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CHAPTER 7

Amine Capture Plant Simulator for Recycle Gain and the Scheduling of Regeneration Energy

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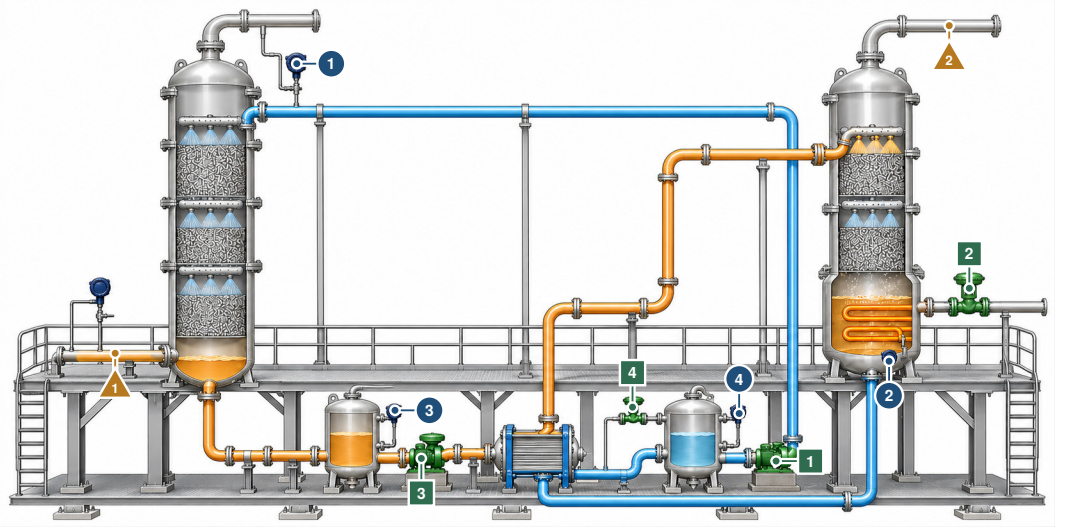
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CHAPTER 7

Amine Capture Plant Simulator for Recycle Gain and the Scheduling of Regeneration Energy



The controller moves 1 lean solvent circulation pump 2 reboiler steam valve 3 stripper feed pump 4 amine makeup valve

The controller reads 1 capture analyzer on the treated gas 2 reboiler temperature 3 rich tank level 4 lean tank level

What disturbs it 1 host load, which sets the flue gas 2 stripper pressure drift

Notice that the solvent leaving the absorber passes the stripper and both tanks before it returns, so a change of circulation comes back to the absorber about seventy minutes later. Illustration, not to scale.

IN PLAIN TERMS **A Cleaning Liquid That Comes Back Round**

The main idea. A capture plant washes the smoke of a coal power station with a liquid that soaks up carbon dioxide. Steam from the station then boils the gas out, and the liquid flows back to wash again about seventy minutes later.

The challenge. More liquid catches more gas at first, but unless the steam rises too, the liquid returns less clean and the gain fades. Nobody measures how clean the liquid is, and the reading used in its place can be fooled.

Why it matters. Steam spent on the liquid is power the station cannot sell, so when to spend it is worth real money.

THREE WAYS TO READ THIS CHAPTER

Explore	13 min	the first page; the history boxes of Section 7.2; the fact box and the try-it box of Section 7.3; the fact box and the try-it box of Section 7.6; the key points
Study	65 min	the whole chapter with its pause points and the exercises
Practice	20 min	the first page; Section 7.6 with its result chart; Section 7.7; Section 7.8; the open challenge of Section 7.9

The control question A capture plant's solvent takes seventy minutes to come back round its circuit, so every move of the circulation acts through a recycle. What sets the gain of the capture loop, and when should the regeneration energy, bought out of the host station's saleable output, be spent?

Learning objectives

- Explain why the capture gain decays with the reboiler duty frozen and why a lean loading loop underneath holds it constant.
- Compute the transport delays and the lap of a solvent circuit from its holdups and the circulation.
- Diagnose an inferred lean loading that a drift in stripper pressure misleads, and name the defense.
- Tune a surge tank level loop for averaging, and read a level setpoint as an energy schedule bounded by the other tank.
- Compare flat operation, an economic supervisor and a predictive controller on margin, captured carbon dioxide and solvent left in store.

Prerequisites Sections 1.4.3 (recycle gain), 1.4.4 (the solvent loop), 1.4.6 (inferred compositions), 1.6.2 (velocity form) and 1.6.4 (scenarios and data). Section 1.6.3 is needed only for the predictive controller, and Chapter 2 shows another large recycle.

The app https://apmonitor.com/apps/co2-capture/

See also Volume 6, Chapter 7 for a recycle whose gain depends on which flow is held. Volume 9, Chapter 6 for a flow that sets its own transport delay, and a price of heat that coordinates the consumers. Volume 5, Chapter 10 for a product quality inferred from a temperature that a second variable misleads.

7.1 Introduction

A cascade is usually justified by speed. The inner loop is described as fast, the outer loop as slow, and the benefit as a disturbance intercepted before it reaches the primary measurement. A post-combustion capture plant offers a different justification, and offers it in numbers. The circuit in this chapter holds 9100 m^3 of 30 wt% monoethanolamine and circulates 130 m^3/min, so a parcel of solvent needs 70 min to return to the point it left. Raising the circulation by 20 m^3/min with the reboiler duty held fixed lifts the capture rate by 3.54 points within ten minutes, an apparent gain of 0.177 points per m^3/min, and 77 % of that rise is handed back over the following eight hours to a settled gain of 0.040. Closing a lean loading loop underneath, so that the reboiler duty follows the solvent flow, removes the decay entirely and holds the gain at 0.177 from ten minutes to eight hours. The inner loop did not make the outer loop faster. It made the outer loop's gain a constant.

What the simulator corrects is the habit of reading a large recycle as a slowness problem. A block diagram absorbs the recycle into a lumped transfer function whose steady-state gain is a single number, and a student who is handed that number never watches it fall by a factor of 4.4 according to what else in the circuit happens to be regulated. The shape is general and it does not require an amine. Whenever a stream returns to the front of a process and something inside the return path is left on manual, the settled gain of the forward loop is set by the unregulated variable rather than by the unit the actuator is attached to, which is the structural property that recycle amplification describes for reactor and separator systems [1] and that Volume 6, Chapter 7 measures on a reactor and column. Refinery hydrogen loops, ammonia synthesis loops such as the one of Chapter 2, hydrometallurgical leach circuits and paper machine broke systems all present it, and so does any solvent regeneration circuit in a gas plant [2]. The second property the plant carries is transport delay that is not a time constant. A pipe holds a fixed number of cubic meters rather than a fixed number of minutes, so the 9.00 min delay in each 1170 m^3 line becomes 7.55 min at 155 m^3/min and a controller tuned around it at one circulation is mistuned at another.

Capture plants have been modeled dynamically for about fifteen years [3, 4], control structures have been proposed for them by plantwide reasoning and by self-optimizing selection [5, 6], and the modeling, identification and control literature has been surveyed in detail [7, 8]. Those studies are written for the engineer who already accepts that the circuit governs the plant, and the measurement

that establishes it is a transient test on a plant nobody will hand to a student. This chapter works on a capture plant, built to be operated in a browser, whose recycle is slow enough and whose inventory is large enough that the change in loop gain can be measured rather than asserted, and whose regeneration energy is bought out of the host station's saleable output so that the timing of that energy becomes a control decision. The plant is a sixteen state absorber, stripper and inventory model with two volume-keyed plug flow lines, an inferential reboiler measurement and an economic supervisor, given here in the detail a reconstruction of it would need. Its fifteen scenarios run from a hand-operated absorber to a sixteen-hour price day against a rolling permit, and every variable the simulator computes can be exported. The solvent chemistry, the plantwide arguments and the tuning arithmetic are standard, and each is cited to the work that produced it. Section 1.4.4 treats the solvent loop as a recycle with a negative return gain on the small solvent unit of S-1, and this chapter measures the same effect on a full-size plant.

Section 7.2 traces amine scrubbing and the loops added to it. Section 7.3 gives the constants and balances the plant is assembled from and the assumptions behind them. Section 7.4 measures what the recycle does to the gain of the capture loop and times the lap item by item. Section 7.5 describes the three PI loops, the tank availability factors, the economic supervisor and the predictive controller. Section 7.6 reports loop performance, the surge tank, the cost and timing of the energy, two silent faults, the graded challenge and the predictive controller against the supervisor. Section 7.7 names the real devices behind the loops. Sections 7.8, 7.9 and 7.10 give the limitations, a discussion and the conclusions, and the exercises in Section 7.11 close the chapter.

7.2 Amine Scrubbing and the Loops Added to It

Washing an acid gas with an aqueous alkanolamine and regenerating the solution with steam is a 1930s technology, and it has been the standard route to sweetening natural gas and to treating refinery and ammonia plant gas ever since [2]. The same solvent applied to a power station flue gas is a much larger and much colder duty, and the reason it stayed a laboratory proposition for decades is the reboiler rather than the absorber [9]. An absorber is a well-behaved contactor. A stripper that has to reverse an 85 kJ/mol heat of absorption on hundreds of tonnes of carbon dioxide an hour is a heat sink comparable with a boiler's own reheat load, and the cost of capture is dominated by what that heat is worth as electricity [10].

> HISTORY **Amines in a Closed Cycle, 1930**
>
> On October 7, 1930 Robert Roger Bottoms applied for a United States patent on a process for separating acidic gases, and named carbon dioxide, sulfur dioxide and hydrogen sulfide as the main ones. He had found that a small group of amines unite chemically with such gases at a low temperature and give them up as gas at a higher temperature, regenerated in the same step. A liquid with that property can circulate continuously in a closed cycle between a cool absorption stage and a hot regeneration stage, with heat interchangers to save heat. Monoethanolamine, the solvent of this chapter's plant, is among the amines the patent lists, although it preferred triethanolamine for its higher boiling point [11]. Amine scrubbing has separated carbon dioxide from natural gas and hydrogen ever since [9].

The operating problem was answered by hand for a long time. A gas treating unit ran a fixed circulation and a fixed steam rate chosen from a design case, the reboiler was managed on its own temperature because the temperature was the only continuous measurement on the regeneration side, and the lean loading that the plant actually cared about arrived on a laboratory report the following day [2]. The equilibrium data that would let a temperature be read as a loading were measured for the 30 mass percent solution over a wide loading range only much later [12]. Two consequences of the manual arrangement survived into the power station application. The first is that the loading is still inferred rather than measured on almost every plant, and an inference is a function of the measurement and of something else, which is the classical situation that secondary measurements

were introduced to handle [13]. The second is that the solvent degrades thermally at a rate that roughly doubles for every eight degrees of reboiler temperature, so running the stripper harder is paid for twice, once in steam and again in amine [14].

Dynamic analysis of the coupled plant is recent. Absorber column models written for transient rather than steady-state duty appeared around 2009 [3], and the first studies aimed at the energy question showed that the lean loading and the stripper pressure are the variables that decide the reboiler bill and therefore the penalty [4]. Control structure followed. Plantwide selection of pairings for the absorber and stripper together was published in 2011 [5], self-optimizing selection of controlled variables for the same process appeared in the same year [6], and a survey of the field a decade later found the arrangement now regarded as standard, which is capture rate on solvent circulation with an inner loop on reboiler temperature or an equivalent inferential loading measurement, and a deliberately slack level controller on the surge tank between the two columns [7, 8].

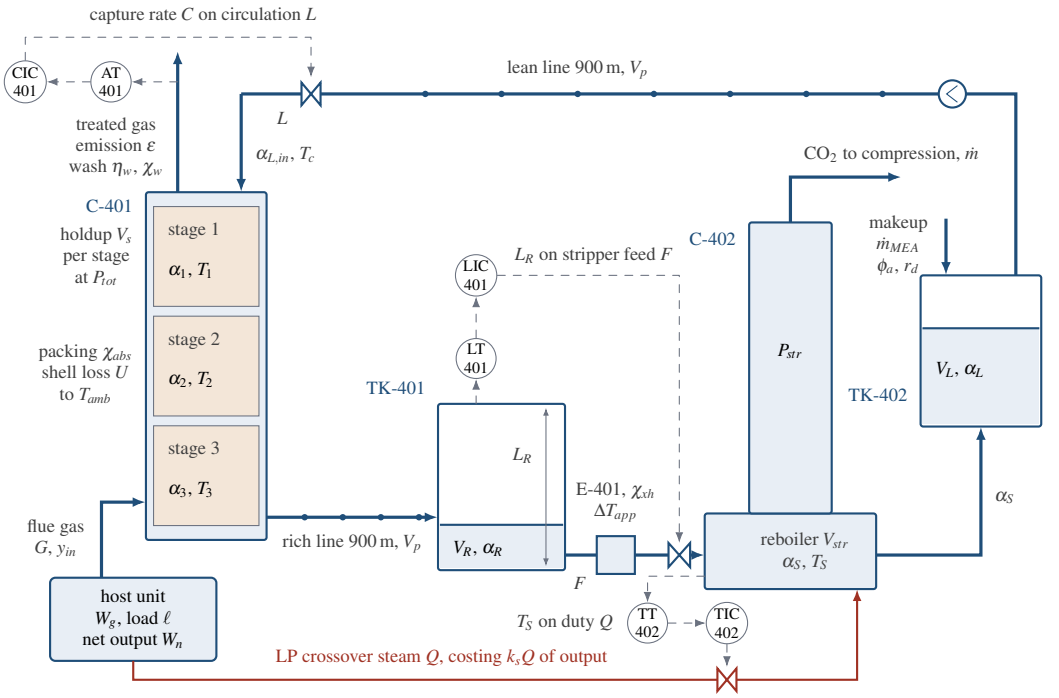
Flexibility arrived as an economic argument rather than a control one. Part load operation of a capture plant on a supercritical coal unit was evaluated early enough to establish that the steam extraction, not the absorber, sets what the host can sell [15], and the observation that the carbon dioxide does not care when it is regenerated turned solvent storage into a scheduling problem against a volatile electricity price [16]. Rolling-average emissions obligations are what make the scheduling legal, because they permit the instantaneous capture rate to move while the total does not. The application implements that argument in full, including the part that is easy to get wrong, which is what a supervisor is allowed to do with the permit when the price is high enough.

> ⧖ HISTORY **Capture Reaches Coal Power Stations, 2014 to 2019**
>
> Amine absorption had removed carbon dioxide from natural gas for decades before it treated a power station’s flue gas at commercial scale. In October 2014 a capture plant on a 110 MW coal-fired unit in Canada opened as the world’s first fully commercial plant of its kind [17]. On December 29, 2016 a second began commercial operation in Texas, treating a slipstream of flue gas equivalent to 240 MW and capturing at least 90 percent of its carbon dioxide, about 5,200 short tons a day at full capacity. Instead of drawing steam from the coal unit, as this chapter’s plant does, it raised most of its steam from the exhaust heat of a separate gas turbine. Over its three-year demonstration, 2017 to 2019, it captured 3,542,537 metric tons of carbon dioxide [18].

7.3 Process Model

Capture plant U-400 treats the flue gas of a 580 MW coal unit. Absorber C-401 receives 21.0 kmol/s of gas carrying 12.4 % carbon dioxide, which is 412.6 t/h presented, and removes 90.0 % of it into 130 m³/min of solvent at the design line-up. Rich solvent leaves the bottom of the column at 0.4472 mol/mol of carbon dioxide per mole of amine, travels 900 m of DN1300 pipe to surge tank TK-401, and is fed through cross exchanger E-401 to stripper C-402, whose reboiler takes 373.3 MW of low-pressure steam from the host turbine crossover and returns the solvent to 0.2375 mol/mol at 115.87 °C and 190 kPa. Lean solvent collects in TK-402 and returns through a second 900 m line to the top of the absorber. Figure 7.1 draws that circuit with its instrument tags and with every symbol the equations below use.

Table 7.1 sorts those quantities by the role each one plays. Units throughout are the ones a utility operator reads, volumetric flow in m³/min, duty in MW, loading in mol/mol, level in percent of tank capacity, and time in minutes. Sixteen states are integrated.



Circuit inventory $\sum V = 9100\,\mathrm{m}^3$: two lines at $1170\,\mathrm{m}^3$ each, lean tank $5100\,\mathrm{m}^3$, rich tank $800\,\mathrm{m}^3$, reboiler $500\,\mathrm{m}^3$, absorber $360\,\mathrm{m}^3$, so one lap at $L = 130\,\mathrm{m}^3/\mathrm{min}$ is 70.0 min.

Figure 7.1 Capture plant U-400 drawn as the circuit it is. Flue gas G of composition y_{in} meets lean solvent of loading $\alpha_{L,in}$ at temperature T_c in the three stages of absorber C-401, each holding V_s at loading α_i and temperature T_i. Rich solvent crosses the 900 m rich line of volume V_p to surge tank TK-401, whose level L_R is held by stripper feed F through cross exchanger E-401 of approach ΔT_{app}. Reboiler duty Q is crossover steam worth $k_s Q$ of the host's saleable output, and it sets the lean loading α_S at bubble point T_S and stripper pressure P_{str}. Lean solvent returns through TK-402 at circulation L, the manipulated variable of the capture loop. Dashed lines are signals and the markers in the two solvent lines are equally spaced parcels whose spacing is the transport delay.

7.3.1 Vapor–Liquid Equilibrium

Every quantity in the plant follows from the equilibrium partial pressure of carbon dioxide over the loaded solvent, which is written as a reference value times three factors in Equation (7.1).

$$P^* = P_0^* \left(\frac{\alpha}{\alpha_0}\right)^n \left(\frac{\alpha_{max} - \alpha_0}{\alpha_{max} - \alpha}\right)^m f_T$$
$$f_T = \exp\left[-\frac{\Delta H_{abs}}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] \tag{7.1}$$

where α is the loading in mol of carbon dioxide per mol of amine, T is the liquid temperature in K, $n = 2$ carries the carbamate stoichiometry of one carbon dioxide to two amines, $m = 1.6$ is the depletion exponent, $\alpha_{max} = 0.58$ is the loading at which the free amine runs out, and $\Delta H_{abs} = 85\,\mathrm{kJ/mol}$ is the heat of absorption. The loading is clamped to $0.004 \le \alpha \le \alpha_{max} - 0.004$ before the depletion term is evaluated, because a transient that overshoots the rich loading otherwise divides by zero and the integrator carries the infinity into every other state within one step. The shape of (7.1) is taken from the measured solubility of the 30 mass percent solution [12] and the constants are fitted rather than regressed. The Arrhenius factor f_T is the separation. At 0.2375 mol/mol it is worth

Table 7.1 Everything the Control System Touches, With Units Carried in the Symbol Column. Each Nominal Is Read at the Design Line-Up Where Every Scenario Begins, and a Range Marked SP Spans the Setpoint Slider.

Symbol and unit	Role	Nominal	Range
C, AT-401 (%)	CV, measured	90.00	60–98 SP
T_S, TT-402 (°C)	CV, measured	115.87	100–126 clamp
L_R, LT-401 (%)	CV, measured	10	5–90 SP
L_L, LT-402 (%)	measured, MPC	63.75	0–100
α_S (mol/mol)	inferred CV	0.2375	0.15–0.34 SP
L (m^3/min)	MV	130	55–170
Q (MW)	MV	373.3	0–560
F (m^3/min)	MV	130	0–175
makeup (kg/min)	MV	0	0–120
host load (pu)	DV, measured	1.00	0.40–1.00
price ($/MWh)	DV, measured	60	0–260
T_c (°C)	DV, measured	40	25–50
P_{str} (kPa)	DV, unmeasured	190	150–240
r_d (%/day)	DV, unmeasured	0	0–8
gas bias (×)	DV, unmeasured	1.00	0.85–1.15
χ_{abs} (×)	DV, unmeasured	1.00	0.50–1.05
χ_{xh} (×)	DV, unmeasured	1.00	0.60–1.05
χ_w (×)	DV, unmeasured	1.00	0.50–3.00
analyzer noise, 1σ (%)	DV, unmeasured	0	0–2
α_1 (mol/mol)	state	0.2841	0.01–0.57
α_2 (mol/mol)	state	0.3680	0.01–0.57
α_3 (mol/mol)	state	0.4472	0.01–0.57
T_1, T_2, T_3 (°C)	states	52.8/60.4/58.5	0–110
V_c (m^3)	state	0	unbounded
V_R (m^3)	state	800	0–8000
α_R (mol/mol)	state	0.4472	0.01–0.57
α_S (mol/mol)	state	0.2375	0.01–0.57
T_S (°C)	state	115.87	40–170
V_L (m^3)	state	5100	0–8000
α_L (mol/mol)	state	0.2375	0.01–0.57
Q_a (MW)	state	373.3	0–900
ϕ_a (×)	state	1.000	0.30–1.05
ℓ_a (pu)	state	1.00	0.05–1.15

a factor of 582 between the 40 °C of the absorber and the 115.87 °C of the reboiler, and no other term in the model moves by anything like that much.

7.3.2 Absorber Stages

The gas side is solved algebraically because it is quasi-steady, with two seconds of gas residence against three minutes of liquid holdup. Within a stage the gas is treated as plug flow over a well-mixed liquid, which integrates in closed form to Equation (7.2).

$$n_{out} = n_{eq} + (n_{in} - n_{eq})\,\mathrm{e}^{-k_i P_{tot}/G}, \qquad n_{eq} = \frac{P^*(\alpha_i, T_i)\,G}{P_{tot}} \tag{7.2}$$

where n is the molar flow of carbon dioxide in kmol/s, G is the total gas flow, $P_{tot} = 101.3\,\mathrm{kPa}$ is the absorber pressure and k_i is the stage transfer coefficient of Equation (7.3). The closed form is worth the algebra. A well-mixed gas stage drives the outlet flow negative once the stage efficiency passes one, which happens as soon as the column runs warm because the kinetics are Arrhenius, and a negative partial pressure propagates into the next stage's driving force. Equation (7.2) is bounded by n_{eq} from both sides whatever the coefficient does.

$$k_i = K_G a\,\chi_{abs}\,\phi_a^{0.8}\left(\frac{L}{L_0}\right)^{n_w}\exp\left[-\frac{E_a}{R}\left(\frac{1}{T_i}-\frac{1}{T_0}\right)\right] \tag{7.3}$$

where $K_G a$ is the design coefficient in kmol/(s kPa), χ_{abs} is the packing condition, ϕ_a is the solvent strength relative to design and floored at 0.2 before the power is taken, $n_w = 0.30$ is the wetting exponent on a liquid load ratio floored at 0.05, $L_0 = 130\,\mathrm{m^3/min}$ and $E_a = 21\,\mathrm{kJ/mol}$. Stage 1 is the top of the column and stage 3 the bottom, and the gas passes from 3 to 1 against liquid passing from 1 to 3. The two state equations per stage are the amine balance and the energy balance of Equations (7.4) and (7.5).

$$H_a \frac{\mathrm{d}\alpha_i}{\mathrm{d}t} = L_a\,(\alpha_{i-1} - \alpha_i) + N_i \tag{7.4}$$

$$\begin{aligned} C_l \frac{\mathrm{d}T_i}{\mathrm{d}t} &= W_{cp}\,(T_{i-1} - T_i) + N_i \Delta H_{abs} - G c_{p,g}\,(T_i - T_{i+1}) \\ &\quad - G\lambda_w\,[x_s(T_i) - x_s(T_{i+1})] - U\,(T_i - T_{amb}) \end{aligned} \tag{7.5}$$

where N_i is the carbon dioxide absorbed on stage i in kmol/s, $H_a = V_s c_a$ is the amine held on a stage in kmol with c_a the amine concentration, L_a is the amine molar flow, $C_l = V_s \rho c_p$ is the stage heat capacity in kJ/K, W_{cp} is the solvent heat capacity flow in kW/K, λ_w is the latent heat of water, $x_s(T)$ is the saturation mole fraction of water from the Buck equation, and U is the shell loss to an ambient at $T_{amb} = 15\,^{\circ}\mathrm{C}$. The upstream liquid for stage 1 is the lean solvent arriving from the pipe and the downstream gas for stage 3 is the flue gas at $T_c + 5\,\mathrm{K}$. Every derivative is written per second and multiplied by 60 in one place, so that the whole model advances on the minute clock the operator reads. The evaporation term in (7.5) is what bounds the bulge, since the gas is water-saturated everywhere and its water content is a steep function of temperature. At the design line-up the profile is 52.8, 60.4 and 58.5 °C from the top down, with the maximum in the middle where the absorption is fastest.

7.3.3 Transport as Volume, Not as Time

The two 900 m lines are true plug flow keyed on cumulative volume rather than on elapsed time, as shown in Equation (7.6).

$$\frac{\mathrm{d}V_c}{\mathrm{d}t} = L, \qquad \alpha_{in}(t) = \alpha_{out}\left(V_c^{-1}[V_c(t) - V_p]\right) \tag{7.6}$$

where V_c is the cumulative volume pumped in $\mathrm{m^3}$ and $V_p = 1170\,\mathrm{m^3}$ is the line volume. A parcel entering the line leaves it when V_p more cubic meters have passed, which is 9.00 min at $130\,\mathrm{m^3/min}$ and 7.55 min at $155\,\mathrm{m^3/min}$. Writing the delay this way needs no variable-delay filter and gets the stretching right for free, which a time-keyed delay does not. The pipes of a district heating network behave the same way, with the delay set by the flow the consumers draw (Volume 9, Chapter 6). The history is held in a ring buffer with linear interpolation and a new sample is pushed only after the cumulative volume has advanced by $V_p/240$, because pushing on every step lets a stalled pump fill the buffer with identical entries and silently empty the line at exactly the moment the plant is slowest.

7.3.4 Tanks, Reboiler and the Duty Split

The two tanks are one inventory seen from opposite ends, which Equation (7.7) makes explicit.

$$\frac{\mathrm{d}V_R}{\mathrm{d}t} = L - F, \qquad \frac{\mathrm{d}V_L}{\mathrm{d}t} = F - L \tag{7.7}$$

Each tank is well mixed in loading, with the holdup floored at $20\,\mathrm{m^3}$ so that a tank running dry cannot turn a finite inflow into an infinite derivative, as shown in Equation (7.8).

$$\max(20, V_R)\, c_a \frac{\mathrm{d}\alpha_R}{\mathrm{d}t} = L_a\,(\alpha_{R,in} - \alpha_R) \tag{7.8}$$

with the identical expression for the lean tank on F and α_S. Equation (7.9) carries the reboiler, which holds a loading, a temperature and the delivered duty.

$$V_{str} c_a \frac{\mathrm{d}\alpha_S}{\mathrm{d}t} = F_a\,(\alpha_R - \alpha_S) - n_{str} \qquad (7.9)$$
$$\frac{\mathrm{d}T_S}{\mathrm{d}t} = \frac{T_b(P_{str}, \alpha_S) - T_S}{\tau_{reb}}, \qquad \frac{\mathrm{d}Q_a}{\mathrm{d}t} = \frac{Q - Q_a}{\tau_Q}$$

where n_{str} is the carbon dioxide released, T_b is the bubble point of Equation (7.11), τ_{reb} is the reboiler thermal lag and τ_Q is the steam valve lag. The stripping rate is written causally, duty in and carbon dioxide out, in Equation (7.10).

$$n_{str} = \frac{Q_a - q_{sens}}{\Delta H_{abs} + \lambda_w \varphi \dfrac{P_{str} - P^*}{P^*}}, \qquad q_{sens} = \frac{\dot{m} c_p \Delta T_{app}}{\chi_{xh}} \qquad (7.10)$$

where the equilibrium pressure is floored at 0.3 kPa and the water-to-product ratio at zero before either is used, φ is the fraction of the reboiler vapor that survives to the overhead instead of condensing against the cold rich feed, $\dot{m}$ is the solvent mass flow, ΔT_{app} is the cross exchanger approach and χ_{xh} is the exchanger condition. The numerator of (7.10) is floored at zero. Three properties of that expression organize the economics. The sensible term is paid on the whole solvent flow whether or not there is carbon dioxide in it, which is what punishes over-circulation. The desorption term is a constant of the chemistry at 1.931 MJ/kg and no column goes below it. The stripping term is the molar ratio of water to carbon dioxide in the reboiler vapor, and because P^* collapses as the solvent is stripped the plant boils more and more water to carry away less and less product. Six equal steps of 0.03 mol/mol from 0.34 down to 0.16 cost 38, 43, 51, 65, 90 and 137 MW, so the last increment is 3.6 times the first. The Manual helper that sets the duty for a nominated lean loading solves this stripper alone, at the present feed and rich loading, and at 0.16 mol/mol it reports the 640 MW required and applies the 560 MW steam limit instead. Its answer holds only until the changed lean solvent has gone round the loop and moved the rich loading the stripper is fed. Raising the duty lowers the loading until the rate has climbed to meet it, which is a stable fixed point and the reason a reboiler sits still with no controller of its own.

7.3.5 The Bubble Point and What the Plant Can Measure

Nothing on the plant measures loading. The reboiler thermocouple stands in for it through the bubble point of the loaded solvent, as shown in Equation (7.11).

$$a_w P_w^{sat}(T_b) + P^*(\alpha, T_b) = P_{str} \qquad (7.11)$$

where $a_w = 0.85$ is the water activity in a solution full of carbamate salts, which is the boiling point elevation written as the thing that causes it. Equation (7.11) is solved by 24 bisections over a bracket from 20 to 180 °C, giving 1×10^{-5} K of resolution, which is four orders finer than the thermocouple and cheap enough to evaluate inside every integration stage. At the design pressure 0.2375 mol/mol boils at 115.87 °C. The control system inverts (7.11) at the assumed reference pressure of 190 kPa rather than at the actual pressure, which is the single most important thing about the second loop. 25 kPa of drift makes the same solvent boil about three degrees hotter, so a controller holding the old temperature holds 0.274 mol/mol while the number reported on the screen is still 0.238.

> **TRY IT IN THE APP 6 · The Lean Loading Nobody Measures**
>
> Load scenario 6 and press Run. At 90 min the stripper pressure drifts 25 kPa high. Watch the reboiler temperature return to its setpoint with nothing alarming, while the loading leaving the reboiler settles near 0.274 and the inference still reports 0.238. Only the circulation shows it, climbing by 24 m^3/min.

7.3.6 Host Station, Emission and Degradation

The gas presented to the absorber follows the host load in both its quantity and its strength, and the load itself is a state because a boiler cannot change output instantly. Equation (7.12) carries all three.

$$\frac{\mathrm{d}\ell}{\mathrm{d}t} = \frac{\ell_{cmd} - \ell}{\tau_\ell}, \qquad G = \max(0.2,\, G_{max}\,\ell\, b_g)$$
$$y_{in} = y_0\,[1 - y_t\,(1 - \ell)] \tag{7.12}$$

where ℓ_{cmd} is the load the operator or the scenario asks for, $\tau_\ell = 4.0\,\mathrm{min}$ is the boiler ramp lag, b_g is the gas bias disturbance, $y_0 = 0.124$ is the design carbon dioxide fraction and $y_t = 0.10$ is the fall in that fraction per unit fall in load, so a station at 60 % presents 40 % less gas at 11.9 % carbon dioxide rather than 12.4. What the host is then left with is one algebraic expression, Equation (7.13).

$$W_n = W_g\,\ell - k_s Q_a - w_c \dot{m}_{str} - W_p \frac{L}{L_0} - W_b\,\ell_c^3 \tag{7.13}$$

where $W_g = 580\,\mathrm{MW}$ is the gross output at full load $\ell = 1$, ℓ_c is the load clamped to the interval 0.05 to 1.15, $k_s = 0.175$ is the electricity lost per unit of extracted heat, $w_c = 0.378\,\mathrm{MJ/kg}$ is the compression and drying work charged on the stripper outlet mass flow $\dot{m}_{str}$ rather than on what the absorber took out, $W_p = 7.5\,\mathrm{MW}$ is the solvent pumping at design circulation and $W_b = 4.5\,\mathrm{MW}$ is the flue gas blower. At the design line-up the four terms are 65.3, 39.0, 7.5 and 4.5 MW, so the capture plant takes 116.3 MW off the station and leaves 463.7 MW, which is 0.3132 MWh/t of lost output per tonne of carbon dioxide captured, of which 0.1759 MWh/t is the steam alone. Amine leaving the top of the absorber is volatility times what the water wash does not catch, as shown in Equation (7.14).

$$\varepsilon = \frac{x_M\, p_M(T_1)}{P_{tot}} \frac{M_{MEA} \times 10^6}{V_{Nm}}\,(1 - \eta_w)\, f_{aero}\, \chi_w \tag{7.14}$$

where p_M is 0.0067 kPa at 40 °C and carries a 62 kJ/mol enthalpy of vaporization, so it roughly doubles every ten degrees, $M_{MEA} = 61.08\,\mathrm{kg/kmol}$, x_M is the effective liquid activity, $\eta_w = 0.90$ is the wash removal, $V_{Nm} = 22.414\,\mathrm{m^3/kmol}$, $f_{aero} = \max(0.2,\, 1 + 0.3[(G/G_{max})^2 - 1])$ is a velocity-dependent aerosol allowance and χ_w is the wash condition. Solvent strength falls with thermal and oxidative degradation and is restored by makeup, as shown in Equation (7.15).

$$\frac{\mathrm{d}\phi_a}{\mathrm{d}t} = -\frac{r_d}{100}\,\frac{2^{(T_S - T_d)/E_d}}{1440} + \frac{\dot{m}_{MEA}}{\sum V \rho\, w_{MEA}} \tag{7.15}$$

where r_d is the degradation rate in percent per day at the reference reboiler temperature $T_d = 120\,^\circ\mathrm{C}$, $E_d = 8\,\mathrm{K}$ is the rise that doubles it [14], and the denominator of the second term is the mass of amine in the whole circuit.

> **+ DID YOU KNOW? The Thermodynamic Floor of Capture**
>
> The minimum work to separate carbon dioxide from coal flue gas and compress it to 150 bar is 0.11 MWh per metric ton, and better processes and solvents are expected to bring the energy used down to about 0.2 MWh [9]. At its design line-up the plant of this chapter costs its host 0.3132 MWh of output per tonne captured.

7.3.7 Constants, the Opening Line-Up and the Numerics

Table 7.2 lists the constants. Those marked hidden are used by the model and never displayed, and they are the quantities a learner has to infer from a trend rather than read from a panel.

No scenario opens at a guessed steady state. The initializer bisects the whole recycle on one scalar, the lean loading leaving the reboiler, until it equals the lean loading arriving at the top of the absorber,

Table 7.2 Model Parameters. Visible Constants Appear in the Model Panel and Are Adjustable There. A Hidden Constant Reaches No Panel.

Symbol	Meaning	Value	Unit	Visibility
W_g	host gross output	580	MW	visible
G_{max}	flue gas at full load	21.0	kmol/s	visible
y_{in}	flue gas CO_2 fraction	0.124	—	visible
τ_ℓ	host load ramp lag	4.0	min	visible
k_s	output lost per unit duty	0.175	MWe/MWth	visible
w_c	compression work	0.378	MJ/kg	visible
W_p	pumping at design flow	7.5	MW	visible
W_b	blower at full load	4.5	MW	visible
c_{MEA}	cost of makeup amine	2.40	\$/kg	visible
V_s	holdup per absorber stage	120	m^3	visible
$K_G a$	transfer coefficient	0.21746	kmol/(s kPa)	visible
w_{MEA}	MEA mass fraction	0.30	—	visible
P_0^*	reference CO_2 pressure	0.30	kPa	visible
α_{max}	free amine exhausted	0.58	mol/mol	visible
n, m	loading exponents	2.0, 1.6	—	visible
ΔH_{abs}	heat of absorption	85 000	J/mol	visible
V_{str}	stripper and reboiler holdup	500	m^3	visible
φ	vapor surviving overhead	0.2144	—	visible
ΔT_{app}	cross exchanger approach	12.0	K	visible
P_{ref}	assumed stripper pressure	190	kPa	visible
τ_{reb}	reboiler temperature lag	4.0	min	visible
τ_Q	steam valve lag	3.0	min	visible
V_p	each pipe run volume	1170	m^3	visible
V_{tk}	tank capacity, each	8000	m^3	visible
—	lean tank level at design	63.75	%	visible
C_{obl}	rolling capture obligation	88	%	visible
W_{roll}	averaging window	240	min	visible
ε_{max}	amine emission limit	4.0	mg/Nm^3	visible
—	pump suction limit	5	%	visible
—	tank full limit	95	%	visible
$T_{s,max}$	degradation limit	127	°C	visible
c_{CO_2}	price of an emitted tonne	95	\$/t	visible
c_{obl}	penalty per tonne short	400	\$/t	visible
τ_{cm}	stack analyzer response	2.0	min	visible
τ_{tm}	thermocouple response	0.8	min	visible
τ_{lm}	level transmitter response	0.5	min	visible
P_{tot}	absorber pressure	101.3	kPa	hidden
n_w	wetting exponent	0.30	—	hidden
E_a	mass transfer activation	21 000	J/mol	hidden
$c_{p,g}$	gas heat capacity	33.0	kJ/(kmol K)	hidden
λ_w	latent heat of water	43.5	kJ/mol	hidden
U	shell loss per stage	12	kW/K	hidden
ρ	solvent density	1050	kg/m^3	hidden
c_p	solvent heat capacity	3.60	kJ/kg/K	hidden
α_0	reference loading	0.35	mol/mol	hidden
T_0	equilibrium reference	313.15	K	hidden
a_w	water activity	0.85	—	hidden
T_d, E_d	degradation reference	120, 8.0	°C, K	hidden
η_w	water wash removal	0.90	—	hidden
x_M	MEA liquid activity	0.056	—	hidden
y_t	CO_2 fraction tilt with load	0.10	—	hidden

and then fills the pipes and the tanks with whatever last passed through them. In manual operation at the design line-up, the largest relative state derivative is 1.8×10^{-15}. The initializer reads the manual circulation, the manual duty and the level setpoint in force, so a value chosen before Run sets where the plant starts, and the same value carried through Reset gives the same run. A second Manual helper sets the duty that holds a nominated capture rate at the present circulation. Both helpers solve the declared design plant, so a plant the learner has changed shows as a missed target. Integration uses

Runge-Kutta of fourth order at a fixed 0.25 min (15 s) step, controller execution falls every 0.5 min (30 s), and the historian keeps two samples per simulated minute (Section 1.6.1). Each run exports 121 columns, with the true lean loading beside the inferred one and every commanded flow beside the flow actually delivered. A generator seeded at 20260913 supplies every random sequence, so a noisy scenario replays identically. The fastest setting of the speed selector runs 120 simulated minutes per second of wall time, so a sixteen-hour price scenario finishes in eight seconds, and the setting changes nothing about the trajectory.

7.3.8 Assumptions

The circuit is where the detail went, and the chemistry is thin, so every simplification below breaks down somewhere.

Three absorber stages rather than a packed height. Three stages are enough for a genuine interior temperature bulge, because the evaporation term in (7.5) is strongly nonlinear and pins the profile. They are not enough to place the bulge in height, and they leave the top stage several degrees hotter than a real twenty meter packing would be, so the amine emission predicted by (7.14) is pessimistic.

The equilibrium is a correlation. Equation (7.1) has the right stoichiometry, the right runaway near $\alpha = 0.58$ and the right heat of absorption, and the design point is anchored to it, but it is not an electrolyte activity model and the bicarbonate route real monoethanolamine takes above $\alpha = 0.5$ is absent [12]. Absolute pressures away from the design region are indicative rather than predictive.

The stripper is one lumped reboiler. Everything between the reboiler and the condenser appears only as φ in (7.10), calibrated so that the design point gives 3.619 MJ/kg and not derived from a column. A model that had to predict the effect of stripper pressure or feed location on specific duty would need the stages [3].

The water balance is not closed. A real plant loses water from the absorber top and gains it in the stripper overhead, and holding 30 wt% needs a wash section and a makeup loop. Solvent strength here moves only through (7.15), so the water balance excursions that are a routine operating problem cannot appear.

The host is a fixed gross output and a fixed conversion factor. A real low-pressure turbine loses efficiency as it is throttled, so the penalty per megawatt of extracted steam rises with the extraction and there is a maximum extraction beyond which the turbine cannot run at all [15]. Both omissions make (7.13) slightly optimistic about very high capture rates and about very deep storage.

The tanks are perfectly mixed and the pipes perfect plug flow. There is no dispersion in either, so a step arrives more sharply here than it would in the field. That is the honest direction to err for this application, because it makes the delay visible rather than hiding it inside a lag.

Aerosol emission is one allowance. Real amine aerosol depends on sulfuric acid mist nuclei in the flue gas and can be an order of magnitude worse than volatility alone, which is why real plants fit demisters that have no equivalent in (7.14).

7.4 What the Recycle Does to the Gain

7.4.1 One Scalar Closes the Plant

Everything downstream of the absorber is transport of loading. The pipes and the tanks change when a parcel of solvent arrives and never what is in it, so the steady state of the whole circuit is fixed by one scalar, the requirement that the lean loading leaving the reboiler equal the lean loading arriving at the top of the absorber. Whether that fixed point moves when the circulation moves is the entire question, and the answer depends on what else is being held. With the reboiler duty frozen the same 373 MW has to regenerate whatever flow is sent to it, so a circulation 15 % higher settles at a lean loading of 0.2630 instead of 0.2375. The solvent arriving at the top of the absorber is a worse absorbent than it was, and it takes back most of what the extra flow gained.

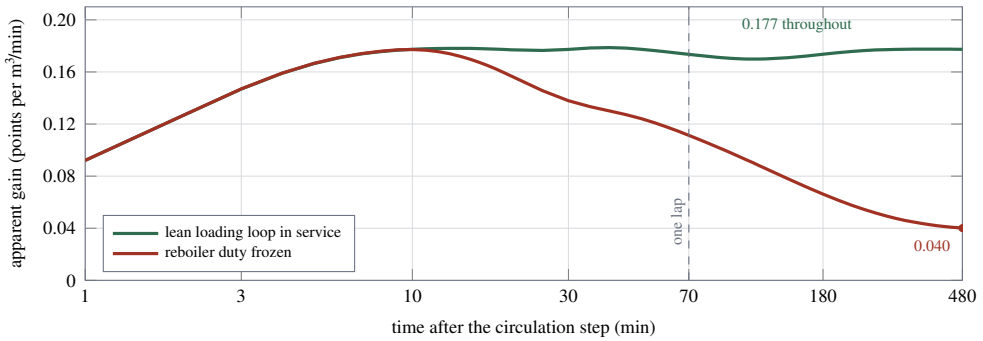


Figure 7.2 Apparent gain of the capture loop against observation time, measured on the running model for a circulation step of 130 to 150 m³/min at $t = 20$ min, with the stripper feed moved with it. The two runs are the same step and differ only in what is regulated underneath. With the reboiler duty frozen at 373.3 MW the gain peaks at 0.177 at ten minutes and decays to 0.040 by eight hours as the returning solvent grows less lean. With the lean loading loop closed underneath the reboiler duty rises from 372 to 401 MW and the gain is 0.177 at ten minutes and 0.177 at eight hours, never leaving the band 0.170 to 0.179 after ten minutes. Both curves are in points of capture per unit of circulation.

7.4.2 The Measured Gain and Its Decay

Figure 7.2 is the apparent gain of the capture loop against the time at which it is read, for the same 20 m³/min step under two conditions.

With the duty frozen the gain reaches 0.177 at ten minutes and falls to 0.040 at eight hours, a loss of 77 %, and the decay is not complete until several laps have passed. With the lean loading loop in service the reboiler duty climbs from 372 to 401 MW as the circulation rises, the returning solvent is the same solvent it always was, and the gain is 0.177 at ten minutes and 0.177 at eight hours. The two curves agree to four figures for their first two minutes, 0.0921 and then 0.1268, because for that long the plant is only an absorber, and they separate from the moment the first affected solvent reaches the reboiler. Scenario 1 makes the frozen-duty step by hand, and its capture readings at 10, 30, 90, 180 and 480 min after the step trace the same fall from 0.177 to 0.040. The circulation station is locked on basic loops, so the held arm cannot be stepped by hand, but in scenario 3 the ratio of capture change to circulation change stays between 0.166 and 0.170 from 180 to 420 min with the lean loading loop in service.

Two consequences follow for the controller. Tuning the capture loop against the gain read at ten minutes and running it with the duty frozen produces a loop whose true gain is 4.4 times smaller than the one it was tuned for, so it never reaches setpoint and the integral term walks the circulation to its stop. Scenario 3 run with the reboiler loop gain at zero shows exactly that, with the capture rate peaking at 93.43 % against a setpoint of 94 and the circulation on its 170 m³/min stop from $t = 316$ min, 256 minutes after the step. Tuning against the settled gain of 0.040 and then closing the inner loop produces the opposite, a loop 4.4 times too aggressive on a plant with a seventy minute memory. The inner loop is not there because it is fast. It is there because it makes one number out of two.

🕮 **Pause.** Try Exercise 7.1 before reading on.

7.4.3 The Lap, Item by Item

The lap time is the circuit inventory divided by the circulation, and the inventory is a sum of holdups no single unit dominates. At design the two lines contribute 9.00 min each, the lean tank 39.2 min, the rich tank 6.2 min, the reboiler 3.8 min and the absorber 2.8 min, which totals 70.0 min. Only the two lines behave as delays. Stepping the circulation from 130 to 155 m³/min moves the loading leaving

Table 7.3 Loop Pairings, Shipped Tunings and the Plant Each Controller Faces

CV	MV	Action	K_c	τ_I (min)	Plant
C	L	reverse	3.5	20	70 min lap
T_S	Q	reverse	30	12	7 min lag
L_R	F	direct	1.5	240	integrator

the absorber within 0.5 min, moves what reaches the rich tank not at all until 8.0 min and then sharply, reaches the reboiler at 9.5 min and reaches the top of the absorber at 21.5 min. Those are the times a student reads off the half-minute trend, taking a move of 2×10^{-4} mol/mol as the first sign. At the 0.25 min integration step the same four moves fall at 0.25, 7.75, 9.25 and 21.25 min, and 7.75 is the first step after the 7.55 min pipe transit. The extra 1.5 min between the pipe and the reboiler is the rich tank, which is stirred and begins to move as soon as its inlet does. A step test on the absorber alone finds 0.5 min and concludes that the plant is fast.

7.5 Controller Design

7.5.1 The Implemented PI Algorithm

All three loops run the velocity-form PI law of Section 1.6.2, Equations (1.14) to (1.17), executed every $\Delta t_c = 0.5$ min. Its action takes the value $+1$ for a reverse-acting pairing and -1 wherever the output has to rise with the measurement. The optional first-order derivative filter is off in every loop, so the rate term would see the raw measurement, and every loop ships with $\tau_D = 0$, leaving the derivative path present and idle. The back-calculation time T_t is left at its default of τ_I, and the integral used at execution k is the one accumulated through execution $k-1$. Saturation reaches the emitted output and stops there, never the running sum of increments, so the emitted output equals the positional law only away from the limits, and nothing else touches the integral except back-calculation, which is dormant unless there is integral action to unwind [19]. Manual solves the same relation for the integral and matches the output to the operator's station, while in automatic mode the three manual stations are set to the controller outputs after every execution, so a transfer in either direction lands without a bump. Rate limiting is absent from all three loops, because the steam valve lag and the two pipe runs already bound how fast anything can move.

7.5.2 Three Pairings, Three Time Scales

Table 7.3 lists the pairings, the shipped tunings and the plant each controller has in front of it.

Each gain carries the units of its own pairing, 3.5 m³/min of circulation per point of capture, 30 MW of duty per °C of reboiler, and 1.5 m³/min of stripper feed per percent of level. Output limits are 55 to 170 m³/min on the circulation, 0 to 560 MW on the duty and 0 to 175 m³/min on the feed, and the tuning sliders span $0 \le K_c \le 25$ with $2 \le \tau_I \le 400$ min on the capture loop, $0 \le K_c \le 200$ with $1 \le \tau_I \le 200$ min on the reboiler, and $0 \le K_c \le 20$ with $10 \le \tau_I \le 2000$ min on the level. Measurements are filtered at 2.0, 0.8 and 0.5 min, and the stack analyzer is the only fast instrument in the capture loop. Only the level loop is direct acting, because it is the only one of the three whose process gain is negative, and getting that sign wrong is invisible until a tank overflows.

The capture loop is tuned against the constant 0.177 of Figure 7.2 rather than against the 0.040 the plant settles at with the duty frozen, which is legitimate only because the loop underneath is in service. Breaking that assumption is a scenario rather than a footnote. Setting the reboiler gain to 3 MW/°C with a 120 min reset and repeating the same setpoint step leaves the lean loading drifting out to 0.2715 while the capture controller chases it with circulation until the pump sits on its 170 m³/min stop, and the capture rate is still only 93.03 % against a setpoint of 94 when the setpoint returns. Nothing is wrong with the loop that is failing.

The reboiler loop is where the inference lives. A lean loading setpoint is converted to a temperature setpoint by inverting (7.11) at the assumed reference pressure and clamping the result to 100 to

126 °C, and the loop then compares two temperatures. The level loop is deliberately slack. One cubic meter per minute of imbalance moves the level 0.0125 %/min, so a tank of this size is an integrator with a very small gain, and there is no reason to hold it tightly.

7.5.3 Two Availability Factors

What the controllers ask for is not always what the plant can do, and the limit is a tank end rather than a valve. Both factors are smooth, because a hard cut-off at a level alarm gives the fixed-step integrator a discontinuous right-hand side and turns the level trace into a staircase, as shown in Equation (7.16).

$$
\begin{aligned}
s(x) &= \operatorname{clamp}\left(x / x_{lo}, 0, 1\right) \\
r(x) &= \operatorname{clamp}\left(\frac{100 - x}{100 - x_{hi}}, 0, 1\right) \\
L' &= L_{cmd}\, s(L_L), \qquad F' = F_{cmd}\, s(L_R) \\
L_a &= F' + (L' - F')\, r(L_R) \\
F_a &= L_a + (F' - L_a)\, r(L_L)
\end{aligned}
\tag{7.16}
$$

where L_L and L_R are the two tank levels in percent, $x_{lo} = 5$ is the level at which the pumps lose suction and $x_{hi} = 95$ is a full tank. A lean tank on its floor cuts the circulation whatever the capture controller has to say about it, which is the constraint that ends every storage maneuver. The factors act after the controller output, and the output limits of the PI law, Equation (1.16), are the pump's 55 to 170 m³/min rather than the delivered flow, so the capture integral keeps winding while a starved pump falls short. In scenario 11 the command first reaches its 170 m³/min stop at $t = 82$ min and spends 119 min there before the price breaks at 420 min, while the pump delivers 105 to 148 m³/min.

7.5.4 The Economic Supervisor

Above the three loops sits an optional supervisor whose entire content is that the capture rate is a law and the energy is a price. It moves two setpoints and never the capture setpoint, as shown in Equation (7.17).

$$
\begin{aligned}
z &= \operatorname{clamp}\left(\frac{p - p_{lo}}{p_{hi} - p_{lo}}, 0, 1\right) \\
u &= \operatorname{clamp}\left(\frac{b - (\bar{C} - C_{obl})}{b}, 0, 1\right) \\
z_e &= z\,(1 - u) \\
L_{R,\mathrm{SP}} &= \ell_c + z_e\,(\ell_d - \ell_c) \\
\alpha_{\mathrm{SP}} &= \alpha_c + z_e\,(\alpha_d - \alpha_c)
\end{aligned}
\tag{7.17}
$$

where p is the electricity price, $p_{lo} = 55$ \$/MWh and $p_{hi} = 175$ \$/MWh bound the price index z, $\bar{C}$ is the rolling-average capture over the last 240 min, C_{obl} is the obligation, $b = 1.2$ points is the credit the supervisor is allowed to spend, and the four targets are $\ell_c = 6\,\%$, $\ell_d = 56\,\%$, $\alpha_c = 0.218$ and $\alpha_d = 0.252$. The rolling average is computed the way a regulator computes it, as carbon dioxide kept out of the stack over carbon dioxide presented across a fixed window, and both z and u are published on every architecture so that a run on basic loops shows what a supervisor would have done.

The product in the third line of (7.17) is the design decision worth arguing about. Multiplying the price index by the remaining credit removes the price signal's authority as the obligation comes under pressure, rather than outweighing it. A layer that added the two would carry an implied exchange rate between dollars and permit compliance, and at a high enough price it would sell the permit.

🕮 **Pause.** Try Exercise 7.2 before reading on.

7.5.5 Model Predictive Control

A fourth control setting replaces the supervisor and the two outer loops with a receding-horizon optimization [20] of the economic kind that industrial practice places above the regulatory layer [21]. Section 1.6.3 describes the shared option, and this one differs from it in its economic objective, its six-state model and its obligation rows. Every $T_s = 10\,\text{min}$, twenty controller executions, it chooses the circulation L, the lean loading setpoint α_{SP} and the stripper feed F and holds them until the next decision. The reboiler temperature loop of Table 7.3 keeps acting beneath the plan with its shipped tuning, turning α_{SP} into a temperature setpoint through (7.11) at 190 kPa as it does under the supervisor. The capture and level controllers track the applied circulation and feed without a preload, so a transfer either way is bumpless, and the factors of (7.16) and every alarm stay in force.

Controller model. The plan predicts with six states written from the declared defaults of Table 7.2 and the design disturbances, never from the running plant, as shown in Equation (7.18).

$$\begin{aligned}
\tau_T \frac{\mathrm{d}\hat{\alpha}_S}{\mathrm{d}t} &= \alpha_{\text{SP}} - \hat{\alpha}_S \\
\frac{V_L}{F_m} \frac{\mathrm{d}\hat{\alpha}_L}{\mathrm{d}t} &= \hat{\alpha}_S - \hat{\alpha}_L, \qquad \hat{\alpha}_{in}(t) = \hat{\alpha}_L(t - T_s) \\
\tau_C \frac{\mathrm{d}\hat{C}}{\mathrm{d}t} &= C_m + g_L\,(L - L_m) + g_\alpha\,\delta\hat{\alpha}_{in} - \hat{C} \\
\frac{\mathrm{d}\hat{L}_R}{\mathrm{d}t} &= \frac{100\,(L - F)}{V_{tk}} \\
\hat{Q} &= Q_m + q_F\,\delta F + q_\alpha\,\delta\hat{\alpha}_S + q_R\,(r_\alpha\,\delta\hat{\alpha}_{in} + r_L\,\delta L)
\end{aligned} \tag{7.18}$$

where the subscript m marks a value measured or estimated at the decision, δ a deviation from it, $\hat{\alpha}_S$, $\hat{\alpha}_L$ and $\hat{\alpha}_{in}$ the lean loadings at the reboiler, in TK-402 and at the absorber inlet, and $\hat{Q}$ the duty the temperature loop will demand. The lag $\tau_T = 9.4\,\text{min}$ folds the 6.4 min lag and 3.0 min dead time identified from α_{SP} to the inferred loading with the temperature loop closed, and $\tau_C = 2.1\,\text{min}$ is the capture lag identified from circulation steps with the cascade closed. A second identification with the outer loops pinned gives 5.2 to 6.8 min plus 3.0 to 3.25 min and 1.3 to 2.0 min, with residuals of 2.9 to 4.5 % of the response. The tank constant V_L/F_m is recomputed at each decision (39.2 min at design), and the lean line is one decision of transport. The gains g_L and g_α are re-read at every decision from the declared absorber at the circulation where it gives the measured capture, 0.241 points per m^3/min and -139 points per mol/mol at design, with a chord from 130 to 150 of 0.179 against the 0.177 of Figure 7.2. The rich tank is the integrator of (7.7). The duty is the declared stripper of (7.10) linearized at design, $q_F = 2.87\,\text{MW}$ per m^3/min, $q_\alpha = -2114\,\text{MW}$ and $q_R = 1311\,\text{MW}$ per mol/mol of lean and rich loading, with a curvature $q_{\alpha\alpha} = 1.86 \times 10^4\,\text{MW}$ per $(\text{mol/mol})^2$ and a rich loading that follows the lean one at $r_\alpha = 0.676$ and falls by $r_L = 0.00105\,\text{mol/mol}$ per m^3/min. There are no recycle states, for the reason of Section 7.4. With the temperature loop acting, a 20 m^3/min step reads a capture gain of 0.1775 at 10 min and 0.1791 at 480 min, and pricing the rich leg's duty 10 or 20 min later changes scenario 10's margin by \$6 and \$13. Both gains are read with the inlet loading capped at 0.32 mol/mol.

Measurements and offset. Each plan starts from the stack analyzer, the thermocouple converted to loading by the same inverse of (7.11) at P_{ref} that the temperature loop uses, so a pressure drift misleads the plan as it misleads every loop, and the two level transmitters, LT-401 and the LT-402 of Table 7.1, both through the 0.5 min lag and without noise. A soft sensor carries $\hat{\alpha}_L$ and $\hat{\alpha}_{in}$ through the declared tank and line. Offset is removed by an output bias, not a Kalman filter. Because C_m anchors the capture equation, a host load, cooling water temperature, packing condition or solvent strength the model omits appears within the absorber's two minutes as a step that the bias holds over the horizon [22].

Horizon and objective. The horizon is $N = 144$ decisions (24 h) in twelve move blocks, two of a single decision followed by 2, 2, 4, 6, 6, 12, 12, 24, 24 and 50, with three handles and one obligation

slack per block, so the quadratic program has 48 variables. The objective is the next day's cost in dollars, Equation (7.19).

$$\begin{aligned} J = \sum_{k=1}^{N} \Big[\pi_k \Big(k_s \hat{Q}_k + k_c \dot{n}_k + W_p \frac{L_k}{L_0} \Big) + \frac{\pi_k k_s q_{\alpha\alpha}}{2} (\delta_0 \hat{\alpha}_{S,k})^2 \\ + w_C (\hat{C}_k - C_{\mathrm{SP}})^2 + w_I (\hat{L}_{R,k} - L_{R,\mathrm{SP}})^2 \Big] \\ + P (\hat{L}_{R,N} - L_{R,\mathrm{SP}})^2 + \sum_j \| \Delta u_j \|_S^2 + \sigma s \\ + \sum_b \rho_b (\varepsilon_b^2 + \varepsilon_b) \end{aligned} \tag{7.19}$$

Here $\pi_k = p_k T_s / 60$ is the published price of decision k in dollars per megawatt held for one decision, k_s, W_p and L_0 are those of (7.13), $k_c \dot{n}_k$ is the compression power on the carbon dioxide the plan predicts the stripper releases, and δ_0 is a deviation from the design lean loading of 0.2375. The weights are $w_C = \$300$ per point^2 per decision, $w_I = \$0.02$ per point^2 per decision and $P = \$2$ per point^2, and the move prices S are \$0.05 per $(\mathrm{m}^3/\mathrm{min})^2$ on L and F and \$3 per $(0.01\,\mathrm{mol/mol})^2$ on α_{SP}, times a move suppression of 1. The inventory weight treats stored rich solvent as a loan, and without it the plan ends scenario 10 at 61.4 % rich instead of 11.0, earning \$1,278 more by leaving that regeneration to the next day.

Constraints. The handles are hard-bounded by the shipped clamps, 55 to 170 m³/min, 0.15 to 0.34 mol/mol and 0 to 175 m³/min. The rich level is soft between 7 % and the smaller of 90 % and the level that leaves the lean tank at 10 %, at $\rho = \$200$ per point^2 and per point, and the duty is soft 15 MW below its 560 MW maximum at \$20 per MW^2 and per MW, each with one slack over the horizon judged at every second decision. The obligation is a hard row for every four-hour window ending inside the horizon, Equation (7.20),

$$\frac{100\, n_j^{cap} + r\, T_s \sum_{k=k_0}^{j-1} \hat{C}_{k+1}}{n_j^{in} + r\, T_s\, (j - k_0)} \;\geq\; C_{obl} + m - s \tag{7.20}$$

where n_j^{in} and n_j^{cap} are the carbon dioxide presented and captured over the part of window j already past, from the regulator's record the supervisor reads, r is the arrival rate over the last decision, $k_0 = \max(0, j - W_{roll}/T_s)$, $m = 0.3$ points is the margin kept, and the slack $s \geq 0$ costs $\sigma = \$2 \times 10^4$ per point-decision (0.69 t at full load), so the row holds whenever it can be met and the problem stays feasible when it cannot. The rows never bind on scenarios 9, 10 and 11 or the challenge (3.375 point-decisions to spare at the tightest on scenario 10), and act when scenario 11's obligation is raised to 89.7 %, holding a rolling minimum of 89.993 % against 89.884.

Preview. The price over the horizon is the scenario's scripted schedule, read as a day-ahead market's hourly prices published the day before, and a price set by hand is not on it. Switching the preview off leaves only the present price over the whole horizon, which is all the supervisor reads. A real plant knows the day-ahead clearing but not the real-time departures from it [23], and nothing announces a dispatch, so there is no load preview.

Acceptance and fallback. A plan is applied only when the solver reports an optimum, everything it returns is finite, no planned command leaves its bounds and its first command is the one being applied. Otherwise the historian is marked, the supervisor takes over with the loops that have been tracking, its two setpoints glide from the plan's values at 1 % and 0.001 mol/mol per minute, until a valid plan reclaims the three handles. Six forced failures across scenario 14 moved the feed by at most 0.75 m³/min at the hand-over, where the supervisor's level target applied at once would have stepped it by up to 84 m³/min. The first plan is solved at $t = 0$. A plan takes 2.71 to 2.77 ms in a warmed-up Chrome page, 0.03 % of one processor core at the slowest playback, a simulated minute each second, and 3.3 % at the fastest, 120, and a frame guard that ends a frame's stepping after 25 ms never engaged at the top speed.

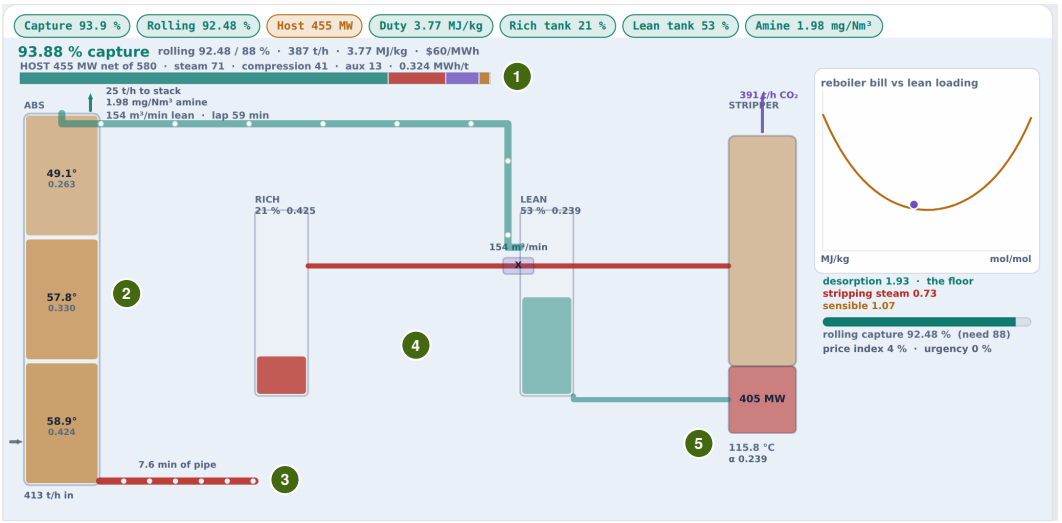


Figure 7.3 Scenario 3 at $t = 240$ min, three hours after the capture setpoint stepped from 90 to 94 % with both inner loops in service, cropped to the plant view. (1) The capture rate has followed the setpoint to 93.88 %, settling into its one-point band 42.5 min after the step, and the host output of 454.6 MW at a specific duty of 3.77 MJ/kg is on the way from 463.9 MW at 90 % capture to the 453.6 MW reached by $t = 420$ min, which is the price of four more points of capture. (2) The three absorber stages, each with its temperature and loading. (3) The rich line, whose markers are equally spaced parcels of solvent. (4) The rich and lean tanks, one inventory seen from opposite ends. (5) The reboiler, whose duty has followed the circulation from 372 to 405.8 MW while the circulation climbed from 130 to 153.6 m^3/min, which is the second loop paying for what the first one spent.

Three models kept apart. The plant is the sixteen-state model of Section 7.3 with its recycle, the true stripper pressure and the solvent strength. The identified model is the set of closed-loop lags read from step tests on it. The controller's model is (7.18) at the declared defaults, relinearized at each decision, so a parameter the learner changes is model mismatch rather than knowledge.

7.6 Results

The simulator carries fifteen scenarios in the order a laboratory would take them: the absorber by hand (scenario 1), the circulation step timed on four loadings (2), capture on circulation with and without the loop underneath (3), the energy penalty on the host (4), lean loading (5), the inferential measurement (6), the surge tank (7), a host load ramp (8), a price spike (9), a day of prices, flat and shifted (10), the rolling obligation (11), solvent degradation (12), a cold night and a hot afternoon (13), the same price day under the predictive controller (14) and the graded challenge. Each one pins the starting mode, the architecture, all thirteen tuning constants (six for the loops and seven for the supervisor), the disturbances it names and any timed event, and it declares an objective, a predicted observation and a completion rule ahead of the run (Section 1.6.4).

7.6.1 Capture Loop Performance

Table 7.4 reports the measures the application computes for itself on four runs of the same three loops. Integrated absolute error accumulates from the start of each run, so the observation window is stated with every column and the columns are read against each other rather than in isolation.

The first two columns separate a controller fault from a structural one. Both carry identical capture tuning and both meet the same four point setpoint step, and both report a settling time of 42.5 min

Table 7.4 Measured Capture-Loop Performance. Every Measure Accumulates From $t = 0$ to the Stated Read Time, and All Four Runs Use the Same Capture Loop Tuning of $K_c = 3.5$ and $\tau_I = 20$ min.

	SP step shipped	SP step weak loop 2	P_{str} drift	load ramp
Scenario	3	3	6	8
Read at (min)	420	420	500	780
K_c reboiler (MW/°C)	30	3	30	30
τ_I reboiler (min)	12	120	12	12
IAE (% min)	128.5	259.2	140.0	709.1
Max. deviation (%)	3.08	3.07	1.20	7.83
Circulation travel (m³/min)	31.4	47.3	24.6	125.2
Time at a stop (%)	0.0	15.5	0.0	0.0
Settling (min)	42.5	42.5	—	—
Final capture (%)	94.01	93.03	90.01	90.03
Final L (m³/min)	153.9	170.0	153.9	130.5
Final α_S (mol/mol)	0.2379	0.2715	0.2740	0.2379
Host output (MW)	453.6	456.7	462.5	461.4

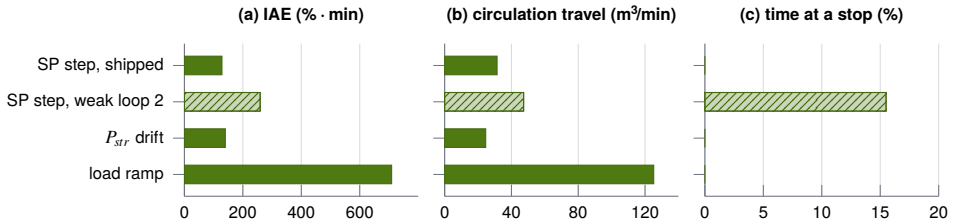


Figure 7.4 Three rows of Table 7.4 as bars, the run with the weak reboiler loop hatched. Notice that the second run carries the same capture tuning as the first and still doubles its error, travels further and is the only run that sits against the pump stop, while the load ramp makes the largest error and the most travel without ever reaching a stop.

because the first approach to the band is the same. What differs afterward is that the second column never holds. Its integrated error is twice the first at the same read time, 259.2 against 128.5 % min, its circulation travel is 47.3 m³/min against 31.4, it spends 15.5 % of the run against the pump stop, and it finishes almost a point short of setpoint with the lean loading at 0.2715 instead of 0.2379. No adjustment to the capture controller repairs that, because the variable that moved is not in its loop. Figure 7.4 draws three rows of the table as bars.

The third column is the inferential failure. The pressure rise lifts the reboiler temperature by 2.1 °C, the reboiler loop has it back within 0.1 °C of its 115.83 °C setpoint 19 min after the rise, nothing alarms, and the capture controller does its job, dipping to 88.80 % and returning to setpoint. The true lean loading nonetheless settles at 0.274 mol/mol while the inference on the screen still reads 0.238, and the only evidence anywhere on the plant is 24 m³/min of extra pumping and 1.4 MW off the host. That shape, in which the loop holds its measurement perfectly while the inferred quantity walks away, is the standard failure of an inference built on a secondary measurement [13], the same shape Volume 5, Chapter 10 meets when an outlet temperature stands in for powder moisture, and the defense is a pressure-compensated calculation or an alarm on the pressure rather than a better controller.

🕮 **Pause.** Try Exercise 7.3 before reading on.

The fourth column is the load ramp, and it is the largest error in the table because feedback alone

Table 7.5 Level Loop Gain Against What the Reboiler Sees, Scenario 7, Measured Over $60 \le t \le 480$ min With $\tau_I = 240$ min Throughout

K_c (m³/min per %)	0.5	1.5	4	8
Stripper feed range (m³/min)	105–130	55–133	0–136	0–142
Reboiler duty range (MW)	304–372	176–380	2–391	0–427
Time to reach setpoint (min)	223	110	55	44

has to reject it through the lap. The host returns to full load in four minutes, the capture rate falls to 82.17 % within 6.0 min because the solvent standing in the absorber was sized for sixty percent load, and the rate climbs back above 89.5 % 108 min after the return to full load. In the other direction the plant is over-circulated rather than under-circulated and the capture rate peaks at 96.90 %, which costs nothing except steam. Feedforward from the host load signal is the first thing a real plant adds, and it is deliberately absent here so that the recycle is visible.

7.6.2 The Surge Tank Is Not a Setpoint

Moving the rich tank level setpoint from 10 to 60 % cuts the stripper feed, and the reboiler duty follows it down because the duty needed is very nearly proportional to the solvent being regenerated. Half an hour into the move the feed is 81.1 m³/min, the duty is 236.8 MW and the host is making 501.6 MW instead of 463.9. That is 38 MW for as long as the tank is filling, and it is the mechanism the whole economics rests on. It is also strictly temporary. The level crosses its setpoint 110 min after the move, overshoots to 67.4 %, and when the setpoint returns to 10 % the feed runs hard and the output falls below where it started while the backlog is worked off.

Table 7.5 is the level gain sweep over the filling period. The tighter tunings track the setpoint faster and pass the whole of the imbalance to the reboiler while doing it.

Raising the gain from 1.5 to 8 cuts the time to setpoint from 110 to 44 min, and widens the reboiler duty swing from 204 MW to 427 MW. A surge tank exists to absorb imbalance so that the downstream unit does not have to see it, and a level controller tight enough to hold a setpoint has thrown away the only thing the tank was bought for. The loop must still keep both ends off the tank. As the rich tank fills the lean tank empties by exactly the same volume and reaches 6.3 % at the worst of the shipped tuning, against a pump suction limit of 5 %.

> **+ DID YOU KNOW? A Level Controller That Shuts Off the Reboiler**
>
> From the simulator: at the tightest level gain of 8, scenario 7's setpoint move swings the reboiler duty from 0 to 427 MW, shutting the reboiler off on the way. At a gain of 0.5 the duty stays between 304 and 372 MW, though the tank takes 223 min instead of 44 to reach its new level (Table 7.5).

7.6.3 What the Energy Costs and When to Spend It

Capture rate is bought in megawatts and the price rises with the rate. Moving the setpoint from 90 to 95 % takes the host from 463.9 to 450.7 MW, a cost of 13.2 MW, moves the circulation from 130 to 164 m³/min and the specific duty from 3.61 to 3.86 MJ/kg. Coming down from 90 to 85 % returns only 7.8 MW, so the last five points cost nearly twice what the five below them do. The convexity in the other variable is stronger, since the six equal loading steps of Section 7.3 run from 38 to 137 MW. Both directions away from the design lean loading are worse for the host, because a leaner solvent needs less circulation and a richer one needs more, and the sum has a shallow optimum near the design point that neither column can find alone.

The only genuine freedom is timing [16]. Scenario 9 puts the supervisor on a five-hour peak at $210 a megawatt-hour. It raises the rich tank setpoint to 72 %, the level controller cuts the feed, the reboiler falls to 209.4 MW and the host output goes from 451.6 to 508.8 MW half an hour into the peak. The carbon dioxide is still being captured, because the absorber has not changed at all. The

limit then arrives, and it is not the tank an operator watches. The rich tank never passes 70.5 %, while the lean tank is at 8 % 90 min into the peak and on its 5 % floor by 98 min, after which the circulation is starved and the feed has to come back up to whatever the absorber is sending. Storage bought ninety good minutes out of a five-hour peak, and the swing available is the lean tank's 4700 m^3.

> **TRY IT IN THE APP** **9 · A Price Spike, and What the Tanks Are Actually For**
>
> Load scenario 9 and press Run. At 60 min power jumps to $210 a megawatt-hour for five hours. Watch the supervisor raise the rich tank setpoint, the stripper feed fall and the host output climb from 451.6 to 508.8 MW. Then watch the lean tank: it is on its 5 % floor 98 min into the peak, and from there the starved circulation ends the storage.

Over the 960 min price day of scenario 10 the supervisor sells $580,549 of electricity against $575,925 on basic loops, a gain of $4,624 or 0.80 %, and once the carbon price on the escaped carbon dioxide is charged its margin is $5,063 or 0.99 % higher. It does that while capturing 90.068 % of the carbon dioxide presented against 89.998 % and finishing with the rich tank at 4.4 % rather than 10.0 %. Both halves of the fairness test pass, so the money is real. It is also thin, and an arbitrage that finished with a full tank would have borrowed the money rather than made it.

Scenario 11 asks what happens when the price outlasts the tanks. Seven hours at $200 against an 88 % obligation on a four-hour rolling average puts the lean tank on its floor within 73 min, drives the instantaneous capture rate down to 77.96 % and the rolling average to 88.51 %. The obligation urgency of (7.17) comes off zero at 82 min, the price begins losing authority, and the plant settles into an uncomfortable equilibrium with the rich tank near 70 % and the lean tank near 4 %. The run finishes 0.00 t short of the obligation, which is the only acceptable answer. The timing problem underneath is worth naming. A four-hour average on a plant with a seventy minute lap means that by the time the average has moved, the decision that moved it is hours old and the correction will take hours more, and the credit band exists to buy that lag back.

7.6.4 Two Faults That Hold Every Setpoint

Degrading the solvent at 6 % per day moves no controlled variable at all. Over eleven and a half hours the capture rate stays at 89.98 % and the reboiler temperature at 115.83 °C, while the strength falls from 1.000 to 0.981, the circulation rises from 130.0 to 132.6 m^3/min and the duty from 372.2 to 374.8 MW, because the sensible term of (7.10) is paid on the whole flow. The host loses 0.7 MW with nothing to show for it on any trend an operator watches. Holding the strength takes 90 kg/min of fresh amine, which at $2.40 a kilogram is $12,960 an hour and an argument for fixing the degradation rather than out-running it [14].

The weather fault is a permit rather than a cost. At 30 °C cooling water the equilibrium pressure over the solvent falls, the driving force widens all the way up the column, and 90 % capture costs 114.7 m^3/min instead of 130, worth 3.8 MW on the host's meter. At 49 °C the same setpoint costs 159.0 m^3/min and 455.3 MW, and the absorber profile lifts from 52.8, 60.4 and 58.5 °C to 59.3, 65.5 and 64.5 °C. Amine volatility roughly doubles every ten degrees, so the emission rises from 1.33 to a peak of 4.60 mg/Nm^3 and the 4.0 mg/Nm^3 permit is breached 2.0 min after the water warms. The capture rate dips to 82.66 % and is back within half a point of setpoint 129 min after the warming, but the emission stays between 3.99 and 4.16 mg/Nm^3 from 500 min to the end of the hot spell and finishes at 4.01 mg/Nm^3, on the permit, with the capture rate held. On a hot day the binding constraint on a capture plant is the amine limit rather than the carbon dioxide one.

7.6.5 The Graded Challenge

The challenge runs sixteen hours with the price from $30 to $195, a five degree warming of the cooling water, the host backed down to 80 % across the start of the peak, and gentle degradation throughout. It starts on basic loops with a capture reset of 250 min on a plant whose lap is seventy, and it asks for the capture rate held within ±2 points through the last third, the rolling average at or

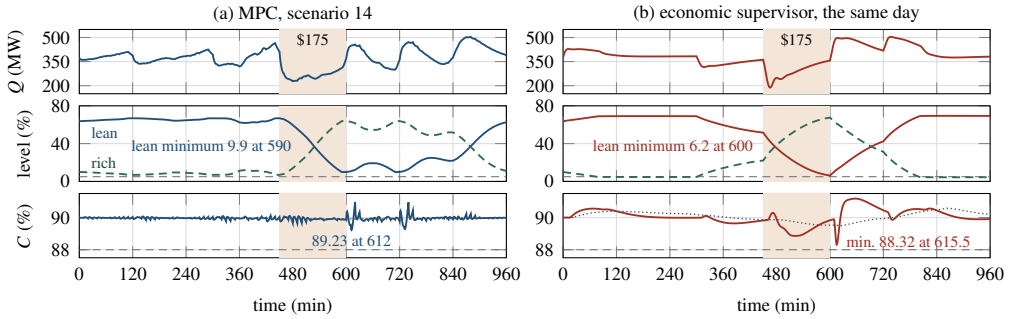


Figure 7.5 The price day of scenarios 10 and 14 over its 960 min under (a) the predictive controller of scenario 14 and (b) the economic supervisor. The prices are \$30, 55, 95, 175, 105, 42 and 24 from 0, 120, 300, 450, 600, 720 and 840 min, with the evening peak shaded. From the top, the reboiler duty, the lean (solid) and rich (dashed) tank levels with the 5 % pump suction limit, and the capture rate with its four-hour rolling average (dotted) above the 88 % obligation. The plan strips deeper before the peak and stops at its 10 % lean margin, while the supervisor empties its lean tank further and its capture dips below 89 % after the peak.

above 88 %, the emission under 4.0 mg/Nm^3 and the rich tank drawn back down to 15 % or less. The shipped settings are basic loops with a capture gain of 0.25 and a 250 min reset, a reboiler loop of 3 MW/°C and 120 min, and a level loop of 0.2 and 1800 min. They fail two of the four parts, with a worst last-third deviation of 3.19 points and a rolling average that sinks to 86.96 %, leaving the plant 17.24 t short with a \$6,897 penalty, although the amine peak of 3.70 mg/Nm^3 and the final rich tank of 11.1 % pass. The suggested configuration puts the loop tunings of Table 7.3 under the economic supervisor, with the dear-power level at 50 %, $\alpha_d = 0.248$, $p_{hi} = 180$\$/MWh and $b = 1.5$ points. It meets all four parts, holding the last third within 1.11 points, 0.89 inside the band, and never letting the rolling average below 88.93 %, with the emission peaking at 3.80 mg/Nm^3 and the rich tank finishing at 4.7 %. Integrated absolute error over the whole sixteen hours falls from 2414 to 677 % min, and the circulation travel rises from 7 to 130 m^3/min, which is the loop doing work rather than watching.

7.6.6 The Predictive Controller Against the Supervisor

Table 7.6 runs scenarios 9, 10, 11, 8 and 13 and the challenge for 960 min from each scenario's own settings, with the shipped seed, instruments and noise in every row. The plan keeps scenario 14's settings with no retuning, and on the challenge both structures carry the suggested tunings. Two supervisors exist only in the measurement script. The first is given the published prices and replaces the price index z of (7.17) by the share of the next eight published hours priced below the present hour, eight being the best of four windows tried over scenarios 9 to 11. The second, the third row of the comparison, is that ranked rule with one setting chosen in hindsight over the same three days from 280 candidates that keep the obligation and end at or under 15 % rich (a four-hour window, levels of 6 and 72 % and lean targets of 0.228 and 0.275). A copy used only by the script decides every 5 min.

Scenario 14 is the price day of scenario 10 under the predictive controller. The plan strips deeper than design before the evening, to a lean loading setpoint of 0.2229 and a duty of 426.2 MW at 420 min while the price is \$95. Through the \$175 hours it holds a mean duty of 268.6 MW against the supervisor's 290.0 and spends the lean tank to 9.89 % at 590 min, its own margin, regenerating the stored solvent overnight, as shown in Figure 7.5. Its capture never falls below 89.23 %, while the supervisor empties its lean tank to 6.21 % and its capture dips to 88.32 %. The plan makes \$523,372 against \$518,267 and the flat plant's \$513,204, with \$74,243 of steam against \$78,648 and \$81,088.

Table 7.6 The Predictive Controller Against the Supervisor Over 960 Minutes, Measured on the Engine

Case	Structure	Margin ($)	Steam ($)	Capture min (%)	Capture <85 (min)	Rolling min (%)	Lean min (%)	Rich max (%)	Rich end (%)	Plans
9	supervisor, shipped	664,951	94,456	79.71	21.5	88.80	3.3	70.5	4.4	–
	MPC	667,086	91,838	89.01	0	89.87	9.9	63.9	10.1	96
	supervisor given the published prices	666,899	93,453	84.61	6.5	88.96	3.5	70.3	4.5	–
	hindsight supervisor (third row)	666,813	92,934	78.77	9.5	89.13	3.4	70.4	4.6	–
	MPC, preview off	653,831	100,146	89.84	0	89.89	63.4	10.3	10.1	96
10	supervisor, shipped	518,267	78,648	88.32	0	89.50	6.2	67.5	4.4	–
	MPC (scenario 14)	523,372	74,243	89.23	0	89.91	9.9	63.9	11.0	96
	supervisor given the published prices	521,841	76,089	88.93	0	89.57	11.9	61.9	4.5	–
	hindsight supervisor (third row)	525,838	73,052	80.74	6.5	88.88	3.5	70.2	14.9	–
	MPC, preview off	513,364	80,456	89.85	0	89.92	63.4	10.4	10.1	96
	basic loops	513,204	81,088	89.98	0	89.99	63.6	10.1	10.0	–
	MPC, 4 h plan	523,327	74,030	89.19	0	89.90	9.9	63.9	11.2	96
11	supervisor, shipped	742,909	105,226	77.96	23.5	88.51	3.1	70.6	4.3	–
	MPC	743,462	104,104	89.00	0	89.88	9.9	63.9	10.1	96
	supervisor given the published prices	743,600	105,674	83.27	18.5	88.82	3.3	70.4	4.4	–
	hindsight supervisor (third row)	744,484	104,820	78.54	10.0	89.09	3.4	70.4	4.6	–
	MPC, preview off	733,460	110,689	89.78	0	89.90	63.5	10.2	10.1	96
Challenge	supervisor, suggested	600,292	90,961	85.46	0	88.93	10.2	63.5	4.7	–
	MPC, suggested loop tunings	604,273	86,942	80.80	11.5	89.17	9.9	63.8	12.6	96
	supervisor given the published prices	602,374	89,732	85.85	0	88.90	16.5	57.2	4.6	–
	hindsight supervisor (third row)	605,113	87,393	85.65	0	88.59	6.5	67.3	4.6	–
	MPC, preview off	594,064	93,297	80.86	12.0	89.15	57.3	16.5	10.1	96
	MPC, 4 h plan	604,012	86,944	80.82	7.0	89.27	9.9	63.8	16.2	96
8	basic loops, shipped	317,837	50,639	82.17	26.5	88.20	54.0	19.8	12.2	–
	MPC	317,330	50,151	64.96	24.5	88.29	52.9	20.9	10.1	96
	MPC deciding every 5 min	318,131	50,220	74.30	13.0	89.22	54.7	19.1	10.1	192
13	basic loops, shipped	381,202	63,529	82.66	5.5	88.92	44.7	29.0	4.7	–
	MPC	380,731	62,621	77.27	16.0	89.11	56.4	17.3	10.2	96
	MPC deciding every 5 min	381,391	62,691	77.40	9.0	89.57	55.8	18.0	10.1	192

Margin is the application's own figure, the revenue at each minute's price less the carbon price on escaped carbon dioxide, makeup and the obligation penalty, c_{obl} for each tonne short of holding every four-hour window at C_{obl}, charged once and paid by no row. Steam is the reboiler duty's cost in electricity at each minute's price. No row spends a minute under the rolling obligation, so the rolling minimum gives the depth. Capture <85 counts minutes below 85 %. The tanks start at 63.75 (lean) and 10 % (rich). No plan was rejected. On scenarios 8 and 13 the price is flat and the plan with its preview off equals the plan.

Most of that gain is knowledge of the prices, and the plan adds the rest. With its preview off the plan makes $513,364, within $160 of the flat plant, because a plan that sees one price has no reason to store. The supervisor given the same published schedule makes $521,841, which apportions the plan's $5,105 lead as $3,574 (70 %) of price knowledge and $1,531 (30 %) of optimization. The split is 91 to 9 on scenario 9 and 52 to 48 on the challenge, and on scenario 11 the ranked supervisor beats the plan by $138. The hindsight supervisor makes more than the plan on scenario 10 ($2,466 more), scenario 11 ($1,022) and the challenge ($840) and $273 less on scenario 9, by letting the capture fall to 80.74, 78.54 and 78.77 % on scenarios 10, 11 and 9, where the plan never lets it below 89.0 %. The capture weight and the lean margin are a decision not to starve the absorber, and the hindsight row prices it. Nor is the horizon the source, since a four-hour plan is within $261 of the 24-hour plan on all four priced cases. With scenario 10's schedule published and other prices realized (the peak an hour late or early, at $130 or $230, or absent), the plan still beats the supervisor by $2,073 to $5,998, and the ranked supervisor on the same wrong schedule ends between $1,057 ahead of the plan and $2,767 behind it.

The plan loses both flat-price days to basic loops, and the cause is its decision period. On scenario 8 it makes $317,330 against $317,837. The decision at 480 min reads the analyzer before the returning gas reaches the absorber and holds the circulation for ten minutes, so the capture falls to 64.96 % against 82.17 % under a capture loop that acts every 0.5 min. On scenario 13 it makes $380,731 against $381,202, with the capture down to 77.27 % at the warming against 82.66. It recovers faster on both, with capture integrated absolute errors of 465 against 711 and 380 against 521 % min, and deciding every 5 min it makes $318,131 and $381,391 and beats basic loops on both days. Scenario

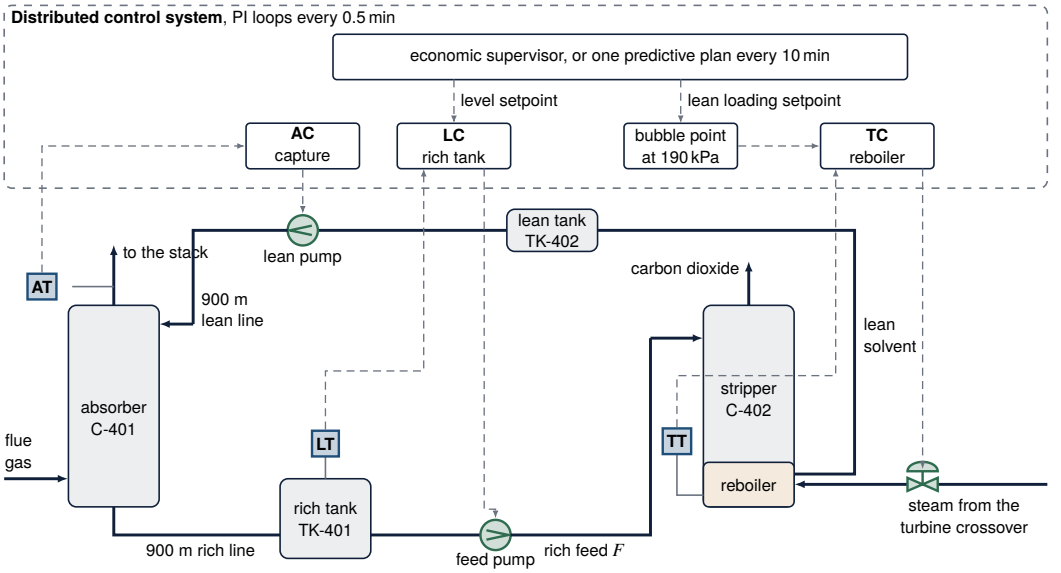


Figure 7.6 The three loops of capture plant U-400 with their hardware. Lettered boxes are sensing devices: the stack analyzer (AT-401) on the treated gas, the thermocouple (TT-402) in the reboiler and the level transmitter (LT-401) on the rich tank. The pump symbols and the steam valve are final elements, and dashed arrows are signals. Notice that the capture controller moves the lean pump at one end of the circuit while the lean loading it depends on is set by steam at the other end, and that the reboiler loop receives its setpoint as a temperature computed at an assumed stripper pressure. The cross exchanger and the makeup are left out. Not to scale, and not a piping diagram.

10's two fairness tests, which the supervisor passes, both fail narrowly for the plan. It captures 0.042 points less carbon dioxide than the flat plant (2.77 t, already charged in the margin) and ends 1.03 points fuller in the rich tank (83 m^3, \$17 to \$41 of steam). On the challenge with the suggested loop tunings the plan meets all four parts of the target, with a worst last-third deviation of 1.48 points, a rolling minimum of 89.17 %, an amine peak of 3.90 mg/Nm^3 and the rich tank at 12.6 %, while the four-hour plan ends at 16.2 % and misses the last part. On the inherited tunings the plan fails, with a worst deviation of 6.73 points and 205 min under the obligation (54.87 t short, a \$21,949 penalty), because the reboiler loop at 3 MW/°C and a 120 min reset takes 312.5 min to reach 63 % of a lean setpoint step where the model assumes 9.4 min.

7.7 Technology in Practice

What Measures It

Figure 7.6 draws the three loops of Section 7.5 with their devices. The capture loop reads the carbon dioxide left in the treated gas, and at a commercial capture unit that reading comes from certified analyzers on the absorber stack, which also measure the stack flow [18]. The reboiler loop reads a thermocouple and the level loop a level transmitter. Lean loading is usually found by titration, an analysis that can take up to two hours while the open sample loses carbon dioxide and the amine degrades [24], which is why the chapter's plant infers it from the reboiler temperature.

TECHNOLOGY Sensor: A Non-Dispersive Infrared Analyzer

Carbon dioxide in a combustion exhaust is the standard example of the non-dispersive infrared analyzer, developed in 1937 and 1938. Sample gas flows through a windowed cell, and a heat-sensitive detector behind it measures how much infrared light the gas did not absorb. Water vapor, carbon monoxide and sulfur dioxide absorb too, so a selective analyzer uses a detector filled with the gas of interest. A sealed reference cell cancels the zero shift of an aging lamp but not its span shift, which calls for recalibration. The sample must arrive clean and dry, since liquid or dust in the analyzer causes anything from delay to gross error [25]. On a trend a span drift is a slow walk of the reading that no move of the plant explains. The model's AT-401 is a 2.0 min lag with optional noise.

What Moves It

The capture loop moves the lean circulation through pumps, the level loop moves the stripper feed, and the reboiler loop moves low-pressure steam. On a coal unit that steam is extracted from the crossover pipe between the intermediate- and low-pressure sections of the steam turbine, and in a reference design its flow is proportional to the rich amine sent to the stripper and depends also on the stripper top temperature [26]. That extraction is the term $k_s Q$ of Equation (7.13). The model gives the steam valve a lag of 3.0 min and bounds the pumps by their stops and by the tank ends of Equation (7.16).

TECHNOLOGY Final Element: A Solvent Pump on a Variable-Speed Drive

Setting a pumped flow by the speed of the pump uses less energy than running it at full speed and throttling its discharge or recycling to its suction, and it leaves the control valve out of the line. A variable-speed machine often cannot change flow as fast as a valve and has limited fail-safe options, and its drive limits speed, current and acceleration and shuts down on overcurrent [25]. A pump held at such a limit cannot follow its command, so on a trend the commanded and the delivered flow part company. The model's circulation is bounded at 55 and 170 m^3/min and falls once the lean tank drops below its 5 % pump suction limit, and every run exports the commanded flow beside the delivered one.

Where the Controller Runs

At the commercial capture unit that began operating in 2016, the capture process and its balance of plant were run from a distributed control system in their own control room, and the carbon dioxide compressor had a dedicated programmable logic controller. The operator changed the plant's load by changing a carbon dioxide production setpoint, and automatic control held it anywhere from 50 to 100 percent load, although the plant ran best at full load [18]. A distributed control system runs nested and cascaded loops under a supervisory level, with cycle times from milliseconds to minutes [27]. The app executes its three PI loops every 0.5 min and its predictive controller every 10 min, inside that range. The three loops belong to the regulatory layer, and the economic supervisor and the predictive controller to the layer above it.

> **IN PRACTICE** **Keeping a Stack Analyzer Certified**
>
> A United States coal unit under the federal acid rain rules measures its carbon dioxide emissions with a certified analyzer and a flow monitor whose data are recorded automatically [28]. On a boiler the analyzer is spanned between 14 and 20 percent carbon dioxide. Every operating day it is checked with zero and upscale calibration gases, and an error above 1.0 percent carbon dioxide puts its data out of control. A linearity check follows each quarter, the relative accuracy against a reference method must stay within 10 percent, or within 1.0 percent carbon dioxide, and the cycle time within 15 min [29, 30]. The commercial capture unit of 2016 carried certified analyzers for flow and carbon dioxide on its absorber stack [18].

What Is Modernizing It

Three developments bear on this plant. Near-infrared spectrometry calibrated on a gas plant's solvent reads amine strength, carbon dioxide loading and water content, and has been proposed to replace titration [24]. An online loading measurement of that kind would expose the pressure-drift failure of Section 7.6. Scheduling amine regeneration for times of surplus power, so that the station's output can rise when it is needed, is proposed as a service capture plants can offer the grid [17]. And economic predictive control that joins scheduling and dynamic control, together with coordinated control of the power station and the capture plant, is named as the next step for the field [7].

7.8 Limitations

No number printed here will size a piece of equipment, because the model was never built as a design tool. The equilibrium of (7.1) is a three-factor correlation anchored at one point rather than an electrolyte activity model, the stripper is one lumped reboiler with a calibrated φ, and three absorber stages cannot place a temperature bulge in height. Specific duty, solvent inventory and emission performance are therefore internally consistent and not transferable to a real plant [7]. The water balance is open, so the excursions that occupy real operators are absent. The host is a fixed gross output and a fixed steam-to-electricity factor, which flatters very deep storage and very high capture rates [15]. There is no feedforward from the host load signal and no analyzer on the lean loading, both withheld deliberately, so scenario 8 takes longer than a real plant would and scenario 6 has something to break. A real plant drifts, while every disturbance here arrives as a commanded step or a timed event, and freezing the random seed alongside the integration step and the controller period returns a trajectory no distributed control system could repeat. Three elements are stylized on purpose. A stripper pressure that rises 25 kPa at an instant is not how a condenser fouls, but it isolates the inferential error from everything a season of fouling would change alongside it. Degradation at 6 % per day compresses months into a shift so the actuator drift reads off one trend. The price arrives as a staircase because a staircase is the disturbance whose response can be timed, while a real pool price moves every five minutes. Five features survived the trimming, the volume-keyed transport of (7.6), the loop-closing scalar of Section 7.4, the convex reboiler bill of (7.10), the inference of (7.11) and the tank ends of (7.16), each because it changes the controller a reader would have to build. Section 7.3.8 says where the remaining assumptions stop holding.

The predictive controller's model omits the host load, the cooling water, the stripper pressure, the solvent strength and the packing, which reach it only through the analyzer bias, and it has no rich-leg recycle state. Its preview is an exact copy of the schedule, and it knows nothing of a dispatch. Its 10 min decision loses scenarios 8 and 13 to basic loops by \$507 and \$471, the hindsight supervisor out-earns it on three of four priced cases by letting capture fall to 78.54 %, and it fails the challenge on the inherited tuning of the temperature loop it relies on.

7.9 Discussion

The plant makes an unusual demand on the control engineer, which is that the manipulated variable of the most important loop is bought out of the product the owner is paid for. Every megawatt of reboiler duty is 0.175 MW the station does not sell, so the design duty of 373 MW is 65.3 MW of lost

revenue before the compressors are counted [10]. Neither end of that trade is negotiable, because the capture rate is written on a permit and the energy per tonne is set by the heat of absorption and the water boiled with it, so the only decision left is when to spend it and the tanks are the only instrument for making it. A level setpoint on the rich tank is therefore an energy schedule worth 38 MW while the tank is filling, bounded not by the tank being filled but by the one being emptied.

The same reasoning explains why the supervisor multiplies rather than adds. An economic layer that traded permit compliance against price at any exchange rate would eventually find a price at which selling the permit is the optimal action, and (7.17) is written so that no such price exists. That is a control structure decision rather than an optimization one, and it is the same distinction that separates a self-optimizing choice of controlled variables from a numerically optimal one [6].

The model supports methods beyond the three implemented loops. A sixteen state balance with two hard tank limits and a convex reboiler bill is what model predictive control is for, and the option of Section 7.5.5 keeps both tank ends inside their alarm levels explicitly and coordinates circulation, lean loading and feed as one three-input problem with the price in the objective rather than as three loops with an hour of interaction between them [5, 16]. The same equations under moving horizon estimation would recover solvent strength and packing condition out of the circulation and duty records, turning the invisible fault of scenario 12 into a soft sensor. The pressure-compensated inference scenario 6 asks for is one line of arithmetic once (7.11) is available, and it is the cheapest improvement anywhere in this plant.

> ⚠ **OPEN CHALLENGE** **Running the Power Station and the Capture Plant as One**
>
> A power station that follows the electricity market changes its flue gas flow and the steam drawn from its turbine often and over a wide range, while a capture plant can take more than two hours to settle after a change in reboiler duty. Most control studies treat the capture plant on its own, although the two are strongly coupled through the flue gas and the extracted steam, and a steady-state optimization cannot see the transients. Loading, flows and concentrations are hard to measure accurately in real time, and the plant itself changes as the solvent degrades and the equipment corrodes [7]. Progress would be coordinated control of station and capture plant, with the schedule and the dynamic control solved together [7].

7.10 Conclusion

This chapter has presented a post-combustion amine capture plant as an interactive laboratory for what a large material recycle does to the gain of a control loop. The simulator integrates sixteen states, keys its two 1170 m^3 transport lines on cumulative volume so that the 9.00 min delay stretches to 7.55 min at 155 m^3/min, and solves rather than assumes a design line-up of 90.00 % capture, 371.3 t/h of carbon dioxide, loadings of 0.2375 and 0.4472 mol/mol, a reboiler at 115.87 °C, 3.619 MJ/kg of specific duty and 463.7 MW left of the host's 580 across a 9100 m^3 circuit whose lap is 70.0 min. With the reboiler duty frozen a 20 m^3/min circulation step is worth 0.177 points of capture per m^3/min at ten minutes and 0.040 at eight hours, while the same step with the lean loading loop in service is worth 0.177 at both times, paid for by the reboiler moving from 372 to 401 MW. Weakening that inner loop to 3 MW/°C leaves the capture controller on its 170 m^3/min stop almost a point short of setpoint with the lean loading at 0.2715, and raising the surge tank gain from 1.5 to 8 shortens the time to setpoint from 110 to 44 min while widening the reboiler duty swing to 427 MW, which is the opposite of what the tank was bought for. Time-shifting regeneration across a sixteen-hour price day sells 0.80 % more electricity and earns a 0.99 % larger margin at the same captured tonnage, and seven hours of expensive power finish 0.00 t short of the obligation because the price signal is multiplied by the remaining credit rather than added to it. On that day the predictive controller earns $5,105 more than the supervisor, and 70 % of it is recovered by a supervisor given the same prices. The next additions to the model would be feedforward from the host load, a pressure-compensated loading inference, a throttled low-pressure turbine and an axial absorber profile. Why an inner loop

earns its cost when the outer loop is wrapped around a recycle is the lesson the capture plant was built to carry, and a browser is all it asks for.

KEY POINTS

- A capture plant's solvent comes back to the absorber about seventy minutes after it leaves, so every move of the circulation acts through a recycle.
- With the reboiler duty frozen the capture gain falls from 0.177 at ten minutes to 0.040 at eight hours. A lean loading loop underneath holds it at 0.177, so the inner loop makes the outer loop's gain a constant.
- An inference built on the reboiler temperature at an assumed pressure holds its measurement perfectly while the true lean loading walks away.
- A surge tank level loop must stay slack, and a rich tank setpoint is an energy schedule bounded by the tank being emptied.

Where else this applies. Volume 6, Chapter 7 measures the same recycle amplification on a reactor and column, and Volume 5, Chapter 10 infers a product quality from a temperature that a second variable misleads.

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7.11 Exercises

7.1 ⌕ Concept check · 2 min

With the reboiler duty frozen at 373.3 MW, a circulation step from 130 to 150 m^3/min raises the capture rate by 0.177 points per m^3/min at ten minutes and by only 0.040 after eight hours. Why does the gain decay?

(a) The absorber packing wets less evenly at the higher flow, so its transfer coefficient falls

(b) The pipe delay grows with the flow, so the extra solvent reaches the absorber later and later

(c) The same duty must regenerate more solvent, so the solvent that returns is less lean

(d) The stack analyzer's lag hides the early response, so the first reading overstates the gain

7.2 ⌕ Concept check · 2 min

The economic supervisor of Equation (7.17) multiplies the price index z by $1 - u$, where u is the obligation urgency. Why a product and not a sum?

(a) A product makes the supervisor answer a price change faster than a sum would
(b) A product gives the price a fixed exchange rate against the permit, which a sum lacks
(c) A product keeps the rich tank below its full limit when the price stays high
(d) A product strips the price of its authority as the credit runs out, so no price can sell the permit

7.3 Concept check · 2 min

In scenario 6 the stripper pressure rises from 190 to 215 kPa at 90 min. The reboiler temperature loop has its temperature back within 0.1 °C of setpoint 19 min later and nothing alarms. Which statement is true once the plant has settled?

(a) The true lean loading is near 0.274 while the inferred one still reads 0.238, and the only sign is extra circulation
(b) The inferred lean loading reads 0.274, so the operator sees the richer solvent at once
(c) The capture rate settles about a point below its setpoint because the solvent is richer
(d) The temperature loop is mistuned, and a higher gain would bring the lean loading back

7.4 Theory and calculation · 6 min

The circuit holds two lines of 1170 m^3 each, a lean tank of 5100 m^3, a rich tank of 800 m^3, a reboiler of 500 m^3 and an absorber of 360 m^3.

(a) Compute the residence time of each holdup at the design circulation of 130 m^3/min and the lap. *Checkpoint:* lap 70.0 min

(b) Scenario 2 steps the circulation to 155 m^3/min. Compute the transit time of one line and the lap at that flow. The trend shows the solvent leaving the absorber moving after 0.5 min and the solvent reaching the top of the absorber after 21.5 min. Why is the second time longer than the absorber's half minute plus two line transits? *Checkpoint:* 7.55 min and 58.7 min

(c) At part load the capture loop cuts the circulation to about 70 m^3/min. Compute the line transit and the lap, and say what this does to a capture loop tuned at design. *Checkpoint:* 16.7 min and 130 min

7.5 Theory and calculation · 7 min

Use the recycle relation of Equation (1.5), settled gain $g_F/(1-g_R)$, with the gains of Figure 7.2: 0.177 points per m^3/min at ten minutes, before any changed solvent has come back, and 0.040 settled with the duty frozen.

(a) Compute the return gain g_R of the solvent loop with the duty frozen. *Checkpoint:* $g_R = -3.4$

(b) Scenario 3 steps the capture setpoint from 90 to 94 %. Estimate the settled circulation with the lean loading loop in service and with the duty frozen, starting from 130 m^3/min. The pump's stop is 170 m^3/min. *Checkpoint:* about 153 and 230 m^3/min

(c) The capture loop has $K_c = 3.5\,m^3/\text{min}$ per point. Compute the loop gain K_c times the process gain for both cases and their ratio, and say which case the shipped tuning was chosen for. *Checkpoint:* 0.62 and 0.14, ratio 4.4

7.6 Theory and calculation · 6 min

At the design line-up the reboiler takes 373.3 MW, the plant captures 371.3 t/h of carbon dioxide, and the host makes 580 MW gross. Use Equation (7.13) with $k_s = 0.175$, $w_c = 0.378\,\text{MJ/kg}$, $W_p = 7.5\,\text{MW}$ and $W_b = 4.5\,\text{MW}$, and take the stripper outlet equal to the capture.

(a) Compute the steam and compression terms, the total the capture plant takes and the net output. *Checkpoint:* 116.3 MW and 463.7 MW

(b) Express the total and the steam alone in MWh of lost output per tonne captured. Give three decimals. *Checkpoint:* 0.313 and 0.176

(c) Scenario 4 measures 13.2 MW for the step from 90 to 95 % and 7.8 MW returned by the step from 90 to 85 %. Compute the cost per point on each side and their ratio. *Checkpoint:* 2.64 and 1.56 MW per point, ratio 1.7

7.7 App challenge · 8 min

Open scenario 1, *The absorber by hand (MANUAL)*, default seed, as loaded.

(a) Run at 1 min/s and pause when the clock reads between 3 and 30 min. Note the time t_s, set Solvent circulation and Stripper feed rate both to 150 m^3/min, and run at 60 min/s to at least $t_s + 480$ min. From the exported CSV (time column `Time (h)`), read `capture_pct` at $t_s + 10$ and $t_s + 480$ min and `a_lean_reb_m` at $t_s + 480$ min, and compute the apparent gain at both times against the design 90.00 %. Give the capture rates to ± 0.02 points and the loading to ± 0.001. *Checkpoint:* 93.55 and 90.81 %

(b) Press the reload button, run a few minutes as in (a), and set Reboiler steam duty to 420 MW. Read `capture_pct` 20 and 60 min after the step (± 0.02 points) and `W_net_MW` just before the step and 60 min after it (± 0.2 MW). *Checkpoint:* 90.25 and 91.73 %

7.8 App challenge · 8 min

Open scenario 3, *Capture on circulation, and the loop underneath that makes it work*, default seed. The capture setpoint steps from 90 to 94 % at 60 min and returns at 420 min.

(a) Run as loaded (Basic loops) at 60 min/s past 420 min. From the exported CSV row at `Time (h)` = 7.000, read `capture_pct`, `L_cmd_m3min`, `a_lean_reb_m` and `W_net_MW`. *Checkpoint:* 94.01, 153.9, 0.2379, 453.6

(b) Set Reboiler temperature loop gain to 3 MW per °C and Reboiler temperature integral time to 120 min, press Reset, and repeat the run. Read the same four values, and the first row with `L_saturated` equal to 1. Give the capture to ± 0.02 points, the loading to ± 0.0005, the host output to ± 0.2 MW and the time to ± 1 min. *Checkpoint:* 93.03, 170.0, 0.2715, 456.7

(c) The capture tuning is the same in both runs. Explain why no change to the capture loop repairs the second run.

7.9 App challenge · 9 min

Open the challenge, *A day of prices, a load ramp and a permit*, default seed. Run every attempt to 960 min at 120 min/s without stopping, and read the result line of the challenge in the progress panel and the CO_2 short and Margin tiles.

(a) Run it as shipped. *Checkpoint:* worst 3.19 points, rolling minimum 86.96 %

(b) Set the six loop tunings to those of Table 7.3 (capture gain 3.5 with 20 min, reboiler 30 with 12 min, level 1.5 with 240 min), stay on Basic loops, press Reset and run again. Give the four values of the result line. *Checkpoint:* worst 0.58 points, rolling minimum 89.10 %

(c) Keep those tunings and set Control to Economic supervisor. In the Economic supervisor group of the advanced controls, set Rich level setpoint when power is dear to 50 %, Lean loading target when power is dear to 0.248, Price the supervisor calls dear to \$180 and Obligation credit the supervisor may spend to 1.5 points. Press Reset and run again. Compare the margins of (b) and (c) over the day. *Checkpoint:* worst 1.11 points, rich tank 4.7 %

Give the result-line values as printed and the margins to $\pm$\$10 per hour.

7.10 Application area · 4 min

In scenario 9 the price goes to \$210 for five hours and the supervisor raises the rich tank setpoint to 72 %. Half an hour into the peak the stripper feed is about 64 m^3/min against a circulation of about

130 m³/min, and the host makes 508.8 MW against 451.6 MW before the peak. The lean tank starts at 63.75 % of 8000 m³, and the pumps lose suction at 5 %.

(a) Compute the lean tank's usable swing and how long it would last at the imbalance above. *Checkpoint:* 4700 m³, about 71 min

(b) What is the extra output worth per hour at $210, and why is the binding tank the lean one rather than the rich one an operator watches?

7.11 Application area · 4 min

Two faults in the chapter hold every setpoint. Use Section 7.6 and Equation (7.15).

(a) Degradation doubles for every 8 K above 120 °C. By what factor is the rate at 128 °C larger than at the design 115.87 °C? What does the makeup of 90 kg/min that holds the strength cost per hour at $2.40 a kilogram? *Checkpoint:* 2.9 times, $12,960 per hour

(b) On a 49 °C afternoon the capture loop holds 90 %. Which limit binds, and what would an operator have to give up to stay inside it?

7.12 Review the agent · 5 min

An AI assistant reads Table 7.6 and writes: "On the price day of scenario 10 the predictive controller earns $523,372 against the supervisor's $518,267. Its optimizer is worth $5,105 a day, so the predictive controller should replace the supervisor on every day the plant runs." Find the flaw, and say how you would check it in the app.