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CHAPTER 12

A Hydrogen Plant Whose Steam Must Lead Its Feed and Whose Waste Is Its Fuel

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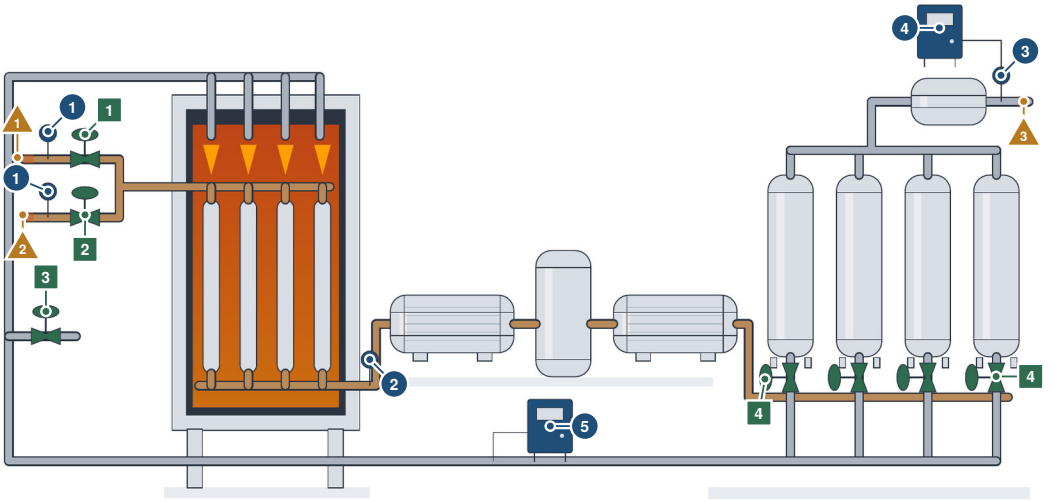
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CHAPTER 12

A Hydrogen Plant Whose Steam Must Lead Its Feed and Whose Waste Is Its Fuel



The controller moves 1 natural gas feed valve 2 process steam valve 3 makeup fuel valve to the burners 4 adsorber switching valves, stepped on the cycle

The controller reads 1 natural gas and steam flow meters 2 reformer outlet temperature 3 hydrogen header pressure 4 hydrogen purity analyzer 5 heating value of the tail gas

What disturbs it 1 more ethane in the natural gas 2 a change in steam supply pressure 3 the users' hydrogen demand

Notice that the tail gas from the four adsorbers runs back along the bottom to the burners on top of the reformer, so the hydrogen the beds do not recover becomes the furnace's fuel. Illustration, not to scale.

IN PLAIN TERMS Steam First, and the Waste Becomes Fuel

The main idea. A hydrogen plant heats natural gas and steam in tubes filled with a catalyst, a material that speeds up the change into hydrogen. Beds of special grains then hold back the other gases and let clean hydrogen through.

The challenge. The gas must never outrun the steam, or carbon builds up on the catalyst, yet the steam can only speed up slowly. The gases the beds give back are burned to heat the tubes, so keeping more hydrogen means buying more fuel.

Why it matters. The order in which the gas and the steam move matters as much as how much of each the plant uses.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	This page, the Did you know? box in Section 12.1, the History boxes in Section 12.2, the Try it boxes and the second Did you know? box in Section 12.5, and Key points in Section 12.9. No equations.
Study	55 min	The whole chapter in order, stopping at the three pause points, then Exercises 1 to 12.
Practice	20 min	This page, Section 12.5 with Figure 12.3, Section 12.6 and Section 12.7 with its Open challenge box.

The control question A hydrogen plant must keep its slow steam ahead of a fast feed, and it burns whatever hydrogen its adsorber does not recover. Which structure keeps the steam-to-carbon ratio above its floor through a rate change, and how does the adsorber's recovery reach the furnace?

Learning objectives

- Compute the steam a feed needs, the ratio left after a feed step with the steam held, and the valve position that restores it.
- Explain why a plain ratio to the measured feed falls through its floor when the steam ramps slowly, and how a lead-lag on the rate demand prevents it.
- Predict the adsorber's recovery and purity from its step time and its feed with the declared correlation.
- Trace a change in recovery through the tail gas to the makeup fuel and to the natural gas used per unit of hydrogen.
- Configure the header, ratio, adsorber and firing layers to pass the eight-hour challenge, and name the target each change protects.

Prerequisites Sections 1.4.2 (heat-balance feedforward and tube metal), 1.4.5 (heat fed back), 1.4.6 (bias update), 1.6.1 and 1.6.2. Section 1.6.3 is needed only for the predictive controller.

The app https://apmonitor.com/apps/hydrogen-plant/

See also Volume 3, Chapter 4 for cross-limiting fuel and air and an override with external reset feedback. Volume 4, Chapter 3 for limiters selected on one fuel valve. Volume 6, Chapter 7 for a recycle that amplifies a production change. Chapter 14 for a header pressure that nobody schedules.

12.1 Introduction

Hydrogen for a refinery's hydrotreaters and hydrocracker is made, in the generic plant simulated here, from 18 700 Nm^3/h of natural gas and 46.9 t/h of steam, three moles of steam for every mole of carbon. The reformer's tubes leave at 860 °C and 25 bar a with 5.37 % of the dry gas still methane, a shift bed converts most of the carbon monoxide, and a four-bed adsorber delivers 50 004 Nm^3/h of hydrogen at 99.96 % to a header at 20 bar g. The adsorber keeps 85.0 % of the hydrogen it is fed. The rest, with the methane and the carbon oxides, returns to the furnace as tail gas, and at the design point it supplies 73.92 MW of the 103.43 MW fired, 71.46 % of the fuel.

> **DID YOU KNOW? Refinery Hydrogen From 2008 to 2014**
>
> From 2008 to 2014 the hydrogen used by United States refineries rose 60 %. The hydrogen they made on site changed by less than 1 %, and the hydrogen bought from industrial gas suppliers rose 135 %. Made on site, the extra hydrogen would have doubled the refineries' natural gas feedstock [1].

The simulator is aimed at two beliefs. The first is that a ratio loop protects its ratio. A steam flow loop in ratio to the measured feed can only follow the feed, and when the steam supply can move only 4 % of its valve a minute while the feed answers in seconds, a plain ratio drops the steam-to-carbon ratio from 3.00 to 2.729 on a 15 % feed rise, below the 2.8 floor at which the catalyst risks carbon. Over 64 tunings of the steam loop the lowest ratio stays between 2.629 and 2.763, so the remedy is in the structure and not in the gains. The second belief is that recovering more hydrogen saves natural gas. Lengthening the adsorber's cycle from 10 to 11 min raises its recovery from 85.0 to 86.4 %, the tail gas carries less heat, and the furnace needs 8.4 % more makeup natural gas. Losing a bed does the reverse and the makeup falls by 16.8 %, while the natural gas per normal cubic meter of hydrogen rises from 0.4323 to 0.4403.

Both shapes recur well beyond reforming. A safety ratio between two streams of different speed appears in fuel and air on every burner, for which Volume 3, Chapter 4 offers cross-limiting, and in reactant feeds to exothermic reactors. A process whose byproduct is its own fuel or feed has the same coupling as a recycle, studied plantwide in Volume 6, Chapter 7, and refinery hydrogen itself is

analyzed as a distribution network between the plants that make it and the units that consume it [2]. However, the published treatments divide this plant among separate specialties. Reformer models are written for the tube and the furnace [3, 4], adsorber control is studied on a cycle with its own optimization [5], and ratio control is taught as a chapter of its own [6].

This chapter works with a complete steam methane reforming hydrogen plant in one browser simulation in which the steam-to-carbon ratio, the reformer outlet, the adsorber's cycle, the header and the furnace's fuel are coupled as they are on a plant. It measures what a lead-lag, a tail-gas feedforward, a cycle that follows the feed and a predictive controller do to that plant. The equilibrium, the radiant firebox, the adsorption correlation and the control laws are all established methods. The findings are measurements on one generic plant at one seed, checked at four more, among them that the lead-lag works by holding the feed back rather than by speeding the steam. The model has 46 states. Its carbon, hydrogen and oxygen balances close to 2.6×10^{-16} in every cell, its fuel balance closes to rounding, its equilibrium constants come from van 't Hoff fitted to the NIST-JANAF tables, and its boiler uses the IAPWS-IF97 module shared by the framework apps. The model is written out in full so that the plant can be rebuilt. Nine cases are provided, the ninth an eight-hour challenge, and each is graded on the learner's own moves.

Section 12.2 follows the domain, from reformer chemistry and the steam floor to the adsorber and the hydrogen header. Section 12.3 sets out the plant as simulated: the equilibrium cells, the constants, the tubes and firebox, the fuel balance, the boiler and shift, the adsorber, the drums and valves, the instruments and the protection. Section 12.4 describes the control layers, from the header loop through the ratio and its lead-lag to the outlet loop, its override and feedforward, and the predictive controller. Section 12.5 measures the nine cases and the challenge. Section 12.6 sets the hardware of a real plant beside the model, Section 12.7 states the limitations, Section 12.8 records where the boiler's property module came from, and Section 12.9 draws the lessons together. Section 12.10 holds the exercises.

12.2 Hydrogen From Natural Gas, and the Adsorber Behind It

Large-scale hydrogen is made from natural gas by catalytic steam reforming, and the engineering of the reformer, its catalyst and its furnace has its own literature [7, 8]. The chemistry is two reactions on nickel, the strongly endothermic reforming of methane and the mildly exothermic water-gas shift. A 1989 study derived intrinsic rate equations for both on a nickel catalyst by discriminating among twenty-one sets of mechanisms [9]. The simulator of this chapter sets kinetics aside and holds each cell at equilibrium, so the methane that slips through follows the outlet temperature, the pressure and the steam-to-carbon ratio through the equilibrium constants. An industrial steam-methane reformer has been modeled for on-line deployment [3], and a reforming reactor has been modeled by computational fluid dynamics with its control designed on the result [4].

> ⧖ HISTORY **1954: Refineries Begin to Need Hydrogen**
>
> After the Second World War, refining processes began to use catalysts and hydrogen to change molecules and remove sulfur. A federal manual dates hydrodesulfurization to 1954 and hydrocracking to 1960. Such units need hydrogen of 95 to 99 % purity, and the hydrogen recovered from the gases of catalytic reformers is often not enough, so refineries make more. The manual describes how. Desulfurized gas is mixed with superheated steam and reformed in tubes filled with a nickel catalyst, then passed through converters with an iron catalyst, where carbon monoxide and steam form carbon dioxide and more hydrogen. Amine washing removes the carbon dioxide, and the carbon monoxide that remains is converted to methane [10]. The plant of this chapter purifies its gas in adsorbers instead.

The steam-to-carbon ratio is a constraint before it is a setpoint. Steam in excess of the reforming stoichiometry is what keeps carbon from forming on the catalyst, and coke formation during steam reforming and its minimization are a subject of their own [11]. Every plant therefore carries a floor on

the ratio that its catalyst supplier sets for its feed, and a feed change becomes a sequencing problem, steam first on the way up and steam last on the way down. In the plant simulated here the steam is also the slower stream, because it comes from a steam system whose response is limited, so the order has to be imposed on the demand before either stream moves.

The adsorber is the plant's purifier. Pressure-swing adsorption separates by holding impurities on an adsorbent at high pressure and releasing them at low pressure. It has a book-length treatment [12] and an industrial commentary on its development [13]. Commercial adsorbers produce high purity hydrogen from steam reformer off-gas and refinery off-gases in several cycle variants, and ideas to raise their recovery by coupling them to membranes or to further adsorbers have been reviewed [14]. The adsorber is a cyclic unit feeding a continuous user. Its beds are switched on a schedule, its product and its tail gas both pulse, and the performance it delivers depends on its steps and its pressure profiles, which is why its design and control have been optimized together and closed with predictive controllers [5]. In a hydrogen plant the tail gas goes to the reformer's burners, so the adsorber's recovery is also a term in the furnace's fuel balance.

> ⧖ HISTORY **1960 and 1969: Beds That Swing in Pressure**
>
> A patent granted in 1960 dried air in two beds of adsorbent that took turns. One adsorbed at pressure while the other was opened to a lower pressure and backwashed with part of the product, without heat from an outside source [15]. A patent filed in 1967 and granted in 1969 purified hydrogen in at least four beds. Each bed stops adsorbing while its front is still inside it, passes the gas left between its grains straight to a cleaner bed until their pressures equalize, is blown down through its inlet and purged, and is brought back up last with product. The patent states that earlier processes, at 70 to 80 % recovery, gave hydrogen of only 95 to 98 % purity, and it names steam reformed hydrocarbons among its feeds [16]. The four beds of this chapter step through the same kinds of steps.

The plant's place in the refinery explains its rate loop. Stricter fuel specifications raised hydrotreating and hydrocracking capacity and with it the refinery's hydrogen consumption, leaving many refineries with a tight hydrogen balance [2]. The users draw on a header and nobody schedules the hydrogen plant for them, so the plant reads the header pressure and sets its own rate, as the fuel gas header of Chapter 14 integrates sources and users that nobody schedules for its sake. The carbon in the feed leaves either in the flue gas or, where it is captured, at one of the points of the reforming process at which capture has been assessed [17], and natural gas per unit of hydrogen is the figure that carries both the fuel bill and the carbon.

12.3 The Plant as Simulated

No plant stands behind the simulation, and every size, flow, correlation and threshold is a generic teaching value for a plant of 50 000 Nm^3/h. The layout, the symbols used in the equations, and the values that case 4 shows at 11.3 min are shown in Figure 12.1. Natural gas of 94 % methane, 5 % ethane and 1 % nitrogen (carbon number $n_C = 1.040$) is mixed with steam and enters a representative reformer tube at 600 °C. The reformed gas passes a waste-heat boiler, a high-temperature shift bed and a cooler, and a four-bed adsorber sends its product through a surge drum to the header and its tail gas through a tail-gas drum to the burners, where natural gas makeup completes the fuel.

The model integrates 46 states, listed by role in Table 12.1. Thirty-two are physical: the catalyst temperature T_i and the tube-metal temperature $T_{w,i}$ of each of eight cells, the bridge-wall temperature T_{bw}, the shift bed temperature T_{HTS}, the feed, makeup and tail-gas flows behind their flow loops, the steam and vent valve positions, the moles in the surge drum, its impurities and the moles in the header, and the moles of each of six species in the tail-gas drum. Fourteen are ledgers that integrate what crosses the boundary (feed, makeup, product, vent, demand, tail gas, adsorber feed, flue carbon dioxide, fired energy, boiler steam, process steam, the drum's inflow and the tail gas burned) and the firebox's energy balance, so that every total can be checked. The clock is the minute, temperatures

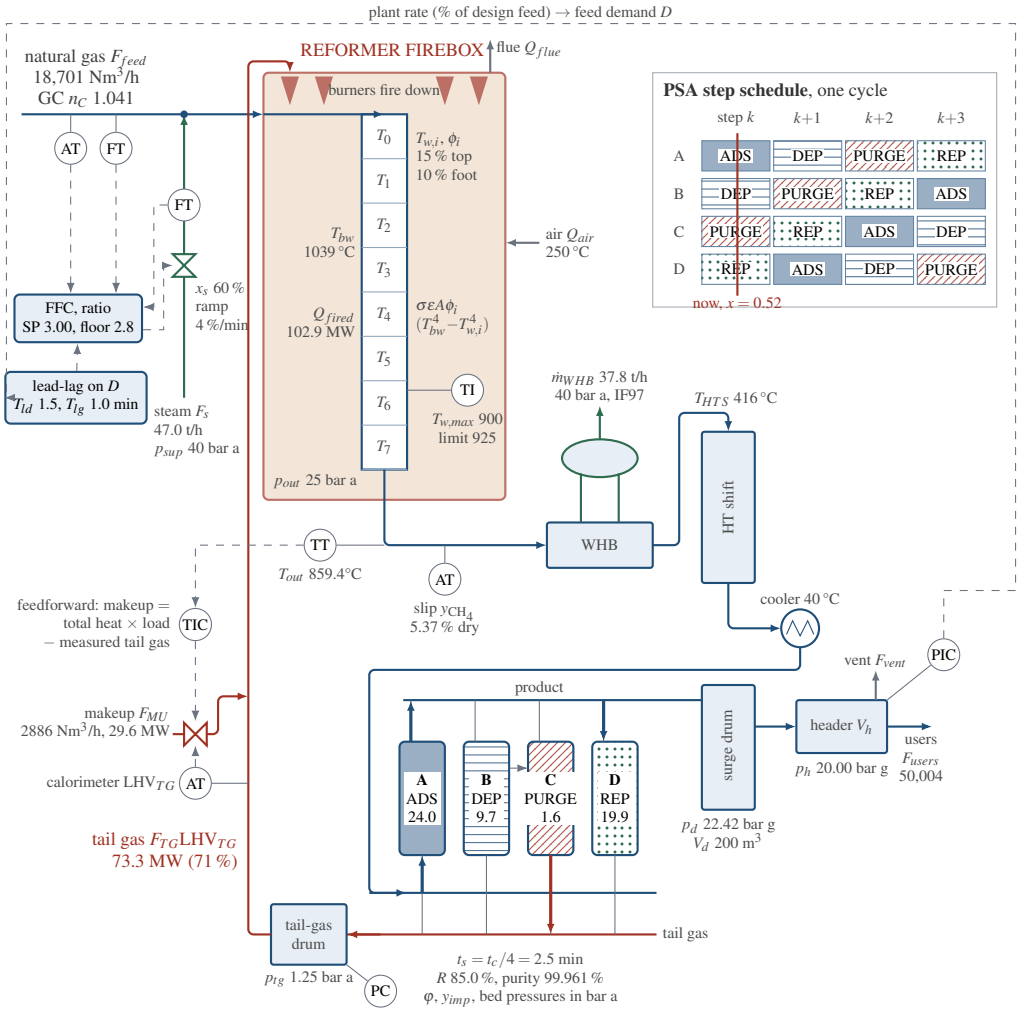


Figure 12.1 The hydrogen plant as modeled, drawn after the Plant view of case 4 at $t = 11.3$ min, when the adsorption step is 52 % done and all four phases are distinct: bed A adsorbs at 24.0 bar a (solid), B depressurizes at 9.7 (ruled) and provides purge gas, C is blown down and purged at 1.6 (hatched) and D is repressurized with product at 19.9 (dotted). Feed and steam meet at the tee under the ratio station, whose lead-lag acts on the feed demand D the header loop sets. The eight cells T_0 to T_7 sit in a top-fired box at T_{bw}, the boiler raises 37.8 t/h at 40 bar a, and the tail gas, 71 % of the 102.9 MW fired by the meters, returns to the burners with the makeup. The adsorber, the surge drum, the header and the tail-gas drum form the lower row, fed by the cooled gas that runs back under the reformer. The inset is the step schedule of one cycle with the present instant marked. Process model only, not to scale.

Table 12.1 Variables by Role at the Design Point

Symbol	Role	Design	Range
p_h	CV, header (bar g)	20.00	SP 18–22
S/C	CV, steam-to-carbon (mol/mol)	3.000	SP 2.5–4, floor 2.8
T_{out}	CV, reformer outlet (°C)	860.0	SP 820–900
r	MV, plant rate (% of design feed)	100	40–140
x_s	MV, steam valve (%)	60.0	0–100
F_{MU}	MV, makeup fuel (Nm^3/h)	2885	0–12,000
t_c	MV, adsorber cycle (min)	10	6–16
d	DV, hydrogen demand (% of design)	100	60–140
$x_{C_2H_6}$	DV, ethane in the feed (mol %)	5	0–20
p_{sup}	DV, steam supply (% of 40 bar a)	100	60–110
—	DV, makeup heating value (%)	100	70–100
T_i, $T_{w,i}$	states, cells, walls (°C)	602–860, 713–900	limit 925
T_{bw}	state, bridge wall (°C)	1040.9	limit 1120
T_{HTS}	state, shift bed (°C)	416.8	—
n_d, n_h	states, drum and header (kmol)	—	—
g_k	states, tail-gas drum species (kmol)	—	p_{tg} 1.25 bar a
y_{CH_4}	output, slip (% dry)	5.367	—
R, x_{H_2}	output, recovery, purity (%)	85.00, 99.960	spec 99.9
Q_{fired}	output, fired heat (MW)	103.43	burners 170
$\dot{m}_{WHB}$	output, boiler steam (t/h)	37.80	—

are in °C, flows in kmol/h inside and Nm^3/h (0 °C, 1.013 25 bar a) on the screen, header and drum pressures in bar gauge, process pressures in bar absolute, and heat in MW on the lower heating value.

12.3.1 Equilibrium in Eight Cells

The gas crosses a cell in a fraction of a second while the catalyst holds its heat, so a cell's composition is solved algebraically while its temperature is integrated. Every cell holds the equilibrium of the tube's inlet elements, reforming evaluated ΔT_{app} colder than the cell and the shift at the cell's own temperature, as shown in Equation (12.1).

$$K_1(T_i - \Delta T_{app}) = \frac{y_{CO}\, y_{H_2}^3}{y_{CH_4}\, y_{H_2O}}\, p_i^2, \qquad K_2(T_i) = \frac{y_{CO_2}\, y_{H_2}}{y_{CO}\, y_{H_2O}}$$
$$p_i = p_{out} + \Delta p_t \left(\frac{F}{F_0}\right)^2 \left(1 - \frac{i + 0.5}{8}\right) \tag{12.1}$$

where reaction 1 is $CH_4 + H_2O \rightleftharpoons CO + 3H_2$, reaction 2 is $CO + H_2O \rightleftharpoons CO_2 + H_2$, y are mole fractions, $p_{out} = 25\,\text{bar}\,a$, $\Delta p_t = 2\,\text{bar}$ at the design total flow F_0, and $\Delta T_{app} = 10\,\text{K}$ stands for the catalyst's activity. The two extents are found by Newton's method on the logarithms of the residuals with a fixed number of iterations (12 in the first cell, 8 after it, warm-started from the cell before), each step cut so that no species falls below a tenth of its value, so the result depends only on its inputs and the derivative function stays pure. Ethane reforms completely where the feed enters, $C_2H_6 + 2H_2O \rightarrow 2CO + 5H_2$. At design the outlet carries 171.32, 1638.00, 427.70, 268.66 and 2316.01 kmol/h of methane, water, carbon monoxide, carbon dioxide and hydrogen, and a hand calculation from the same constants reproduces every figure to the last digit.

12.3.2 Equilibrium Constants From the Tables

Each species' enthalpy is a straight line $h_k(T) = a_k + c_k T$ fitted to the NIST-JANAF tables [18] from 600 to 1200 K, its largest error 1.15 kJ/mol for methane. The reaction enthalpies follow from those lines, and van 't Hoff integrated with them fixes $\ln K$ up to one constant, as shown in Equation (12.2).

$$\ln K = -\frac{\Delta A}{RT} + \frac{\Delta c}{R} \ln T + I, \qquad \Delta H(T) = \Delta A + \Delta c\, T \tag{12.2}$$

where ΔA and Δc are the stoichiometric sums of a_k and c_k and only I is fitted to the tables' $\log K_f$ from 700 to 1200 K ($\Delta A = 209.84$ and −44.97 kJ/mol, $\Delta c = 0.01531$ and 0.010 148 kJ/(mol K), $I = 15.776$ and -13.475, K_1 in bar^2). The constants and the heats of reaction are therefore one consistent set. Against JANAF interpolated in $1/T$, K_1 is −1.44 % low at 850 °C and −1.11 % at 900 °C, and within 1.6 % from 700 to 900 °C (−1.51 % at 800 °C is the worst). The NIST WebBook's Shomate fit of the same tables gives −1.34 % and −1.12 %. K_2 is within 0.25 % of JANAF at 850 and 900 °C and within 0.19 % from 350 to 450 °C, the shift bed's range. At 900 °C $\Delta H_1 = 227.80\,\mathrm{kJ/mol}$ against JANAF's 227.1 and $\Delta H_2 = -33.06\,\mathrm{kJ/mol}$ against −33.1. With JANAF's own constants the design slip would be 5.321 % instead of 5.367 %. Ethane's formation enthalpy, −84.0 kJ/mol, is the WebBook's. Equilibrium makes the slip a function of temperature, pressure and ratio alone: at the design ratio it is 6.79, 5.37 and 4.17 % at 840, 860 and 880 °C, and 4.10 and 6.56 % at 20 and 30 bar a.

12.3.3 Tubes and a Radiant Firebox

Each cell's catalyst is heated by its wall through an inside conductance, each wall by radiation from a well-stirred firebox at the bridge-wall temperature, and the firebox by the burners, as shown in Equation (12.3).

$$\begin{aligned} C_{cat}\frac{\mathrm{d}T_i}{\mathrm{d}t} &= \dot{H}_{i-1} - \dot{H}_i + UA_i(T_{w,i} - T_i) \\ C_w\frac{\mathrm{d}T_{w,i}}{\mathrm{d}t} &= \sigma\,\varepsilon A\,\phi_i\left(T_{bw}^4 - T_{w,i}^4\right) - UA_i(T_{w,i} - T_i) \\ C_{fb}\frac{\mathrm{d}T_{bw}}{\mathrm{d}t} &= Q_{fired} + Q_{air} - \textstyle\sum_i Q_{rad,i} - Q_{flue} \end{aligned} \tag{12.3}$$

where C_{cat} and C_w are each an eighth of the totals, $UA_i = UA/8$, $\dot{H}$ is the enthalpy flow with formation enthalpies included (so the reaction heats need no separate term), $\dot{H}_{-1}$ is the mixed feed's, temperatures in the radiation term are in kelvin, and the flux shares ϕ_i of a top-fired box are 0.15, 0.15, 0.14, 0.13, 0.12, 0.11, 0.10 and 0.10 from the top. The flue gas is computed species by species from the fuels and the air, and $Q_{flue} = \sum_k n_k c_k (T_{bw} - 298.15)/3600$ and Q_{air} likewise at the 250 °C air preheat. At design the tubes absorb 52.14 MW of the 103.43 MW fired, 50.41 %, the bridge wall is at 1040.9 °C and the hottest wall, in the bottom cell, at 899.6 °C. A test of the application confirms that the heat stored in the firebox, walls and catalyst equals the integrated balance over a disturbed hour.

12.3.4 The Fuel Balance

The burners release the lower heating value of the tail gas and the makeup, as shown in Equation (12.4).

$$Q_{fired} = F_{TG}\sum_k x_k\,\mathrm{LHV}_k + F_{MU}\,\mathrm{LHV}_{NG} \tag{12.4}$$

where x_k is the tail-gas drum's composition, k runs over hydrogen, methane and carbon monoxide at 241.826, 802.3 and 282.995 kJ/mol (from the same formation enthalpies), and natural gas carries 802.3 and 1428.5 kJ/mol for methane and ethane. At design $Q_{fired} = 73.917 + 29.515 = 103.432$ MW, closing to 4×10^{-15}, so the tail gas, 9.279 MJ/Nm^3 at 28 678 Nm^3/h, supplies 71.46 % of the fuel and the makeup is 2885 Nm^3/h. The instantaneous firebox residual at $t = 0$, $103.432 + 9.463 - 60.735 - 52.137 = 0.023$ MW, comes from the air controller's initial estimate. Two simplifications of the furnace are declared and kept. The flue and air sensible heats use the slopes of the fitted lines from 298.15 K rather than the tables' own enthalpy rise. With JANAF enthalpies at the design bridge wall the flue would carry 58.37 MW instead of 60.65 and the air 8.48 instead of 9.45, and a hand balance needs 102.03 MW fired against 103.33 on the model's basis, so the model over-fires by about 1.3 MW and buys about 4 % more makeup (2855 against 2728 Nm^3/h by hand). The same linear enthalpies put the shift outlet at 416.8 °C, 3.5 K below the 420.3 that JANAF enthalpies give, with 3.43 % carbon monoxide dry against 3.52, and ethane's mean heat capacity overstates the feed's sensible heat by 0.134 MW.

12.3.5 Boiler, Shift and Cooler

A bypass holds the boiler's gas outlet at 350 °C, and the duty raises saturated steam at 40 bar a from feedwater at 105 °C, $\dot{m}_{WHB} = Q_{WHB}/(h'' - h_{fw})$. The properties come from the IAPWS-IF97 formulation [19] in the framework's shared module, $h'' = 2800.90\,\mathrm{kJ/kg}$ at $T_{sat} = 250.358\,^{\circ}\mathrm{C}$ and $h_{fw} = 443.45\,\mathrm{kJ/kg}$ at 45 bar a, so the 24.752 MW duty raises 37.80 t/h. That is less than the 46.9 t/h of process steam, so the boiler is not an export. The module's table stops at 25 bar, and the boiler calls its direct saturation functions, which match Region 2 at saturation to the printed digit. The shift bed is one adiabatic vessel with a heat capacity C_{HTS}, its gas at the shift equilibrium evaluated 10 K hotter than the bed, $C_{HTS}\,\mathrm{d}T_{HTS}/\mathrm{d}t = \dot{H}_{in}(350\,^{\circ}\mathrm{C}) - \dot{H}_{out}(T_{HTS})$. The cooler condenses water down to its IF97 vapor pressure at 40 °C, 0.073 84 bar, which leaves 3077 ppm in the adsorber's feed at 24 bar a.

12.3.6 The Adsorber

Four beds stand on a ring of four positions, adsorption, cocurrent depressurization, blowdown and purge, and repressurization, and every step of $t_s = t_c/4$ each bed moves one position, so exactly one bed adsorbs at every instant. Within a step each bed's pressure follows a prescribed shape: an equalization from $p_{hi} = 24\,\mathrm{bar}\,a$ toward $p_{eq} = (p_{hi} + p_{lo})/2$ in the first fifth, a provide-purge ramp to 5 bar a, a blowdown to $p_{lo} = 1.6\,\mathrm{bar}\,a$ in the first quarter, and product repressurization, each segment an exponential that ends exactly on its target. The flows these imply are exact derivatives, $C_b\,\mathrm{d}p/\mathrm{d}t$ with $C_b = 0.6\,\mathrm{kmol/bar}$, so the product taken by the repressurizing bed and the tail gas sent by the blowdown and purge both pulse once a step. The cycle-average performance follows a declared teaching correlation, as shown in Equation (12.5).

$$\begin{aligned} R &= 1 - \ell_N \frac{t_{s,0}}{t_s}\frac{F_{\mathrm{H}_2,0}}{F_{\mathrm{H}_2}}, \qquad \varphi = \varphi_0 \frac{F_{imp}}{F_{imp,0}}\frac{t_s}{t_{s,0}} \\ y_{imp} &= y_0\,\mathrm{e}^{(\varphi-\varphi_0)/w}\,(0.4 + 1.2x) \end{aligned} \tag{12.5}$$

where F_{H_2} and F_{imp} are the hydrogen and the impurities fed, the subscript 0 marks design, $\ell_4 = 0.15$ with four beds and $\ell_3 = 0.20$ with three, φ is the bed's loading per step ($\varphi_0 = 0.80$), $y_0 = 400\,\mathrm{ppm}$, $w = 0.12$, and x is the fraction of the step elapsed, so the impurity rises as the front climbs the bed. A fixed hydrogen loss per step makes recovery rise and purity fall with a longer step: 81.25, 85.00, 86.36 and 87.50 % recovery and 99.989, 99.960, 99.922 and 99.848 % purity at steps of 2.0, 2.5, 2.75 and 3.0 min, and the same with 20 % more feed. These are the directions of the usual adsorber trade [12], in which a longer adsorption step wastes less void gas per mole fed but runs the front nearer breakthrough. The purge pressures shape the pulses only, and setting them to 3 and 2.5 bar a leaves recovery and purity unchanged. With a bed out the ring closes to three positions at the next step boundary, the adsorption step is kept, and the cycle shortens to three steps. The product sent to the drum is the cycle-average product less the repressurization pulse about its mean, and the tail gas is the remainder of the feed plus the blowdown pulse, carrying its average composition.

Pause. Try Exercise 12.2 before reading on.

12.3.7 Drums, Header and Valves

The surge drum, the header and the tail-gas drum are isothermal ideal-gas volumes, as shown in Equation (12.6).

$$\begin{aligned} \frac{\mathrm{d}n_d}{\mathrm{d}t} &= F_{prod} - k_{dh}(p_d - p_h) \\ \frac{\mathrm{d}n_h}{\mathrm{d}t} &= k_{dh}(p_d - p_h) - F_{users} - F_{vent} \\ \frac{\mathrm{d}g_k}{\mathrm{d}t} &= F_{tail}\,z_k - F_{TG}\,x_k, \qquad p = \frac{nRT}{V} \end{aligned} \tag{12.6}$$

where k_{dh} passes the design product across a 2.5 bar drop, $V_d = 200\,\mathrm{m}^3$ and $V_h = 1000\,\mathrm{m}^3$ at 40 °C, $V_{tg} = 1000\,\mathrm{m}^3$ at 35 °C, z_k is the tail gas's composition and F_{users} is the demand. An imbalance of 5000 Nm^3/h moves the header 0.0968 bar a minute. The drum's time constant $V_d/(RTk_{dh})$ is 0.13, 0.52 and 1.03 min at 50, 200 and 400 m^3. The feed follows its setpoint through a 0.1 min lag up to 145 % of design, the makeup and tail gas through 0.1 min lags, and the process steam passes a valve whose stem follows its command through a 0.5 min lag and at most 4 % of travel a minute, as shown in Equation (12.7).

$$\begin{aligned} \frac{\mathrm{d}x_s}{\mathrm{d}t} &= \mathrm{clip}\left(\frac{x_s^* - x_s}{\tau_{sv}},\ \pm r_{sv}\right) \\ F_s &= F_{s,\max}\, x_s \sqrt{\frac{p_{sup} - p_{mix}}{p_{sup,0} - p_{mix}}} \end{aligned} \tag{12.7}$$

where $F_{s,\max}$ passes the design steam at 60 % open and $p_{mix} = 28\,\mathrm{bar}\,a$ at the tee. The ramp stands for the steam system behind the valve, which can raise the reformer's draw only so fast.

🕮 **Pause.** Try Exercise 12.3 before reading on.

12.3.8 Instruments

The controllers see only a packet of instrument readings, and a test of the application whitelists its keys. The feed, steam, makeup, tail-gas, product and demand meters have a 2 s lag and 0.3 % noise. A feed chromatograph reports ethane and nitrogen, and so the carbon number, from a sample every 5 min analyzed in 3 min behind 30 s of line. A calorimeter reports the tail gas's heating value every 30 s, 1 min after sampling. The outlet chromatograph reports the dry slip every 6 min, 5 min late, and a purity analyzer the header's impurities every minute. The outlet, tube-metal (an infrared scan), bridge-wall and shift temperatures have a 12 s lag and 0.3, 1.5, 1.0 and 0.3 K noise, the flue oxygen a 20 s lag, and the pressures a 2 s lag. Every execution consumes a fixed count of random numbers regardless of the settings, which keeps two runs that differ in a single setting aligned draw for draw. In the exported file every true value carries the prefix `truth_`, so a controller tested on the file can be restricted to the measured columns.

12.3.9 Initialization, Protection and Numerics

Table 12.2 gives every parameter with its default. Each case begins lined out on whatever settings it ships with. A bisection on the bridge-wall temperature brings the tube's outlet to its setpoint, the shift and the adsorber follow from the outlet gas, the makeup closes the firebox balance at the oxygen setpoint of 2 % wet, and the drums are filled to the header setpoint. The status strip raises CARBON RISK below the floor on the true ratio, TUBE METAL LIMIT above 925 °C, PURITY LOW below 99.9 % and HEADER LOW below 19.0 bar g, and five minutes below the floor stops the run. The integrator is fourth-order Runge-Kutta with a step of 0.5 s, the controllers run every second and the historian writes a row every 5 s, on the clocks of Section 1.6.1. Halving the step changes no verdict of the challenge and moves its reported figures by at most 0.006 bar on the header, and case 2's lowest ratios not at all.

12.3.10 Assumptions

The reformer is one representative tube at equilibrium with a declared approach, so no kinetics [9] enter and the result does not depend on the catalyst's activity profile, and the model is least reliable where a real tube is far from equilibrium near its inlet. The firebox is one well-stirred volume with a fixed exchange area and flux profile, and the convection section that preheats the feed and the air and raises more steam is not modeled. The flue and air enthalpies use the fitted slopes, which over-fires the furnace by about 1.3 MW. The adsorber's recovery and purity follow a teaching correlation, not an isotherm, and its pulses come from prescribed pressures, not from bed dynamics. Gases are ideal and the drums isothermal. Every limit is a teaching value: real steam-to-carbon floors come from the

Table 12.2 Parameters and Defaults. A, Adjustable in the Parameters Panel. C, a Control on a Card. F, Fixed in the Source

Symbol	Meaning	Value	Unit	
F_0	design natural gas feed	18,700	Nm^3/h	A
T_{in}	mixed feed into the tubes	600	°C	A
τ_F, —	feed loop lag, feed valve capacity	0.1, 145	min, %	A
τ_{sv}, r_{sv}	steam valve lag, ramp limit	0.5, 4	min, %/min	A
$p_{sup,0}$	steam supply pressure	40	bar a	A
p_{out}, Δp_t	outlet pressure, tube drop	25, 2	bar	A
ΔT_{app}	approach to reforming equilibrium	10	K	A
UA, εA	wall conductance, radiant area	0.75, 600	MW/K, m^2	A
C_{cat}, C_w, C_{fb}	catalyst, metal, firebox capacity	30, 70, 30	MJ/K	A
—	burner capacity, air preheat	170, 250	MW, °C	A
$T_{w,\max}$, —	tube-metal, bridge-wall limits	925, 1120	°C	A
—	shift inlet, approach, capacity	350, 10, 40	°C, K, MJ/K	A
—	boiler steam pressure	40	bar a	A
p_{hi}, p_{lo}, p_{pp}	adsorber pressures	24, 1.6, 5	bar a	A
C_b	bed gas holdup	0.6	kmol/bar	A
ℓ_4, ℓ_3	hydrogen loss share at design	0.15, 0.20	—	A
φ_0, y_0, w	loading, impurity, sharpness	0.80, 400, 0.12	—, ppm, —	A
—	drum-to-header drop at design	2.5	bar	A
V_d	surge drum (50, 100, 200, 400)	200	m^3	C
V_h, V_{tg}	header, tail-gas drum	1000, 1000	m^3	A
—	vent capacity	15,000	Nm^3/h	A
p_{tg}	tail-gas drum setpoint	1.25	bar a	A
$(S/C)_{\min}$, —	floor, time below it to stop	2.8, 5	mol/mol, min	A
—	purity spec, HEADER LOW	99.9, 19.0	%, bar g	A
ϕ_i	flux shares, top to bottom	0.15 to 0.10	—	F
—	makeup valve capacity	12,000	Nm^3/h	F
h_k, K_1, K_2	enthalpy lines, constants	Sec. 12.3.2		F

catalyst supplier's carbon-limit data for the feed [11], real tube-metal limits from the tube alloy's creep-rupture life under API Standard 530, and real purity specifications and header alarms from the users.

12.4 The Control Layers

Each physics step runs the controllers, then the integrator, then the adsorber's ring and the protection, and finally the outputs, in the order of Figure 1.11. The controllers execute every $\Delta t_c = 1$ s. The header, steam flow, oxygen trim and tail-gas drum loops are the velocity-form PID of Section 1.6.2, Equations (1.16) to (1.19), with $a = \pm 1$ setting the direction, the running sum never clamped, a limit correcting the integral alone through a tracking time equal to the integral time, and no derivative action. Setting the integral time to its 60 min maximum leaves a proportional loop. In Manual each loop solves for the integral that reproduces the station's value, so every transfer is bumpless.

12.4.1 Header Pressure and the Plant Rate

The header loop raises the plant rate r when the measured header falls ($a = +1$), with output limits of 40 and 140 % and the shipped tuning 15 % per bar and 8 min. The rate then passes a rate-of-change limit of 20 % a minute that binds operator and controller alike, and the feed demand is $D = rF_0/100$. A proportional vent opens 50 % per bar above a setpoint 1 bar over the header's. The header Manual/Auto switch belongs to this loop alone, and the ratio and outlet loops have their own switches on their cards.

12.4.2 The Ratio and Its Lead-Lag

The ratio station multiplies a steam-to-carbon setpoint by the carbon fed, the feed meter times the chromatograph's carbon number. With the lead-lag on it works from the demand D instead of the

meter, and the two streams get opposite dynamics, as shown in Equation (12.8).

$$\begin{aligned} f_k &= \begin{cases} f_{k-1} + \alpha_{ld}(D_k - f_{k-1}) & D_k > f_{k-1} \\ D_k & \text{otherwise} \end{cases} \\ c_k &= \begin{cases} c_{k-1} + \alpha_{lg}(D_k - c_{k-1}) & D_k < c_{k-1} \\ D_k & \text{otherwise} \end{cases} \\ F_{feed,SP} &= f_k, \qquad F_{s,SP} = (S/C)_{SP}\, n_{C,m}\, c_k \end{aligned} \tag{12.8}$$

where $\alpha_{ld} = 1 - \mathrm{e}^{-\Delta t_c/T_{ld}}$ with the lead time $T_{ld} = 1.5\,\text{min}$ and $\alpha_{lg} = 1 - \mathrm{e}^{-\Delta t_c/T_{lg}}$ with $T_{lg} = 1\,\text{min}$. Going up the steam setpoint takes the new demand at once while the feed follows through a lag, and going down the feed falls at once while the steam follows. With the lead-lag off $F_{feed,SP} = D_k$ and $F_{s,SP} = (S/C)_{SP}\, n_{C,m} F_{feed,m}$. A steam flow PI ($a = +1$ on percent of design steam, 0.5 % per percent and 1 min) moves the valve. The lead-lag acts on the demand and not on the feed meter, because no filter on a feed that has already moved can make the steam lead it. The single floor of 2.8 serves the status flag, the run stop and the challenge. It sits 0.2 below the design so that the feed steps of cases 1 and 2 reach it, while case 1's held steam bottoms at 2.609 and every plain-ratio dip measured falls between 2.63 and 2.76, so a floor of 2.5 would never be crossed.

Pause. Try Exercise 12.1 before reading on.

12.4.3 Outlet Temperature, Override and Feedforward

The outlet loop and the tube-metal override are a pair of PI laws written with external reset feedback under a low select, the same form as the carbon monoxide override of Volume 3, Chapter 4 with a high select, as shown in Equation (12.9).

$$\begin{aligned} u_T &= K_T\, e_T + \rho_T, \qquad u_O = K_O\, e_O + \rho_O \\ q &= \min(u_T, u_O) \\ \rho_j &\leftarrow \rho_j + \left(1 - \mathrm{e}^{-\Delta t_c/\tau_j}\right)(q - \rho_j), \quad j \in \{T, O\} \end{aligned} \tag{12.9}$$

where $e_T = T_{out,SP} - T_{out,m}$, $e_O = (T_{w,\max} - 10) - T_{w,m}$, the shipped tuning is $K_T = 0.5\,\text{MW/K}$ with $\tau_T = 5\,\text{min}$ and $K_O = 1\,\text{MW/K}$ with $\tau_O = 2\,\text{min}$, and both resets follow the selected output, so the law not selected stays higher by the size of its own proportional term and cannot wind up. The build record reports that a low select with ordinary PID tracking, tried first, ratcheted the makeup to zero on the tube-metal signal's 1.5 K of noise, which external reset feedback cannot do. On *Loops* q is the makeup's heat and the tail gas is a disturbance the loop meets only through the outlet. With the tail-gas feedforward q is the total heat at the design feed, scaled by the measured load, and the makeup is what the measured tail gas does not bring, the heat-balance feedforward of Equation (1.2) with the tail gas as the measured load, as shown in Equation (12.10).

$$F_{MU,SP} = \frac{3600}{\text{LHV}_{NG}} \left(q\, \frac{F_{feed,m}}{F_0} - F_{TG,m}\, \text{LHV}_{TG,m} \right) \tag{12.10}$$

where the tail gas's heating value is the calorimeter's. The load factor keeps the feedforward from over-firing when the header loop cuts the feed. The burners cap the total at 170 MW.

12.4.4 Air, Adsorber Step, Tail-Gas Drum and Slip

The combustion air is the oxygen the measured fuels need, from the calorimeter and the design tail gas's oxygen per megajoule, times one plus an excess that holds 2 % wet oxygen, trimmed by a PI on the flue oxygen. The adsorber's step is $t_c/4$, or with *cycle follows the feed* $(t_c/4)\,\text{clip}\big(C_0/(F_{feed,m} n_{C,m}), 0.5, 1.5\big)$ with C_0 the design carbon, so each bed takes the same load. An averaging PI on the tail-gas drum, 1200 kmol/h per bar and 4 min, sets the tail gas to the burners

through a valve capped at three times the design flow scaled by the drum's pressure over the burners' 1.05 bar a. A softer loop let the drum rise past the purge pressure or let Loops fall into a limit cycle. The slip is inferred by Equation (12.1) at the measured outlet, the measured ratio and 25 bar a with the commissioned 10 K approach, and a bias updater with a factor of 0.5 trims it each time the outlet chromatograph reports, the update of Equation (1.14).

12.4.5 Model Predictive Control as a Comparison

The predictive controller plans three setpoints every 30 s over 15 min: the plant rate, the ratio setpoint and the outlet setpoint, which the loops below then follow. Its model is linear and was identified by steps on the plant at design: the header integrator $\dot{p} = K_h(Gr - F_{users,m} - b)$ with K_h from the declared volume and a bias b updated from the measured pressure, a 1.2 min feed lag, the ratio as the steam lags the feed by 1.5 min, first-order outlet (4 min), tube-metal (5 min) and bridge-wall (3 min) responses. The quadratic program, discretized exactly with a zero-order hold, is Equation (12.11).

$$\begin{aligned} \min\ & \textstyle\sum_{k=1}^{30} \left[w_p e_{p,k}^2 + w_{S/C} e_{S/C,k}^2 + w_T e_{T,k}^2 \right] \\ & + w_{\Delta u} \textstyle\sum_j \| S \Delta u_j \|^2 + \rho \| s \|^2 \\ \text{s.t. } & 40 \le r \le 140, \quad 2.8 \le (S/C)_{SP} \le 3.6 \\ & 840 \le T_{SP} \le 880 \\ & |p - p_{SP}| \le 0.4 + s, \quad S/C \ge 2.85 - s \\ & T_w \le T_{w,\max} - 5 + s, \quad T_{bw} \le 1120 + s, \quad s \ge 0 \end{aligned} \tag{12.11}$$

where $w_p = 100$ per bar^2, $w_{S/C} = 50$, $w_T = 1$ per K^2, $w_{\Delta u} = 30$ with move scales $S = (0.05, 5, 0.05)$, a terminal header weight of $5w_p$, $\rho = 10^4$, 30 steps of 30 s in 10 graduated move blocks, and moves capped at 5 % of rate, 0.2 and 5 K per decision. Without the cycle following the feed a rate ceiling keeps the inferred bed loading, judged against the feed at which that loading was adsorbed, under that of a 99.92 % product. The framework's solver applies Goldfarb and Idnani's dual method [20] to the program, only the first planned move is sent, which is the receding-horizon practice of industry [21] described in Section 1.6.3, and a solve that fails or leaves its box hands the setpoints to the loops with the feedforward. No solve was rejected in any challenge run of this chapter. The controller is offered as a comparison and not as the challenge's answer.

The model starts each decision at the measured ratio, and its gains are sized once from the declared defaults, so a learner's change to the plant is model mismatch. The ceiling's feed is the measured feed delayed by the purity analyzer's 1.5 min and mixed through the product drum. Before a correction in November 2026 the predicted ratio started mirrored about its setpoint, and the challenge passed at two seeds of five.

12.4.6 Three Models

Section 12.3 is the plant. What a learner identifies is the header's integrating gain and the ratio's dip on a step. The controllers' models are the ratio station's carbon number, the feedforward's design heat and meters, the slip inference's equilibrium with the commissioned approach, and the predictive controller's linear plant at design. None of them knows a catalyst that has aged, a makeup carrying inert gas, or a bed that has failed until a measurement shows it.

12.5 Nine Cases, Measured

The cases appear in Table 12.3. Each starts from the defaults above on Loops with the lead-lag off and the cycle fixed, and a row lists what differs. Every number below was measured headless on the engine at seed 20261005, stepped as the browser steps it (Section 1.6.1), with a row's settings entered before Run. Four more seeds, 0 to 3, were run for the challenge, and seeds 1 and 2 for cases 1, 2, 6 and 8. Every case runs identically loaded first, chosen after another case, and after Reset.

Table 12.3 The Nine Cases

#	Case and events	Teaching point
1	header Manual, ratio on Man, cycle follows, demand and rate +15 % at 2 min	the steam held
2	header Manual, ratio Auto, cycle follows, lead-lag off, same step	plain ratio, lead-lag
3	approach aged to 20 K	outlet, slip inference
4	surge drum 200 (or 50, 400) m^3	the sawtooth
5	header Manual, cycle 10 to 11 min at 5 min	recovery is firing
6	demand +10 % at 5 min, cycle follows	every loop moves
7	demand +40 % at 5, firm header, lead-lag, follows	infeasible
8	a bed valve fails at 5 min	three beds
9	challenge, 8 h: demand +20 % at 1, ethane 10 % at 4, demand back at 5, a bed fails at 6 h	the whole plant

12.5.1 The Steam Held, Then a Plain Ratio

In case 1 the operator raises the plant rate to 115 % at 2 min with the ratio loop on Man, and the ratio falls from 3.00 to 2.609 by 5.80 min, the same 15 % the carbon rose. CARBON RISK appears at 2.45 min and five minutes below the floor stop the run at 7.45 min. Switching the ratio loop to Auto at 3 min has the ratio back above 2.95 at 7.11 min, and the *Set S/C to design* helper, which commands the valve to 69.0 % from the meters and the supply pressure transmitter, does it at 5.03 min. Because the valve ramps, a late remedy cannot beat the stop. In quarter-minute steps Auto saves the run up to 5.75 min and not at 6.00, and the helper up to 6.25 and not at 6.50 min. The stop was left at 5 min on purpose. A 10 min stop moves the deadlines to 10.75 and 11.25 min, which is 4.2 s of wall time at the default 2 min/s rather than 1.65 s, so the Pause the briefing asks for is needed either way, it pushes the stop outside the case's 10 min trend window, and a real low-ratio trip acts faster, not slower.

> **TRY IT IN THE APP** **1 · More feed, the same steam (Manual)**
>
> Load the case and press Run. At 2 min the plant rate goes to 115 % and nobody touches the steam. Watch the Steam-to-carbon trend: the ratio falls from 3.00 to 2.609 by 5.80 min, the same 15 % the carbon rose, and CARBON RISK appears at 2.45 min. Left alone, five minutes below the floor stop the run at 7.45 min.

In case 2 the ratio loop is on Auto with the lead-lag off, and the same step drops the true ratio to 2.729 at 2.84 min, 0.78 min below the floor, as shown in Figure 12.2a. With the lead-lag on it never falls below 2.994. The cause is the steam's ramp, not the loop's tuning. A steam loop of 3 % per percent and 0.2 min still reaches 2.753, a ramp of 20 % a minute with the shipped loop 2.758, and only both together hold 2.957. Over 64 tunings from 0.05 to 5 % per percent and 0.05 to 60 min the plain ratio's low lies between 2.629 and 2.763. A bound by hand, a valve ramping at 4 % a minute from the instant the rate starts to rise, before any meter sees the feed, with the feed following the 20 %-a-minute rate through its 0.1 min lag, reaches at best 2.774, 0.85 min after the step. The claim is therefore proved for this case's rise and not for every rise. At a rate limit of 10 or 5 % a minute the best of nine steam tunings holds 2.870 or 2.984. Figure 12.2b shows how the lead-lag succeeds. The steam valve moves the same way in both runs, ramping from 60 to 69 %, and what changes is the feed, which the lead-lag holds back through its 1.5 min lag until the steam has caught up. Seeds 1 and 2 give 2.732 and 2.729 plain and 2.998 and 2.996 with the lead-lag, and halving the step changes neither.

12.5.2 A Slow Furnace and an Inferred Slip

Case 3 ages the catalyst to a 20 K approach that the inference still assumes to be 10 K. At 0.5 min the true slip is 6.08 % and the inference reads 5.43. The first chromatograph report, 6.08 % at 4.01 min, moves the bias to 0.39, and later reports take it to 0.54 and 0.64. Raising the outlet setpoint to 875 °C at 15 min brings the outlet past 874 °C only at 24.14 min, the furnace's slowness from burner to firebox to wall to catalyst, while the makeup climbs from 2375 to a peak of 3447 Nm^3/h and settles at

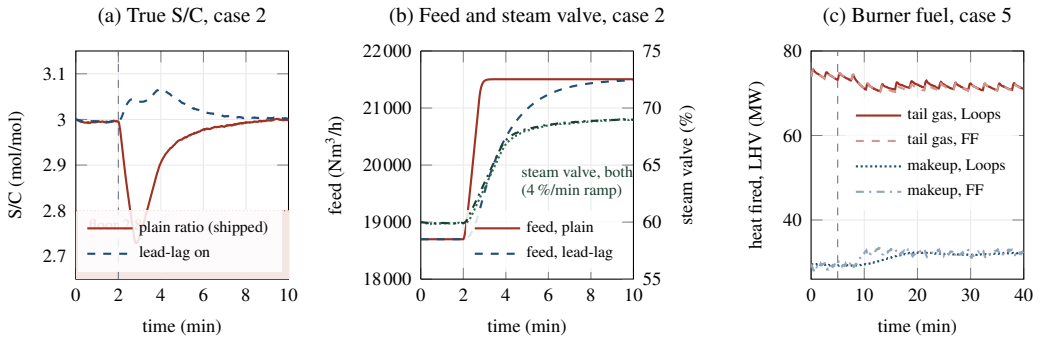


Figure 12.2 Three measured responses. (a) The true steam-to-carbon ratio in case 2 after the 15 % feed step at 2 min, plain ratio as shipped (solid) against the lead-lag (dashed), with the 2.8 floor (dotted) and the region below it shaded. (b) The feed (solid plain, dashed lead-lag) and the steam valve (dotted plain, dash-dotted lead-lag) in the same two runs. The valve ramps alike in both, and the lead-lag works by holding the feed back. (c) The heat the tail gas and the makeup bring to the burners in case 5, whose adsorber cycle lengthens from 10 to 11 min at 5 min: the tail gas solid on Loops and dashed with the tail-gas feedforward (FF), the makeup dotted on Loops and dash-dotted with FF. Data written from the engine by a measurement script.

3136, the hottest tube rises from 898.5 to 914.2 °C, and the true slip falls from 6.09 to 5.07 %, which the chromatograph confirms as 5.18 at 30 min and 4.95 at 35 min.

12.5.3 A Cyclic Unit on a Continuous Header

In case 4 the adsorber's product swings from 43,213 to 53 693 Nm^3/h each step as the repressurizing bed draws on it, and its tail gas leaves the beds at 25,780 to 42 997 Nm^3/h. Over 20 to 30 min the 200 m^3 surge drum swings 0.221 bar and the header 0.030 bar, against 0.390 and 0.052 with 50 m^3 and 0.132 and 0.018 with 400 m^3. The swing falls less than in proportion to the volume because the drum's time constant, 0.13 to 1.03 min, is short against a repressurization that draws product for most of a 2.5 min step. The tail-gas drum holds 1.240 to 1.267 bar a and sends 28,392 to 29 049 Nm^3/h to the burners, so the furnace barely sees the pulses.

12.5.4 Recovery Is Firing

Case 5 lengthens the cycle from 10 to 11 min at 5 min with the header on Manual. On Loops the recovery rises from 85.01 to 86.37 %, the tail gas's heat falls from 73.19 to 72.31 MW and its heating value from 9.274 to 9.229 MJ/Nm^3, the makeup rises from 2862 to 3102 Nm^3/h, 8.4 %, and the purity falls from 99.959 to 99.922 % by 30 min, as shown in Figure 12.2c. The outlet dips to 857.37 °C at 16.7 min before the loop catches up. With the feedforward the makeup moves as the tail gas's meters change and the outlet stays within 0.23 K of its setpoint.

> **TRY IT IN THE APP** **5 · A longer cycle: recovery is a firing change**
>
> Load the case and press Run on Loops. At 5 min the adsorber's cycle lengthens from 10 to 11 min. The recovery rises from 85.01 to 86.37 %, the makeup fuel from 2862 to 3102 Nm^3/h, and the outlet dips to 857.37 °C. Choose Loops + tail-gas feedforward as the Control architecture and press Reset: the outlet now stays within 0.23 K of its setpoint.

Case 8 fails a bed at 5 min, and the adsorber closes to three beds at the next step. On Loops the recovery falls from 85.03 to 80.98 %, the tail gas's heat rises from 73.24 to 82.12 MW and its heating value from 9.277 to 9.367 MJ/Nm^3, and the outlet loop cuts the makeup from 2864 to 2382 Nm^3/h, 16.8 % less (16.6 and 17.0 % at seeds 1 and 2). The plan for the application expected the makeup to

Table 12.4 The Eight-Hour Challenge at Five Seeds (20261005, 0 to 3)

Settings	$\lvert p_h - p_{SP} \rvert$ (bar)	Purity (%)	Lowest S/C	Hottest tube (°C)	Verdict
shipped	0.829–0.831	99.760–99.761	2.858–2.862	914.8–915.0	fails
suggested	0.392–0.395	99.927–99.929	2.884–2.886	916.3–916.7	passes
lead-lag off	0.312–0.317	99.930–99.932	2.711–2.725	914.4–914.7	fails
cycle fixed	0.371–0.373	99.671–99.673	2.888–2.889	912.9–913.0	fails
15 %/bar, 8 min	0.952–0.957	99.944–99.945	2.868–2.870	916.7–917.2	fails
on Loops	0.393–0.400	99.920–99.923	2.910–2.916	926.9–927.1	fails
MPC[a]	0.432–0.580	99.938–99.941	2.862–2.868	921.6–922.4	3 of 5

[a]With the lead-lag on and the cycle following the feed. Passes at the default seed (0.463 bar), seed 0 (0.437) and seed 3 (0.432).

climb, and the balance does the opposite: the lost hydrogen is burned. The header loop raises the feed from 18,730 to 19 640 Nm^3/h to deliver the same product, so the natural gas fed and fired per Nm^3 of hydrogen rises from 0.4323 in the first 5 min to 0.4403 from 30 to 45 min, and that is the number the case teaches. The richer tail gas first over-fires the furnace on Loops, the outlet reaching 865.2 °C at 16.3 min and the hottest tube 907.4 °C, while the feedforward holds the outlet within 1.66 K with the tube at 903.9 °C.

12.5.5 A Demand Step and a Demand Too Large

In case 6 the users draw 10 % more at 5 min. Under the shipped header tuning the header falls to 19.54 bar g at 16.2 min, the rate peaks at 115.7 % at 23.3 min, the header is back within 0.15 bar from 26.0 min, the worst error is 0.463 bar, the outlet dips to 854.4 °C, the makeup reaches 3537 Nm^3/h, the step shortens to 2.167 min, and the ratio stays at or above 2.956. At 40 % per bar the worst error is 0.245 bar (0.245 and 0.242 at seeds 1 and 2) and the ratio's low 2.919, and at 60 per bar and 3 min 0.152 bar and 2.874, so a firmer header loop buys pressure with ratio margin.

Case 7 asks for 40 % more and is infeasible by design. The rate reaches its 140 % maximum at 7.28 min, the firing peaks at 168.7 MW, the outlet sags to 834.0 °C at 11.0 min with the slip at 7.53 %, and the tube override takes the firing from 16.96 min, the hottest tube peaking at 919.0 °C. From 60 to 360 min the drum sends a mean 69 021 Nm^3/h to a demand of 70,006, and the header falls from 17.73 to 12.01 bar g, about 0.019 bar a minute. Across header gains of 30, 60 and 120 % per bar and outlet setpoints of 840, 860 and 880 °C the header spends 50.3 to 51.8 min of the first hour below 19.0 bar g and the rate is at its maximum in all nine. Shedding demand to 125 % at 12 min brings the header above 19.5 bar g by 20.5 min.

12.5.6 Eight Hours on the Header

The challenge lasts 8 h, with the demand 20 % up in half a minute at 1 h, the feed ethane-rich at 4 h, the demand back at 5 h and a bed failure at 6 h. Its target, checked against the simulator's truth at each physics step after the first minute, is the header within ±0.5 bar, the purity at least 99.9 %, the ratio never below 2.8 and the hottest tube never above 925 °C. The outcomes are in Table 12.4, and Figure 12.3 draws its four columns against their limits. As shipped the gentle header loop lets the demand step take the header 0.831 bar off at 69.6 min, and the fixed cycle loads each bed past breakthrough so the purity falls to 99.760 %. The suggested settings make four changes, the lead-lag, 60 % per bar and 3 min, the cycle following the feed and the tail-gas feedforward, and pass at every seed with the header within 0.395 bar. Each change is needed. Without the lead-lag the firm header loop moves the rate fast enough to drop the ratio to 2.711, with the cycle fixed the purity falls to 99.671 %, and with the shipped header tuning the header strays 0.957 bar.

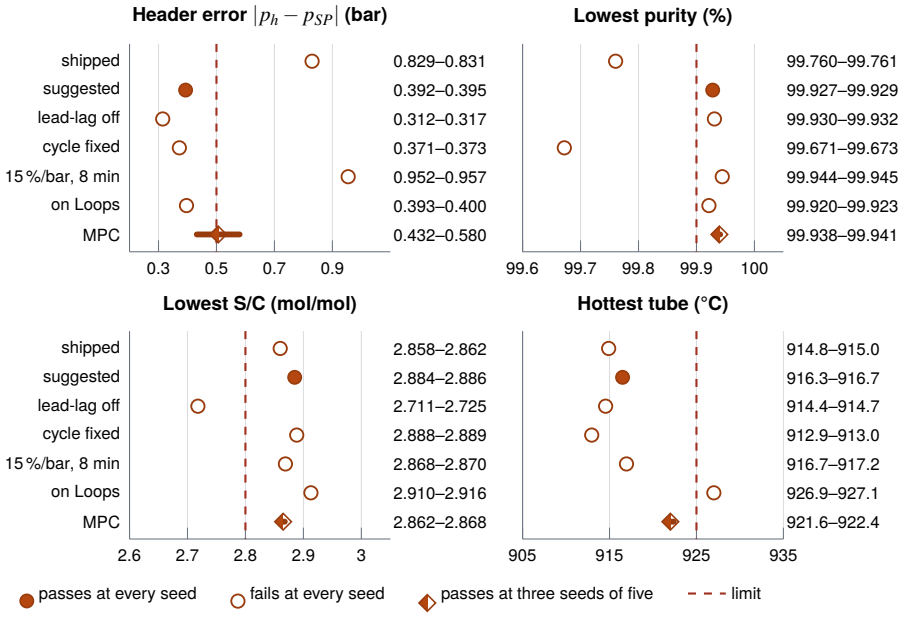


Figure 12.3 Table 12.4 drawn against the challenge's limits (dashed). Each bar runs from the lowest to the highest value over the five seeds, and rows three to six each undo one of the suggested settings. Notice that each of those four rows crosses a limit in a different panel: the lead-lag off on the ratio, the fixed cycle on the purity, the gentle header loop on the header and Loops on the tube. The shipped settings cross two, and the predictive controller straddles the header's limit.

> ✦ **DID YOU KNOW?** **The Steadiest Header Still Fails**
>
> From the simulator (Table 12.4). With the lead-lag switched off, the suggested settings hold the header closer than any other configuration, within 0.312 to 0.317 bar at five seeds. They still fail the challenge, because the firm header loop moves the rate fast enough to drop the steam-to-carbon ratio to 2.711.

On Loops the hottest tube passes 925 °C 11 to 13 times between 74.9 and 296.9 min across the five seeds, in a sustained cycle of 18.3 to 20.2 min in which, at the default seed, the rate swings from 98.8 to 140 % and the outlet from 831.0 to 884.2 °C. The firm header loop moves the rate, the outlet loop hears of it only when the outlet has cooled, and the two chase each other through the 120 % hours. A first account of the failure blamed the bed failure's richer tail gas, but after the failure the tube reaches only 911.8 °C, so the app's texts were corrected during its technical review. With the feedforward there is no cycle (rate 113.5 to 124.6 %, outlet 855.1 to 865.3 °C), nor with the shipped gentle header loop on Loops (rate 110.8 to 118.3 %). The cycle is a true interaction of a firm rate loop with a slow outlet loop and is the measured reason the feedforward is needed, so it was explained rather than detuned away.

The predictive controller, given the lead-lag and the following cycle, keeps the ratio at or above 2.862, the purity at or above 99.938 % and the tube at or below 922.4 °C, but its linear model hunts at 120 % load and the header strays 0.432 to 0.580 bar, so it passes at three seeds of five. Its weights were tuned by search to a header weight of 100 and a move weight of 30. Played at 120 min/s, the fastest speed, the eight hours take 240 frames and 2.3 s of computation headless. Case 2 at 10 min is shown in Figure 12.4.



Figure 12.4 Case 2 as shipped (lead-lag off) at $t = 10$ min on the Reformer view, light theme, cropped to the plant view with numbered callouts. (1) The status chips. (2) The tube walls, up to 906 °C against the 925 °C limit (dashed). (3) The catalyst, from 601 °C at the inlet to 855.5 °C measured at the outlet. (4) The S/C scale, which shows 3.00 against its hatched floor with the lead-lag off. (5) The slip strip, with the inference at 5.30 % and the chromatograph's last report of 5.38, the true slip of 5.64 hidden while the teaching overlay is off.

12.6 Technology in Practice

Figure 12.5 draws the ratio station, the outlet loop with its override and the header loop of Section 12.4 with the hardware a refinery installs.

What Measures It

The ratio needs three readings: the feed flow, the steam flow and the carbon number of the feed. The carbon number comes from a chromatograph, which separates the species of a sample in time, so its cycle takes minutes and some dead time is inevitable [22]. The chapter's chromatograph samples every 5 min and reports 3 min later, and between reports the ratio station uses its last value. The override reads the tube walls through an infrared scan, whose 12 s lag and 1.5 K of noise in Section 12.3 are the noise that once made an ordinary low select ratchet the makeup to zero.

> **TECHNOLOGY** **Sensor: Flow Meters Behind the Ratio**
>
> The ratio station multiplies a measured flow, so the steam-to-carbon ratio is only as good as its meters. An orifice plate infers flow from the pressure drop across a restriction, which grows with the square of the flow, and it is commonly understood not to keep good accuracy much below a third of its full range, a turndown of 3 to 1. Modern differential pressure sensors stretch that to about 10 to 1. A vortex meter counts the vortices that a bluff body sheds, at a frequency in proportion to the flow, and so reads a wider range, but below a low-flow cutoff its signal falls to zero [22]. The chapter's feed, steam, makeup and tail-gas meters have a 2 s lag and 0.3 % of noise.

What Moves It

Four handles move the plant: the feed valve under its flow loop, the steam valve, the makeup fuel valve and the adsorber's switching valves, which a sequence opens and closes on the step schedule.

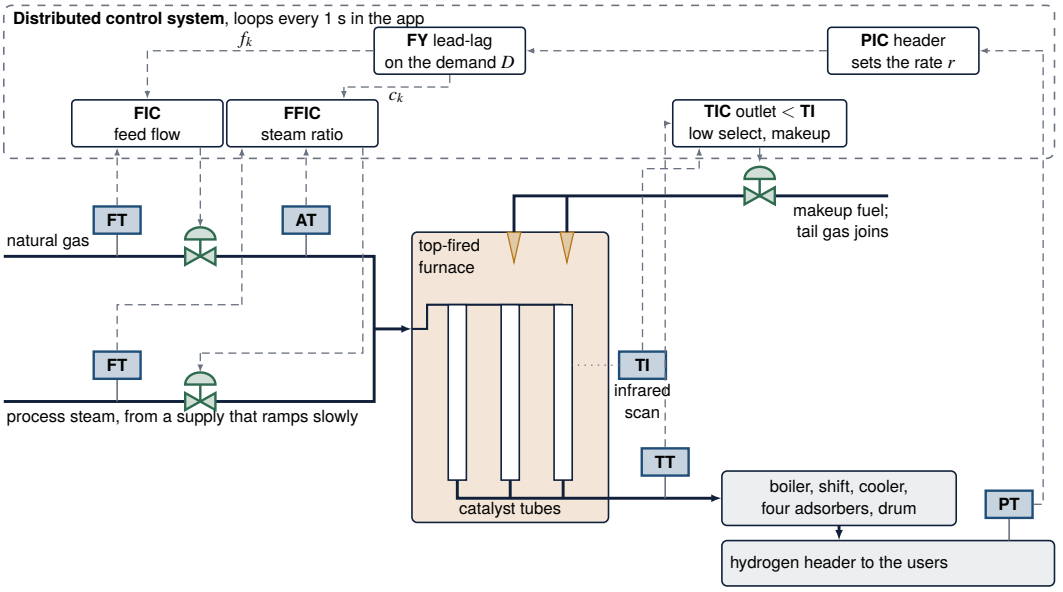


Figure 12.5 The ratio station, the outlet loop with its tube-metal override and the header loop with their hardware. Lettered boxes are sensing devices: the header pressure transmitter (PT), the feed and steam flow meters (FT), the feed chromatograph (AT), the outlet thermocouple (TT) and the infrared scan of the tube walls (TI). Valve symbols are final elements, and dashed arrows are signals. Notice that the lead-lag acts on the rate demand before it reaches either flow loop, and that the steam valve sits behind a slow steam supply. The adsorber, the tail-gas drum, the oxygen trim and the feedforward are left out. Not to scale, and not a piping diagram.

The steam valve is the slowest of them in this model, and the bed valve that fails in case 8 is one of the switching valves.

> **TECHNOLOGY** **Final Element: The Steam Control Valve**
>
> The process steam reaches the mixing tee through a control valve. A pneumatic valve with a spring takes a set position when its air fails, fixed by the actions of its actuator and its body: an air-to-open valve fails closed. Good practice chooses that position from the risks of the process, not from convention or habit. Friction in the stem makes a valve move in steps, a behavior called stiction, and leaves it deaf to small reversals of its signal, worst in valves that are poorly maintained or lack a positioner [22]. The chapter's valve follows its command through a 0.5 min lag and at most 4 % of travel a minute, and the ramp stands for the steam system behind the valve.

Where the Controller Runs

A refinery runs such loops in a distributed control system, in which a supervisory level oversees local controllers, loops are sometimes nested, and cycle times range from milliseconds to minutes [23]. The app executes its loops every second and its predictive controller every 30 s, inside that range. The header, steam flow, oxygen trim and tail-gas drum loops are PI blocks. The lead-lag is a dynamic function block, which modern control systems provide as digital function blocks [22], and the outlet loop and the override meet in a low select. Burners get the same order of moves from selectors instead: in a cross-limited air and fuel ratio the air leads when the firing rate rises and the fuel leads when it falls [22]. The lead-lag of Equation (12.8) obtains that order from dynamics.

> **IN PRACTICE** **Reading the Tubes Through the Peep Holes**
>
> At one industrial reformer studied in a 2008 thesis, the plant's data were logged every second, but the tube walls were read by hand. Each night the operators measured them at an upper and a lower peep hole with a hand-held infrared pyrometer and logged the readings, and a consultant surveyed the tubes every quarter [24]. The care has a reason. Reformer tubes are designed for a life of typically 100,000 hours, and by a rule of thumb a wall 20 °C hotter halves that life for a given alloy at its design pressure [24]. The reading itself needs judgment, because a surface's emittance is uncertain and it also reflects radiation from other hot bodies [22].

What Is Modernizing It

Three developments touch this plant. The first is the tube wall. The thesis behind the nightly readings built a model of the reformer for the on-line monitoring of tube-wall temperatures [24], and thermal imaging, a dense array of infrared sensors, shows hot spots as a picture where a pyrometer reads one spot [22]. The second is the inferred slip. Predicting a quality that is analyzed slowly is the original and still dominant use of soft sensors, and their predictions deteriorate as the process changes [25], as the aged catalyst of case 3 shows before its bias catches up. The third is predictive control, with more than 4600 applications reported and refining the largest share [21]. The chapter's controller plans the rate, the ratio and the outlet together, and it passes the challenge at three seeds of five.

12.7 Limitations

Nothing in the simulation was fitted to an operating unit. Its sizes, compositions, correlation and limits are teaching values that make one consistent design, a 50 000 Nm^3/h plant firing about 103 MW. The reformer is one tube at equilibrium with a declared approach, so maldistribution between tubes, kinetics near the inlet and the catalyst's own activity profile are absent. The firebox is one stirred volume, the convection section is not modeled, and the linear enthalpies over-fire the furnace by about 1.3 MW and put the shift outlet 3.5 K low, which no lesson depends on. The adsorber's recovery and purity come from a correlation whose directions match practice but whose numbers were not fitted, and its purge pressures do not enter it. The boiler's steam is not exported and its drum is not modeled. Carbon formation is represented by a floor, not by a kinetic criterion.

The controllers carry the plant's declared design values, and they meet a mismatch only where a case creates one. The predictive controller's model is linear at design, it hunts at 120 % load, and it passes the challenge at three seeds of five, which is why it is offered as a comparison. The lead-lag's necessity is proved by hand for case 2's 20 %-a-minute rate rise and measured for the challenge's, and a slower rise does not need it. The figures come from a single model run at the application's seed, and extra seeds and a halved integration step were tried only where noise or timing could change them.

> **OPEN CHALLENGE** **Capturing the Carbon of a Fired Reformer**
>
> In this chapter the tail gas is burned, so its carbon leaves in the flue gas. A federal study of 2022 found only a few hydrogen plants capturing carbon, at less than 90 %, and several in development above it. To capture more than 90 % of its feed's carbon, a steam methane reformer must treat both its process gas at pressure and the low-pressure flue gas of its externally heated furnace, a step that a reformer heated from inside does not need. The study also found that the absence of rules on such emissions limits capture [26]. Progress would be a plant that captures nearly all of its carbon while its furnace still burns the adsorber's tail gas.

12.8 Implementation History

The boiler's water and steam properties first lived in the flash-steam application of Volume 1, Chapter 6. The hydrogen plant's build moved that module unchanged in arithmetic into the shared framework, kept the flash-steam simulator's fifteen cases logging byte-identical runs before and after the move, and added a shared test that reproduces every verification value of the IAPWS release the

module computes, to 0.37 of the release's tolerance at worst. The hydrogen plant is the module's second user. After the build, three reviews by separate agents changed texts and the display but no behavior: every case's logged run kept the same hash through the usability, graphics and technical stages.

12.9 Conclusion

A steam methane reforming hydrogen plant is a ratio with a floor, a furnace that burns the adsorber's waste and a cyclic purifier on a continuous header, and this simulator logs all three side by side from an equilibrium reformer whose constants are within 1.6 % of the JANAF tables.

With the steam supply ramping at 4 % a minute, a plain ratio drops to 2.729 on a 15 % feed rise and no steam tuning of 64 lifts it past 2.763, while a lead-lag on the demand holds 2.994 by holding the feed back. The tail gas supplies 71.46 % of the fuel, so a longer cycle needs 8.4 % more makeup and a failed bed 16.8 % less while natural gas per hydrogen rises from 0.4323 to 0.4403.

The challenge needs the lead-lag, a firmer header loop, a cycle that follows the feed and the tail-gas feedforward at every seed, and without the feedforward a firm header loop and a slow outlet loop cycle the tubes past their limit. The model is lumped, its adsorber a correlation and its limits teaching values. A fuller model would add reforming kinetics near the inlet, the convection section and its steam, an adsorber model with breakthrough fronts, and a carbon criterion in place of the floor. The simulator shows that in this plant the order in which two streams move matters as much as the ratio between them.

KEY POINTS

- A hydrogen plant must raise its steam before its feed, because steam short of the carbon lets carbon form on the catalyst.
- With the steam ramping at 4 % a minute, a plain ratio drops to 2.729 on a 15 % feed rise, while a lead-lag on the demand holds 2.994 by holding the feed back.
- The tail gas supplies 71.46 % of the fuel, so a longer cycle needs 8.4 % more makeup and a failed bed 16.8 % less.
- Without the tail-gas feedforward, a firm header loop and a slow outlet loop cycle the tubes past their limit.

Where else this applies. Volume 3, Chapter 4 cross-limits fuel and air so that the air leads on the way up and follows on the way down, and Volume 6, Chapter 7 studies the recycle whose coupling the tail gas shares by returning as fuel.

References

[1] U.S. Energy Information Administration, "Hydrogen for refineries is increasingly provided by industrial suppliers," Today in Energy, January 20, 2016, eia.gov/todayinenergy/detail.php?id=24612, read November 2026.

[2] J. J. Alves and G. P. Towler, "Analysis of refinery hydrogen distribution systems," *Industrial & Engineering Chemistry Research*, vol. 41, no. 23, pp. 5759–5769, 2002.

[3] D. A. Latham, K. B. McAuley, B. A. Peppley, and T. M. Raybold, "Mathematical modeling of an industrial steam-methane reformer for on-line deployment," *Fuel Processing Technology*, vol. 92, no. 8, pp. 1574–1586, 2011.

[4] L. Lao, A. Aguirre, A. Tran, Z. Wu, H. Durand, and P. D. Christofides, "CFD modeling and control of a steam methane reforming reactor," *Chemical Engineering Science*, vol. 148, pp. 78–92, 2016.

[5] H. Khajuria and E. N. Pistikopoulos, "Optimization and control of pressure swing adsorption processes under uncertainty," *AIChE Journal*, vol. 59, no. 1, pp. 120–131, 2013.

[6] F. G. Shinskey and B. G. Lipták, "Ratio control," in *Process Control*. Elsevier, 1995, pp. 102–105.

[7] J. R. Rostrup-Nielsen and T. Rostrup-Nielsen, "Large-scale hydrogen production," *CATTECH*, vol. 6, no. 4, pp. 150–159, 2002.

[8] J. Rostrup-Nielsen and L. J. Christiansen, *Concepts in Syngas Manufacture*, ser. Catalytic Science Series. London: Imperial College Press, 2011.

[9] J. Xu and G. F. Froment, "Methane steam reforming, methanation and water-gas shift: I. Intrinsic kinetics," *AIChE Journal*, vol. 35, no. 1, pp. 88–96, 1989.

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

[11] D. L. Trimm, "Coke formation and minimisation during steam reforming reactions," *Catalysis Today*, vol. 37, no. 3, pp. 233–238, 1997.

[12] D. M. Ruthven, S. Farooq, and K. S. Knaebel, *Pressure Swing Adsorption*. New York: VCH Publishers, 1994.

[13] S. Sircar, "Pressure swing adsorption," *Industrial & Engineering Chemistry Research*, vol. 41, no. 6, pp. 1389–1392, 2002.

[14] S. Sircar and T. C. Golden, "Purification of hydrogen by pressure swing adsorption," *Separation Science and Technology*, vol. 35, no. 5, pp. 667–687, 2000.

[15] C. W. Skarstrom, "Method and apparatus for fractionating gaseous mixtures by adsorption," U.S. Patent 2 944 627, Jul. 12, 1960.

[16] J. L. Wagner, "Selective adsorption process," U.S. Patent 3 430 418, Mar. 4, 1969.

[17] R. Soltani, M. A. Rosen, and I. Dincer, "Assessment of CO_2 capture options from various points in steam methane reforming for hydrogen production," *International Journal of Hydrogen Energy*, vol. 39, no. 35, pp. 20 266–20 275, 2014.

[18] M. W. Chase, Jr., *NIST-JANAF Thermochemical Tables*, 4th ed., ser. Journal of Physical and Chemical Reference Data, Monograph 9. Washington, DC and Woodbury, NY: American Chemical Society and American Institute of Physics for the National Institute of Standards and Technology, 1998.

[19] W. Wagner, J. R. Cooper, A. Dittmann, J. Kijima, H.-J. Kretzschmar, A. Kruse, R. Mareš, K. Oguchi, H. Sato, I. Stöcker, O. Šifner, Y. Takaishi, I. Tanishita, J. Trübenbach, and T. Willkommen, "The IAPWS industrial formulation 1997 for the thermodynamic properties of water and steam," *Journal of Engineering for Gas Turbines and Power*, vol. 122, no. 1, pp. 150–184, 2000.

[20] D. Goldfarb and A. Idnani, "A numerically stable dual method for solving strictly convex quadratic programs," *Mathematical Programming*, vol. 27, no. 1, pp. 1–33, 1983.

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

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

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

[24] D. A. Latham, "Mathematical modelling of an industrial steam methane reformer," M.Sc.(Eng.) thesis, Queen's University, Kingston, Ontario, Dec. 2008, hdl.handle.net/1974/1650.

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

[26] E. Lewis, S. McNaul, M. Jamieson, M. Henriksen, H. Matthews, L. Walsh, J. Grove, T. Shultz, T. Skone, and R. Stevens, "Comparison of commercial, state-of-the-art, fossil-based hydrogen production technologies," National Energy Technology Laboratory, Pittsburgh, PA, Report DOE/NETL-2022/3241, 2022.

12.10 Exercises

12.1 ○ Concept check · 2 min

In case 2 the same 15 % feed step drops the true steam-to-carbon ratio to 2.729 under the plain ratio, while with the lead-lag on it never falls below 2.994. What does the lead-lag change?

(a) It drives the steam valve faster than its ramp allows while the rate is rising

(b) It holds the feed back through a lag on the rate demand while the steam setpoint moves at once

(c) It raises the gain of the steam flow loop whenever the measured feed is rising

(d) It filters the feed meter so that the steam setpoint no longer follows its noise

12.2 Concept check · 1 min

In case 5 the adsorber's cycle is lengthened from 10 to 11 min while the plant rate is held. What happens to the natural gas makeup to the burners?

(a) It falls, because the plant recovers more hydrogen from the same feed

(b) It is unchanged, because the outlet loop holds the outlet temperature

(c) It rises, because the tail gas carries less hydrogen to the burners

(d) It rises, because the purity falls and the header loop raises the feed

12.3 Concept check · 2 min

In case 4 the 200 m^3 surge drum is replaced by one of 50 m^3. How does the drum's pressure swing from 20 to 30 min change?

(a) It grows four times, because the swing is inversely proportional to the volume

(b) It is unchanged, because the adsorber's product pulse does not depend on the drum

(c) It shrinks, because a smaller drum passes the pulse to the header more quickly

(d) It grows less than four times, because the pulse is long against the drum's time constant

12.4 Theory and calculation · 5 min

The design feed is 18 700 Nm^3/h of natural gas with a carbon number $n_C = 1.040$, at a steam-to-carbon ratio of 3.00. Take 22.414 Nm^3/kmol and 18.015 kg/kmol for water. The steam valve passes the design steam at 60 % open, its flow is proportional to its opening at a fixed supply pressure, and its stem moves at most 4 % a minute.

(a) Compute the carbon fed and the process steam at design, in t/h. *Checkpoint:* 867.7 kmol/h of carbon and 46.9 t/h of steam.

(b) The feed rises 15 % with the steam held, as in case 1. Compute the new ratio. *Checkpoint:* 2.609.

(c) Compute the valve opening that restores 3.00 at the new feed, and the shortest time the ramp allows to reach it. *Checkpoint:* 69.0 %, at least 2.25 min.

12.5 Theory and calculation · 6 min

The header holds $V_h = 1000\,m^3$ of hydrogen at 40 °C, and the surge drum $V_d = 200\,m^3$ at the same temperature. The drum passes the design product of 50 004 Nm^3/h to the header across a 2.5 bar drop, so k_{dh} is that flow divided by 2.5 bar. Take $R = 0.083\,14\,\text{bar}\,m^3/(\text{kmol}\,\text{K})$ and 22.414 Nm^3/kmol.

(a) Compute how fast the header pressure moves when the users draw 5000 Nm^3/h more than the drum supplies. *Checkpoint:* 0.0968 bar a minute.

(b) With the plant rate unmoved, how long would the case 6 step take to pull the header 0.5 bar down, and how fast does the challenge's 20 % step pull it? *Checkpoint:* 5.2 min, and 0.194 bar a minute.

(c) Compute the drum's time constant $V_d/(RTk_{dh})$ at 200 m^3 and at 50 m^3, and compare them with the adsorber's 2.5 min step. *Checkpoint:* 0.52 min and 0.13 min.

12.6 Theory and calculation · 7 min

Use the adsorber correlation of Equation (12.5) with four beds ($\ell_4 = 0.15$), a design step $t_{s,0} = 2.5$ min, $\varphi_0 = 0.80$, $y_0 = 400$ ppm and $w = 0.12$. Take the product's impurity as the step average of y_{imp}, and the hydrogen and the impurities fed in proportion to the feed.

(a) Compute the recovery and the purity for an 11 min cycle at the design feed, as in case 5. *Checkpoint:* 86.36 % and 99.922 %.

(b) The feed rises 20 % with the cycle fixed at 10 min, as in the challenge. Compute the recovery, the purity and the impurity at the end of a step, where $x = 1$. *Checkpoint:* 87.50 %, 99.848 %, 2428 ppm.

(c) With *cycle follows the feed* the step shrinks in proportion to the carbon fed. Compute the step, the loading and the purity at the same 20 % rise, with the carbon number unchanged. *Checkpoint:* 2.083 min, 0.80, 99.960 %.

12.7 App challenge · 8 min

Load scenario 2, Ratio control, then the lead-lag, and change no setting. The users draw 15 % more and the plant rate steps to 115 % at 2 min. Use the default seed, run to 12 min at the default speed of 2 min/s, and export the CSV file.

(a) Read the Lowest S/C tile, and find in the file the lowest true ratio, column `truth_sc`, and its time, column `time_min`. *Checkpoint:* 2.73 on the tile. 2.729 at 2.83 min, within 0.02 min.

(b) Set Lead-lag On on the S/C ratio card, press Reset, run to 12 min again and export the file. Read the Lowest S/C tile. *Checkpoint:* 2.99.

(c) In both files read the true feed, column `truth_feed_nm3h`, in the row at 3.0 min, and explain the difference. *Checkpoint:* 21 477 Nm^3/h plain and 19 527 Nm^3/h with the lead-lag, within 10 Nm^3/h.

12.8 App challenge · 8 min

Load scenario 8, A PSA bed fails: three beds, and change no setting. A bed valve fails at 5 min. Use the default seed, run to 45 min at 10 min/s, and export the CSV file.

(a) In the rows at 5.0 and 45.0 min read the recovery, `psa_recovery_pct`, and the true makeup, `truth_makeup_nm3h`. Compute the change in makeup. *Checkpoint:* 85.03 % and 2866 Nm^3/h, then 80.98 % and 2382 Nm^3/h, a change of −16.9 %.

(b) From the ledger columns `truth_feed_total_nm3`, `truth_makeup_total_nm3` and `truth_product_total_nm3`, compute the natural gas fed and fired per Nm^3 of hydrogen from 0 to 5 min and from 30 to 45 min. *Checkpoint:* 0.4323 and 0.4403, within 0.0005.

(c) Read the NG per H_2 tile at 45 min and say why it differs from the second value of (b). *Checkpoint:* 0.440.

12.9 App challenge · 10 min

Load scenario 9, Challenge, 8 h on the header. Before Run, set the Pressure gain to 60 % per bar and the Pressure integral time to 3.0 min on the PIC card, Lead-lag On on the S/C ratio card, Cycle follows the feed On on the PSA card, and Control architecture to Loops + tail-gas feedforward. Use the default seed and the top speed, 120 min/s, so that each 8 h run takes four seconds.

(a) Run 8 h and read the verdict at the end. *Checkpoint:* Target met: header within 0.394 bar, purity at least 99.929 %, S/C at least 2.886, hottest tube 916.7 °C.

(b) Set Lead-lag Off, press Reset and run 8 h again. Read the verdict, and find in the exported file the time of the lowest `truth_sc`. *Checkpoint:* Missed on S/C: 2.720, at 63.8 min, within 0.2 min.

Explain why the plain ratio fails with this header tuning, although the challenge as shipped, with the same plain ratio, keeps the ratio at 2.861 or above at the default seed.

12.10 Application area · 4 min

The chapter calls its steam-to-carbon floor of 2.8, its tube limit of 925 °C, its 99.9 % purity specification and its header alarm teaching values.

(a) Say where each value comes from on a real plant. *Checkpoint:* The catalyst supplier, the tube alloy's creep-rupture life, the users.

(b) Explain why a feed change on a reformer is a sequencing problem, and give the order of the two streams going up and going down. *Checkpoint:* Steam first up, steam last down.

12.11 Application area · 4 min

In case 8 a failed bed cuts the makeup natural gas by 16.8 %, and the natural gas fed and fired per Nm^3 of hydrogen rises from 0.4323 to 0.4403. The plant delivers its design product of 50 004 Nm^3/h.

(a) Compute the relative rise in natural gas per unit of hydrogen and the extra natural gas the plant uses each hour. *Checkpoint:* 1.85 %, and about 400 Nm^3/h.

(b) If all the carbon of that natural gas, $n_C = 1.040$, leaves in the flue gas, how much more carbon dioxide does the plant emit? Use 22.414 Nm^3/kmol and 44.01 kg/kmol. *Checkpoint:* About 0.82 t/h.

Say why a fuel report would describe this failure wrongly.

12.12 Review the agent · 5 min

An AI assistant is asked why the plain ratio of case 2 falls to 2.73 and replies as follows. “The steam flow loop is far too gentle at 0.5 % per percent and 1 min. Raise its gain to 3.00 % per percent and cut its integral time to 0.20 min. The steam will then track the ratio setpoint within seconds, and the plain ratio will stay above the 2.8 floor without any lead-lag.” Find the flaw in the claim and say how it could be checked.