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CHAPTER 10

A Synthetic Base Oil Simulator for Mid-Ranging, Inferential Control and Constraint Back-Off

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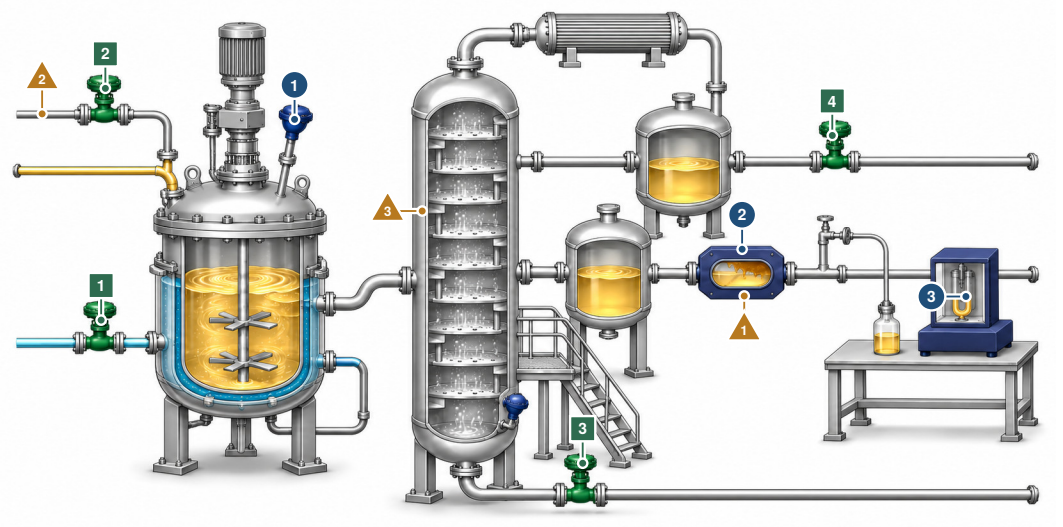
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CHAPTER 10

A Synthetic Base Oil Simulator for Mid-Ranging, Inferential Control and Constraint Back-Off



The controller moves 1 jacket water valve, which sets the reactor temperature (the slow handle) 2 catalyst dosing valve 3 bottom cut point, the fast handle (heavy product valve) 4 top cut point (light product valve)

The controller reads 1 reactor temperature 2 in-line viscometer on the motor oil 3 laboratory viscosity and viscosity index, every 75 minutes

What disturbs it 1 fouling that makes the viscometer read high 2 a more active catalyst lot 3 a column that loses cut sharpness

Notice the viscometer on the middle product line, which can foul and read high, and the laboratory bench that checks it only every 75 minutes. Illustration, not to scale.

IN PLAIN TERMS Two Handles for One Oil

The main idea. A synthetic motor oil is made by growing chains of molecules in many lengths and keeping the middle ones. The plant sets the thickness by changing which chains it keeps, and the slow reactor brings that choice back to the middle.

The challenge. Two routes to one thickness give oils that thin differently when hot, and only a slow laboratory test shows it. The thickness meter slowly gets dirty, so the controller can hold its reading while the oil goes wrong.

Why it matters. Failed oil sells for less, so the plant must decide how far to stay from a limit it cannot see.

THREE WAYS TO READ THIS CHAPTER

⊘	**Explore**	13 min	The first page, the history boxes in Section 10.2, the two try-it boxes and the fact boxes in Sections 10.5 and 10.8, and the key points
🕮	**Study**	45 min	The whole chapter with its pause points and the twelve exercises
⛰	**Practice**	20 min	The first page, Section 10.5, Section 10.6, Section 10.7 with its open challenge

The control question A reactor and a column cut point can both put a base oil on its viscosity, one in about an hour and one in a quarter of an hour, and the two routes make different oils. How should the two handles be arranged, how is a drifting meter corrected from a late laboratory, and how far should the plant stay from a viscosity index limit that only the laboratory can see?

Learning objectives

- Explain why two routes to the same viscosity give different viscosity index and yield, from the distribution and the cut.
- Derive the reactor and cut point gains from the model and work out the action of a mid-ranging loop whose gain runs through another controller.
- Predict the offset a laboratory bias update leaves behind a steadily drifting meter, for a given update gain.
- Recognize a loop in perfect control while the plant goes off specification, and name the layer that catches it.
- Price the back-off from a laboratory-measured constraint and compare classical mid-ranging with a predictive controller that prices the cut.

Prerequisites Sections 1.4.6 (the laboratory bias update), 1.6.2 (velocity-form PI and its action) and 1.6.4 (running a scenario). Section 1.6.3 is needed only for the predictive controller.

The app https://apmonitor.com/apps/pao-lubricant/

See also Volume 4, Chapter 10 for mid-ranging on a power cycle and Volume 4, Chapter 9 for valve-position control in a trigeneration plant. Volume 5, Chapter 10 for a soft sensor corrected from a delayed laboratory and Volume 5, Chapter 3 for composition control through a slow analyzer.

10.1 Introduction

When one controlled variable has two manipulated variables, the textbook question is which to pair it with. On the plant modeled here the answer is both, and the interesting work is arranging them. Decene oligomerizes over a metallocene catalyst into a distribution of chain lengths, and a column cuts motor oil base stock out of the middle of it with a lighter grade off the top and a bright stock for gear oils and grease off the bottom. The viscosity can be moved by the reactor, which changes what the molecules are and takes most of an hour, or by the cut point, which changes only which tank each molecule goes into and takes a quarter of one.

Measured on the model, both reach 6.30 cSt from the design point and the oils are not the same. Cooling the reactor eleven degrees gives a viscosity index of 138.5 at 51.0 % yield, and opening the bottom cut by four carbons gives 134.8 at 60.9 %. Ten points of yield against nearly four of viscosity index, at an identical number on the certificate.

The misconception the simulator corrects is that hitting the specification is the job. The specification is one functional of a distribution and the customer buys three, so two routes to the same viscosity are two different products, and a viscosity controller on its own cannot say which one was made. The measured consequence is severe. A column that loses cut sharpness leaves nine percent dimer in the product, the viscosity controller corrects the viscosity to exactly 6.000 cSt by opening the bottom cut six carbons, and the viscosity index ends below specification with a hundred and fifty tonnes downgraded in a day. The loop is in perfect control throughout.

Two structural answers follow and both generalize. The first is mid-ranging: control with the fast handle and use a slow outer loop, whose measurement is the fast loop's output, to return that output to the middle of its range [1]. The second is inferential correction: the fast on-line viscometer fouls and reads high, and a laboratory result up to eighty-seven minutes old corrects it through a bias, which is the structure most polymer and refinery quality loops run on [2, 3]. Above both is a constraint that no continuous measurement can see, and the distance the plant keeps from it is set by how late the news is rather than by how good the control is.

This chapter works on an interactive base oil plant whose chain growth probability, cut sharpness and property correlations are hidden, so that the two handles must be compared by experiment, a

mid-ranging loop signed correctly, and a back-off chosen against a measured cliff. The app runs in a browser and exports its complete time history. Section 10.2 gives the domain history. Section 10.3 builds the model, a Schulz-Flory reactor with a two-cut column, three product specifications, a fouling viscometer and a laboratory, in the detail needed to rebuild it. Section 10.4 describes the implemented loops, the laboratory bias update, the viscosity index cap and an optional predictive controller. Section 10.5 reports the measured scenarios, among them a sign error that produces no oscillation and a controlled variable that stays perfect while the plant goes off specification. Section 10.6 names the real devices behind the loops, and Sections 10.7 and 10.8 state the limitations and the three results that carry over to other plants. The oligomerization chemistry, mid-ranging and bias updating are all established methods, and the chapter uses them as they stand.

10.2 Background

Polyalphaolefins are the base stock in most full synthetic motor oils. They are made by oligomerizing a linear alpha olefin, most commonly 1-decene, then hydrogenating the residual unsaturation and distilling the product into grades. The grades are named by their kinematic viscosity at 100 °C, so PAO 4, PAO 6 and PAO 8 are motor oil base stocks and the heavier cuts go into gear oils and grease [4]. What the customer pays for is not the viscosity alone. Viscosity index, the degree to which viscosity resists temperature, is the reason a synthetic oil exists at all, and it is measured on finished base stocks alongside the pour point [5].

The chemistry determines the control problem. Cationic oligomerization over boron trifluoride was the original route and gives a broad distribution. Metallocene catalysts, which arrived in the 1990s and have been developed for olefin oligomerization specifically [6], give a narrower one and higher viscosity index, and the chain length distribution is set by the competition between propagation and chain transfer. Since transfer carries the larger temperature dependence, a hotter reactor makes a lighter oil, and the whole product is described by one number, the probability that a growing chain adds another monomer.

> HISTORY **Synthetic Oils for Jet Engines (1961 to 1973)**
>
> A patent application of 1961 sought synthetic lubricants for aircraft engines flying high, which needed a low pour point and a high viscosity index, and for jet engines, whose oil had to stay stable at about 500 degrees Fahrenheit and above. Alpha olefins polymerized over catalysts such as boron trifluoride already gave a low pour point and a high viscosity index, but hydrogenating them for stability raised the pour point sharply. The answer was to distill the dimer out before hydrogenation [7]. A 1971 application oligomerized the olefins at about 10 °C to 60 °C over boron trifluoride promoted by an alcohol, hydrogenated the product, and kept the low pour point without removing the dimer [8]. The dimer that troubled both is the light cut that the column of this chapter sends overhead.

Control of such a plant follows the polymer industry rather than the refining one. The controlled variable is a property of a distribution, it is measured in a laboratory on a cycle of an hour or more, and the practical answer is an on-line measurement corrected by the laboratory. Inferential estimation of polymer properties has a long literature and is now pursued with data-driven methods [3], and the maintenance and drift problems that come with any soft sensor are surveyed generally [2]. What is specific to a plant with a downstream fractionation is that the property can be moved after the reactor as well as inside it, and the two handles have different speeds and different costs.

The structure that arranges them is mid-ranging, also called valve position control, whose history the box at the end of this section tells. Volume 4, Chapter 10 adds a mid-ranging layer to a power cycle whose three actuators differ in speed. Its defining feature is that the outer loop measures the inner loop's output rather than a process variable, and its characteristic failure is a sign error, because the process gain seen by the outer loop runs through the inner controller. Above it, the economic trade between yield and viscosity index is what a real time optimizer or a multivariable controller with an

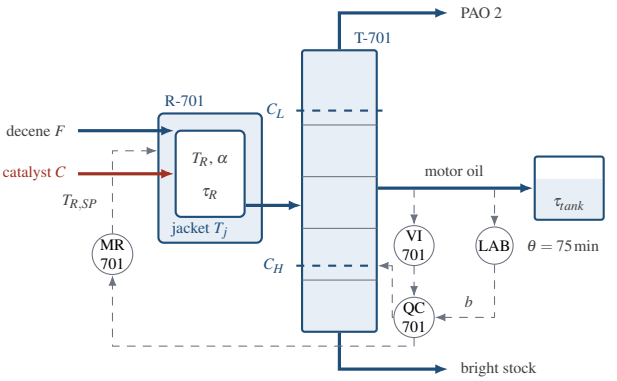


Figure 10.1 Synthetic base oil plant. Decene F and catalyst C react in R-701 at temperature T_R with residence time τ_R to a distribution described by the propagation probability α. Column T-701 cuts at C_L and C_H, sending PAO 2 overhead, motor oil base stock from the middle at viscosity KV, viscosity index VI and pour point PP, and bright stock from the bottom. The product tank has turnover τ_{tank}. VI-701 is the on-line viscometer, which drifts, and the laboratory reports every θ minutes on a sample drawn 12 min earlier. QC-701 holds the meter reading corrected by the laboratory bias b on the bottom cut point, and MR-701 returns that cut point to its target by moving the reactor setpoint $T_{R,SP}$, which a cap driven by the laboratory viscosity index (not drawn) can only lower.

economic objective handles [9], and the plantwide question of which unit owns which specification is the same one that arises on any train of units in series [10].

> ⧖ HISTORY **One Idea Under Many Names (1981 to 2005)**
>
> Mid-ranging has been in the control literature since the 1980s, traced to a publication of 1981, and has gone by names such as valve position control, input resetting, coordinated control and habituating control [11]. The problem is always the same: two inputs and one output, with the faster input in some way costlier to use than the slow one [12]. A 1998 study analyzed it on paper drying with steam and infrared heat [1, 12]. By 2003 most mid-ranging controllers in industrial use were valve position controllers, designed and tuned largely ad hoc, and a systematic method was shown on a pilot plant and on paper mill examples [13]. In 2005 the idea was described as common in the process industry and normally built from PID controllers [12].

10.3 Process Model

Reactor R-701 takes 12.0 t/h of 1-decene with 260 ppm of metallocene at 124.5 °C, giving a propagation probability of 0.633. Column T-701 cuts at 25 and 67 carbons, and the middle cut is 6.000 cSt at 100 °C with a viscosity index of 133.6, a pour point of −59.5 °C and a yield of 57.4 %. Figure 10.1 shows the arrangement.

10.3.1 The Plant Makes a Distribution

If α is the probability that a growing chain adds another decene rather than terminating, the mass fraction of the n-mer is Equation (10.1), and α is set by the ratio of chain transfer to propagation, Equation (10.2).

$$w_n \propto n\,(1-\alpha)\,\alpha^{n-2} \tag{10.1}$$

$$\alpha = \frac{1}{1+r}, \qquad r = r_0\, e^{E/R\,(1/T_{ref}-1/T_R)} \left(\frac{C}{C_0}\right)^m \tag{10.2}$$

The C90+ bin sums $n \geq 9$: its unnormalized mass is $\alpha^7[9+\alpha/(1-\alpha)]$. All bins are normalized by $(2-\alpha)/(1-\alpha)$. Chain transfer carries the larger activation energy, so hotter is lighter. Measured near

Table 10.1 Classification of Variables at the Design Operating Point

Symbol	Role	Nominal	Range
KV100	CV, inferred	6.000 cSt	5.70–6.30 spec
C_H	CV of MR-701	67.0 carbons	52–88
VI	constraint	133.6	≥ 130
PP	constraint	−59.5 °C	≤ -50
bright stock	constraint	30.4 cSt	≥ 33
C_H	MV, fast	67.0 carbons	52–88
T_R	MV, slow	124.5 °C	100–150
C_L	MV	25.0 carbons	18–34
C	MV	260 ppm	80–600
F	DV, measured	12.0 t/h	6–18
catalyst lot	DV, unmeasured	1×	0.5–1.8×
cut sharpness	DV, unmeasured	1×	0.6–3×
meter fouling	DV, unmeasured	off	0–4×

the design point, the viscosity moves −0.0281 cSt per degree of reactor temperature and 0.0016 cSt per part per million of catalyst removed. At $\alpha = 0.633$ the mass is 19.7 percent dimer, 18.7 percent trimer and 15.8 percent tetramer, with 11.7 percent in the lump of C90 and heavier.

10.3.2 The Column Decides Which Tank, Not What

Two cut points and a sharpness give each oligomer a fraction that stays in the product, Equation (10.3).

$$f_i = \sigma\!\left(\frac{C_i - C_L}{s}\right)\left[1 - \sigma\!\left(\frac{C_i - C_H}{s}\right)\right] \tag{10.3}$$

Measured over two carbons either side of the design cut, the viscosity moves 0.0522 cSt per carbon of bottom cut, nearly twice the reactor gain, and arrives in 14 min against the reactor's 38 plus 14. Nothing in Equation (10.3) changes a single w_n. It moves mass between three tanks, each with a specification of its own.

10.3.3 Three Functionals of One Shape

Viscosity blends on the Refutas index, Equation (10.4), and the two other specifications are correlations on the same cut and on the reactor temperature, Equations (10.5) and (10.6).

$$\nu = \sum_i x_i \,\mathrm{VBI}(\nu_i), \qquad \mathrm{VBI}(\nu) = a \ln\ln(\nu + 0.8) + b \tag{10.4}$$

$$\mathrm{VI} = c + d\ln\nu - e\,x_{dimer} - g\,[T_R - T_{iso}]^{+} \tag{10.5}$$

$$\mathrm{PP} = h + k\ln\nu + l\,x_{C70+} \tag{10.6}$$

The last term of Equation (10.5) is what stops the plant simply running hotter for yield: a hot metallocene isomerizes the chain as well as growing it, and the cost is 0.55 points of viscosity index per degree above 118 °C. It is also the only constraint on the unit that no continuous measurement can see.

10.3.4 The Tank

What is shipped is the tank, not the line, and the tank is a first-order filter with a 210 min turnover. Measured, a forty minute excursion reaches 6.297 cSt in the line and 6.049 cSt in the tank. The same excursion left for four hundred minutes takes the line to 6.315 cSt, above the band from 102 to 461 min with 41 t booked off specification, while the tank reaches only 6.266 cSt. The tank hides exactly the excursions that are easy to see and shows exactly the ones that are hard, because the things that move slowly are drifting instruments, fouling columns and aging catalyst.

Table 10.2 Model Parameters

Symbol	Meaning	Value	Class
r_0	transfer to propagation at T_{ref}, C_0	0.5152	adjustable
E/R	activation temperature of r	4100 K	adjustable
m	order of r in catalyst	0.38	adjustable
τ_R	reactor residence time	38 min	adjustable
τ_{col}	column response to a cut move	14 min	adjustable
τ_{tank}	product tank turnover	210 min	adjustable
s	cut sharpness	1.6 carbons	adjustable
g	VI lost per °C of reactor	0.55	adjustable
T_{iso}	isomerization onset	118 °C	adjustable
τ_{vis}	on-line viscometer response	3.0 min	adjustable
drift	viscometer fouling rate	0.020 cSt/h	adjustable
θ	laboratory cycle	75 min	adjustable
τ_{lab}	laboratory transport delay	12 min	adjustable
VI minimum	grade specification	130	visible

10.3.5 Assumptions

With the corrected C90+ sum, the nominal bright cut is 30.4 cSt, below its illustrative 33 cSt target; the challenge grades the motor oil, not that side product. The distribution is Schulz-Flory with a single propagation probability. A real metallocene gives a narrower distribution than that and the shape depends on the ligand [6].

Oligomers are lumped by carbon number with one viscosity each and everything from C90 upward in a single lump whose viscosity stands for a long tail.

The column is two logistic cut points with a sharpness parameter. A real column produces that shape from a tray count and a reflux ratio, and the sharpness would be a consequence rather than a knob.

Hydrogenation of the residual unsaturation is assumed complete and is not modeled.

Viscosity index and pour point are fitted correlations in the blend viscosity, the dimer content and the reactor temperature. Real structure-property relationships for these oils are considerably less tidy [5].

The reactor is one well mixed stage whose distribution follows the instantaneous one with a first-order lag, and the catalyst does not deactivate within a run.

10.4 Controller Design

10.4.1 Velocity Form PI

Every loop uses the velocity-form PID of Section 1.6.2, Equations (1.14) to (1.17), with the derivative time zero, so each of the three loops of this plant is a PI controller. The output bias u_b is zero, so the integral state starts at the actuator's initial value, and the tracking time of the back-calculation is $T_t = \tau_I$. The controller scan is $\Delta t = 0.1$ min and integration is fixed-step fourth-order Runge-Kutta at 0.02 min. The third PI loop, not drawn, holds the reactor at $T_{R,SP}$ with the jacket ($K_c = 3.0$, $\tau_I = 9$ min).

10.4.2 Mid-Ranging, and Its Sign

QC-701 holds the inferred viscosity on the bottom cut point. A wider cut keeps heavier molecules, so the viscosity rises with the cut and the loop takes the action $a = +1$, which is reverse acting in the convention of Section 1.6.2. Its gain is $K_c = 7.0$ carbons per cSt, its integral time $\tau_I = 30$ min and its output range 52 to 88 carbons.

MR-701 holds the cut point at its target by moving the reactor setpoint between 100 and 150 °C. The sign must be worked out rather than guessed, because the gain runs through QC-701. A hotter

reactor makes a lighter oil, so the viscosity controller answers a hotter reactor by opening the cut, and along the line of constant 6.00 cSt at the design point $\mathrm{d}C_H/\mathrm{d}T_R = +0.58$ carbons per degree. A cut point above its target therefore means the reactor is too hot and its setpoint must come down, which is a positive process gain and the action $a = +1$, a reverse acting controller in the convention of Section 1.6.2. The app's Mid-ranging action control uses the same convention: Reverse for this setting and Direct for the wrong sign. Its gain is 0.55 °C per carbon and its integral time is 180 min against the inner loop's 30, because two controllers acting on the same viscosity at similar speeds argue rather than cooperate [1]. What has to differ is closed-loop speed rather than integral time, and the reactor's hour of lag already slows MR-701, as Section 10.5 measures.

10.4.3 The Bias Update

The on-line viscometer answers in three minutes and fouls, reading about 0.02 cSt an hour high. The laboratory is exact and reports every seventy-five minutes on a sample drawn twelve minutes before, so the correction is a bias, Equation (10.7).

$$b \leftarrow b + \lambda \left(\nu_{lab} - \hat{\nu}\big|_{t-\tau_{lab}} \right), \qquad \hat{\nu} = \nu_{meter} + b \tag{10.7}$$

Because $\hat{\nu}$ carries the bias, Equation (10.7) is the laboratory update of Equation (1.11) with the raw meter in the place of the model, as long as the laboratory cycle is longer than the transport delay, so that no update falls between a sample and its report. Volume 5, Chapter 10 corrects a psychrometric soft sensor from a delayed laboratory in the same way. Two details decide whether such an update converges. The lab result describes a sample drawn $\tau_{lab} = 12$ min before it is reported, so it must be compared against what the controller believed then rather than against what it believes now, and against the corrected value rather than the raw meter, because comparing against the raw meter makes the corrections add up instead of converging. The gain $\lambda = 0.40$ is a compromise between injecting laboratory scatter into the product at $\lambda = 1$ and letting the drift outrun the correction at $\lambda = 0.1$ [2, 3].

🕮 **Pause.** Try Exercise 10.3 before reading on.

10.4.4 The Viscosity Index Cap

A one-directional override lowers the reactor setpoint when the laboratory viscosity index comes within 2.0 points of its minimum, to the operator's setpoint less 2.5 °C per point of shortfall. It can only lower, and it acts on the slow handle because the viscosity index is a property of what the reactor makes rather than of what the column keeps. The cap is computed before MR-701 runs and becomes MR-701's upper limit, so the back-calculation of Equation (1.17) unwinds the mid-ranging integral against it while it holds.

10.4.5 Model Predictive Control

An optional third structure, never the default, hands both handles to a quadratic program, set up as Section 1.6.3 describes for every app. Every $T_s = 2$ min from $t = 0$ it chooses the bottom cut C_H and the reactor setpoint request $T_{R,SP}$ over $N = 90$ steps (180 min) in twelve move blocks of $\{1, 1, 1, 1, 2, 2, 3, 4, 6, 9, 15, 45\}$ steps, sends only the first move, which stands until the next plan [9, 14]. The jacket loop, the cap below the request and every alarm stay as they are, and the plan acts only with the temperature and viscosity loops in Auto.

The controller's model is not the plant of Section 10.3. It is that plant's balances, linearized a single time about the design point using the declared parameter values, so a parameter changed in a run is mismatch the controller is not told about, and it sees the plant only through the corrected meter, the filtered reactor temperature and the laboratory index. In deviations from the design point, marked

by a tilde, it is Equation (10.8).

$$\begin{aligned}
\tau_J \dot{\tilde{T}}_j &= -\tilde{T}_j + \tilde{I}_T + K_T\left(\tilde{T}_{R,SP} - \tilde{T}_m\right) \\
\tau_{I,T} \dot{\tilde{I}}_T &= K_T\left(\tilde{T}_{R,SP} - \tilde{T}_m\right) \\
\tau_T \dot{\tilde{T}}_R &= \tilde{T}_j - (1-h)\,\tilde{T}_R, \qquad \tau_m \dot{\tilde{T}}_m = \tilde{T}_R - \tilde{T}_m \\
\tau_R \dot{\tilde{\alpha}} &= a_T\,\tilde{T}_R - \tilde{\alpha} \\
\tau_{col} \dot{\widetilde{\mathrm{KV}}} &= k_\alpha \tilde{\alpha} + k_H \tilde{C}_H - \widetilde{\mathrm{KV}} \\
\tau_{col} \dot{\widetilde{\mathrm{VI}}} &= v_T \tilde{T}_R + v_\alpha \tilde{\alpha} + v_H \tilde{C}_H - \widetilde{\mathrm{VI}}
\end{aligned} \tag{10.8}$$

Here T_j is the jacket temperature with lag $\tau_J = 2.5$ min, I_T the integral of the temperature PI at its commissioned $K_T = 3.0$ and $\tau_{I,T} = 9$ min, $\tau_T = 7$ min the reactor's thermal lag, $h = -0.0319$ the slope of the reactor-to-jacket temperature difference that the reaction heat sustains, and T_m the measured temperature behind its $\tau_m = 1$ min filter. Central differences of Equations (10.1) to (10.5) give $a_T = -0.00602$ per °C, $k_\alpha = 4.660$ cSt, $k_H = 0.0485$ cSt per carbon, $v_T = -0.55$ per °C, $v_\alpha = 21.44$ and $v_H = 0.199$ per carbon. Two constant output biases b_{KV} and b_{VI} complete nine states, the predicted outputs being $\nu = \widetilde{\mathrm{KV}} + b_{KV}$ and $\mathrm{VI} = \widetilde{\mathrm{VI}} + b_{VI}$, and an exact zero-order hold over T_s discretizes the model. A degree of request moves the steady viscosity $k_\alpha a_T = -0.0281$ cSt, the reactor gain of Section 10.3.

In step tests on the plant with the temperature loop closed, QC-701 and MR-701 open and no noise, read 270 min after a step at 60 min, ±2 °C of request gives −0.0281 and –0.0279 cSt per degree against the model's −0.0280, with root-mean-square residuals under 0.0002 cSt. The cut gain is local. Two carbons up moves the viscosity 0.0676 cSt per carbon and two down 0.0368 cSt, against the model's 0.0485, with residuals of 0.037 and 0.023 cSt, and the mean of the two is the 0.0522 cSt secant gain of Section 10.3.

The estimator propagates the jacket and catalyst lags from the controller's own applied commands, the distribution from the measured reactor temperature through Equation (10.2), and the viscosity and index through the declared correlations and the column lag at the applied cuts. The viscosity bias filters, over 12 min, the difference between the corrected meter $\hat{\nu}$ of Equation (10.7) that QC-701 uses and the model's viscosity. The index bias moves by 0.4 of each laboratory residual, taken against the index the model held when the sample was drawn. The two biases make the prediction offset free [15], and no future event or target is shown to the controller.

Each plan minimizes Equation (10.9) subject to Equation (10.10).

$$\begin{aligned}
J = &\sum_{k=1}^{N} q\,(\nu_k - \nu_{SP})^2 + p\,(\nu_N - \nu_{SP})^2 + \rho_\nu \varepsilon_\nu^2 + \rho_{VI} \varepsilon_{VI}^2 \\
&+ \sum_{j=1}^{12} \left[s_C\,\Delta C_{H,j}^2 + s_T\,\Delta T_{R,SP,j}^2 \right] \\
&+ r \sum_{k=1}^{N} \left(C_{H,k} - C_H^{tgt} \right)^2
\end{aligned} \tag{10.9}$$

$$\begin{aligned}
&52 \le C_{H,j} \le 88, \qquad 100 \le T_{R,SP,j} \le 150 \\
&5.70 - \varepsilon_\nu \le \nu_k \le 6.30 + \varepsilon_\nu, \qquad \mathrm{VI}_k \ge 130 + g - \varepsilon_{VI}
\end{aligned} \tag{10.10}$$

Here $q = p = 100$ per cSt^2, $s_C = 0.1$ per carbon squared and $s_T = 0.2$ per degree squared weigh the block moves, the first measured from the command applied now, and $r = 0.02$ per carbon squared prices each step the cut spends away from its target C_H^{tgt}. That term is the whole of the mid-ranging. An industrial valve position controller returns the fast handle with a slow integrating loop [1, 13],

Table 10.3 Scenario Sequence

#	Scenario	Teaching point
1	The plant makes a shape	the CV is a functional
2	Two ways to make the same number	the two routes differ
3	The fast handle	speed and cost
4	Where the handle ends up	integrators keep corrections
5	Mid-ranging	a loop on a loop's output
6	The sign that runs through another controller	no oscillation, wrong place
7	The meter that drifts	believing an instrument
8	Fast and wrong, slow and right	the bias update
9	What the viscosity controller cannot see	perfect control, bad product
10	The constraint, and how far to stand back	what margin is worth
11	The tank remembers	filtering quality
12	Mid-ranging as a weight	a loop or a price
13	Challenge: a day on a drifting plant	graded run

Table 10.4 Two Routes to 6.30 cSt

Route	VI	Yield (%)	PP (°C)
Reactor to 113.2 °C	138.5	51.0	−58.6
Cut out to 70.8 carbons	134.8	60.9	−56.6

and the plan replaces that loop by a price, while the reactor's displacement costs nothing. The input limits are hard and are the clamps the PI loops use. The bands are soft, with nonnegative slacks priced at $\rho_v = 1000$ and $\rho_{VI} = 100$ and the cap's guard g (2.0 points by default). Each output has a single slack shared by every step of the horizon, so a plan with zero slack is a forecast and not a guarantee at every step. The program has 26 variables and is solved by a dual active-set method. With no constraint active its first move agrees with independently formed normal equations to 3×10^{-14}.

A plan is applied only if it is optimal and its moves, predictions, cost and slacks are finite and inside their bounds. Otherwise the applied commands are held for that scan, the run is marked, QC-701 and MR-701 take over, and the next valid plan takes back control. Both PI loops track the applied cut and request while the plan acts. A failure forced from 300 to 306 min in scenario 12 with the noise off moves neither handle at the rejection, and the largest single-step moves during the fallback are 7.5×10^{-5} carbon and 5.3×10^{-5} °C.

10.5 Results

Thirteen scenarios run from the distribution to a graded challenge. Table 10.3 lists them with the names the app shows, where the challenge carries no number, and Section 1.6.4 describes how a scenario is run and scored.

10.5.1 Two Routes to One Number

Table 10.4 reports both ways of reaching 6.30 cSt in scenario 2, read at 180 min for the reactor route and at 480 min for the cut point route. In Manual nothing acts on the reactor setpoint, so the scenario cools the reactor through its jacket, from 93.6 to 81.9 °C.

Ten percentage points of yield against nearly four points of viscosity index, at 6.300 cSt and 6.298 cSt. Neither is wrong. They are different products and the choice belongs to whoever is selling the oil, and what is wrong is not knowing which one the plant just made.

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

Table 10.5 A More Active Catalyst Lot, at 600 min

Configuration	C_H	T_R (°C)	VI
Viscosity loop only	68.04	124.5	133.6
Mid-ranging, reverse acting	67.52	123.3	134.3
Mid-ranging, direct acting	69.14	127.7	131.8

TRY IT IN THE APP **2 · Two Ways to Make the Same Number**

Load the scenario and press Run. It runs in Manual, first cooling the reactor through its jacket, then returning it and opening the bottom cut instead. Watch the Viscosity index minimum / laboratory trend over about eight hours. Both moves take the oil to 6.30 cSt, and the index settles near 138.5 on the reactor route and 134.8 on the cut route.

10.5.2 Mid-Ranging and Its Sign

Table 10.5 reports a catalyst lot fifteen percent more active, with and without the outer loop, and with the outer loop signed the wrong way, all read 600 min into the run, just before the viscosity index cap first acts in the wrong-sign case. The action is named in the convention of Section 1.6.2, with the app's label of the Mid-ranging action control in parentheses.

Without the outer loop the cut point keeps its correction permanently, because an integrator moves error out of its measurement and into its output. With the outer loop correctly signed the cut is a third of a carbon from its target at 900 min (67.34) and within a sixth of a carbon (67.16) by 1400 min, with the reactor at 122.7 °C carrying the disturbance.

Pause. Try Exercise 10.2 before reading on.

Equal integral times do not make the two loops argue here, because the reactor's lag already slows MR-701. At $\tau_I = 30$ min the cut point undershoots by 0.08 carbon and stays within 0.02 of its target after 745 min, sooner than at 180. Only the 10 min slider minimum produces a cycle, about 380 min long, with the cut between 66.74 and 67.15 carbons and the reactor between 121.6 and 123.1 °C.

With it signed the wrong way the reactor walks 4.5 °C hotter than the correct sign puts it and the viscosity index sits 1.8 points from its minimum instead of 4.3. The viscosity ripples by 0.06 cSt and never leaves its band. What stops the walk is the cap, not the controller. Each time the laboratory index falls inside the cap's guard, on every third result from 600 min, the cap pulls the setpoint to about 124 °C, and the wrong sign walks it back. For the rest of the day the reactor cycles between 123.2 and 127.6 °C, the index in the line stays above 131.7 and nothing is downgraded. A sign error running through another controller does not announce itself, and here the protection does the controller's work.

DID YOU KNOW? **A Wrong Sign That Does Not Oscillate**

From the simulator: a wrong sign is usually pictured as an oscillation, but here it is a quiet walk. At 600 min (Table 10.5) the wrongly signed loop holds the reactor at 127.7 °C against 123.3 °C and the viscosity index at 131.8 against 134.3, while the viscosity never leaves its band.

10.5.3 Perfect Control and a Bad Product

Table 10.6 reports a column that loses cut sharpness at 60 min, with and without the two protective layers, after the 1400 min day the scenario runs.

The viscosity loop does its job perfectly and the plant makes a hundred and fifty tonnes of downgraded oil. The blurred cut takes the dimer in the product from 1.45 to 9.1 %, which pulls the viscosity down, and the controller puts it back by opening the bottom cut six carbons without removing one molecule of dimer. Viscosity index is not made of viscosity.

Table 10.6 A Column That Loses Cut Sharpness

Configuration	KV (cSt)	C_H	VI	Downgraded (t)
Viscosity loop alone	6.000	73.9	129.4	163.5
Mid-ranging and VI cap	6.004	67.7	133.5	5.4

Table 10.7 Yield Is Bought With Viscosity Index at Constant Viscosity

T_R (°C)	Yield (%)	VI
120	53.6	136.2
124.5	57.3	133.6
128	59.7	131.7
130	61.0	130.5

The mid-ranging loop does the protective work in this case. Armed alone it gives the same 5.4 t and 133.5, because returning the cut toward 67 cools the reactor to 115.3 °C, below the isomerization onset. The cap alone leaves 58 t downgraded. It is proportional to the laboratory shortfall and releases as soon as a laboratory result is back above its guard, so the reactor alternates between 124.5 and 117.5 °C on a cycle of about 300 min and the index in the line drops below 130 in every one.

> **TRY IT IN THE APP 9 · What the Viscosity Controller Cannot See**
>
> Run the scenario for a day. The Product viscosity trend stays on 6.000 cSt while the Bottom cut point opens to 73.9 carbons, the index falls to 129.4 and 163.5 t are booked off specification. Reset, switch on Viscosity index cap and Mid-ranging (cut → reactor) before the column fouls at 60 min, and run again: 5.4 t.

A controller in perfect control is not evidence that the plant is well. It is evidence that one measurement is where it was put, and the more tightly it is held the less that measurement can say.

10.5.4 The Drifting Meter

With the bias update off, a fouling viscometer leads the controller to hold the meter within 0.023 cSt of 6.00 cSt for the first 525 min while the real oil falls to 5.865 cSt. By then MR-701 has warmed the reactor to bring the falling cut point back, the laboratory index has dropped inside the cap's guard, and the cap starts pulling the setpoint down. From there the reactor moves between 116.2 and 129.8 °C and the meter stays within 0.073 cSt of its setpoint. At 1400 min the real oil is at 5.540 cSt, well outside the band, the viscosity index is 129.9, and 40 t are downgraded with an indication that never looked wrong.

With the update on, the true viscosity holds at 5.945 cSt and nothing is downgraded. The remaining five hundredths is a ramp-following offset, because the meter drifts continuously and the correction arrives in steps. The scenario has no laboratory scatter, so $\lambda = 1$ does better, at 5.984 cSt, while $\lambda = 0.1$ lets the oil sag to 5.77 cSt by 1350 min, inside the band, with nothing downgraded.

10.5.5 The Back-Off

Table 10.7 reports the line of constant 6.00 cSt viscosity with the cut point moved to match each reactor temperature.

The specification minimum is 130, so there is a cliff at about 131 °C. The arithmetic either side of it is wildly asymmetric. A percentage point of yield moves roughly 0.12 t/h from the bright stock tank into the motor oil tank and is worth about sixty dollars an hour. Crossing the viscosity index specification downgrades the entire motor oil production, about seven tonnes an hour at fifteen hundred dollars of lost value, which is about eleven thousand dollars an hour. The gradient toward the constraint is tens of dollars per degree and the cliff is thousands.



Figure 10.2 The synthetic base oil application at $t = 1400$ min of scenario 9, What the viscosity controller cannot see, with the viscosity loop in automatic, the mid-ranging loop and the viscosity index cap off, and the column cut sharpness tripled at 60 min, cropped to the plant view, its status chips and its alarm strip. (1) The status chips: the viscosity is 6.000 cSt in the line and in the tank, the cut has opened to 73.9 carbons, and 163.5 t are booked off specification. (2) The reactor and what it is making. (3) The chain length distribution drawn as bars by carbon number with the two cut points as dashed lines across it, so that moving a cut changes the color of the bars and not their height. Below it are the three product tanks with their rates and their own viscosities. (4) The meter, the bias, the laboratory result and the viscosity index, 129.37 against its minimum of 130. (5) The inset plots viscosity index against reactor temperature along the line of constant viscosity with the specification minimum marked.

The cliff is also invisible. Viscosity index is a laboratory number that is twelve minutes old when it arrives and eighty-seven minutes old when the next one replaces it, on a plant whose reactor takes thirty-eight minutes to respond, so anything done now is committed for about two hours before the plant can be told it was a mistake. That is what sets the back-off, and the number comes from the measurement rather than from the tuning.

10.5.6 The Graded Challenge

The challenge runs twenty hours with a catalyst lot change at 90 min, a fouling viscometer from 300 min, a rate increase to 13.5 t/h at 520 min and a loss of cut sharpness at 700 min, under viscometer noise and laboratory scatter. It starts with cautious tuning, three of the five structural decisions switched off and the reactor at 128 °C. It is met when the viscosity in the line stays within 0.10 cSt of target from 792 min, the last third of the run, the viscosity index in the line stays above 130 throughout, and less than five tonnes are downgraded. As loaded the run fails all three parts. The worst viscosity error from 792 min is 0.299 cSt, the lowest index 127.9 and 63.7 t are downgraded. With the suggested configuration, which also starts the reactor at 124.5 °C, the worst error is 0.084 cSt, the lowest index 131.2 and nothing is downgraded, so the target is met by 0.016 cSt on the viscosity. The app gives the same run whether the configuration is revealed before Run or carried through Reset. The noise seed is fixed, and 11 other seeds give 0.077 to 0.093 cSt, all passing. No part of the configuration is spare. Leaving out any one of the bias update, mid-ranging, the cap, the 124.5 °C

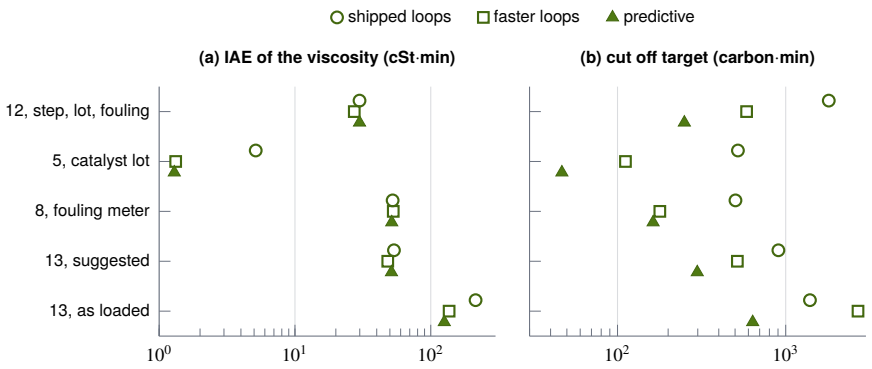


Figure 10.3 Table 10.8 drawn on logarithmic axes, one row per case. (a) The integral of the absolute viscosity error. (b) The time the cut spends away from its target, in carbon·min. Notice that the predictive controller (filled triangles) holds the cut closest to its target in every case, while on viscosity error it trails the faster loops (open squares) in two of the five cases.

start or the faster tuning fails, and the structural changes without the faster tuning leave a 0.196 cSt error.

10.5.7 Comparison With Model Predictive Control

Table 10.8 runs three structures for 1200 min on each case: the shipped loops at their shipped tuning, the same loops faster (QC-701 at $K_c = 14.0$ carbons per cSt and $\tau_I = 14$ min, MR-701 at $\tau_I = 30$ min), and the plan with the settings of scenario 12. Each triple shares its initial state, seed, instruments, noise and events, and neither structure is shown a disturbance or target in advance. The faster tuning is one stated setting, not an optimized bound on classical control. Scenarios 5 and 8 are the catalyst lot and the fouling meter above, run here to 1200 min, and the challenge runs as loaded and with its suggested configuration. Figure 10.3 draws the viscosity error and the cut's distance from its target of every row.

Scenario 12 raises the viscosity target from 6.00 to 6.20 cSt at 60 min, brings a catalyst lot fifteen percent more active at 360 min and starts the meter fouling at 600 min, without noise and with every structural element of the loops armed at the shipped tuning. The plan answers the step with both handles at once. It opens the cut to 73.12 carbons by 64.1 min and takes the request down to 115.18 °C by 84.1 min, so the viscosity reaches 6.18 cSt 7.8 min after the step against 110 min under the loops, and then overshoots to 6.254 cSt at 78 min, 27 percent of the step. From 116 min the cut stays within 0.2 carbon of its target to the catalyst lot. Under the loops the cut is still 2.04 carbons out at 240 min, with the request at 122.31 °C, as shown in Figure 10.4.

Over the whole 1200 min the viscosity error is a tie, 29.889 against 29.886 cSt · min, and the faster loops beat both at 27.341. Divided at the events, the plan wins the step (4.63 against 9.24 from 60 to 360 min, 2.50 faster) and loses the fouling (23.67 against 19.13 from 600 to 1200 min, 24.04 faster). Between 64 and 88 percent of each total accrues after the meter starts fouling, where all three end 0.052 to 0.060 cSt low, the ramp-following offset of the shared bias update. With half the integration step the totals are 29.968, 29.893 and 27.321, and with the challenge's instrument noise on eight other seeds the plan is below the shipped loops on five, with means of 29.71, 30.49 and 29.34, so the faster loops lead and the other two are not separated.

What the price buys is centering. The cut spends 249.7 carbon·min away from its target against 1803.7 and 585.5, and 275 to 312 against 1766 to 1832 under noise. The plant pays with the largest excursion, 6.12 carbons against 2.16 and 3.20, and with three and almost four times the shipped loops' travel, 18.65 carbons of cut and 21.85 °C of request. One likely cause of the excursion and the

Table 10.8 Shipped Loops, Faster Loops and Model Predictive Control Over 1200 min, Seed 20260923

Case	Structure	IAE KV	Cut off target	Peak cut off	Cut travel	Request travel	Down-graded	Lowest VI	Plans, fallbacks
12, target step, catalyst lot, fouling meter	shipped loops	29.886	1803.7	2.16	6.10	5.90	0	133.63	—
	faster loops	27.341	585.5	3.20	12.06	13.32	0	133.63	—
	predictive	29.889	249.7	6.12	18.65	21.85	0	133.62	600, 0
5, catalyst lot	shipped loops	5.141	519.9	0.72	1.24	1.71	0	133.57	—
	faster loops	1.323	111.5	0.70	1.41	2.05	0	133.60	—
	predictive	1.292	46.7	0.50	1.02	2.09	0	133.58	600, 0
8, fouling meter	shipped loops	52.396	502.7	0.76	4.78	4.12	0	132.45	—
	faster loops	52.946	178.5	0.51	10.44	8.15	0	132.27	—
	predictive	51.611	162.8	0.27	12.29	14.67	0	132.22	600, 0
13, suggested	shipped loops	53.576	904.8	1.81	21.07	13.99	0	131.17	—
	faster loops	48.240	515.9	2.96	43.16	26.04	0	131.53	—
	predictive	51.361	298.0	2.60	21.15	26.20	0	131.26	600, 0
13, as loaded	shipped loops	213.852	1393.7	1.83	5.53	0.00	67.28	127.90	—
	faster loops	136.523	2690.9	4.33	39.95	0.00	68.30	127.95	—
	predictive	125.788	636.4	9.04	39.71	31.07	3.80	129.44	600, 0

Shipped and faster are the PI loops at the two tunings of the text, and predictive is the plan. IAE is the integral of the absolute difference between the viscosity target and the true viscosity in the line, in cSt · min, the definition of the application's scorecard. Cut off target integrates $|C_H - C_H^{tgt}|$, in carbon·min, and peak cut off is its largest value, in carbons. Travel sums the absolute changes of the logged cut, in carbons, and request, in °C. Downgraded oil is in tonnes. The challenge's worst viscosity error in its last third is 0.084, 0.067 and 0.074 cSt with the suggested configuration, all passing, and 0.299, 0.291 and 0.251 cSt as loaded, all failing. A plan took 0.31 to 0.38 ms on average in Node.js on the machine that ran the table.

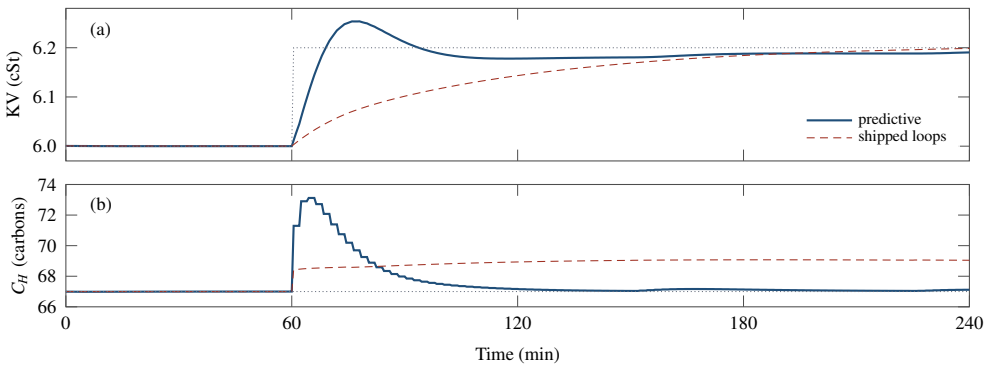


Figure 10.4 Viscosity and bottom cut in the first 240 min of scenario 12, with the plan (thick solid line) and with the shipped loops (dashed) in control. (a) True viscosity in the line against the target (dotted), which steps from 6.00 to 6.20 cSt at 60 min. (b) Bottom cut point against its 67 carbon target (dotted).

overshoot is the local cut gain, since the model understates the plant's answer to two carbons up by 28 percent.

Taking the price away shows what it is for. With $r = 0$ and every other setting of scenario 12 unchanged, the 1200 min run gives the lowest viscosity error of the three, 28.7 against 29.9 with the price and 29.9 under the shipped loops, and the least request travel, 5.3 °C against 21.8 and 5.9 °C. The cut then spends 2564 carbon·min away from its target against 250 with the price and 1804 under the loops. Without the price nothing returns the fast handle, so the plan leaves each correction in the cut, as the viscosity loop alone does in scenario 4, and the range the cut has used is gone when the

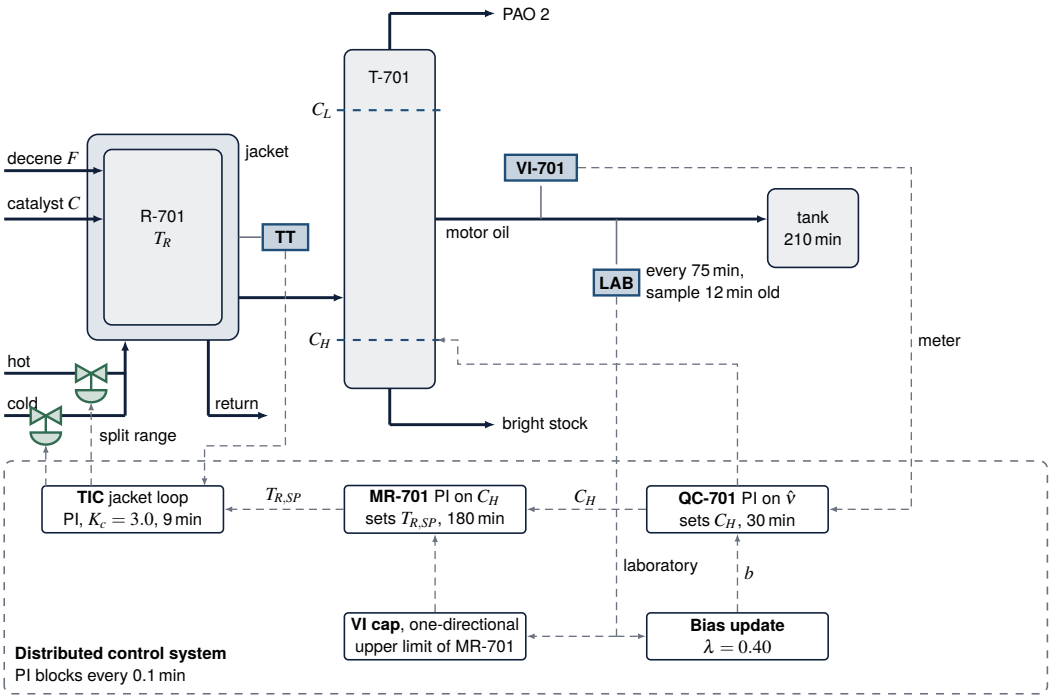


Figure 10.5 The loops of the base oil plant drawn with their hardware. The viscometer VI-701 on the motor oil line and the laboratory feed QC-701 through the bias update, QC-701 sets the bottom cut C_H, MR-701 reads the cut and moves the reactor setpoint under the viscosity index cap, and the jacket loop holds the reactor through split-ranged hot and cold water valves. Notice that MR-701 has no transmitter of its own: its measurement is another block's output. The split-ranged valves are one real form of the jacket the model lumps into a lag. The top cut, the catalyst and the optional predictive controller are left out.

next disturbance asks for it.

On the catalyst lot of scenario 5 the plan has the lowest error, 1.292 against 5.141 and 1.323, and the cut closest to its target, 46.7 against 519.9 and 111.5 carbon·min, although the faster loops alone come within 2.4 percent of its error. On the fouling meter of scenario 8 the errors lie within 2.6 percent of one another and the plan moves most, 12.29 carbons and 14.67 °C against 4.78 and 4.12. With the suggested configuration of the challenge all three pass.

The challenge as loaded is not like-for-like, and the plan fails it. The loaded loops have cautious gains with mid-ranging, the bias update and the cap off, while the plan prices the cut's distance and holds a soft index floor, so it supplies structure they lack. It also reads the uncorrected meter and predicts a temperature loop at 3.0 and 9 min that runs at 1.0 and 25 min. It downgrades 3.80 t against 67.28, but the index falls to 129.44 and the viscosity is 0.251 cSt off in the last third, failing two of three parts with an index slack of 0.50. The faster gains on the loaded structure still downgrade 68.30 t and the loops with the suggested structure none, so the reduction measures the missing structure rather than prediction. No plan was rejected in any run, nor in any of the thirteen scenarios run 1200 min under the plan.

10.6 Technology in Practice

The loops of Section 10.4 run on real instruments, valves and a control system, drawn together in Figure 10.5. This section names them and says what each one does in service.

What Measures It

The viscosity has two measurements of different kinds. The on-line viscometer VI-701 reads the oil continuously in the line. The laboratory measures the kinematic viscosity by ASTM D445 and calculates the viscosity index by ASTM D2270 from the kinematic viscosities at 40 and 100 °C, and the pour point has a test method of its own [16]. That is why the index exists in this chapter only as a laboratory number.

> **TECHNOLOGY** **Sensor: An In-Line Viscometer**
>
> An in-line viscometer measures the oil without drawing a sample. A rotational type turns a spindle and reads the shear stress, a pipe type reads the pressure drop along a straight pipe, and a vibrating type infers viscosity and density from the amplitude and frequency of a vibrating fork and sends both on a 4 mA to 20 mA signal [17]. A vibrating element responds to the product of density and viscosity [18], so the kinematic viscosity of a specification needs the density as well [19]. In field trials a rotational unit plugged with solids and read consistently above the standard bench instrument, and a vibrating unit was checked against manual readings at the start of every shift [17]. No range or accuracy is given here because no open, vendor-neutral source states one.

In the model the meter is a 3.0 min lag that fouls and reads 0.020 cSt/h high, and the laboratory reports every 75 min on a sample drawn 12 min earlier, exact apart from a repeatability term.

What Moves It

The fast handle is the bottom cut point. The model treats it as a number of carbons that the product follows in 14 min and does not name the column hardware that moves it, so this section describes the slow handle's hardware. The reactor temperature loop drives the jacket, which the model holds as a 2.5 min lag between 40 and 150 °C.

> **TECHNOLOGY** **Final Element: Split-Ranged Jacket Valves**
>
> A reactor that must be heated or cooled can take hot or cold water into one jacket through two valves driven by one controller. With exclusive sequencing both valves are shut at half output, the cooling valve opens over the lower half of the signal and the heating valve over the upper half, so water flows through one or the other but never both. Each valve fails in the position safest for the process: in the textbook example the heating valve fails closed and the cooling valve fails open, so a lost signal or lost instrument air gives full cooling [19]. On this plant full cooling makes a heavier oil, and QC-701 would answer by closing the bottom cut.

Where the Controller Runs

A distributed control system holds this structure. Its loops may be nested so that the setpoint of one comes from another, at cycle times from milliseconds to minutes [20]. A valve position controller is normally a PID block and can be built on any such system [12, 13]. In this chapter every PI loop runs every 0.1 min, the bias moves on each laboratory report, and the optional predictive controller plans every 2 min. MR-701 reads QC-701's output rather than a transmitter, and the cap enters as MR-701's upper limit before it runs.

> **IN PRACTICE** **Tuning the Slow Loop of a Mid-Ranging Pair**
>
> Most mid-ranging controllers in plants are valve position controllers, and their tuning has been largely ad hoc [13]. A published rule of thumb keeps the response of the fast input an order of magnitude faster than that of the slow one, to avoid exciting cross-coupling and driving the slow input into its limits [12]. The slow controller is traditionally integral-only and tuned slow. Its target need not be mid-range: on a paper mill feed line, a valve in series with a variable-speed pump is held near 90 percent open, to save pump energy yet keep room to reject disturbances [11].

What Is Modernizing It

Three developments bear on this loop. The first is on-line measurement: the demand to measure and manage viscosity on line is growing [18], and where properties are mainly measured in a laboratory, real-time instruments are sought because the laboratory hinders real-time optimization and decisions [17]. The second is the soft sensor. A data-driven estimate must be maintained and tuned on a regular basis, and most still have no automated mechanism for it [2], which is the work the bias update of Equation (10.7) does on one number. The third is model predictive control, with a solid foundation in refining and petrochemicals [9]. A multivariable controller can produce the mid-ranging effect directly [12], and the plan of Section 10.5.7 does so with a price on the cut's distance from its target.

10.7 Limitations

The distribution is Schulz-Flory with one parameter, which is broader than a real metallocene product [6], and the oligomers are lumped by carbon number with a single tail lump.

The column is two logistic cut points rather than a tray model, so the cut sharpness is a disturbance rather than a consequence of reflux, and the application cannot show what a column operator would actually do about it.

Viscosity index and pour point are fitted correlations. A reader would not learn here how either is measured or why the correlations are difficult, and the absolute values carry less meaning than their changes [5].

Hydrogenation is absent and the catalyst does not deactivate, so a campaign has no history and the slow drifts a real plant manages are represented only by the explicit disturbance sliders.

The laboratory is exact apart from a repeatability term. A real laboratory has systematic differences between analysts and between instruments, which is the harder half of maintaining a bias update [2].

The predictive controller keeps its design-point linearization and the commissioned temperature tuning whatever the plant does. The plant moves 39 percent more than its cut gain for two carbons up and 24 percent less for two down, and a catalyst lot, a loss of cut sharpness or a retuned temperature loop reaches it only through the two output biases. It omits the 3 min viscometer lag, the jacket's 40 to 150 °C limits and the cap, and its objective leaves out the tank, the pour point and the side products. Its index is corrected by laboratory results up to 87 min old. On its own scenario it ties the shipped loops and loses to a faster tuning, 29.889 against 27.341 cSt · min.

Finally, the economic trade between yield and viscosity index is left to the reader rather than to an optimizer [9], and the plantwide question of which stream carries which specification is posed rather than answered [10].

> **OPEN CHALLENGE** **Tuning Two Handles of Different Speed**
>
> Tuning the slow controller of a mid-ranging pair has long rested on trial and error. A 2003 study named the lack of a systematic procedure, a 2013 application found the tuning not straightforward, and a 2025 method that turns the pair into one PI loop covers only inputs with identical dynamics and different gains [11]. Anti-windup for the moment the fast input saturates was said to need further attention in 2005 [12]. The reactor and the cut of this chapter differ in speed, not only in gain. Progress would be a rule that takes the speed, the sign and the limits of both handles and returns settings a plant can commission without hours of field tests.

10.8 Discussion

Three results generalize past base oils.

The first is the pairing rule for one controlled variable with two manipulated variables of different speeds. Control with the fast one, because control needs speed, and position it with the slow one, because the slow one is the one that costs something. The outer loop's measurement is then another controller's output, which is the defining feature of mid-ranging and the source of its characteristic

sign error [1]. Working that sign out on paper is worth doing, because the field test is slow and the primary measurement never moves.

> **DID YOU KNOW? The Same Loop in a CD Player**
>
> Mid-ranging is not confined to process plants. A 2005 study names it as a key idea in positioning the pickup head of a CD player [12], and a 2025 paper lists uses from paper machines, separators and bioreactors to drug delivery and cryogenic systems [11].

The second is that tight control of one variable can conceal the failure of another. The measured case here is a viscosity held at exactly 6.000 cSt while a hundred and fifty tonnes are downgraded on viscosity index in a day. The defense is not a better viscosity loop. It is to watch the manipulated variable, because the cut point is three carbons from where it lives 29 min after the column fouls, an hour before the laboratory reports the first low viscosity index at 150 min.

The third is that the distance a plant keeps from a constraint is a design variable with a price on it, and the price is set by the age of the measurement. With laboratory results up to eighty-seven minutes old and a thirty-eight minute reactor, this plant is committed for two hours before it can be told it was wrong, and the back-off has to cover that. The value of a faster measurement is exactly the back-off it removes, which is a number an engineer can compute and put in a proposal.

10.9 Conclusion

A base oil plant makes a distribution, and the specification is three functionals of it. In the simulated plant of this chapter both the reactor and the column cut point reach 6.30 cSt from the design point, and the two oils differ by 3.7 points of viscosity index and 9.9 points of yield. The cut point moves viscosity by 0.0522 cSt per carbon in fourteen minutes and the reactor by −0.0281 cSt per degree in fifty-two, so the cut point controls and the reactor positions it. Mid-ranging returns the cut to within a sixth of a carbon of its target, and the same loop signed the wrong way walks the reactor 4.5 °C hotter in ten hours, with the viscosity trend showing nothing, until the viscosity index cap catches it. A column that loses cut sharpness is corrected to exactly 6.000 cSt by opening the cut six carbons and downgrades 164 t on viscosity index in a day, against 5 t with the mid-ranging loop and the viscosity index cap armed. A fouling viscometer takes the true oil to 5.540 cSt without a bias update and holds 5.945 cSt with one. A predictive controller that does the mid-ranging with a price ties the loops on viscosity error (29.889 against 29.886 cSt · min) and keeps the cut 249.7 rather than 1803.7 carbon·min from its target, at three to four times the movement of both handles. Further work would add a tray model so that cut sharpness becomes a consequence rather than a disturbance, a moment model for the distribution breadth, catalyst deactivation over a campaign, a laboratory with systematic as well as random error, and an optimizer for the yield against viscosity index trade. The base oil plant is a browser platform for learning what a second handle is for.

KEY POINTS

- A base oil plant makes a distribution, and its specification is three properties of it.
- The cut acts in fourteen minutes and the reactor in fifty-two, so the cut controls and the reactor positions it.
- Signed the wrong way, mid-ranging walks the reactor 4.5 °C hotter with a flat viscosity trend.
- A viscosity held at exactly 6.000 cSt can hide 164 t downgraded on viscosity index in a day.
- The back-off from a laboratory-measured limit is set by the age of the measurement, not the tuning.

Where else this applies. Mid-ranging in Volume 4, Chapter 10, and a laboratory-corrected soft sensor in Volume 5, Chapter 10.

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10.10 Exercises

10.1 Concept check · 2 min

From the design point, the motor oil cut is moved from 6.00 to 6.30 cSt twice: once by cooling the reactor and once by opening the bottom cut. Which statement matches the two oils the model makes?

(a) The reactor route has the higher viscosity index and the lower yield
(b) The cut route has the higher viscosity index and the higher yield
(c) Both routes give the same viscosity index, because it follows the viscosity
(d) The reactor route has the lower viscosity index and the higher yield

10.2 Concept check · 1 min

In scenario 3, the viscosity loop alone absorbs a catalyst lot fifteen percent more active and returns the viscosity to 6.000 cSt. Mid-ranging is off. Where is the disturbance fifteen hours later?

(a) In the reactor temperature, which the viscosity loop has lowered by about a degree
(b) In the bottom cut point, which stays about a carbon above its 67-carbon target
(c) In the viscosity, which settles a few hundredths of a centistoke below target
(d) Nowhere, because the integral action has removed it from the plant

10.3 Concept check · 2 min

A laboratory viscosity is reported at time t for a sample drawn at $t - 12\,\text{min}$. The on-line meter drifts steadily. Against which value must the bias update compare the laboratory result so that the bias converges to the meter's own error, whatever the plant does in those twelve minutes?

(a) The raw meter reading at t, when the result arrives
(b) The raw meter reading at $t - 12\,\text{min}$, when the sample was drawn
(c) The corrected meter value the controller held at $t - 12\,\text{min}$
(d) The corrected meter value the controller holds at t

10.4 Theory and calculation · 4 min

Equation (10.1) gives the mass fraction of the n-mer. At the design propagation probability $\alpha = 0.633$ the model puts 19.7 % of the mass in dimer.

(a) Show that the ratio of the mass fractions of two successive oligomers is $w_{n+1}/w_n = \alpha\,(n+1)/n$. *Checkpoint:* $w_{n+1}/w_n = \alpha(n+1)/n$

(b) From the dimer fraction, compute the trimer and tetramer mass fractions to one decimal place (the key accepts ± 0.1 point). *Checkpoint:* 18.7 % and 15.8 %

10.5 Theory and calculation · 6 min

At the design point the reactor runs at 124.5 °C with $\alpha = 0.633$ and $E/R = 4100\,\text{K}$ in Equation (10.2). At fixed cuts the steady viscosity moves $k_\alpha = 4.660\,\text{cSt}$ per unit of α, and the local cut gain is $k_H = 0.0485\,\text{cSt}$ per carbon.

(a) Differentiate Equation (10.2) with respect to T_R at fixed catalyst and evaluate $a_T = \mathrm{d}\alpha/\mathrm{d}T_R$ at the design point, to three significant figures. *Checkpoint:* $a_T = -0.00602$ per °C

(b) Compute the steady reactor gain $k_\alpha a_T$ and the reactor cooling it predicts for a rise of 0.30 cSt, to one decimal place. *Checkpoint:* −0.0281 cSt per °C, about 10.7 °C

(c) With QC-701 holding the viscosity, find the slope $\mathrm{d}C_H/\mathrm{d}T_R$ along the line of constant viscosity, to two decimal places. State the action a MR-701 needs and name it in the convention of Section 1.6.2. *Checkpoint:* +0.58 carbons per °C, $a = +1$, reverse acting

10.6 Theory and calculation · 8 min

The viscometer drifts high at $\rho = 0.020\,\mathrm{cSt/h}$. The laboratory is exact, reports every $\theta = 75\,\mathrm{min}$ and each result describes a sample drawn $\tau_{lab} = 12\,\mathrm{min}$ earlier. QC-701 has integral action, so over a laboratory cycle it holds the average of the corrected meter $\hat{v} = v + D + b$ at the setpoint, where v is the true viscosity and D the accumulated drift.

(a) Let $e_k = D(t_{s,k}) + b_{k-1}$ be the error of the corrected meter at the k-th sampling instant. Use Equation (10.7) to show that $e_{k+1} = (1-\lambda)e_k + \rho\theta$, and find the settled e for $\lambda = 0.40$ to three decimal places. *Checkpoint:* $e = \rho\theta/\lambda = 0.0625\,\mathrm{cSt}$

(b) Show that the average of $D + b$ over a cycle is $(1-\lambda)e + \rho(\tau_{lab} + \theta/2)$, and predict the average true viscosity for a setpoint of 6.00 cSt at $\lambda = 0.40$ and at $\lambda = 1$, to three decimal places. *Checkpoint:* 5.946 cSt and 5.984 cSt

10.7 App challenge · 8 min

Load scenario 2, Two ways to make the same number, as shipped (Manual, default seed). Run it to at least 480 min at the default speed of 20 min per second, then export the CSV, whose time column is in hours.

(a) In the row at 3 h (180 min, the reactor route), read `kv_cst` to three decimal places and `vi_true`, `yield_pct` and `tr_C` to one (key ±0.1). *Checkpoint:* 6.300 cSt, VI 138.5, 51.0 %, 113.2 °C

(b) In the row at 8 h (480 min, the cut route), read the same three properties. *Checkpoint:* 6.298 cSt, VI 134.8, 60.9 %

(c) Explain in two sentences which term of Equation (10.5) makes most of the difference in viscosity index, and why the cut route gains yield. *Checkpoint:* the isomerization term, the cut moves mass between tanks

10.8 App challenge · 8 min

Run scenario 5, Mid-ranging, and scenario 6, The sign that runs through another controller, each as shipped at the default seed. Scenario 6 differs from scenario 5 only in the Mid-ranging action control, which it sets to Direct. Run each to 1440 min at 60 min per second and export the CSV (time in hours).

(a) In the row at 10 h (600 min) of each file, read `cut_h` (key ±0.02 carbon), `tr_C` and `vi_true` (key ±0.1). *Checkpoint:* scenario 5: 67.52, 123.3 °C, 134.3, scenario 6: 69.14, 127.7 °C, 131.8

(b) In the scenario 6 file, find the lowest and highest `kv_cst` over the whole day. Does the true viscosity ever leave its 5.70 to 6.30 cSt band? *Checkpoint:* about 5.97 to 6.03 cSt, no

(c) Name the action of MR-701 in each scenario in the convention of Section 1.6.2, and say which layer stops the walk in scenario 6. *Checkpoint:* 5: $a = +1$, reverse acting, 6: $a = -1$, direct acting, the viscosity index cap

10.9 App challenge · 9 min

Load scenario 9, What the viscosity controller cannot see, as shipped (default seed): the viscosity loop is in Auto, mid-ranging and the viscosity index cap are off, and the column loses cut sharpness at 60 min.

(a) Run to 1400 min at 60 min per second and export the CSV. In the row at 1400 min (23.333 h), read `kv_cst`, `cut_h`, `vi_true` and `metric_offspec_t`, the last to one decimal place (key ±0.1). *Checkpoint:* 6.000 cSt, 73.9 carbons, 129.4, 163.5 t

(b) Press Reset, set Viscosity index cap and Mid-ranging (cut → reactor) to On before Run, and run to 1400 min again. Read `metric_offspec_t`, `vi_true` and `tr_C` in the same row (key ±0.1). *Checkpoint:* 5.4 t, 133.5, 115.3 °C

(c) The chapter reports that the cap alone still downgrades 58 t. Explain in two sentences why the cap does so much worse than mid-ranging on this disturbance. *Checkpoint:* the cap waits for the laboratory and releases at once, mid-ranging acts on the cut point

10.10 Application area · 4 min

The app's economics put the motor oil cut $500 per tonne above the bright stock and a downgraded tonne $1500 below on-specification motor oil. The plant takes 12.0 t/h of decene at a yield of 57.4 %.

(a) What is one percentage point of yield worth per hour, and what does an hour of downgraded motor oil cost? Give both to two significant figures. *Checkpoint:* about $60 per hour and about $10,000 per hour

(b) How many hours of one extra point of yield pay for one hour off specification, and what sets how far the reactor should stay from the viscosity index limit? *Checkpoint:* about 170 h, the age of the laboratory result and the reactor lag

10.11 Application area · 3 min

The product tank turns over in 210 min. Treat it as a first-order filter on the viscosity in the line. A bottom cut left four carbons wide lifts the line to about 6.30 cSt from 6.00 cSt.

(a) What fraction of that rise reaches the tank if the excursion lasts 40 min, and if it lasts 400 min? Give two decimal places. *Checkpoint:* 0.17 and 0.85

(b) Which disturbances does the tank hide from the customer, and which does it pass on? *Checkpoint:* it hides short upsets and passes slow drifts

10.12 Review the agent · 5 min

An AI assistant reviewing the mid-ranging loop writes: "A valve position controller must be much slower than the loop it watches, so its integral time should be at least five times the inner loop's. MR-701 at 180 min against QC-701's 30 min is right, and setting it to 30 min would make the two loops fight over the viscosity and cycle." Find the flaw and say how to check it in the app.