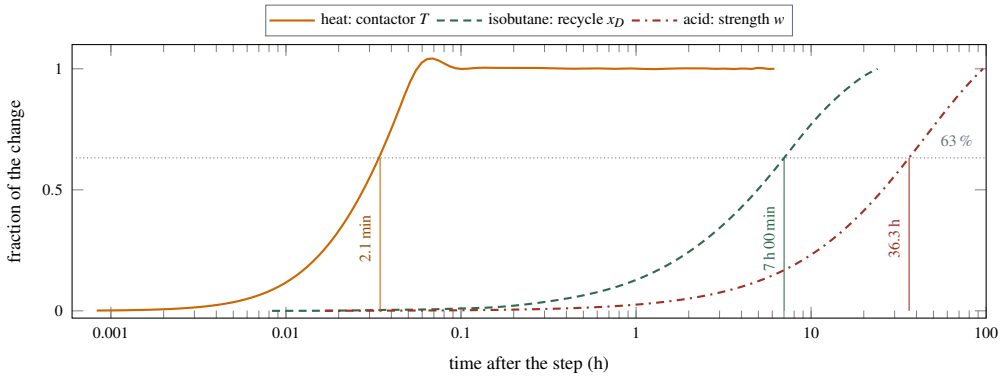


Figure 10.2 The three clocks, from the app's engine, each response divided by its own change. Heat: the contactor after a 0.05 bar suction cut with the temperature loop in Manual (it overshoots by 4 %). Isobutane: case 2 as shipped, the recycle's purity after 15 % more olefin, against its value a day later. Acid: Fixed flows, the strength after 20 % less fresh acid, over 96 h.

10.4.2 An Activity That Collapses

The floor is chemical. Below about 89 wt% the activity of Equation (10.2) collapses, each mole of olefin makes more ASO, and the ASO dilutes the acid further. In case 5 the unit lines out at 90 wt% on 3211 kg/h of fresh acid, and the acid is withheld from 5 min. The strength passes 89 wt% at 2 h 53 min and 88 wt% at 5 h 28 min, falling 0.35 points in the first hour and 0.52 in the last, the ASO grows from 283 to 504 kg/h, and the ACID RUNAWAY stop comes at 7 h 35 min. The stop latches on the first step below 87 wt% and never above it. Restoring the design point's 3831 kg/h at 87.6 wt% turns the strength back without a stop, while the case's own 3211 kg/h recovers from 88.0 wt% but not from 87.6.

With the strength loop in Auto the floor is out of reach of any single disturbance slider for a day. Feed water at its 1000 kg/h maximum takes the strength to 88.52 wt% at 5 h 14 min with no stop. The floor comes only when the fresh acid falls short of what dilutes the acid. On Fixed flows, with the design acid held, 130 % olefin kept from 30 min runs the acid away at 14 h 03 min, feed water raised from 20 to 420 kg/h at 13 h 37 min, and a recycle held at 3000 kmol/h, an I/O of 5.6, at 18 h 14 min. On Loops with feedforward the acid runs away at 5 h 48 min only with the olefin, water, propylene and cooling water sliders all at their limits and the contactor at 14 °C, the fresh acid pinned at its 12 t/h maximum. A contactor at 14 °C, cooling water at 42 °C and 60 % propylene never reach the floor even with the acid held, ending the day at 89.34, 91.89 and 88.80 wt%.

10.4.3 A Trip on the Isobutane

A unit short of isobutane polymerizes its olefin. The low-I/O interlock stops the run once the true I/O has been below 5 for 2 min, a teaching value. It was added because a lost makeup otherwise ran the I/O down into a second, isobutane-driven path to the acid floor, which the app's design review asked to exclude. In case 7 the makeup supply is lost at 30 min, the receiver loop asks for 689 kmol/h by 2 h, the receiver falls below 30 % at 1 h 42 min and below 10 % at 2 h 51 min, the recycle pump loses suction, and the trip comes at 4 h 00 min with the I/O at 4.22. Cutting the olefin to 60 % at 1 h 42 min delays it to 4 h 23 min, and to 40 % only to 4 h 39 min. The feed's isobutane, 30 % of the stream, is less than its olefin, 55 %, consumes, and the side draw keeps taking isobutane, so no olefin rate or I/O setpoint in the app's sweep holds the ratio, every run tripping between 4.00 and 4.93 h.

Table 10.3 Loops, Pairings and Default Tunings

Loop	PV → MV	K_c	τ_I	Output
IIC	$I \to R$ (over FF)	300 per unit	30 min	0–9000 kmol/h
TIC	$T \to P_{s,SP}$	0.03 bar/K	3 min	0.6–2.5 bar a
AIC	$w \to F_f$ (over FF)	3000 per point	120 min	0–12 000 kg/h
LIC	$M_D \to F_{MU}$	8 kmol/h per %	60 min	0–1200 kmol/h
TIC	$T_{23} \to V$ (over L+R+S)	100 kmol/h K	20 min	0–10 500 kmol/h
LIC	$M_B \to B$, reverse	20 kmol/h per %	—	0–1500 kmol/h

10.5 Loops, a Soft Sensor and a Supervisor

Six loops act on the unit, with the header's Manual and Auto belonging to the I/O loop alone. The temperature, strength and three column loops carry their own Auto and Manual switches, because case 1 needs the strength loop live while the recycle is in the learner's hands. A control structure option sets how the quality loops act: Fixed flows holds the recycle and the fresh acid at their stations with only the temperature loop acting, Loops puts a PI controller on each measurement, Loops + FF adds ratio feedforwards from the olefin meter, Supervisor takes the I/O, temperature and strength setpoints from the economic optimization, and MPC replaces the three quality loops with the predictive controller of Section 10.5.5. Under the loops every manipulated flow is a feedforward plus a PI trim, and in Manual the trim tracks the station minus the feedforward, so every switch is bumpless. A single function builds the measurement packet the controllers read, and an application test checks that it carries measurements only.

10.5.1 The Shared PI Law

The loops share the framework's velocity-form controller of Section 1.6.2, Equations (1.16) to (1.19), with no derivative action in any loop here, a control period $\Delta t = 0.1$ min and the tracking time T_t equal to τ_I. Only the emitted output is limited, and back-calculation drags the integral back toward what the clamp let through. At the largest value its slider allows, τ_I removes integral action. Table 10.3 gives each pairing with its default tuning. The bottoms loop is proportional and reverse acting. The temperature loop's output is the suction pressure setpoint, and when the governor reports that the compressor is at its capacity the loop's lower limit closes onto the measured suction pressure less 0.005 bar, so its integral does not wind down against a pressure that is not coming.

10.5.2 Ratio Feedforwards and the Recycle Analyzer

The I/O the loop sees is computed from the meters and a purity π, and the feedforwards supply the recycle and the fresh acid that a ratio needs, as shown in Equation (10.11).

$$
\begin{aligned}
I_m &= \frac{R_m\,\pi + z_I F_{OF,m}}{z_O F_{OF,m}} \\
R_{ff} &= \frac{(I_{SP} z_O - z_I) F_{OF,m}}{\pi} \\
F_{f,ff} &= \frac{w_{SP}(M_{C_4} r_0 + \dot{m}_{w,0})}{w_f - w_{SP}} + k_w\,\Delta\dot{m}_w \\
r_0 &= \frac{\rho_0}{1+\rho_0}\, z_O F_{OF,m}
\end{aligned}
\tag{10.11}
$$

where π is the chromatograph's last report or the design 89.3 %, ρ_0 is the design ASO ratio, so r_0 is the ASO the metered olefin makes at design, $M_{C_4} = 56.11$ kg/kmol, $k_w = w_{SP}/(w_f - w_{SP})$ is the acid per kilogram of water, $\Delta\dot{m}_w = \dot{m}_{w,m} - \dot{m}_{w,0}$ is the measured water above design, and the last term, the moisture feedforward, acts on the feed analyzer when it is switched on. The ratio feedforward and the strength term follow the olefin meter, and the PI controllers trim them.

10.5.3 The Soft Sensor and the Laboratory

The density soft sensor solves Equation (10.10) for the strength by bisection, assuming the diluent is water and ASO in their design shares, 23.6 % water by mass, and adds a bias, as shown in Equation (10.12).

$$\hat{w} = w(\rho_m;\ \varphi_0) + b, \qquad b \leftarrow b + \lambda\left(w_{lab} - \hat{w}_{raw}(t_s) - b\right) \tag{10.12}$$

where $\lambda = 0.5$, the residual is taken against the raw value at the instant t_s the sample was drawn, and the bias is bounded at 3 wt%. This is the laboratory bias update of Equation (1.14), and Volume 5, Chapter 10 corrects a psychrometric soft sensor from a sampled, delayed laboratory in the same way. Because ASO lowers the density 6.6 times as much as water per kilogram, the soft sensor reads a water dilution at 19 % of its size and an ASO dilution at 125 %. The bias starts where a lined-out unit's titrations would have left it, at the case's own strength setpoint less the raw reading, a choice made after a zero bias left case 5 adding acid to a unit its briefing calls lined out. With the soft sensor Off the strength loop acts once per laboratory report, over the time since the previous one, and holds between reports. The STRENGTH LOW alarm reads the soft sensor either way, because an alarm on the titration would be four hours late.

Pause. Try Exercise 10.2 before reading on.

10.5.4 The Economic Supervisor

Every 30 min the supervisor chooses the I/O, temperature and strength targets on the app's own steady-state correlations, fed with the measured olefin, water, propylene, cooling water and recycle purity, as shown in Equation (10.13).

$$\begin{aligned} &\max_{I,T,w}\ p_R\,\mathrm{RON}\,\dot{m}_{alk} - p_a F_f^{*} - p_e W - p_s \dot{m}_{st} \\ &\text{s.t. } F_c \le 0.97 F_{cap}, \qquad V \le 0.97 V_{max} \\ &\qquad 7 \le I \le 12, \quad 4 \le T \le 12\,^{\circ}\mathrm{C}, \quad 89.5 \le w \le 95\,\mathrm{wt\%} \end{aligned} \tag{10.13}$$

where $p_R = \$4$ per RON and tonne, $p_a = \$150$ per tonne of acid, $p_e = \$70$ per MWh, $p_s = \$20$ per tonne of steam, $V = L + R + S$ and $\dot{m}_{st} = \lambda V / 2000\,\mathrm{MJ/t}$. Colder always pays in this economics, so the temperature is the coldest the compressor holds, an optimum on a limit as Section 1.4.7 explains, found by bisection on its capacity row. The I/O and the strength are found by successive linear programming, with the margin and the reboiler row linearized by central differences, the framework's bounded simplex solving each linear program inside a trust region, and the longest of 1, 1/2, 1/4 or 1/8 of the step that improves the margin taken. A start beyond the reboiler row, where a feed increase leaves the previous target, is brought back inside it by the same row linearized there with an elastic slack priced a thousand times above the margin's own rate, a step being taken when it lowers the excess. The problem is reduced to two variables because a three-variable version stalled on the active compressor row. The targets move at most 1 in I/O, 1 K and 0.5 wt% a period. Against a grid of 0.05 over the boxes the reduced problem is \$0.43, \$1.52 and \$0.66 an hour better at 80, 150 and \$250 per tonne, its temperature sits on the compressor row at 97.00 % of capacity, and 0.2 K warmer costs \$8.5 to \$12.0 an hour. It is a real-time optimization in the sense of [11], a steady-state optimization that runs, not a dynamic one.

10.5.5 Model Predictive Control

The fifth structure gives the three quality handles to one model predictive controller (MPC) of the kind described in Section 1.6.3, and leaves the column loops, the supervisor and every protection acting as they do under Supervisor. Every $\Delta t_M = 2$ min, twenty scans of the loops, it solves a quadratic program over $N_p = 120$ steps, a horizon of 4 h, for the I/O request u_1, the suction pressure setpoint u_2 and the fresh acid u_3, applies the first move and holds it to the next decision. The recycle is not itself

a handle. At every scan the recycle station sets $R = (u_1 z_O - z_I) F_{OF,m}/\pi$, the ratio of Equation (10.11), so an olefin step reaches the recycle within 6 s instead of at the next decision. The setpoints I_{SP}, T_{SP} and w_{SP} it tracks are the targets of Equation (10.13), which the supervisor keeps choosing beneath it every 30 min, and the price of the fresh acid enters only there.

The controller's model has five states, as shown in Equation (10.14).

$$\begin{aligned} \tau_i \frac{\mathrm{d}\hat{z}_i}{\mathrm{d}t} &= K_i v_i - \hat{z}_i, \qquad i = 1,2,3 \\ \hat{T} &= T_{ref} + \hat{z}_1 + \hat{z}_2 + \hat{z}_3 + b_T \\ \widehat{I} &= u_1 + b_I, \qquad \tilde{w} = \hat{w} + b_w \\ \frac{\mathrm{d}\hat{w}}{\mathrm{d}t} &= \frac{(w_f - \tilde{w}) F_f - \tilde{w}\,(\dot{m}_{w,m} + M_O \hat{r}_{ASO})}{60\,\hat{M}} \\ \hat{M} &= M_{weir} + F_{s,m}\tau_w/60 \end{aligned} \tag{10.14}$$

where a hat marks a quantity of the controller's model, $v_1 = u_2$, $v_2 = R$, v_3 is the metered olefin feed in percent of design, T_{ref} places $\hat{T}$ on the measured temperature at the start, $\tilde{w}$ is the strength the MPC controls, the strengths and w_f are in wt%, $\dot{m}_{w,m}$ and $F_{s,m}$ are the moisture analyzer and the spent acid meter, and F_f is the fresh acid meter in the estimate and u_3 in the prediction. The ASO rate $\hat{r}_{ASO}$ is that of Equation (10.1) at the declared parameters, evaluated at the metered olefin, the measured I/O and contactor temperature, $\tilde{w}$ and the propylene share f_{C_3}, which a feed chromatograph reports as an ideal instrument, without lag, noise or sampling.

The three temperature paths are first-order-plus-dead-time fits to steps up and down at the lined-out design point, each dead time added to its lag. The suction pressure gives $K_1 = 19.63\,\mathrm{K/bar}$ with $\tau_1 = 1.1\,\mathrm{min}$, the recycle $K_2 = -0.000\,552\,\mathrm{K}$ per kmol/h with $\tau_2 = 18.2\,\mathrm{min}$, the contactor's composition time N_R/F_{out} of 16.5 min plus its dead time, and the olefin, with the I/O held by the ratio, $K_3 = 0.0155\,\mathrm{K}$ per percent with $\tau_3 = 0.75\,\mathrm{min}$. An independent refit with the noise off gives 19.58 and 19.80 K/bar upward and downward, −0.000528 and −0.000584, and 0.01477 and 0.01499, with residuals of 0.3 to 3.2 % of the step. Through the station one unit of I/O cools the contactor by 0.33 K at design.

The strength row is not identified. It is the plant's own acid balance, Equation (10.7) written for the strength with the weir law inverted for $\hat{M}$, and its declared ASO law, with the declared parameters frozen when the application loads and fed by instruments only, so it is not an independent model. At the shipped parameters, integrated for a day after a step in the fresh acid, the I/O, the olefin, the feed water or the propylene, with the strength loop open, it stays within 0.0056 wt% of the true strength, a difference set by the instruments. With the plant's κ_0 raised 29 % the same steps leave it 0.99 to 1.81 wt% away. At each decision the row is linearized by central differences about $\tilde{w}$ and the applied commands, the temperature entering it through its predicted paths, and the five states are discretized with an exact zero-order hold over Δt_M.

The model runs at every 6 s scan under whichever structure acts, and the MPC therefore takes over from an estimate that is already current. The biases b_T and b_I are the measured less the modeled temperature and I/O, filtered over 0.5 and 1 min. The strength bias takes half of each titration's residual, $b_w \leftarrow b_w + 0.5\big(w_{lab} - \hat{w}(t_s) - b_w\big)$, bounded at 3 wt% and taken against the model at the instant t_s the sample was drawn, as Equation (10.12) does for the soft sensor. With the soft sensor On, b_w follows the corrected soft sensor through a 30 min filter instead. Such biases are the integrating disturbances through which predictive control absorbs plant-model mismatch [22], and Volume 9, Chapter 4 builds an offset-free predictive controller whose estimator carries a fuel bias of this kind. Here b_w corrects the output alone while $\hat{w}$ keeps integrating its own rate between titrations, so a rate the model gets wrong returns at every report as a fresh offset, and the MPC is not offset-free when the plant's acid law departs from the declared one.

Each decision minimizes the objective of Equation (10.15), a case of Equation (1.21) with a funnel on the floor band, over the three handles held in twelve move blocks, which lengthen from a single

step at the front of the horizon to 75 steps at its end, 36 decisions and one slack ε.

$$\begin{aligned}\min_{u,\varepsilon}\ &\sum_{k=1}^{N_p}\Big[100\big(\widehat{I}_k - I_{SP}\big)^2 + 100\big(\hat{T}_k - r_T\big)^2 \\ &\qquad + 400\big(\tilde{w}_k - r_w\big)^2\Big] + 10^5\varepsilon^2 + 10^5\varepsilon \\ &+ \Lambda\sum_{j=1}^{12}\Big[100\,\Delta u_{1,j}^2 + \Big(\frac{\Delta u_{2,j}}{0.01}\Big)^2 + 10\Big(\frac{\Delta u_{3,j}}{1000}\Big)^2\Big] \\ \text{s.t. } & u_{i,min} \le u_{i,j} \le u_{i,max}, \qquad \varepsilon \ge 0 \\ & \tilde{w}_k \ge w_b - \max(0,\, w_b - \tilde{w}_0)\,\mathrm{e}^{-k\Delta t_M/\tau_f} - \varepsilon\end{aligned} \tag{10.15}$$

where the tracking weights are the inverse squares of 0.1 in I/O, 0.1 K and 0.05 wt%, $\Delta u_{i,j}$ is the change of handle i at block j, the first of them taken from the command in force, u_2 is in bar and u_3 in kg/h, and $\Lambda = 10$ is the move suppression, chosen once on case 9 and never retuned. The floor band w_b is the run's runaway floor, read as the protection reads it, plus 2 wt%, 89 wt% at the default, $\tilde{w}_0$ is the estimate now, and $\tau_f = 60$ min is a funnel by which an estimate already below the band is brought back. The band is soft and priced far above tracking, with one slack for the whole horizon. The strength target is $r_w = \max(w_{SP}, w_b)$, so the target never pulls the plan under the band. While the governor reports the compressor at its capacity the temperature target is $r_T = \max(T_{SP}, \hat{T}_0)$, the temperature loop's own rule, and $r_T = T_{SP}$ otherwise. Without that rule the plan reached for a temperature the compressor could not give through the recycle's cooling, which in the challenge raised the I/O request by 0.461 in all while it stood above its target and the butanes in the alkylate to 32.3 %, against 0.030 and 16.3 % with it.

The bounds on the handles are hard and are those the shipped loops clamp to, the I/O request between the ratios the station gives at 0 and 9000 kmol/h of recycle, the suction pressure between 0.6 and 2.5 bar a with its lower bound closing onto the held pressure less 0.005 bar while the compressor is at its capacity, and the fresh acid between 0 and 12 000 kg/h. A handle whose own loop is in Manual is pinned at its station, so the plan works around a recycle held by hand. The framework's dense quadratic program solver returns each plan, and a plan is kept only if the solver's status is optimal, the first move, the plan, the predictions, the cost and the slack are finite, the slack is nonnegative and every move lies inside its bounds. A plan that fails is rejected, the historian records MPC FALLBACK, and the Supervisor structure, whose PI controllers track the applied commands at every scan without preload, holds the unit until the next valid plan takes back. With the noise off, a rejection forced on a quiet scan of case 9 moves no handle, and one on the scan a titration arrives moves the fresh acid by 867.3 kg/h, the same move the shipped structure makes when its strength loop goes from Manual to Automatic on that scan, its proportional response to the new titration. No plan was rejected in any run reported here (718 to 720 a day). The runaway stop, the low-I/O trip and the alarms act above the MPC on the run's own limits. A plan takes 0.78 to 0.95 ms in Node and 0.75 to 0.83 ms in Chrome, 0.04 % of one core at 1 min/s and 11 to 12 % at the top speed of 300 min/s, which the application still holds at 59 to 60 frames a second.

10.5.6 Three Models Kept Apart

Section 10.3 is the plant the engine integrates. A learner who steps the recycle and fits its gain on the I/O builds an identified model of it. What the loops and the supervisor assume is narrower still: PI gains, the feedforwards' design ASO ratio and design purity, the soft sensor's design diluent split, and the supervisor's copy of the correlations with the scenario's parameters, which sees an upset only through the instruments. The MPC's model of Equation (10.14) is identified in its temperature row, while its strength row is the plant's own acid law at the declared parameters read through the instruments, exact on the shipped plant but for those instruments and wrong in its rate on a changed one. The status strip, the verdict and the protection layer read the truth and act on no controller.

Table 10.4 The Nine Cases and the Challenge

#	Case and events	Teaching point
1	Manual recycle, olefin 115 % at 10 min	I/O, octane, acid use
2	Ratio on the design purity, olefin 115 % at 30 min	the recycle's purity
3	105 % olefin, learner sets 6 °C, water 38 °C from 2 h	refrigeration limit
4	Manual recycle, olefin 115 % at 1 h, titration alone	sampled strength
5	Lined out at 90 wt %, learner withholds acid	the runaway floor
6	30 % propylene at 30 min	a poorer olefin
7	Makeup lost at 30 min	an infeasible ratio
8	Supervisor at $80 then $250/t acid	the economic optimum
9	MPC against Supervisor, titration alone, 30 % propylene at 1 h	a model between titrations
10	Challenge, 24 h: olefin 115 % at 2 h, slug at 8 h, 38 °C 12–18 h	the whole unit

Table 10.5 Case Outcomes Measured on the Engine

Case and condition	Result
1, as shipped	I/O 9.0 → 7.9; ASO 251 → 353 kg/h; acid use 73.4 (2 h), 82.0 kg/t (6 h); product RON 94.69 (40 min), 94.45 (6 h)
1, recycle 5775 at 20 min	RON 94.94, acid use 65.0 kg/t at 6 h
2, design purity	purity 88.1, 87.6, 86.7, 86.1 % (4, 6, 12, 24 h); loop I/O 9.0, true 8.88 (4 h), 8.75 (12 h)
2, analyzer at 2 h 56	recycle 5770 → 5842 kmol/h; within 0.1 of 9 0.6 min later
3, SP 6 °C	suction 1.409 → 1.362 bar a; within 0.15 K in 11 min
3, afternoon	at capacity 2 h 17; +0.3 K at 2 h 37; peak 7.10 °C at 5 h 26; back 6 h 39
4, titration alone	strength 91.45–92.31 wt %; fresh acid 3205–6472 kg/h
4, soft sensor	strength 91.92–92.03 wt %
5, acid withheld	89 at 2 h 53, 88 at 5 h 28; ACID RUNAWAY 7 h 35; ASO 283 → 504 kg/h
6, as shipped	inferred RON 95.00 → 93.18; ASO 250 → 335 kg/h; acid use 64.1 → 89.1 kg/t (4 h)
6, I/O 11	RON 94.00 (4 h); ASO 249 kg/h; acid use 66.7 (4 h), 64.4 kg/t (12 h); steam 89.4 → 101.9 t/h
7, as shipped	receiver < 30 % 1 h 42, < 10 % 2 h 51; LOW I/O TRIP 4 h 00 (I/O 4.22)
7, olefin 60 / 40 %	trip 4 h 23 / 4 h 39
8, $80/t	targets I/O 10.90, 4.93 °C, 94.25 wt % at 4 h
8, $250/t	strength target < 93 at 5 h 06; 12.00, 4.87, 92.79 at 12 h; true 92.70 at 24 h
9, MPC / Supervisor	strength from 4 h 93.12–93.23 / 92.68–93.78 wt %; IAE 1.20 / 6.18 wt % h; fresh acid 79.8 / 89.0 t

10.6 Nine Cases and a Day

The cases are listed in Table 10.4 and their outcomes in Table 10.5, and Section 1.6.4 describes how scenarios, completion rules and the challenge work. Each value comes from the engine stepped headless on the default seed, as the browser steps it, with the case as published and the learner's moves made at the instants its briefing names. A measuring script re-run on the app reproduces all 122 values the app's texts quote, and runs at seeds 1 and 2 and with a halved step keep every lesson.

10.6.1 A Ratio on Flows and a Column's Purity

Case 1 raises the olefin 15 % at 10 min against a recycle the learner holds. The I/O falls from 9.0 to 7.9 at once, and with less isobutane around it a larger share of the olefin polymerizes, so the ASO rises from 251 to 353 kg/h, 41 % for 15 % more olefin. The strength loop answers with acid, and the acid use climbs from about 64 to 73.4 kg/t two hours later and 82.0 kg/t at 6 h, while the product octane slips from 95.00 to 94.69 within 40 min. A recycle raised to about 5775 kmol/h at 20 min holds the I/O near 9 and leaves 94.94 and 65.0 kg/t at 6 h. In case 2 the feedforward moves the recycle from 5018 to 5774 kmol/h at the step, and the loop reads 9.0 for the rest of the day while the purity drifts. The analyzer's I/O falls below 8.9 at 2 h 56 min, the true I/O at 3 h 13 min, and switched to the chromatograph then, the loop raises the recycle from 5770 to 5842 kmol/h in 30 min and the analyzer's I/O is back within 0.1 of 9 0.6 min later.

🕮 **Pause.** Try Exercise 10.1 before reading on.

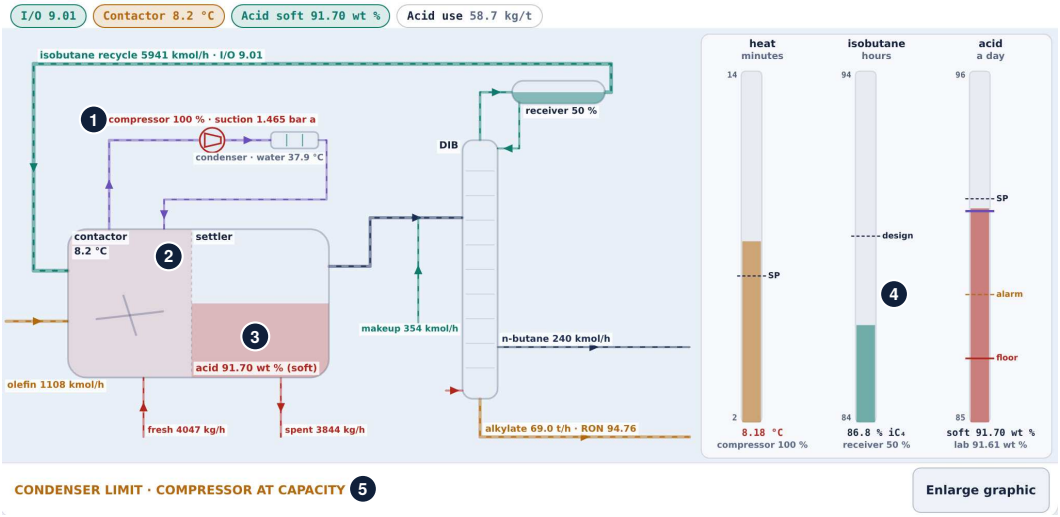


Figure 10.3 The challenge on its suggested settings at $t = 13$ h, Unit view, light theme, an hour into the hot afternoon, cropped to the plant view with numbered callouts. The badges read an I/O of 9.01, the contactor at 8.2 °C (2), the acid at 91.70 wt% on the soft sensor (3) and an acid use of 58.7 kg/t. The compressor is at 100 % of its capacity holding 1.465 bar a with the condenser water at 37.9 °C (1), the olefin is 1108 kmol/h, the recycle 5941 kmol/h on its meter, the makeup 354, the fresh and spent acid 4047 and 3844 kg/h, and the alkylate 69.0 t/h at an inferred RON of 94.76. The three gauges (4) show the heat at 8.18 °C above its setpoint, the recycle at 86.8 % isobutane below its 89.3 % design mark and the acid at 91.70 against its last titration of 91.61, all three inventories off their marks at once, under CONDENSER LIMIT and COMPRESSOR AT CAPACITY (5). The true strength is 91.46 wt%.

10.6.2 Refrigeration Until It Runs Out

In case 3, at 105 % olefin, a setpoint lowered from 7 to 6 °C takes the suction pressure from 1.409 to 1.362 bar a and the temperature within 0.15 K of it 11 min later, with the compressor carrying 2452 of its 2570 kmol/h. As the cooling water warms to 38 °C from 2 h, the compressor reaches its capacity at 2 h 17 min, the contactor is 0.3 K above its setpoint at 2 h 37 min, and it peaks at 7.10 °C at 5 h 26 min while the machine holds the suction pressure it can, 1.416 bar a at 4 h. When the water cools the temperature is back within 0.15 K at 6 h 39 min.

10.6.3 An Acid on a Four-Hour Laboratory

Case 4 raises the olefin at 1 h with the recycle fixed, so the ASO rises from 251 to 354 kg/h. On the titration alone, with the default gain of 3000 kg/h per point and 120 min of integral time, the strength swings between 91.45 and 92.31 wt% over the day and the fresh acid between 3205 and 6472 kg/h, because each report moves the loop by a whole period of integral action on an error that is already hours old. On the soft sensor, with the same tuning, the strength stays between 91.92 and 92.03 wt%. The soft sensor's value is in the variance of the strength, which a minimum on a single day does not see.

10.6.4 A Poorer Olefin, a Lost Makeup and Two Prices

In case 6 30 % propylene takes the inferred octane from 95.00 to 93.18 within the hour and the acid use from 64.1 to 89.1 kg/t by 4 h. Raising the I/O to 11 buys about half of the octane back, 94.00 at 4 h, because the tanh term flattens above 9 while the propylene penalty does not depend on the I/O, and it costs the column 12.5 t/h more steam. Case 7 is honestly infeasible, as Section 10.4 measured.

Table 10.6 Shipped Structures Against the MPC, Default Seed, 24 h. IAE Is That of the True Strength Against the Target in Force in Each Run, Travel the Sum of the Fresh Acid's Moves, and Margin the Supervisor's Objective Evaluated on the Simulator's Truth

Case	Structure	IAE (wt % h)	Largest error (wt %)	Fresh acid (t)	Acid and power ($)	Margin ($)	Acid travel (kg/h)	Plans, rejected
9, titration alone, propylene at 1 h	Supervisor (the comparison)	6.182	0.551	88.96	17 961	459 372	14 198	—
	MPC as loaded	1.202	0.329	79.78	16 583	460 939	18 821	720, 0
	Supervisor, hindsight K_c 6000, τ_I 480 min	4.256	0.351	79.24	16 503	460 875	14 706	—
	Supervisor on the soft sensor	1.483	0.298	79.14	16 488	461 011	108 069	—
	the same, hindsight 12 000, 240 min	1.007	0.305	79.60	16 556	460 955	419 501	—
	Supervisor's PI on the MPC's estimate, no plan	2.026	0.296	78.88	16 449	461 000	12 983	—
	the same, hindsight 12 000, 30 min	1.259	0.327	79.84	16 592	460 905	29 326	—
	Supervisor with a propylene feedforward	13.407	1.378	89.22	18 001	458 987	27 133	—
	MPC without the propylene	6.835	0.458	71.71	15 373	461 672	27 205	720, 0
	MPC, propylene sampled every 10 min	1.184	0.329	79.76	16 581	460 939	18 876	720, 0
	Loops + FF on 11.4, 4.9 °C, 93.5 wt %	2.399	0.223	89.75	18 071	460 484	12 125	—
	MPC on the same fixed setpoints	0.771	0.078	92.34	18 461	460 098	5 626	720, 0
6, propylene at 30 min	Loops + FF, soft sensor (shipped)	1.195	0.113	118.58	22 003	451 321	107 537	—
	the same, hindsight 12 000, 240 min	0.672	0.065	118.99	22 065	451 298	429 600	—
	MPC on the shipped setpoints	0.754	0.057	119.28	22 108	451 291	5 484	720, 0
	Supervisor	5.458	1.084	99.94	19 605	456 819	110 007	—
	MPC	3.359	0.823	99.62	19 556	456 794	27 166	720, 0
	Loops + FF on the model's optimum	6.245	1.200	99.51	19 542	456 861	105 583	—
4, recycle by hand, olefin at 1 h	Loops + FF, titration (shipped)	3.853	0.549	122.31	23 188	555 277	12 031	—
	the same, hindsight 12 000, 240 min	2.340	0.347	132.79	24 760	553 589	12 421	—
	MPC on the shipped setpoints	0.751	0.078	128.14	24 061	554 403	5 980	720, 0
	Supervisor, titration	20.577	1.786	149.52	27 285	554 215	31 086	—
	MPC	2.168	1.022	165.86	29 736	551 800	21 641	720, 0
8, acid $80, $250/t	Supervisor (the case's path)	12.336	1.455	76.17	16 037	490 925	93 556	—
	MPC on the same path	6.720	1.175	75.77	15 975	490 985	35 551	718, 0

Case 8 switches the supervisor on at $80 a tonne of acid. Within four hours it settles on an I/O of 10.90, 4.93 °C and 94.25 wt%, cheap acid buying octane. At $250 its strength target is below 93 wt% at 5 h 06 min, and by 12 h it reads an I/O of 12.00, its upper box, 4.87 °C and 92.79 wt%, with the compressor at 97 % of its capacity. Dear acid is used weaker, and more isobutane makes less ASO for it to absorb. The strength itself follows over a day, to 92.70 wt% at 24 h. With the acid above its new target the strength loop stops the fresh acid altogether from 6 h 46 min to 12 h 57 min, using the strength already paid for in the settler, and the strength's lowest after the change is 92.44 wt% at 17 h 10 min, more than three points above the alarm. The stop is physical and intended, and the case's explanation says so.

10.6.5 A Predictive Controller Between Titrations

Case 9 starts lined out where the supervisor places the unit, an I/O of 11.4, 4.9 °C and 93.5 wt%, with the strength on the titration alone, and at 1 h turns 30 % of the olefin to propylene. The ASO rises from 141 to about 182 kg/h, and the supervisor moves its strength target to 93.17 to 93.23 wt%. The case loads under the MPC and is compared with the same day under the Supervisor structure after Reset, whose targets differ from the MPC run's by at most 0.0001 wt%. Table 10.6 measures cases 9, 6, 4 and 8 under the shipped structures and under the MPC with the settings case 9 ships, on the default seed over 24 h with the same instruments, noise and events in every row. Beside them stand the stronger classical settings, the best of 20 strength tunings (K_c of 1000 to 12 000 per point, τ_I of 30 to 480 min) chosen in hindsight, the classical loop given the signal the MPC's model reads, the MPC given the loops' fixed setpoints, and the MPC without the propylene.

Under the MPC the true strength stays within 93.12 to 93.23 wt% from 4 h on, its largest error in each later four-hour period is 0.042 to 0.097 wt%, and the six titrations differ from the model at their

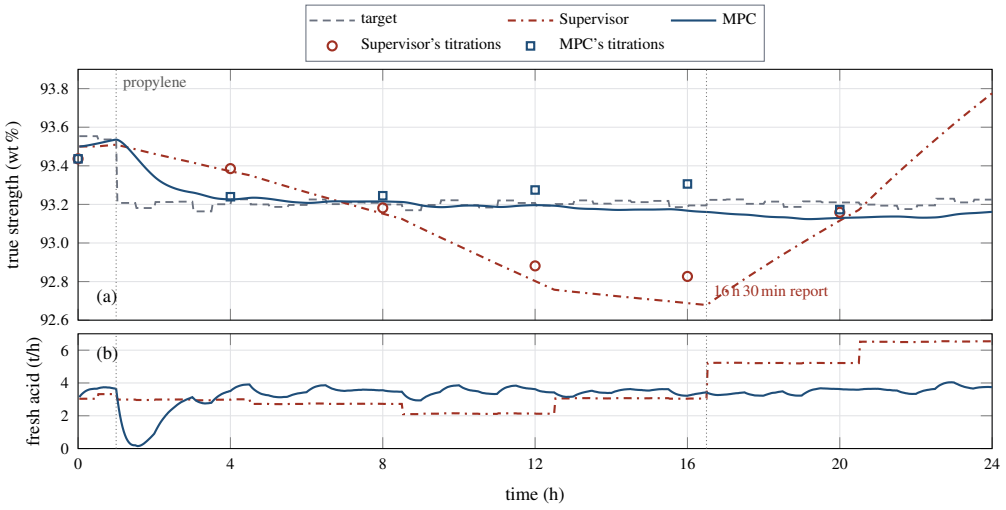


Figure 10.4 Case 9 on the default seed with the strength on the titration alone, the MPC run as the case loads (solid) and the Supervisor run after Reset (dash-dotted). (a) The true strength against the supervisor's target in force (gray, dashed), with each run's titrations at their sample times (squares for the MPC, circles for the Supervisor), each reaching its controller 30 min later. The floor band at 89 wt% lies below the panel. (b) The fresh acid applied, in the same line styles. The dotted lines mark the propylene step at 1 h and the Supervisor's report at 16 h 30 min.

samples by −0.064 to 0.099 wt%, inside the titration's own scatter. The supervisor's loop acts once per report on an error already hours old. Its strength swings between 92.68 and 93.78 wt%, and its largest error grows from 0.151 in the second period to 0.551 wt% in the last, as shown in Figure 10.4. At the 16 h sample its true strength is 92.69 wt%, and the titration, reported at 16 h 30 min, reads 92.83 against a target of 93.22, so its fresh acid jumps from 3050 to 5233 kg/h, while the MPC's strength at the same sample is 93.17 wt%. Over the day the MPC integrates 1.20 wt% h against 6.18 on 79.8 t of fresh acid against 89.0 t, and spends $1,378 less on acid and power. Over seeds 1 to 3 it scores 0.76 to 1.31 against 5.93 to 8.15, and halving the step leaves both rows unchanged to the third decimal.

The gain belongs mostly to the model between titrations and less to the plan. With the propylene left out of its model the MPC scores 6.84, no better than the titration alone. The supervisor's own PI controller acting every scan on the MPC's titration-corrected estimate, with no plan, scores 2.03, and 1.26 with the best of the 20 tunings, against the MPC's 1.20, so the quadratic program contributes the last part. A propylene feedforward of the design ASO law makes the titration loop worse (13.41), and so does one computed from the measured I/O, temperature and propylene (9.95), because a static feedforward does not carry the strength between reports. The feed chromatograph is ideal, but one sampled every 10 min and reported 5 min later changes the MPC's day only to 1.18. On the case's fixed setpoints, with the supervisor off, the MPC scores 0.77 against 2.40 for the loops with feedforward on the titration.

The density soft sensor closes most of the gap without any model. The supervisor on it scores 1.48 on 79.1 t, and with its best tuning in hindsight 1.01, better than the MPC's 1.20 but with 22 times its fresh-acid travel, while none of the 20 tunings moves the acid as little as the MPC. On margin the MPC does not lead. It earns $460,939 against $459,372 for the supervisor on the titration, but the supervisor on the soft sensor earns $461,011, and with its acid price raised to $250 a tonne $462,520, by running the acid down to 91.97 wt%.

✦ DID YOU KNOW? A Feedforward That Makes the Loop Worse

From the simulator (Table 10.6). In case 9 the supervisor's strength loop on the four-hourly titration integrates an error of 6.182 wt% h over the day. A propylene feedforward added to it scores 13.407, because a static feedforward does not carry the strength between reports. The MPC, whose model does, scores 1.202.

The MPC loses when its acid law is wrong. With the plant's κ_0 at 0.011, 29 % more ASO than the model expects, each titration corrects the estimate's offset but not its rate, the estimate stands 0.50 wt% above the truth before the last titration, and the MPC scores 7.71 against 5.58 for the supervisor on the titration alone. With fresh acid of 97.5 wt% instead of 98.5 it scores 5.92 against 5.62. With κ_0 at 0.0065 or c_3 at 2.5 it still leads (5.66 against 6.84 and 5.53 against 5.97), and a weir raised to 90 t costs it little (1.28 against 6.25). A drift estimate updated from each residual over the time since the previous sample cuts the κ_0 case to 3.43 but raises the nominal one from 1.20 to 1.97, because it also integrates the titration's noise, and it is not part of the controller.

Case 6 ships the loops with feedforward and the soft sensor on fixed setpoints of 9, 7 °C and 92 wt%. There the MPC, on the supervisor's targets, scores 3.36 against the Supervisor's 5.46 with a quarter of its fresh-acid travel and an equal margin ($456,794 against $456,819). A comparison with the shipped loops must hold their setpoints, and on them the MPC scores 0.75 against 1.20, while the loops tuned in hindsight reach 0.67, better than the MPC, with 78 times its travel. The $5,473 a day the MPC earns over the shipped loops belongs to the operating point, since the loops on the model's optimum as fixed setpoints earn $456,861.

Case 4 is a loss. With the recycle held by hand, the MPC follows the supervisor's targets of 93.21 to 93.31 wt% at 2.17 against the shipped loop's 3.85 on its 92 wt%, but it spends 165.9 t of fresh acid against 122.3 t and earns $3,477 less margin. The loss belongs to the supervisor's targets, which assume an I/O the fixed recycle cannot give. On the loop's own setpoints the MPC scores 0.75 on 128.1 t, against 2.34 for the loop tuned in hindsight, and the Supervisor on the titration reaches 20.58 on 149.5 t. In case 8, switched at 5 min with the acid raised from $80 to $250 a tonne at 4 h 05 min, the MPC follows the moving target at 6.72 against 12.34, with 35 551 against 93 556 kg/h of fresh-acid travel at an equal margin.

10.6.6 A Day of Olefins, Water and Heat

The challenge runs 24 h. The olefin rises 15 % at 2 h, a coalescer upset sends 400 kg/h of free water with the feed for 90 min from 8 h, and the cooling water warms to 38 °C over the hour from 12 h and cools again from 18 h. It is met when the product octane averages at least 94.5 and never falls below 94.0, the true strength never falls below 91 wt%, and the day's fresh acid at $150 a tonne plus compressor power at $70 a megawatt hour cost at most $24,500, with no stop. The verdict reads the simulator's truth every step and its bill uses those fixed prices, whatever the learner's price boxes say. The bill was moved to fixed prices after a strength setpoint of 94 wt% with the acid box at $20 passed while it cost $31,003. It ships on Fixed flows with the soft sensor and the moisture feedforward off. The configurations are compared in Table 10.7, and Figure 10.5 draws three of its columns against their limits.

As shipped the unit misses the octane and the strength. The I/O falls to 7.9 at 2 h 05 min and drifts to 7.6 by the end of the day as the recycle's purity falls, the octane's lowest is 93.52 at 18 h 08 min, and the acid weakens under the extra ASO and the slug to 89.08 wt%. The soft sensor, reading the heavier ASO a quarter high (8.76 wt% of the acid against 6.11 at design), puts it at 88.87 and sounds STRENGTH LOW from 22 h 44 min. The suggested settings close the ratio and strength loops with feedforward, the chromatograph, the soft sensor and the moisture feedforward, and pass with 94.91, 94.65, 91.45 wt% and $21,995, and they pass at seeds 1 to 3 with 94.90 to 94.92 and $22,040 to $22,277. The supervisor passes at 95.89 for $23,839, spending more acid on a stronger acid because the octane is worth it, and at seeds 1 to 3 for $23,933 to $24,218. The MPC with the same sensors passes at 95.91 for $23,185, and at seeds 1 to 3 for $23,186 to $23,449, but the verdict does not

Table 10.7 Configurations Tried on the Challenge Day, Default Seed

Configuration	Avg RON	Low RON	w_{min} (wt %)	Cost ($)	
Fixed flows (shipped)	94.02	93.52	89.08	18 738	fail
Loops + FF, GC, soft, FF (sugg.)	94.91	94.65	91.45	21 995	pass
Supervisor, same sensors	95.89	95.00	92.00	23 839	pass
MPC, same sensors	95.91	95.00	92.00	23 185	pass
suggested, strength loop Man	94.72	94.44	90.76	18 719	fail
suggested, no moisture FF	94.91	94.72	91.38	21 889	pass
suggested, no soft sensor	94.91	94.66	91.43	21 914	pass
suggested, neither	94.95	94.66	91.37	24 250	pass
neither, design purity	94.86	94.53	91.33	24 916	fail
suggested, I/O 10	95.31	95.00	91.41	19 899	pass
suggested, strength 94, box $20	95.43	95.00	92.00	31 003	fail

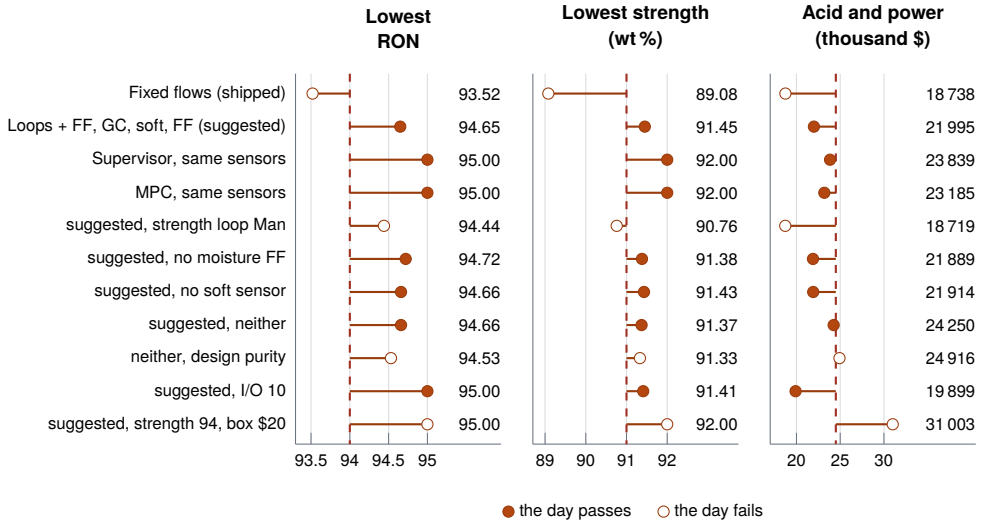


Figure 10.5 Three columns of Table 10.7 against their limits (dashed): the lowest product octane against 94.0, the lowest true strength against 91 wt% and the day's acid and power against $24,500. A stem runs from the limit to each value, and a filled circle marks a day that passes. Notice that the two cheapest days fail because they let the acid weaken, and that two other days fail on cost alone. The average octane is not drawn, because the only day that misses its 94.5 is the shipped one, which misses the lowest octane as well.

score the column. At its first period after the olefin step, 2 h 30 min, the supervisor lowers its I/O target from 11.44 to 10.75 to bring the boilup back inside its own reboiler row, and the targets stay on that row for the rest of the day. The deisobutanizer's reboiler therefore sits at its steam limit only within the hour after the step, for 32 min under the Supervisor and 52 min under the MPC. Until 2 h 30 min the MPC holds the I/O within 0.04 of its target with 105 to 165 kmol/h more recycle than the Supervisor's loop, whose I/O runs 0.16 to 0.23 below its target, and then brings its request down over about 20 min, so the alkylate carries up to 16.3 % butanes for 38 min, against 4.9 % under the Supervisor. On the loops' fixed setpoints the MPC passes at $21,786 with no minute at the steam limit.

The strength target was first set at 89 wt% and then raised to 91. At 89 the suggested settings with the strength loop left in Manual passed for $18,719, less than the suggested $21,995, by running the acid inventory down to 90.76 wt% to keep the bill low, so the day needed only the I/O loop. With the strength loop in Manual the day ends at 90.70 to 90.76 wt% at seeds 0 to 3, with or without the

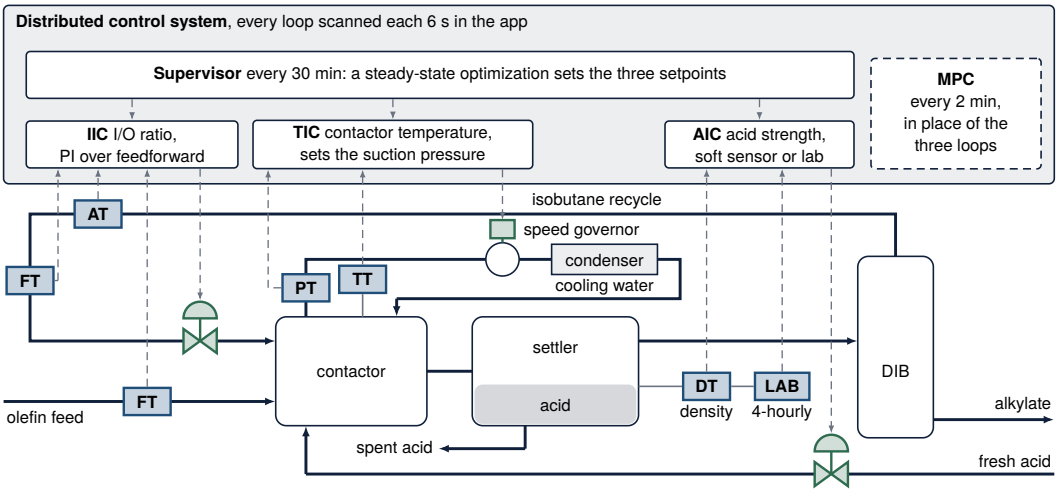


Figure 10.6 The three quality loops with their hardware. Lettered boxes are sensing devices: flow meters (FT), the recycle chromatograph (AT), the contactor thermometer (TT), the suction pressure (PT), the acid density meter (DT) and the laboratory sample (LAB). The two valve symbols and the compressor's governor are final elements, and dashed arrows are signals. Notice that the strength loop is the only one whose reference measurement is carried to a laboratory by hand, and that the temperature loop ends in a machine and not in a valve. Not to scale, and not a piping or safety diagram.

feedforwards, and the weakest closed-loop structure keeps 91.26 wt%, so 91 separates them while the alarm keeps its place at 89.

Neither the soft sensor nor the moisture feedforward is necessary for the verdict. Without either the day still passes, and with both off the cost reaches \$24,250 on the chromatograph, inside the cap at the default seed and outside it at seeds 1 to 3 (\$25,221 to \$25,423), and \$24,916 on the design purity, a miss. The two interact. The slug takes 0.65 wt% off the strength with the soft sensor and no feedforward, and 0.13 wt% with the feedforward on the titration alone, but 0.50 wt% with both on. The soft sensor reads only 0.11 of the 0.65 drop, a water dilution being nearly invisible to it, and with both on it reads 92.01 then 92.00 while the feedforward's acid lifts the true sulfuric acid share, so the PI controller trims the added fresh acid over 8 to 12 h from 6397 kg, on the titration, to 2389 kg. The 600 kg of water slugged would need 8490 kg of acid. The largest error of the corrected soft sensor over the suggested day, 0.61 wt% high, comes at 9 h 35 min, just after the slug. The bill leaves out the column's steam, so a higher I/O is free here, and an I/O setpoint of 10 on the suggested settings averages 95.31 for \$19,899.

The suggested day at 13 h is shown in Figure 10.3. In this day the compressor reaches its capacity at 12 h 00 min and stays there for 99 % of the steps from 13 to 18 h, and the contactor peaks at 8.36 °C at 17 h 20 min, 1.36 K over its setpoint, before it is back under 7.15 °C at 18 h 50 min.

10.7 Technology in Practice

Figure 10.6 draws the three quality loops of Section 10.5 with the hardware a refinery installs.

What Measures It

The ratio loop reads two flow meters and a chromatograph on the recycle. A chromatograph separates the species of a sample in time, so cycle times of minutes are not uncommon and some dead time is inevitable [23]. The model carries it as a sample every 10 min reported 5 min later. The strength

has no such instrument in the model. A laboratory titrates it every 4 h, and a soft sensor fills the gaps from a density meter. A review of soft sensors names this as their original and still dominant use, the prediction of variables that can be determined only at low sampling rates or by off-line analysis [10].

> **TECHNOLOGY** **Sensor: Acid Strength by Titration and by Density**
>
> The reference for acid strength is a titration. In the laboratory runs of a process patent the acid sample was centrifuged and a weighed portion titrated with standardized sodium hydroxide to an indicator's end point [4]. A federal case study describes a refinery sample station that gave two samples, one for an immediate density analysis by the operator and one for the laboratory to determine the weight percent of acid [24]. A vibrating-tube meter makes the density continuous. In a Coriolis flow meter, which reads density the same way, the tubes are shaken at resonance, the resonant frequency changes with the density of the fluid, and a resistance thermometer corrects for the change of the metal's elasticity with temperature [23]. Density cannot tell one diluent from another. In Section 10.5 the soft sensor reads a water dilution at 19 % of its size.

What Moves It

Two control valves and one machine carry the three loops. The recycle is the captive flow of a ratio whose wild, uncontrolled flow is the olefin [23]. The fresh acid valve moves an inventory of 80 t that it renews at 4.79 % an hour, so the valve's speed never limits its loop. The compressor does limit its loop. It gives the suction pressure that the temperature controller asks for only up to a capacity that falls on a hot afternoon.

> **TECHNOLOGY** **Final Element: Refrigeration Compressor**
>
> The contactor's temperature is moved through the compressor that draws vapor off the boiling hydrocarbon. Varying a compressor's speed sets a gas flow with less energy than running at full speed and throttling the discharge or recycling gas to the suction. Such a machine often cannot change a flow as rapidly as a control valve and offers limited options for a fail-safe state. A centrifugal compressor surges, violently, when the pressure across it is too high and the flow through it too low, and a recycle valve from discharge to suction prevents it [23]. A federal manual warns that loss of the cooling water needed to maintain process temperatures could upset an alkylation unit [19]. The model's machine has a 0.5 min governor and a capacity that falls as its condenser water warms, and it carries no surge limit.

Where the Controller Runs

A refinery runs these loops in a distributed control system, in which a supervisory level oversees local controllers, loops are sometimes nested and cycle times range from milliseconds to minutes [25]. The app scans its loops every 6 s, solves its MPC every 2 min and its supervisor every 30 min. The acid controller of the History box in Section 10.1 executed every 15 min [13], a pace that suits a strength whose clock is longer than a day. The ratio and strength loops are PI blocks over a feedforward, under a supervisor and an MPC that write setpoints. Industrial predictive controllers meet a measurement that is not available at every execution, as from an analyzer, by skipping the bias update for a number of intervals [12]. On the titration alone the chapter's MPC corrects its strength bias only when a titration reports.

> **IN PRACTICE** **An Acid Run Close to Its Limit and Sampled by Hand**
>
> The runaway of case 5 is a known event in service. A federal case study of two acid releases at one refinery in 2014 states that runaways can occur when the acid concentration falls below the operating limit, that they cost alkylation capacity and can damage equipment, and that running close to the limit is more economical, so there is a financial incentive to run weak. Operators there doubted that their controls could hold the unit at that edge, while nearby refineries ran economically with more advanced control systems. The study also shows what a sample costs. Strength control requires frequent sampling and testing, and a tubing connector beside a sample station came apart and sprayed two operators with acid [24].

What Is Modernizing It

The first development is the inferred measurement. Soft sensors also back up a hardware instrument and detect its faults, and their predictions deteriorate after launch as the process changes [10], which is why this chapter's sensor keeps a laboratory bias. The second is predictive control, of which a 2003 survey counted more than 4600 applications, with refining holding 67 % of those classified [12]. The third stands outside the control room. One refinery designed closed-loop sample stations, with a spring-loaded isolation valve that must be held open, to protect operators from the acid. Its stations plugged, foamed and were taken out of service, while another refinery made the change to more robust stations with success [24].

10.8 Limitations

The unit is generic, and its sizes, laws and limits serve teaching. The selectivity and activity laws have published directions but no fitted constants, so the floor near 87 wt%, the collapse below 89 and the clocks of 36.3 h and 7 h belong to this model, its 80 t of acid and its 24 trays. The octane correlation's strength term lies on Putney's curves, its temperature term is about three times the patent's, and its I/O term has only its sign, while the curves' maximum near 95 to 96 wt% is absent because the term only saturates. The contactor is one holdup without an emulsion, the refrigerant returns at once, and the column is ideal at a fixed pressure.

The feedforwards assume the design ASO per olefin and the soft sensor the design diluent split, so both are wrong by design when the feed or the water changes, which is the lesson of the slug. The supervisor optimizes the same correlations the plant uses and meets model error only through the instruments, and its bill and the challenge's leave out the column's steam. The loop tunings stay fixed as the feed changes, and an acid dump and refill, a contactor trip and a start-up are outside every case.

The MPC's model leaves out the deisobutanizer and its steam limit, which the column reaches for 52 min after the challenge's olefin step, and holds the compressor's capacity only as a bound on the suction pressure. Its strength row is the plant's own acid law at the declared parameters, so on the shipped plant the comparison credits a model that is exact but for its instruments, which no real unit offers, and its titration bias corrects an offset and not the drift a changed acid law produces. The feed chromatograph that gives it the propylene share is ideal, although a sampled one moves case 9 by only 0.02 wt% h.

> **OPEN CHALLENGE** **Alkylation Without a Liquid Acid**
>
> Every clock of this chapter belongs to a liquid acid that is diluted, titrated, renewed and regenerated. A review of 2003 counted four widely used processes, two on sulfuric acid and two on liquid hydrofluoric acid, and none yet on a solid catalyst [14]. In 2009 the solid catalysts proposed all showed rapid deactivation [2]. A kinetic study of 2022 reports that the liquid acids in use raise problems of safety and environmental protection, and that solid acids and ionic liquids had not reached large-scale production, the first because they deactivate easily and the second because they are expensive [16]. Progress would be a catalyst that keeps its activity at a cost near that of sulfuric acid.

10.9 Conclusion

A sulfuric acid alkylation unit holds its octane with three inventories, and this chapter measured their clocks on one engine whose balances close to 7.4×10^{-8}: 2.1 min for the contactor's temperature, 7 h 00 min for the recycle's purity behind a 24-tray column and 36.3 h for the acid's strength. A ratio on the meters reads 9.0 while the true I/O falls to 8.75, a loop on a four-hourly titration swings 0.86 points where a density soft sensor holds 0.11, and an acid withheld from 90 wt% reaches the 87 wt% floor in seven and a half hours, faster at the end than at the start. On a day of olefin, water and heat, loops with feedforward, the chromatograph, the soft sensor and the moisture feedforward pass at $21,995, the supervisor at $23,839 with the contactor on its compressor's row and the boilup on its reboiler's, while the soft sensor's blindness to water trims back the feedforward's acid so that

neither aid is necessary on its own. A model predictive controller added to the unit holds the strength between four-hourly titrations at 1.20 against the supervisor's 6.18 wt% h because its acid balance reads the feed, and it trails at 7.71 against 5.58 once the plant's acid law departs from that balance. A fuller model would fit the selectivity and octane laws to measured data, model the emulsion and several contactors, and add the column's steam to the bill. The simulator shows that a quality loop is only as fast as the slowest inventory behind it.

KEY POINTS

- An alkylation unit holds its octane with three stocks, the contactor's cold, the recycle's isobutane and the acid's strength, and each moves at its own speed.
- The clocks are 2.1 min for the temperature, 7 h 00 min for the recycle's purity and 36.3 h for the strength.
- A ratio on the meters reads 9.0 while the true I/O falls to 8.75.
- A loop on a four-hourly titration swings 0.86 points where a density soft sensor holds 0.11, and the soft sensor reads a water dilution at 19 % of its size.
- A quality loop is only as fast as the slowest inventory behind it.

Where else this applies. A soft sensor corrected by a delayed laboratory returns in Volume 5, Chapter 10, a loop on a slow analyzer in Volume 5, Chapter 3, a predictive controller with a bias in its estimator in Volume 9, Chapter 4, and a supervisor whose optimum sits on a moving constraint in Volume 9, Chapter 8.

References

[1] A. Corma and A. Martínez, "Chemistry, catalysts, and processes for isoparaffin–olefin alkylation: Actual situation and future trends," *Catalysis Reviews*, vol. 35, no. 4, pp. 483–570, 1993.

[2] L. F. Albright, "Present and future alkylation processes in refineries," *Industrial & Engineering Chemistry Research*, vol. 48, no. 3, pp. 1409–1413, 2009.

[3] J. H. Gary, J. H. Handwerk, M. J. Kaiser, and D. Geddes, *Petroleum Refining*. CRC Press, 2007.

[4] K. Kranz, "Cold temperature alkylation process," U.S. Patent 5 095 168, Mar. 10, 1992.

[5] L. F. Albright, "Alkylation of isobutane with C_3–C_5 olefins: Feedstock consumption, acid usage, and alkylate quality for different processes," *Industrial & Engineering Chemistry Research*, vol. 41, no. 23, pp. 5627–5631, 2002.

[6] E. Worrell and C. Galitsky, "Energy efficiency improvement and cost saving opportunities for petroleum refineries: An ENERGY STAR guide for energy and plant managers," Lawrence Berkeley National Laboratory, Berkeley, CA, Tech. Rep. LBNL-56183, 2005.

[7] U.S. Energy Information Administration, "Alkylation is an important source for octane in gasoline," Today in Energy, February 13, 2013, eia.gov/todayinenergy/detail.php?id=9971, read November 2026.

[8] W. L. Luyben, "Snowball effects in reactor/separator processes with recycle," *Industrial & Engineering Chemistry Research*, vol. 33, no. 2, pp. 299–305, 1994.

[9] B. Joseph and C. B. Brosilow, "Inferential control of processes: Part I. steady state analysis and design," *AIChE Journal*, vol. 24, no. 3, pp. 485–492, 1978.

[10] P. Kadlec, B. Gabrys, and S. Strandt, "Data-driven soft sensors in the process industry," *Computers & Chemical Engineering*, vol. 33, no. 4, pp. 795–814, 2009.

[11] M. L. Darby, M. Nikolaou, J. Jones, and D. Nicholson, "RTO: An overview and assessment of current practice," *Journal of Process Control*, vol. 21, no. 6, pp. 874–884, 2011.

[12] S. J. Qin and T. A. Badgwell, "A survey of industrial model predictive control technology," *Control Engineering Practice*, vol. 11, no. 7, pp. 733–764, 2003.

[13] N. Petit, Y. Creff, L. Lemaire, and P. Rouchon, "Minimum time constrained control of acid strength on a sulfuric acid alkylation unit," *Chemical Engineering Science*, vol. 56, no. 8, pp. 2767–2774, 2001.

[14] L. F. Albright, "Alkylation of isobutane with C_3–C_5 olefins to produce high-quality gasolines: Physicochemical sequence of events," *Industrial & Engineering Chemistry Research*, vol. 42, no. 19, pp. 4283–4289, 2003.

[15] J. R. Langley and R. W. Pike, "The kinetics of alkylation of isobutane with propylene," *AIChE Journal*, vol. 18, no. 4, pp. 698–705, 1972.

[16] Z. Xin, H. Jiang, Z. Zhang, Y. Chen, and J. Wang, "Kinetic model of olefins/isobutane alkylation using sulfuric acid as catalyst," *ACS Omega*, vol. 7, no. 11, pp. 9513–9526, 2022.

[17] J. D. Freel, "A study of an alkylation reaction," M.Eng. thesis, McMaster University, Hamilton, Ontario, Sep. 1969.

[18] S. F. Birch, A. E. Dunstan, F. A. Fidler, F. B. Pim, and T. Tait, "High-octane isoparaffinic fuels production by the addition of olefins to isoparaffins," *Industrial & Engineering Chemistry*, vol. 31, no. 7, pp. 884–891, 1939.

[19] Occupational Safety and Health Administration, "OSHA technical manual, section IV, chapter 2: Petroleum refining process," U.S. Department of Labor, Washington, DC, osha.gov/otm/section-4-safety-hazards/chapter-2, read November 2026.

[20] E. C. Oden and W. J. Burch, "Alkylation of isobutane with propylene: Commercial production using sulfuric acid catalyst," *Industrial & Engineering Chemistry*, vol. 41, no. 11, pp. 2524–2530, 1949.

[21] E. C. Hughes, D. G. Stevens, and F. Veatch, "Lower acidity sulfuric acid alkylation," *Industrial & Engineering Chemistry*, vol. 43, no. 6, pp. 1447–1451, 1951.

[22] G. Pannocchia and J. B. Rawlings, "Disturbance models for offset-free model-predictive control," *AIChE Journal*, vol. 49, no. 2, pp. 426–437, 2003.

[23] T. R. Kuphaldt, *Lessons in Industrial Instrumentation*, version 2.33 ed. Open textbook, Creative Commons Attribution 4.0 license, ibiblio.org/kuphaldt/socratic/sinst, 2024.

[24] U.S. Chemical Safety and Hazard Investigation Board, "Tesoro Martinez refinery process safety culture case study, Martinez, California, February 12, 2014 and March 10, 2014 sulfuric acid release incidents," U.S. Chemical Safety and Hazard Investigation Board, Washington, DC, Case Study 2014-02-I-CA, 2016.

[25] K. Stouffer, M. Pease, C. Tang, T. Zimmerman, V. Pillitteri, S. Lightman, A. Hahn, S. Saravia, A. Sherule, and M. Thompson, "Guide to operational technology (OT) security," National Institute of Standards and Technology, Gaithersburg, MD, Special Publication 800-82r3, 2023.

10.10 Exercises

10.1 Concept check · 2 min

In case 2 the I/O loop holds the ratio on the meters with the recycle's design purity of 89.3 % isobutane. The olefin rises 15 % at 30 min, and the loop reads an I/O of 9.0 for the rest of the day while the true I/O is 8.75 at 12 h. Why does the loop not see the shortfall?

(a) The olefin meter reads low after the step, so the loop counts less olefin than the contactor receives

(b) The integral time of 30 min is too long for the loop to follow a step of 15 % in the olefin

(c) The contactor's 1500 kmol holdup delays the new ratio by half a day, longer than the loop looks

(d) The recycle carries more n-butane as the column fills with it, while the loop still counts the design purity

10.2 Concept check · 2 min

The density soft sensor assumes the acid's diluent is water and ASO in their design shares. In the challenge a coalescer upset sends 400 kg/h of free water with the feed for 90 min. How does the soft sensor read the dilution this slug causes?

(a) It sees only about a fifth of it, because a kilogram of water lowers the density far less than a kilogram of ASO does

(b) It sees all of it within its 1 min meter lag, because density falls in proportion to the diluent's mass

(c) It sees a quarter more than the truth, because the design split counts every kilogram of diluent as ASO

(d) It sees none of it until the next titration, because its reading moves only when the laboratory bias updates

10.3 Concept check · 2 min

On Fixed flows, 20 % less fresh acid moves the strength 63 % of the way to its new value in 36.3 h, while a linearization of the acid balance at the design point gives 29.4 h. Why is the measured response slower?

(a) The titration reports four-hourly and 30 min late, which adds its delay to the measured time constant

(b) The activity's slope steepens as the strength falls, so each point lost adds more ASO and weakens the restoring rate

(c) The weir holds spent acid in the settler for 30 min, which slows the renewal of the whole inventory

(d) The acid inventory grows as ASO accumulates, so the same fresh acid renews a smaller share of it each hour

10.4 Theory and calculation · 7 min

Use the acid balance of Equations (10.7) and (10.8) at the design point: dilution $D = 270.7\,\mathrm{kg/h}$ (250.7 kg/h of ASO and 20 kg/h of water), strength 92.00 wt%, fresh acid 98.5 wt% and 80 051 kg of acid held.

(a) Compute the steady fresh acid F_f^* and spent acid F_s^*. *Checkpoint:* 3831 kg/h and 4102 kg/h

(b) How much fresh acid does each kilogram of water cost at 92 wt%, and how much would the 600 kg of the challenge's slug need? *Checkpoint:* 14.15 kg, about 8490 kg

(c) Hold F_f at its design value and linearize the strength balance, with M constant and the ASO rising 14.96 kg/h per point of strength lost. Find the time constant, and the value it would have if the ASO did not respond to the strength. *Checkpoint:* 29.4 h and 19.5 h

10.5 Theory and calculation · 7 min

Case 5 lines the unit out at 90 wt% with the design I/O of 9, the contactor at 7 °C, no propylene and 20 kg/h of feed water, then withholds the fresh acid. Use Equation (10.1) with $\kappa_0 = 0.0085$, $F_O = 530\,\mathrm{kmol/h}$, $M_O = 56.11\,\mathrm{kg/kmol}$ and the chapter's values $1/a = 1.131$ at 90 wt% and 2.025 at 87 wt%.

(a) Compute the ASO made, in kg/h, at 90 wt% and at 87 wt%. *Checkpoint:* 283 kg/h and 503 kg/h

(b) What fresh acid holds the unit at 90 wt%? *Checkpoint:* 3211 kg/h

(c) With the fresh acid at zero the acid held settles near 78.2 t, at the weir. Estimate the rate at which the strength falls at 90 wt% and at 87 wt%, and compare with the 0.35 points lost in the first hour and 0.52 in the last. *Checkpoint:* 0.35 and 0.58 wt%/h

10.6 Theory and calculation · 7 min

The ratio feedforward of Equation (10.11) sets the recycle $R = (I_{SP}\,z_O - z_I)F_{OF}/\pi$ with $z_O = 0.55$, $z_I = 0.30$ and the design olefin feed $F_{OF} = 963.6\,\mathrm{kmol/h}$.

(a) Compute the recycle for an I/O of 9 at the design purity $\pi = 0.893$. *Checkpoint:* 5018 kmol/h

(b) Case 2 raises the olefin feed by 15 %. What recycle does the feedforward now ask for? *Checkpoint:* 5770 kmol/h

(c) At 12 h of case 2 the recycle's true purity is 86.7 % while the loop still uses 0.893. With the recycle of part (b), compute the true I/O from Equation (10.1), and the recycle that would restore an I/O of 9. *Checkpoint:* 8.75 and 5943 kmol/h

10.7 App challenge · 6 min

Load case *4 · Acid strength on a four-hour laboratory*, default seed, which opens with the recycle in Manual and the Soft sensor Off. Run the full 24 h at a speed of 300 min/s and export the CSV.

(a) Read the lowest and highest true strength (column `truth_w_wt`) and the lowest and highest fresh acid command (column `fresh_cmd_kgh`) over the day. *Checkpoint:* 91.45 to 92.31 wt%, 3205 to 6472 kg/h

(b) Set the Soft sensor On, press Reset, run the day again and read the same four values. *Checkpoint:* 91.92 to 92.03 wt%, 3774 to 5774 kg/h

(c) Why does the loop on the titration alone swing so much more, on the same tuning?

10.8 App challenge · 6 min

Load case *5 · Withhold the acid: the runaway floor*, default seed. Before pressing Run, put the Strength loop on Man and set the Fresh acid to 0 kg/h. Run at 30 min/s. The run stops itself. Export the CSV.

(a) Read the times at which the true strength (`truth_w_wt`) first falls below 89 wt% and below 88 wt%, and the time of the ACID RUNAWAY stop, each within 1 min. *Checkpoint:* 2 h 48 min, 5 h 23 min, 7 h 30 min

(b) Read how many points of strength are lost in the first hour and in the last hour before the stop. *Checkpoint:* 0.35 and 0.52

(c) The case's completion rule asks for the same two moves after Run. If they are made at 5 min instead, what changes?

10.9 App challenge · 7 min

Load the challenge, *a day of olefins, water and heat*, default seed, and run all 24 h at 300 min/s as shipped (Fixed flows, Soft sensor and Moisture feedforward Off).

(a) Read the verdict: average product RON, lowest RON, lowest true strength and the cost of acid and power. Which targets fail? *Checkpoint:* 94.02, 93.52, 89.08 wt%, $18,738

(b) Press Reveal suggested tuning, then Reset, and run the day again. Read the same four values. *Checkpoint:* 94.91, 94.65, 91.45 wt%, $21,995

(c) Set both the Soft sensor and the Moisture feedforward Off, press Reset and run again. Does the day still pass, and what does the result say about whether either aid is necessary? *Checkpoint:* 94.95, 94.66, 91.37 wt%, $24,250

10.10 Application area · 4 min

Refiners run the contactor of a sulfuric acid unit cold.

(a) The chapter's octane law gives $b = 0.12\,\mathrm{K}^{-1}$. The cited patent reports about half an octane number gained over the 11.7 K from 49 to 28 °F. Compare the two slopes. *Checkpoint:* 0.043 K^{-1}, about a third

(b) Name two things that limit how cold a real contactor can run, from the chapter's history and model.

(c) In case 8 the supervisor places the contactor on its compressor row. What does a contactor 0.2 K warmer cost there, and why is this optimum on a limit?

10.11 Application area · 4 min

At design the isobutane balance closes as 289.09 kmol/h in the feed plus 322.90 of makeup against 525.53 alkylated, 85.46 in the side draw and 1.00 in the bottoms. In case 7 the makeup supply is lost.

(a) Suppose the alkylation and the feed's isobutane both scale with the olefin while the side draw and bottoms losses stay as they are. What isobutane deficit remains with the olefin cut to 60 %? *Checkpoint:* about 228 kmol/h

(b) Is there an olefin rate that holds the ratio without makeup? What does the app do when the true I/O stays below 5, and where would a real unit's setting for such an interlock come from?

10.12 Review the agent · 5 min

An AI assistant reads case 9, where the MPC scores an IAE of 1.20 against the supervisor's 6.18 wt% h on the titration alone, and writes: "The quadratic program plans four hours ahead, so it sees each titration coming. That plan is the source of the fivefold gain, and the same controller on a real unit, where the acid law is only roughly known, would hold the strength about five times closer than a PI loop on the laboratory." Find the flaw and say how to check it in the app.