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CHAPTER 3

A Hydrogen Shaft Furnace Whose Product Answers Six Hours After Its Gas

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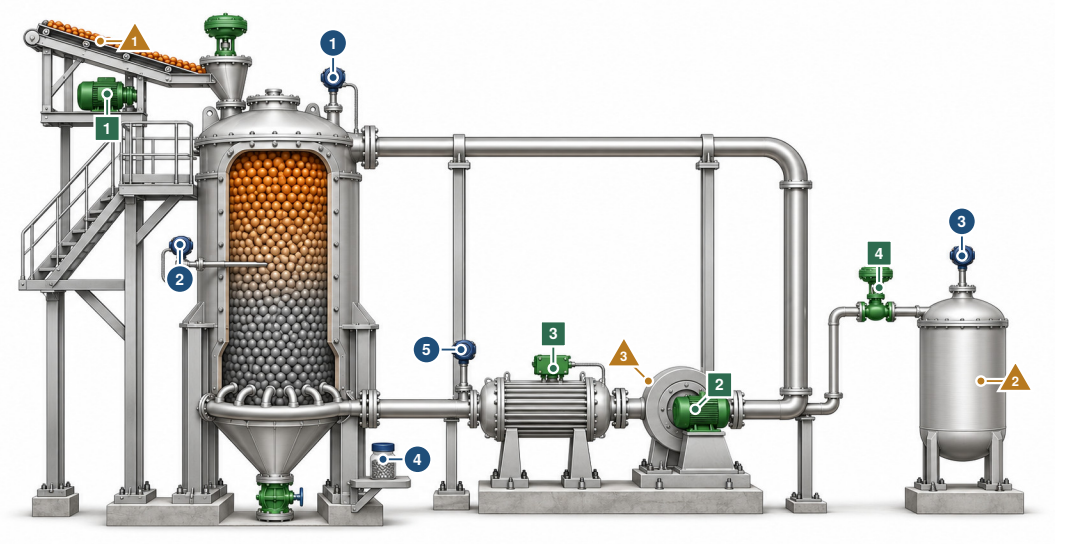
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CHAPTER 3

A Hydrogen Shaft Furnace Whose Product Answers Six Hours After Its Gas



The controller moves 1 pellet feed rate 2 recycle compressor, which sets the gas ratio 3 gas heater, which sets the bustle temperature 4 makeup hydrogen from the buffer

The controller reads 1 top pressure and top-gas analysis 2 burden thermocouple for the sticking margin 3 hydrogen left in the buffer 4 laboratory sample of the product every two hours 5 bustle gas flow and temperature

What disturbs it 1 a richer pellet lot 2 a wind lull that starves the buffer 3 a recycle compressor trip

Notice that the pellets take hours to fall from the feed at the top to the sample at the bottom while the gas loops through the bed in seconds, and that the buffer at the right is all the plant has when the wind drops. Illustration, not to scale.

IN PLAIN TERMS **Iron Made With Hydrogen, Checked Hours Later**

The main idea. Iron ore pellets slide slowly down a tall furnace. Hot hydrogen rises through them and carries off their oxygen as steam. A pellet takes six hours to reach the bottom, but the gas crosses the furnace in seconds.

The challenge. The controller must judge the finished iron from the gas that leaves the top. A laboratory test arrives only every two hours. The hydrogen is made with wind power, so when the wind drops the plant must choose. It can make less iron, or it can make poorer iron.

Why it matters. Making iron this way could remove most of the carbon dioxide that steelmaking puts into the air.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	The first page, the fact box of Section 3.1, the two history boxes of Section 3.2, the try-it boxes of Sections 3.4 and 3.6, the fact box of Section 3.6, and the key points
Study	55 min	The whole chapter with its pause points and the twelve exercises
Practice	15 min	The first page, Section 3.6, Section 3.7, Section 3.8 and the open challenge after it

The control question How can a hydrogen shaft furnace hold the metallization of a product that leaves six hours after its gas, is inferred from a top-gas balance and is checked by a late laboratory sample, while its hydrogen follows the wind?

Learning objectives

- Explain why the top gas answers a gas step within minutes while the product answers over the residence, and why the soft sensor leads the product.
- Compute the residence, the wüstite ceiling and the hydrogen a lull demands from the model's equations and constants.
- Judge when a laboratory report may correct the soft sensor's bias, and run the correction against a wrong pellet analysis.
- Compare a turndown override and a forecast-based MPC on the buffer, and say what each costs in tons or in quality.
- Use a temperature push to buy rate up to a measured sticking margin.

Prerequisites Sections 1.4.2, 1.4.5 and 1.4.6 of Chapter 1, the framework and the velocity-form PI of Sections 1.6 and 1.6.2, and for the buffer MPC Section 1.6.3. Chapter 2 shows the bias update on a hearth soft sensor.

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

See also Volume 5, *Delays, Slow Measurements, and State Estimation*: Volume 5, Chapter 4 (a charge that descends for hours ahead of its analyzer) and Volume 5, Chapter 10 (a laboratory-corrected soft sensor and a push against a sticky margin). Volume 9, *Model Predictive Control and Economic Optimization*: Volume 9, Chapter 7 (decisions on a forecast) and Volume 9, Chapter 6 (a delay that follows the flow).



3.1 Introduction

In the simulated shaft, 140 t/h of iron ore pellets enter cold at the top and leave as direct reduced iron (DRI) at the bottom of the reduction zone six hours later, while 10 556 kmol/h of hot hydrogen enters at the bustle and crosses the bed in seconds. Raising the gas from 1690 to 1800 Nm^3 per tonne of pellets warms the top gas from 440.4 to 450.8 °C within three minutes. The metallization of the iron that leaves needs 2.4 h to make a tenth of its move and 6.7 h to make half of it, from 94.5 to 98.5 %. Between those two clocks sits everything the plant can measure about its product, an oxygen balance on the top gas and a laboratory sample drawn every two hours and reported half an hour late.

Steelmaking emits between 4 and 7 % of the world's anthropogenic carbon dioxide, and reducing the ore with hydrogen instead of carbon cuts that by roughly 90 % on the route's own accounting [1]. A route of this kind reduces pellets in a shaft furnace and melts the product in an electric arc furnace for 3.48 MWh per tonne of liquid steel, mostly to run the electrolyzer [2]. Shaft furnaces already make most of the world's DRI with natural gas [3], and their reduction zone is a counter-current moving bed whose models range from one dimension [4] to the detailed and multiscale models of the last decade [3, 5]. Shafts run on pure hydrogen have been simulated as well, with a gas flow several times the stoichiometric need [6, 7]. The control problem belongs to a wider class, a quality known only from an inference corrected by sparse laboratory results [8], on a plant with a long transport delay, under constraints that a selector or an override must arbitrate [9]. Kilns, grain dryers, polymer reactors with grade transitions and any plant whose laboratory reports after the next decision share that shape. The kraft digester of Volume 5, Chapter 4 is another vessel whose charge descends for hours before an analyzer and a later laboratory grade it.

DID YOU KNOW? 21.4 Kilograms an Hour Against 140 Tonnes

The world made 86 million tonnes of direct reduced iron in 2017, against 1180 million tonnes of blast furnace pig iron [3]. The first pilot shaft in the United States run on hydrogen was fed 21.4 kg of pellets an hour [10]. The simulated shaft of this chapter is fed 140 t an hour.

The cases of this chapter are built against two beliefs. The first is that a fast measurement of the gas reports the product. In the model the soft sensor, which counts the oxygen the whole bed is losing now, makes half the product's move in 2.2 h, and at hour 8 it reads 99.0 % against a true 96.6 %. The second is that the equilibrium sets the gas flow. The wüstite equilibrium caps the steam a hydrogen stream can carry at 36.9 % at 900 °C, but the designed top gas leaves at 27.0 %, because the hydrogen must also carry the heat that warms the pellets and drives an endothermic reduction.

However, the published shaft models are steady designs or plant validations, the hydrogen-route studies are flowsheets and energy balances, and none puts the inferred quality, the laboratory, the moving bed and the variable hydrogen supply in one loop that a learner can operate. This chapter works with a browser model of a shaft furnace fed by wind hydrogen and prices on its own scorecard what a soft sensor, a laboratory correction, a temperature push, a turndown override and a forecast-based model predictive controller (MPC) each contribute. The equilibria come from published tables, the kinetics are declared teaching values, and the controllers are established forms. What is particular to this plant is a moving-bed cell stack whose oxygen, energy and buffer ledgers close to the solver's precision. Every equation and constant of that stack appears below, and its controllers see only instruments, never the bed's states. Nine cases run from a hand step of the gas to a day on a wind forecast with an honestly infeasible lull. Section 3.2 follows the domain. Section 3.3 gives the bed, the gas loop, the buffer and the instruments, and Section 3.4 measures the design point and the two clocks of the open loop. Section 3.5 describes the soft sensor, the three PI loops, the turndown override and the optional MPC. Section 3.6 measures the nine cases, the challenge and the ledgers. Section 3.7 sets the loops in their hardware, Section 3.8 states the limitations, Section 3.9 concludes, and Section 3.10 holds the exercises.

3.2 Direct Reduction and Its Control

Direct reduction removes the oxygen from iron ore below its melting point and leaves a porous metallic product that an arc furnace can melt. Its gas-based form began with batch retorts and became a continuous shaft, as the history box below tells. Shaft furnaces make over 82 % of the world's DRI, two processes known by their trade names, MIDREX and HYL-ENERGIRON, holding 65 and 17 % [3]. Both reduce with a mixture of hydrogen and carbon monoxide reformed from natural gas, at up to about 950 °C [3, 5].

HISTORY From Batch Retorts to the Continuous Shaft (1957 to the 1960s)

The first generation of one gas-based direct reduction process, developed in 1957 in Monterrey, Mexico, reduced its charge in batches in four fixed-bed retorts. Its next generation was built around a shaft furnace, and the one after that kept the shaft. A second process was developed in the United States in the 1960s, and its first demonstration plant was built in Portland, Oregon. Its pellets or lumps are charged and preheated at the top, reduced as they descend by gas supplied in the middle of the furnace, cooled below the gas inlets and discharged, and ports sealed with gas let the furnace be charged and discharged continuously [11].

Graphical balances of the furnace predate the numerical models of the shaft. A dual graphic representation of the blast furnace's mass and heat balances was published by Rist and Meysson in 1967 [12], and the simulator's Map view, which plots the gas's steam share against the solids' reduction, is drawn in the spirit of such operating diagrams. One-dimensional models of the counter-current moving bed followed, with shrinking-core kinetics for one overall reaction [4], and later models resolved the three steps from hematite through magnetite and wüstite to iron and validated

them against an industrial shaft at 119.2 t/h, 93.8 % metallization and a 285 °C top gas [3]. Multiscale models link the pellet, the bed and the plant, with pellets of 7 to 15 mm reduced between 600 and 950 °C [5]. The kinetics of hydrogen reduction were measured in the laboratory step by step [13] and have been reviewed as a whole [14].

Hydrogen changes the balance of the shaft. The overall reduction is endothermic with hydrogen and exothermic with carbon monoxide, the stoichiometric need for hematite is 54 kg of hydrogen per tonne of iron, and the top gas is cooled to condense its water before the hydrogen is recycled with fresh makeup and reheated [1]. A shaft run on pure hydrogen was simulated at 3.8 times the stoichiometric gas flow with gas entering at 800 °C, and a reduction zone about 4 m high was enough to reach full metallization with 12 mm pellets [6, 7]. The doctoral work behind those studies read the wüstite equilibrium at 36 % steam for 800 °C and found that pellets reduced in pure hydrogen stuck together from 900 °C under load, from 1000 °C without it, and only once metallic iron had formed [15].

> ⧖ HISTORY **Hydrogen Alone (1999 to 2021)**
>
> A two-stage fluidized-bed process that reduced fine ores with pure hydrogen, made by reforming natural gas, is the only direct reduction process on pure hydrogen known to have operated commercially. It was decommissioned for economic rather than technical reasons [1], after running in Trinidad and Tobago from 1999 to 2001 and from 2004 to 2006 [10]. The first comprehensive study of steelmaking with hydrogen was a subproject of a European program on ultra-low carbon dioxide steelmaking, 2004 to 2010, which compared fluidized beds of fine ore with a shaft furnace of pellets and selected the shaft [1]. A pilot plant in Sweden was commissioned in August 2020 and made the first sponge iron reduced with fossil-free hydrogen in June 2021 [16].

The newest problem is the supply. An electrolyzer on renewable electricity makes hydrogen when the wind blows, while the shaft is the one part of the route designed to run continuously, so hydrogen storage acts as a buffer that detaches the electrolyzer from the rest of the process [2]. Techno-economic studies of wind-powered hydrogen for steelmaking size that storage to turn an intermittent production into the constant flow a steelworks needs [16]. What the operator does when the buffer runs low is a control decision. Selector logic is a simple and effective way to switch a plant between the constraints that bind [9], model predictive control is established industrial practice [17], and soft sensors corrected against laboratory results carry the quality between samples [8].

3.3 The Shaft and Its Gas Loop as Modeled

The simulated plant is the reduction zone of a generic hydrogen shaft, its gas loop and its hydrogen supply, as shown in Figures 3.1 and 3.2. The model is built for teaching from published sources. It ports no supplier's or licensed simulation and uses no plant data. Pellets of 67.5 % iron enter at 25 °C at 140 t/h, 1692.2 kmol/h of iron, and the zone holds $n_{Fe} = 10\,153$ kmol of it, a residence of 6.000 h. Gas leaving the top is dried in a condenser, purged of 2 %, compressed, mixed with makeup hydrogen from a 30 t buffer and reheated to the bustle temperature. A 350 MW electrolyzer follows a 600 MW wind farm into the buffer. The model runs in hours, kilomoles and degrees Celsius. The variables are classified in Table 3.1.

3.3.1 Solids Moving Down

The solids carry four states in each of $N = 80$ cells of equal iron holdup $n_c = n_{Fe}/N$. The fraction a of the cell's iron is still in the higher oxides, hematite and magnetite lumped at an oxygen-to-iron ratio of 1.5, m is metallic, and $w = 1 - a - m$ is wüstite, taken as FeO in the balances. T is the solids temperature and g the pellet grade the cell carries, a tracer that nothing else touches. The solids move

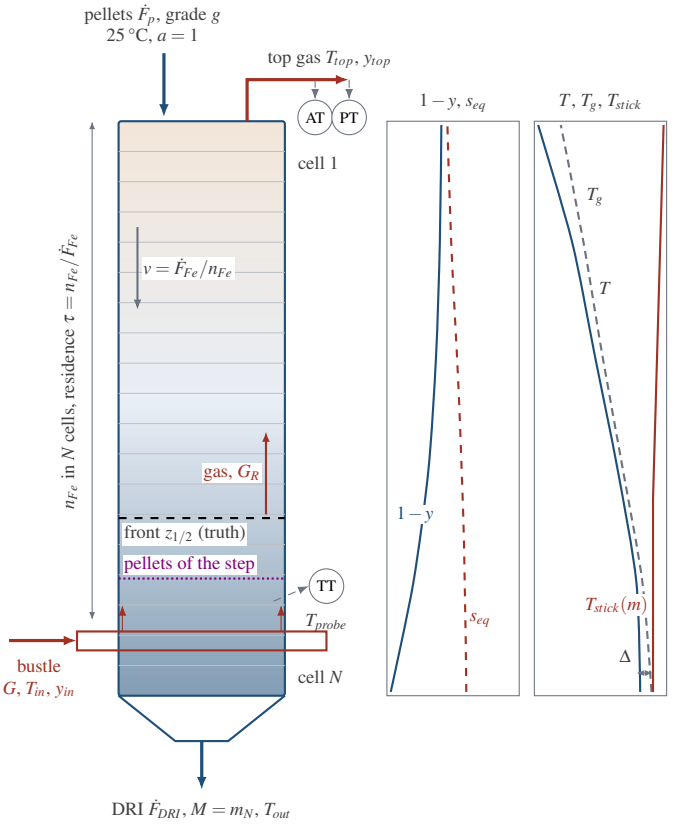


Figure 3.1 The reduction zone of the hydrogen shaft furnace as modeled, after the application's Shaft view. The zone of N cells holds n_{Fe} of iron, with pellets $\dot{F}_p$ of grade g entering at the top, solids descending at v, the bustle gas G at T_{in} and steam share $1 - y_{in}$ rising to the top gas at T_{top}, the reduction front $z_{1/2}$, the pellets charged at a step of the gas, the burden thermocouple T_{probe} and the product $M = m_N$ at T_{out}. Beside the bed, the profiles of the gas's steam share $1 - y$ against the wüstite wall s_{eq} and of the solids and gas temperatures against the sticking curve $T_{stick}(m)$ with the margin Δ. Process model only. Not to scale.

as a plug written in flux form, as shown in Equation (3.1).

$$\begin{aligned}
\frac{\mathrm{d}\phi_i}{\mathrm{d}t} &= \frac{\dot{F}_{Fe}}{n_c}\left(\phi_{i-\frac{1}{2}} - \phi_{i+\frac{1}{2}}\right) + S_{\phi,i} \\
\phi_{i+\frac{1}{2}} &= \phi_i + \tfrac{1}{2}\,\psi(r_i)\,(\phi_i - \phi_{i-1}), \qquad \psi(r) = \frac{2r}{1+r} \\
S_a &= -r_1, \quad S_m = r_2, \quad S_g = 0 \\
S_T &= \frac{Q_i - n_c\left(\frac{1}{2}r_1\Delta H_1 + r_2\Delta H_2\right)}{n_c c_s}
\end{aligned} \tag{3.1}$$

where $\dot{F}_{Fe} = 1000\,\dot{F}_p g/M_{Fe}$ is the iron fed in kmol/h, $r_i = (\phi_{i+1} - \phi_i)/(\phi_i - \phi_{i-1})$, $\psi = 0$ for $r \le 0$, the feed is the ghost value above cell 1 ($a = 1$, $m = 0$, 25 °C, the grade g), and the discharge face is first order, so the product is the bottom cell. The van Leer limiter keeps a front sharp without oscillation, and because each cell receives exactly what the one above gives, the oxygen and heat inventories close. A tracer charged at the top leaves with a mean delay of 6.000 h, equal to $n_{Fe}/\dot{F}_{Fe}$.

Table 3.1 Signals and States of the Shaft, Classified, at the Start of Case 1

Symbol	Role	Design	Range
M	CV, metallization of the DRI (truth)	94.54 %	SP 88–99
$\hat{M}_c$	measured, corrected soft sensor	94.5 %	0–100
M_{lab}	measured, laboratory, 2 h, 0.5 h late	—	held
R	MV, gas ratio	1690 Nm^3/t	900–2600
T_{in}	MV, bustle temperature	900 °C	800–1000
$\dot{F}_p$	MV, pellet feed	140 t/h	40–170
$\dot{H}_{mu}$	MV of the pressure loop, makeup	2670 kmol/h	0–6000
P	CV, top pressure	3.00 bar	SP 2.0–3.5
Δ	CV, measured sticking margin	51 K	SP 0–60
B	CV of the override, buffer	100 %	floor 20
g, g_m	DV, pellet grade and its analysis	67.5 % Fe	64–69.5
$f(t)$	DV, wind capacity factor	60 %	0–100
—	DVs, lull, trip, lot, outlier	events	—
a_i, m_i, T_i, g_i	states, 80 cells	—	—
n_L, B, P_{el}, T_{in}, $\dot{F}_p$, χ	states, plant	—	—
y_i, $T_{g,i}$	algebraic, gas in each cell	—	—

With first-order upwind cells, going from 20 to 40 cells moved the design metallization 3.1 points, which is why the model carries 80 cells of the second-order scheme.

3.3.2 Reduction Rates and the Equilibrium Walls

Two lumped steps remove the oxygen. The higher oxides go to wüstite with half an oxygen per iron and wüstite goes to iron with one, at shrinking-core rates under chemical control with an equilibrium driving force, as shown in Equation (3.2).

$$\begin{aligned} r_1 &= k_1(T)\, a^{2/3}\, P' x_R \Big[y - \frac{1-y}{K_1(T)} \Big]^+ \\ r_2 &= k_2(T)\, \frac{w}{(1-m)^{1/3}}\, P' x_R \Big[y - \frac{1-y}{K_2(T)} \Big]^+ \\ k_j(T) &= k_j \exp\Big[-\frac{E_j}{\mathscr{R}} \Big(\frac{1}{T} - \frac{1}{T_{ref}} \Big) \Big], \qquad K_j = \mathrm{e}^{A_j - B_j/T} \end{aligned} \tag{3.2}$$

where $y = H_2/(H_2 + H_2O)$ in the cell's gas, $x_R = 0.95$ is the reducing share, P' the top pressure over its 3 bar reference, T in kelvin, $T_{ref} = 1173.15\,\mathrm{K}$ and $[\cdot]^+ = \max(0, \cdot)$, so nothing reoxidizes. The factor $a^{2/3}$ is the unreacted core's surface and $w(1-m)^{-1/3}$ the iron front's surface times the share of the unconverted iron that is wüstite. The constants $A_2 = 1.0836$, $B_2 = 1899\,\mathrm{K}$ fit the NIST-JANAF Gibbs energies [18] of $Fe_{0.947}O + H_2 = 0.947\,Fe + H_2O$ between 900 and 1300 K within 0.31 %. The tables give $K_2 = 0.5026$, 0.5859 and 0.6657 at 800, 900 and 1000 °C, so the steam share over wüstite, $s_{eq} = K_2/(1+K_2)$, cannot exceed 33.45, 36.94 and 39.96 %, and the fit gives 33.5, 36.9 and 39.9 %. The iron-oxide stability (Chaudron) diagram read in a doctoral study of hydrogen reduction gives 36 % at 800 °C [15], about 2.5 points above the tables, and a reading offset by as much would put the ceiling near 39.5 % at 900 °C. The "40 % at 900 °C" of the model's first specification matches the tables only at 1000 °C, so the model keeps the tables' 36.9 %. The magnetite–wüstite step ($A_1 = 7.2464$, $B_1 = 7354.3\,\mathrm{K}$) allows 72.7 % steam at 900 °C. The rate constants $k_2 = 1.0\,\mathrm{h}^{-1}$ with $E_2 = 70\,\mathrm{kJ/mol}$ and $k_1 = 6\,\mathrm{h}^{-1}$ with $E_1 = 60\,\mathrm{kJ/mol}$ are teaching values chosen so that a pellet held in the bustle gas at 900 °C reaches 95 % metallization in 2.29 h. The activation energies lie in the range measured for hydrogen reduction of hematite and magnetite, 39 to 88 kJ/mol between 220 and 680 °C [13].

3.3.3 Gas Rising Through the Cells

The gas crosses the bed in seconds, so each cell's gas is algebraic. Hydrogen swaps for steam mole for mole, so the reducing flow $G_R = x_R G$ is the same in every cell and only y changes. Each cell's

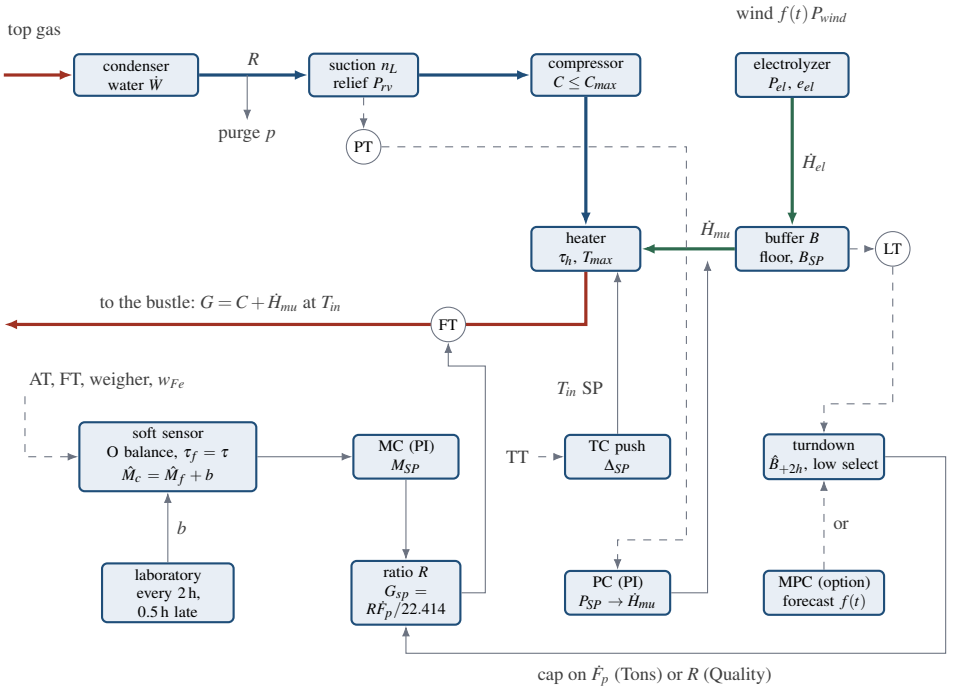


Figure 3.2 The gas loop and its control layers as modeled, after the application's Gas loop view: condenser, purge p, suction header n_L, compressor C, heater, makeup $\dot{H}_{mu}$ from the buffer B, electrolyzer P_{el} on the wind $f(t)P_{wind}$. Below, the control layers: the soft sensor corrected by the laboratory, the metallization loop MC on the gas ratio R, the temperature push TC, the pressure loop PC on the makeup and the turndown override with its optional MPC. Process model only. Not to scale.

gas is well mixed at its outlet value, which makes the oxygen it takes linear in y, and the gas gives heat to the solids through one conductance, as shown in Equation (3.3).

$$\begin{aligned} G_R\,(y_{i+1} - y_i) &= n_c\left(\tfrac{1}{2}r_1 + r_2\right)\Big|_{y_i}, \qquad y_{N+1} = \frac{x_R - x_W}{x_R} \\ T_{g,i} &= T_i + (T_{g,i+1} - T_i)\,\mathrm{e}^{-UA/(NGc_g)} \\ Q_i &= Gc_g\,(T_{g,i+1} - T_{g,i}) \end{aligned} \tag{3.3}$$

where $x_W = 0.025$ is the bustle's steam share, $T_{g,N+1} = T_{in}$ and the sweep runs from the bottom cell to the top. The first equation is solved in closed form with the active set of the two reactions found in at most three passes, so the sweep needs no iteration and is a pure function of the state. The top gas leaves at y_1 and $T_{g,1}$. The reaction heats $\Delta H_1 = 34$ and $\Delta H_2 = 16$ MJ per kilomole of oxygen are the JANAF enthalpies at 1100 K with gas-phase water, 33.93 and 16.18 MJ, which sum to +64.3 kJ per mole of hematite against +100.0 kJ at 298 K.

3.3.4 Gas Loop, Buffer and Electrolyzer

The bustle receives the compressor's recycle and the makeup $\dot{H}_{mu}$, and the top gas returns to a suction header whose inventory sets the pressure, as shown in Figure 3.2 and Equation (3.4).

$$\begin{aligned} P &= P_{ref}\, n_L / n_{L,0}, \qquad G = C + \dot{H}_{mu} \\ C &= \min\!\big(\alpha C_{max} \min(1.2, P/P_{ref}),\; G_{sp} - \dot{H}_{mu}\big) \\ S_{top} &= x_R G (1 - y_1), \qquad G_c = \frac{G - S_{top}}{1 - x_W} \\ \dot{W} &= S_{top} - (G_c - G + S_{top}), \qquad R_c = (1 - p)\, G_c \\ \frac{\mathrm{d}n_L}{\mathrm{d}t} &= R_c - C - V, \quad V = \frac{\max(0,\; n_L - n_{rv})}{0.02\,\mathrm{h}} \end{aligned} \tag{3.4}$$

where α is 1, or 0 while the compressor is tripped, G_c is the gas after the condenser at the bustle's steam share, $\dot{W}$ the condensed water, $p = 0.02$ the purge and n_{rv} the inventory at the 3.6 bar relief. The buffer and the electrolyzer follow Equation (3.5).

$$\begin{aligned} \frac{\mathrm{d}B}{\mathrm{d}t} &= \dot{H}_{el} - \dot{H}_{mu} - \dot{H}_{cu}, \qquad \dot{H}_{el} = \frac{1000\, P_{el}}{e_{el} M_{H_2}} \\ \frac{\mathrm{d}P_{el}}{\mathrm{d}t} &= \mathrm{clip}\!\left(\frac{\min(P_{el,max},\, f P_{wind}) - P_{el}}{0.02\,\mathrm{h}},\; \pm\rho_{el}\right) \\ \dot{H}_{mu} &\le \min\!\big(\dot{H}_{mu,max},\; \dot{H}_{el} + B/\Delta t\big) \end{aligned} \tag{3.5}$$

where $\dot{H}_{cu}$ curtails what would overfill a full buffer in one step and $e_{el} = 52\,\mathrm{kWh/kg}$. The makeup is written $\dot{H}_{mu}$ here because M is the metallization. The wind factor is a declared forecast plus a colored deviation of standard deviation 0.015 and correlation time 1 h. The forecast day falls from 0.78 at midnight to 0.06 for a lull from hour 10 to hour 16 and recovers to 0.66 by hour 24. The heater and the feeder are lags, $\tau_h \dot{T}_{in} = T_{in,cmd} - T_{in}$ with $\tau_h = 0.1\,\mathrm{h}$ and $T_{in} \le 1000\,^{\circ}\mathrm{C}$, and the same 0.1 h lag on the pellet feed. The heater duty is reported as $G c_g (T_{in} - 40\,^{\circ}\mathrm{C})$, 78.2 MW at design.

3.3.5 Sticking, Pressure Drop and the Product

Freshly metallized pellets sinter together above a temperature that depends on their composition. The teaching curve and its consequences are Equation (3.6).

$$\begin{aligned} T_{stick}(m) &= T_{st} + 150\,\mathrm{clip}\!\left(\frac{0.9 - m}{0.4},\, 0,\, 1\right) \\ \frac{\mathrm{d}\chi}{\mathrm{d}t} &= \frac{0.05}{N} \sum_i \max\big(0,\; T_i - T_{stick}(m_i)\big) - \frac{\chi}{2\,\mathrm{h}} \\ \Delta P &= 0.9 \left(\frac{G}{10^4}\right)^{1.8} \frac{P_{ref}}{P}\,(1 + \chi)\ \mathrm{bar} \end{aligned} \tag{3.6}$$

with $T_{st} = 950\,^{\circ}\mathrm{C}$, inside the range in which hydrogen-reduced pellets were found to stick in the laboratory [15]. The rise toward oxide is a teaching shape and the cluster index χ a teaching state. The product is the bottom cell. Its metallization is $M = m_N$ and its mass per kilomole of iron is $M_{Fe} + 16(1 - m + a/2) + \gamma(g)$ with gangue $\gamma = M_{Fe}/g - M_{Fe_2O_3}/2$, which gives the DRI rate, its total iron and its gangue. The model has no transition or cooling zone, so the product leaves at the temperature of the bottom cell.

3.3.6 Measurements

The controllers read only a measurement packet: the pellet weigher and the bustle flow meter (0.3 % noise each), the pellet analysis $g_m = g + \delta g$ with a declared error, the bustle and top-gas thermocouples (1 and 2 K), a top-gas analyzer of hydrogen and steam with a 2 min lag and 0.05

Table 3.2 Model Parameters and Their Sources. All but N and g Are Adjustable in the Parameters Panel

Symbol	Meaning	Value	Source
n_{Fe}	iron in the zone	10 153 kmol	6.0 h of feed
N	cells	80	refinement
k_2, E_2	wüstite step	1.0 h^{-1}, 70 kJ/mol	teaching
k_1, E_1	higher oxides	6 h^{-1}, 60 kJ/mol	teaching
A_2, B_2	wüstite–iron	1.0836, 1899.0 K	JANAF fit [18]
A_1, B_1	magnetite–wüstite	7.2464, 7354.3 K	JANAF fit
ΔH_1, ΔH_2	reaction heats	34, 16 MJ/kmol O	JANAF, 1100 K
c_s	solids heat capacity	65 kJ/(kmol Fe K)	teaching
c_g	gas heat capacity	31 kJ/(kmol K)	teaching
UA	gas–solid, whole bed	4×10^7 kJ/(h K)	teaching
g	pellet grade	67.5 % Fe	DR grade
x_R, x_W	reducing, steam share at bustle	0.95, 0.025	teaching
p	purge share	0.02	teaching
P_{ref}, $n_{L,0}$	top pressure, loop gas	3 bar, 400 kmol	teaching
P_{rv}	relief	3.6 bar	teaching
C_{max}, $\dot{H}_{mu,max}$	compressor, makeup valve	9000, 6000 kmol/h	teaching
τ_h, T_{max}	heater lag, limit	0.1 h, 1000 °C	teaching
P_{wind}, $P_{el,max}$	wind farm, electrolyzer	600, 350 MW	teaching
e_{el}, ρ_{el}	specific energy, ramp	52 kWh/kg, 2100 MW/h	teaching
B_{max}, floor	buffer	30 t, 20 %	teaching
T_{st}	sticking, metallized	950 °C	level [15]
T_{lab}, θ_{lab}, σ_{lab}	laboratory	2, 0.5 h, 0.3 points	teaching

points of noise, the top pressure (0.005 bar), the bed pressure drop, a burden thermocouple at the bustle reading the bottom cell's solids (3 K), the buffer as a level (0.2 %) and the electrolyzer and makeup meters (0.5 %). The laboratory draws a spot sample of the discharge every 2 h from $t = 0$, reports it 0.5 h later with 0.3 points of noise and holds it until the next report. The report shown before the run is a noisy sample of the lined-out product dated hour −2. Every sample is stored with the product's true metallization at the moment it was drawn, which the scorecard and the challenge judge and no controller reads, and a source-level test of the application rejects any controller or estimator that names a truth field. Where a controller needs a plant constant, namely the buffer size, the electrolyzer and wind farm ratings, the specific energy, the holdup, the bustle composition or the sticking temperature, it takes the shipped value, and a second test checks that a parameter edit leaves every controller output unchanged at fixed measurements. The CSV export of Section 1.6.4 writes one row per simulated minute with the soft sensor before and after its bias, the laboratory report and its sampling hour, the gas ratio requested, commanded and applied, the bustle and top-gas measurements, the sticking margin, the buffer, feed, makeup and wind, and, under a `truth_` prefix, the product, the margin, the front and the cluster index.

3.3.7 Parameters, Initialization and Numerics

Table 3.2 lists the parameters with their defaults. Each case starts lined out. A pseudo-transient Euler integration at 0.004 h finds the bed's steady state for the case's stations, and the makeup is set to the difference between the bustle gas and the returning recycle. The solve is deterministic and cached by its inputs, so Reset replays exactly. The framework's engine (Section 1.6.1) integrates the whole plant with explicit Euler at $\Delta t = 5$ s, clamps the solid fractions to the simplex, runs the controllers every minute and logs a row every minute. Halving Δt moves case 1's metallization at hour 12 from 97.5069 to 97.5121 %. Doubling the cells to 160 moves the design metallization by 0.385 points, from 94.540 to 94.925 %, moves no case's measured lesson by more than 0.41 points and changes the verdict of none of 15 challenge policies on five seeds. The suggested challenge day takes 17 287 steps in 0.24 s headless, about 14 µs a step, and Chrome needs 24.0 s for the whole 24 h day at 1 h/s.

3.3.8 Assumptions

Hydrogen is the only reductant, with 5 % inert and 2.5 % steam at the bustle, so the natural-gas routes, carbon monoxide and carbon in the product are out of scope. The bed has one dimension and uniform pellets, with no radial gradients, channeling or gas distribution, which a real shaft's cone and bustle do not achieve. Hematite and magnetite are lumped, wüstite is FeO in the balances and $Fe_{0.947}O$ in the equilibrium, and the equilibrium fits are extrapolated below 570 °C, where wüstite is not stable but little reduces. The kinetics omit pore diffusion, gas-film resistance, swelling and disintegration. Heat capacities are constant, the walls lose nothing, and one conductance couples gas and solids. The bustle composition is declared rather than computed from the recycle and the dry makeup, and the makeup is the total-gas difference $G - R_c$, so at design it is 77 kmol/h, 3.0 %, above an exact species balance. Of the 53.4 kg of makeup hydrogen per tonne of DRI, 48.9 are consumed, 2.9 purged and 1.5 are this closure, and the condenser removes 45.2 t/h of water against 44.1 t/h made. The electrolyzer has no minimum load, no stack degradation and no grid purchase.

3.4 Dynamic Character

3.4.1 The Design Point and the Heat That Sets the Flow

At the shipped stations, 1690 Nm^3 of bustle gas per tonne of pellets at 900 °C and 3 bar, the bed lines out at 94.54 % metallization and makes 100.87 t/h of DRI with 93.69 % total iron, 6.58 % FeO, 4.85 % gangue and no carbon, discharged at 899 °C. The top gas leaves at 440 °C with 27.0 % steam against a 36.9 % ceiling at the bustle, and 74.7 % of the bustle gas is recycle. The bustle carries 3.99 times the hydrogen the reduction consumes (4.10 counting its steam), and on the basis of the pure-hydrogen study, hydrogen fed over the hydrogen that reduces all the iron fed, the design is 3.85 against the study's 3659.3/976.9 = 3.75 [15], reported there as 3.8. That study's adiabatic balance gives a 384 °C top gas at a 900 °C inlet against 440 °C here. The reduction consumes 52.2 kg of hydrogen per tonne of iron, against 54 kg for full reduction of hematite [1].

The equilibrium does not set this flow. The upper shaft, cells 9 to 40, averages 729 °C in the solids, where the wall is near 30.8 %, so the gas leaves even the coolest part of the bed below its local wall, as Figure 3.3d shows for the whole range of ratios. At 900 °C the top-gas utilization peaks at 27.3 % near 1600 Nm^3/t and falls on both sides, at lower ratios because the cold upper bed reduces nothing and at higher ratios because there is more gas than oxygen. No ratio approaches the ceiling. The compressor caps the applied ratio at 1887 Nm^3/t for 140 t/h at 900 °C. Below about 1600 Nm^3/t the metallization falls steeply, to 64.7 % at 1400 and 13.3 % at 1000, and a hotter bustle shifts the whole curve left, as shown in Figure 3.3c.

🕮 **Pause.** Try Exercise 3.2 before reading on.

3.4.2 A Fast Gas and a Slow Product

Case 1 raises the ratio from 1690 to 1800 Nm^3/t at hour 1. Within three minutes the top gas warms from 440.4 to 450.8 °C and its steam share falls from 27.04 to 26.45 %, as shown in Figure 3.3a. The product rises from 94.54 to 98.52 % by hour 30, reaching 10, 50, 63 and 90 % of that move 2.37, 6.73, 8.62 and 16.75 h after the step, as shown in Figure 3.3b. The gas reaches every pellet at once, but a pellet leaving the bottom has spent hours under the old gas, and the upper bed must warm before its reduction speeds up. The pellets charged at the step reach the bustle one residence later, at hour 7, 83.3 % of the way down at hour 6, as the application draws them in Figure 3.5.

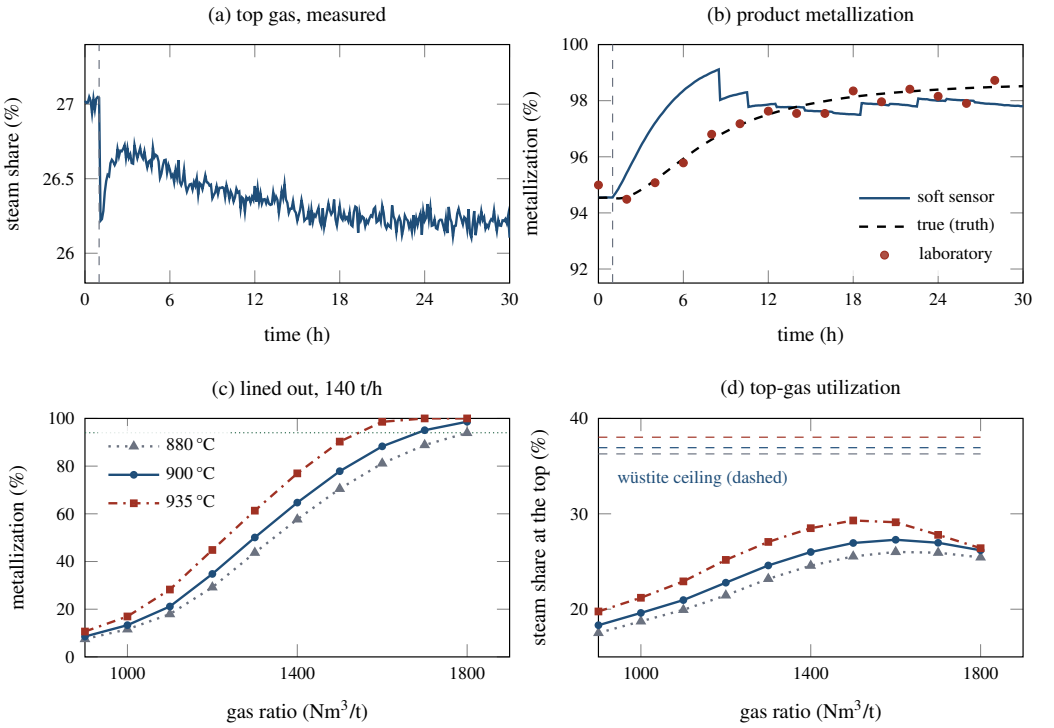


Figure 3.3 Two clocks and one operating map, computed by the application's engine. (a), (b) Case 1 in Manual with the gas ratio raised from 1690 to 1800 Nm^3/t at hour 1 (dashed line). The measured top-gas steam share steps within minutes, while the true product turns over the residence time and the soft sensor leads it until the laboratory reports, drawn at their sampling instants, move its bias from hour 8.5. (c), (d) The lined-out bed at 140 t/h against the applied gas ratio at three bustle temperatures, with the 94 % specification (dotted) and the wüstite ceiling at each bustle temperature (dashed, higher for a hotter bustle). The curves of the coolest bustle are dotted with triangles, those at 900 °C solid with circles and those at 935 °C dash-dotted with squares. In (b) the soft sensor is solid, the true product dashed and the laboratory samples dots. Points above 1887 Nm^3/t at 900 °C are not reachable because the compressor caps the flow.

TRY IT IN THE APP 1 · Raise the Gas: The Top Answers Now, the Product Later

Load the scenario, press Run and, after the start, raise Gas ratio to 1800 Nm^3/t. Watch the top-gas trend: its steam share falls from 27.04 to 26.45 % within three minutes. On the metallization trend the true product needs 6.73 h to make half its move, while the soft sensor gets there in 2.18 h.

A pellet lot shows the residence alone. In case 2 a lot with one point more iron enters at hour 1. The DRI rate rises at once from 100.87 to 102.41 t/h, because the bed's iron holdup is fixed, so the discharge iron rate rises at once with the richer feed while the old gangue-to-iron ratio is still leaving the bed. It falls back to 100.56 t/h at hour 7.5, half its drop at hour 6.90, when the lot's lower gangue per iron reaches the discharge. The DRI's total iron makes 10, 50 and 90 % of its step from 93.69 to 95.37 % at 4.38, 5.92 and 6.18 h. A change of the feed rate is not a lot. Cutting the feed from 140 to 120 t/h speeds or slows the whole bed at once and moves the product 10 % of its way in 0.58 h.

3.5 Implemented Control System

The controllers execute every minute on the measurement packet. A header switch selects Manual or Auto, and each loop has its own Auto and Man with a station that is live only in Man. Layer 1 is the gas-ratio station, $G_{sp} = R\dot{F}_{p,m}/22.414$ on the weigher, the heater setpoint and the top pressure loop on the makeup. Layer 2 is the metallization loop on the corrected soft sensor and the temperature push on the sticking margin. Layer 3 is the turndown supervisor on the buffer. The 94 % specification, the 20 % buffer floor and the sticking curve are teaching values. The real metallization target comes from the arc furnace's energy and slag balance and the buyer's specification, the real sticking limit from laboratory tests on the pellets in use [15] and the real buffer floor from the storage vessel's minimum pressure and the trip logic.

3.5.1 The Soft Sensor and Its Laboratory Correction

The soft sensor closes the oxygen balance on the top gas against the oxygen the pellets bring, filters it with the residence and adds a bias that the laboratory moves, as shown in Equation (3.7).

$$\begin{aligned} \hat{X} &= \frac{G_m x_R\,(s_{top} - x_W/x_R)}{1.5\,\dot{F}_{Fe,m}}, \qquad \hat{M} = 1 - 1.5\,(1-\hat{X}) \\ \hat{M}_{f,k} &= \hat{M}_{f,k-1} + \left(1 - \mathrm{e}^{-\Delta t_c/\tau_f}\right)(\hat{M}_k - \hat{M}_{f,k-1}) \\ \tau_f &= n_{Fe}/\dot{F}_{Fe,m}, \qquad \hat{M}_c = \mathrm{clip}(\hat{M}_f + b,\ 0,\ 1) \\ b &\leftarrow b + \lambda\left(M_{lab} - \hat{M}_f(t_s) - b\right) \end{aligned} \tag{3.7}$$

where s_{top} is the analyzer's steam share of the reducing gas, $\dot{F}_{Fe,m}$ the iron fed from the weigher and the pellet analysis, $\Delta t_c = 1\,\mathrm{min}$, $\tau_f \le 24\,\mathrm{h}$, t_s the sample's drawing time and $\lambda = 0.5$ with $|b| \le 8$ points. The update is the framework's bias updater, the exponentially weighted form of Equation (1.6) applied at each accepted report, as the hearth soft sensor of Chapter 2 applies it at each cast. In a steady bed with the right analysis the balance equals the product to 0.005 points. A report moves b only when the gas ratio and the feed applied over the 6 h before the sample stayed within 3 % and 3 t/h and the report is below 98.5 %, because a balance read during a transient charges the bed's stored oxygen to the bias.

Pause. Try Exercise 3.3 before reading on.

The clamp corrects an earlier build of the application. The balance counts the oxygen the bed gives up against the oxygen fed now, so after a feed cut or with a hotter bustle it passes 100 %, to 103.21 % at hour 17.5 of case 6 for 4.8 h and to 107.74 % at 965 °C in case 4, while the true product sits at 100 %. The corrected inference is now held within 0 to 100 %, the unclamped balance is logged as `met_raw_pct`, and the bias is computed on it.

3.5.2 Three PI Loops in the Velocity Form

The metallization loop, the temperature push and the pressure loop use the framework's velocity-form proportional-integral (PI) controller of Section 1.6.2 without derivative action, executed every Δt_c. In the symbols of Equations (1.13) to (1.16), this chapter writes the action a as σ, the output bias u_b as u_0 and the gain as K_c, and the tracking time T_t is τ_I. The metallization loop reads $\hat{M}_c$ and moves the ratio within 900 to 2600 $\mathrm{Nm^3/t}$ with $\sigma = +1$, reverse acting in the convention of Section 1.3 because more gas raises the metallization, $K_c = 10\,\mathrm{Nm^3/t}$ per point and $\tau_I = 3\,\mathrm{h}$. While the feed command has moved more than 3 t/h in the last 2 h it tracks the applied ratio instead of integrating, because the balance then reads the bed's transient. The push reads the measured margin $\Delta = T_{stick}(0.9) - T_{probe}$, the curve's metallized end less the burden thermocouple, and moves the heater setpoint within 800 to 1000 °C with $\sigma = -1$, direct acting because a hotter bustle closes the margin, $K_c = 0.5$ and $\tau_I = 0.5\,\mathrm{h}$, so it heats while the margin exceeds its setpoint. This is the constraint push that the spray dryer of Volume 5, Chapter 10 applies to its inlet temperature against a sticky margin. The push never reads

the curve at the soft sensor's value, which an early build did and which let a transient talk the push into sticking. The pressure loop moves the makeup within 0 to 6000 kmol/h with $\sigma = +1$, reverse acting, $K_c = 2000$ kmol/h per bar and $\tau_I = 0.25\,\mathrm{h}$. In Man each loop tracks its station, so Man to Auto is bumpless. The application also applies a station entry made since the last scan before the loop goes to Auto. In an earlier build without that rule, revealing the suggested settings in mid-run set the push to Auto and the bustle station to 935 °C in one instant, the push started from the old 900 °C, and the sample of hour 2 read 93.81 %. The mid-run failure was a lost station entry, not the bed. A grade feedforward, when switched on, scales the ratio by the pellet analysis over its value at the switch, so that the gas follows the iron fed.

3.5.3 The Turndown Override

When the buffer runs low, the supervisor caps either the pellet feed (priority Tons) or the gas ratio (priority Quality) with a low selector whose reset is fed back from the applied value, as shown in Equation (3.8).

$$\begin{aligned} \hat{B}_{+2h} &= B_m + \frac{2\,\mathrm{h}\,(\dot{H}_{el,m} - \dot{H}_{mu,m})}{B_{max}} \\ u_B &= \bar{u} + K_{c,B}\,\Delta u\,\big(\hat{B}_{+2h} - B_{SP}\big) \\ u &= \min(u_{req},\, u_B) \\ \bar{u}_k &= \bar{u}_{k-1} + \big(1 - \mathrm{e}^{-\Delta t_c/\tau_{I,B}}\big)\,(u_{applied} - \bar{u}_{k-1}) \end{aligned} \tag{3.8}$$

where Δu is the span of the capped station, 40 to 170 t/h or 900 to 2600 $\mathrm{Nm^3/t}$, $K_{c,B} = 1$, $\tau_{I,B} = 0.5\,\mathrm{h}$ and $B_{SP} = 40\,\%$ as shipped. The cap sits above the request while the projected buffer is above its setpoint, takes over at the request's value when it reaches it, integrates while selected and hands back when the buffer recovers. Nothing latches. The feed moves at most 30 t/h per hour whoever asks, and while the override holds the ratio the metallization loop tracks the applied value, so it does not wind up. The supervisor reads the measured imbalance projected two hours ahead and has no forecast.

3.5.4 The Optional Buffer MPC

The Advanced turndown method "MPC" replaces the override with a receding-horizon quadratic program on the framework's linear MPC (Section 1.6.3), as shown in Equation (3.9).

$$\begin{aligned} \min_{u}\ & -\sum_{k} u_k + 0.02 \sum_{j} \Delta u_j^2 + 2000\,\varepsilon^2 \\ & + 200\,\varepsilon \\ \text{s.t. } & B_{k+1} = B_k - T_s \hat{h}\, u_k + T_s\, \hat{w}_k \\ & B_{SP} B_{max} - \varepsilon \le B_k \le B_{max}, \qquad \varepsilon \ge 0 \\ & 40 \le u_k \le \dot{F}_{p,SP}, \qquad |\Delta u_j| \le 15\,\mathrm{t/h} \end{aligned} \tag{3.9}$$

where u is the pellet feed, B the buffer in tonnes of hydrogen, $T_s = 0.5\,\mathrm{h}$ over 48 steps in 12 move blocks, $\hat{w}_k = \min(P_{el,max}, f(t_k) P_{wind})/e_{el}$ the hydrogen the declared forecast promises, and $\hat{h}$ the makeup per tonne of pellets learned from the meters through a 1 h filter. The weights are those declared to the module. The electrolyzer capacity, wind farm, specific energy and buffer size in $\hat{w}_k$ and in the bounds are the shipped values, so a change to those parameters is model mismatch that the MPC meets in the measured buffer. The program is re-solved every half hour from the measured buffer and its first move caps the feed. It never sees the actual wind's deviation and it cuts only tons, while the metallization loop and the push hold the quality. "One plan" is the same program held to a single move block. The MPC therefore has information the override does not, the wind forecast, much as the scenario-tree program of Volume 9, Chapter 7 plans its releases on an ensemble rain forecast, and the comparison in Section 3.6 states that difference rather than credit it to the method. Over the challenge day the MPC and One plan made 48 solves without a failure.

Table 3.3 The Eight Cases and the Challenge

#	Case and events	Teaching point
1	Manual, raise the ratio after the start	two clocks
2	Manual, lot of 68.5 % Fe at 1 h	the residence
3	Auto, the same lot at 2 h, analysis still 67.5 %	soft sensor, laboratory
4	Auto, loop in Man, bustle by hand or the push	rate against sticking
5	Auto, lot at 1 h, feedforward off or on	measured grade
6	Auto, forecast day, buffer at 90 %, supervisor on	tons or quality, infeasible lull
7	Auto, compressor trip at 2 h for 0.5 h	pressure and bed
8	Manual, Map view, ratio changed at 0.25 h	the equilibrium wall
9	Challenge: 24 h on the forecast, lot at 3 h	the whole problem

Table 3.4 Measured Results, Default Seed. Metallization Is the True Product

Case and setting	Result
1, ratio 1690 → 1800	top gas in 3 min, product half in 6.73 h, 98.52 % at 30 h
1, soft sensor	half in 2.18 h, 99.01 against 96.61 % at 8 h
2, lot	DRI iron 50 % of its step at 5.92 h
3, correction on	low 93.37 % at 13.7 h, 94.44 % at 30 h, 10 of 16 short
3, correction off	92.55 % at 30 h and falling, 13 of 16 short
4, 965 °C by hand	sticking from 1.21 h, ΔP 0.99 → 1.17 bar
4, push at 15 / 5 K	935.4 / 945.1 °C, 99.41 / 99.86 %, no sticking
5, feedforward off / on	92.85 / 94.16 % at 24 h, ratio 1690 → 1715
6, Tons	1991 t, worst 94.53 %, buffer low 27.9 %
6, Quality	2518 t, worst 43.40 % (6 of 13), 42.6 kg/t
6, supervisor off	buffer dry at 15.7 h, worst 77.34 %
7, trip	3.69 bar, below 94 % from 2.33 to 9.33 h, low 86.74 %
8, ratio 1400	5 cells at the wall at 10.27 h, 67.71 % at 24 h
8, ratio 1000	no cell at the wall, 13.48 % at 24 h

The application keeps three models apart. The plant is the model of Section 3.3. The identified model is a learner's fit to case 1's step. The controllers' models are the residence filter, the declared holdup and pellet analysis inside the soft sensor, and the one-state buffer model of the MPC.

3.6 Nine Cases, Measured

The cases are listed in Table 3.3. Each value in this section is the shaft's own output under Node on seed 20261027, with five-second steps identical to the page's, a learner's change made after the run started where a row says so, and the challenge repeated on four further seeds. Loading a case first, picking it after another case and pressing Reset give the same nine runs, with Reset and the reload arrow as Section 1.6.4 describes them. The results are collected in Table 3.4.

> ✦ **DID YOU KNOW?** **Half an Hour Without Gas, Seven Hours Off Grade**
>
> From the simulator: in Table 3.4, a recycle compressor trip of half an hour at hour 2 leaves the product below 94 % from hour 2.33 to hour 9.33, with a low of 86.74 %. The burden kept moving while the bustle had no gas.

3.6.1 An Inferred Product and a Late Laboratory

The soft sensor is faster than the product because it reads the bed, not the discharge. In case 1 it makes half the product's move in 2.18 h against the product's 6.73 h. The first report it accepts after the step is from the sample of hour 8, drawn after six hours of steady burden, and the bias moves to −1.10 points at hour 8.5 and to −1.90 by hour 16.5, as the saw-tooth of Figure 3.3b shows. The gate's six hours are shorter than the product's 8.62 h to 63 %, so the bias absorbs part of the transient, and at hour 30 the soft sensor reads 97.81 % against a true 98.52 % with an analysis that is correct.

Pause. Try Exercise 3.1 before reading on.

Case 3 charges the same rich lot at hour 2 while the analysis still reads 67.5 %. The pellets then bring 1.5 % more oxygen than the balance counts, the soft sensor reads about two points high, and the metallization loop holds the ratio where the product slides. Without the correction the product falls to 92.55 % by hour 30 and is still falling, with 13 of 16 samples short. With it, the bias reaches −2.56 points, the loop raises the ratio from 1689 to 1730 Nm^3/t, and the product turns at 93.37 % at hour 13.7 and recovers to 94.44 % at hour 30, with 10 of 16 samples short. The correction is slow because each report describes the product of hours ago and the product answers the ratio over the residence. Case 5 shows the cheaper answer. A feedforward on the measured grade raises the ratio from 1690 to 1715 Nm^3/t at once and holds the product at 94.16 %, against 92.85 % at hour 24 without it. The ratio scaled by the iron alone leaves the product short because the bed holds a fixed amount of iron. The richer feed passes more iron through it, so each pellet spends less time under the gas. Raising the feed by the same share of iron, with no new lot, costs the same metallization.

3.6.2 Temperature, Sticking and a Trip

Hotter gas reduces faster and carries more heat. In case 4 a bustle set by hand to 965 °C at hour 1 lifts the product to 99.67 % by hour 5, but the metallized pellets at the bustle follow the gas within a quarter of an hour, sticking starts at hour 1.21, and the cluster index reaches 0.19 with the bed pressure drop rising from 0.99 to 1.17 bar by hour 10. The push in Auto at a 15 K margin settles the heater at 935.4 °C with the product at 99.41 % and no sticking, and at 5 K it reaches 945.1 °C. In every heating case the measured margin stayed within 10.3 K, 3.4 standard deviations of its thermocouple noise, of the true margin of the cell closest to the curve. Case 7 trips the recycle compressor for half an hour at hour 2. The top pressure rises to 3.69 bar at the relief, the bustle flow falls to nothing by hour 2.5, and the bed pressure drop from 0.98 to 0.04 bar. The burden keeps moving, so the product is below 94 % from hour 2.33 to hour 9.33 with a low of 86.74 % at hour 3.35, and three of the first six samples are short. A half-hour upset costs seven hours of off-specification iron.

3.6.3 The Wind, the Buffer and an Infeasible Lull

Case 6 runs the forecast day with the buffer starting at 90 %. With priority Tons the supervisor cuts the pellets from 140 to 40 t/h through the lull, the buffer bottoms at 27.9 % at hour 16.4, every sample stays at or above 94.53 % and the day makes 1991 t at 54.2 kg of makeup hydrogen per tonne. With priority Quality the tons stay, 2518 t at 42.6 kg/t, but the ratio falls to its 900 Nm^3/t floor and the worst sample is 43.40 % with 6 of 13 short. With the supervisor off the buffer runs dry at hour 15.7 and the worst sample is 77.34 %. A tonne of iron needs its oxygen removed, and hydrogen saved at the same tonnage is iron left unreduced.

> **TRY IT IN THE APP** **6 · The Electrolyzer Follows the Wind: Tons or Quality**
>
> Run the day with Scarce hydrogen costs at Tons and watch the pellet feed on the Gas loop view: it falls from 140 to 40 t/h through the lull, and every sample stays at or above 94.53 %. Then set it to Quality and press Reset. The day makes 2518 t instead of 1991 t, but the worst sample is 43.40 %.

The case also holds the honestly infeasible variant, full tons and every sample at 94 % through the six-hour lull with the shipped buffer. The oxygen alone needs 29.5 t of hydrogen over the lull at 140 t/h, while the buffer above its floor holds 24.0 t and the electrolyzer makes 4.2 t in the lull. The bed can shift some reduction around the lull, so the count is not a proof. A sweep of 24 constant settings of ratio, bustle temperature and a hand-set makeup station, and then of 960 schedules that pre-reduce the bed before the lull at up to 2600 Nm^3/t and 940 °C, starve it in the lull and repay it after, found none that kept both the buffer at 20 % and every sample at 94 %. The closest kept the buffer at 19.0 % with a sample at 80.85 %, and the best buffer with every sample at specification was 0.3 %.

Table 3.5 The Challenge Over 24 h on Five Seeds

Configuration	Pass	Tons	Worst (%)	Buffer low (%)
shipped	0/5	2443–2459	70.7–80.6	0
suggested	5/5	2085–2123	97.6	22.7–29.5
laboratory correction off	5/5	2083–2123	97.6	22.1–29.5
no push, 900 °C	0/5	2101–2145	88.7	15.6–22.2
no push, 140 t/h	0/5	1910–1962	94.3	30.2–36.6
fixed ratio 1690	5/5	2074–2111	98.7	20.4–27.5
supervisor off	0/5	2798–2817	54.5–61.5	0
priority Quality	0/5	2893–2912	25.1–32.8	13.0–20.0
override at 30 %	0/5	2183–2231	97.6	10.4–14.5
MPC at 30 %	5/5	2225–2297	97.6–97.8	33.8–36.0
One plan at 30 %	0/5	2159–2192	99.1	0–4.5
MPC at 50 %	5/5	2090–2160	97.9–98.0	53.9–56.8

LP bound with the forecast known and the design's 38.4 kg of hydrogen per tonne of pellets: 2417 t above a 20 % buffer, 2361 above 30 and 2248 above 50 %.

3.6.4 The Challenge

The challenge runs 24 h on the forecast with a richer lot at hour 3. It is met when the true metallization of every laboratory sample is at least 94 %, the true buffer never falls below 20 %, no cell rises above the sticking curve and the day makes at least 2050 t, with every parameter as shipped. Table 3.5 gives the configurations on five seeds. As shipped, with a fixed ratio of 1690 Nm^3/t, 900 °C, 140 t/h and the supervisor off, the day makes 2443 to 2459 t but runs the buffer dry at hour 15.7, and nine of 13 samples fall short. The suggested settings put the metallization loop in Auto at 95.5 %, set the bustle station to 935 °C and the push in Auto, raise the feed to 160 t/h and turn the supervisor on at Tons from 50 % with a gain of 3. They pass on five of five seeds with 2085 to 2123 t, a worst sample of 97.6 % and the buffer bottoming at 22.7 to 29.5 %. Revealed in mid-run at hour 0.75 they still meet the target with 2082.6 t, and at hour 3 they miss it on tons with 2048.4 t.

The table separates what the day needs from what it does not. The hotter bustle is what lets the compressor carry 160 t/h. Without the push the same feed leaves six or seven samples short at 88.7 %, and at 140 t/h the day falls short of the tons. The metallization loop and the laboratory correction are not needed, since a fixed ratio of 1690 Nm^3/t passes with 56.65 kg of hydrogen per tonne against 55.2 kg/t, so the loop's value on this day is the hydrogen it saves. The MPC plans the feed on the wind forecast, which the override does not have. At the suggested 50 % setpoint it makes 2129 t on the default seed against the override's 2096 t, and with the setpoint at 30 % it makes 2225 to 2297 t with the buffer at 33.8 % or more, where the override lets it fall to 10.4 to 14.5 % and One plan, with the same forecast, to 0 to 4.5 %. The advantage over the override is information, while the advantage over One plan is the freedom to shape the feed. A linear program that knows the forecast and holds the design's hydrogen per tonne bounds the day at 2361 t above a 30 % buffer, so the MPC at that floor leaves 64 to 136 t unmade. Figure 3.4 draws the table's ranges against the three limits of the challenge.

3.6.5 Verification Against the Ledgers and the Literature

The ledgers test the code and the literature tests the numbers, and the two are reported separately. On the code side, over a disturbed 12 h run with a trip, a ratio step, a temperature step and a lot, the oxygen fed less the oxygen discharged, the oxygen removed by the gas and the change of inventory closes to 3.8×10^{-9} of the oxygen removed, the buffer to 10^{-9} kmol, and the solids energy to below 5×10^{-10} of the reaction heat in three disturbed runs. Over 1.85 million reducing cell-steps no cell's gas passed its wüstite wall, the largest excursion being 1.1×10^{-16}. The design point was reproduced by hand in every printed digit. The suite of the application passes 45 of 45 checks and 10 of 10 completion checks. Against the literature, the agreement is of order only. The design carries 3.85 times the hydrogen on the pure-hydrogen study's basis against its 3.75 [15], a top gas 56 K hotter

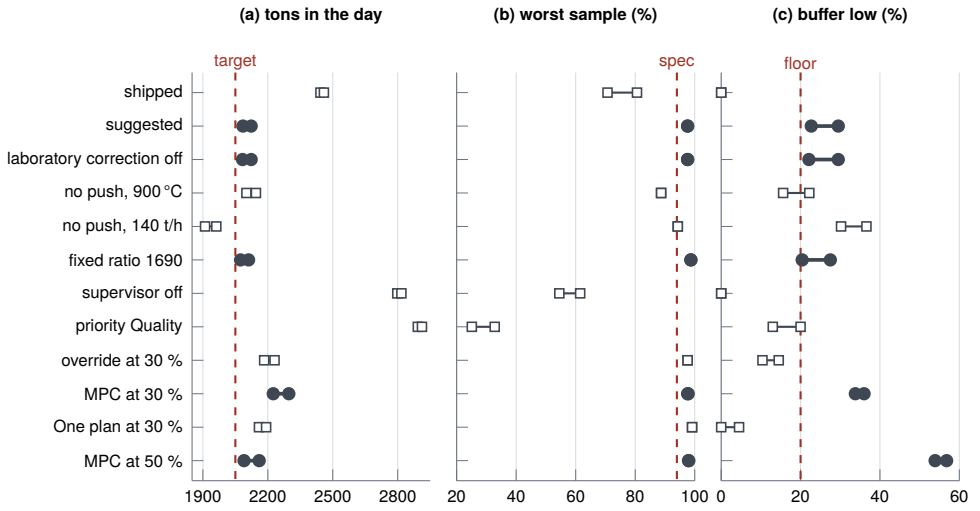


Figure 3.4 The challenge of Table 3.5 redrawn: for each configuration, the range over five seeds of (a) the tons made in the day, (b) the worst laboratory sample and (c) the lowest buffer, against the 2050 t target, the 94 % specification and the 20 % floor (dashed). Filled circles passed on five of five seeds, open squares on none. Notice that the settings that make the most tons fail on quality or on the buffer, that removing the push fails in both of its rows, and that at a 30 % setpoint the MPC keeps the buffer at 33.8 % or more where the override lets it fall to 10.4 %.

than its adiabatic balance, and 52.2 kg of hydrogen consumed per tonne of iron against 54 kg for full reduction [1]. A pellet reaching 95 % in 2.29 h matches the order of a zone a few meters tall in the pure-hydrogen simulations [6], but the rate constants were chosen, not fitted.

The shaft's product is the charge of the arc furnace application of Chapter 5, which declared its DRI before this model existed. The arc furnace declares 94 % metallization, no carbon, 92 % total iron, 4.5 % gangue and a cold charge at 25 °C, with about 600 °C for a hot charge. At design this shaft makes 94.5 %, no carbon, 93.7 % total iron and 4.85 % gangue at 899 °C. It matches in metallization and carbon, and because the model has no cooling zone its product would need to be cooled or charged hot. Neither application reads the other.

3.7 Technology in Practice

Figure 3.6 draws the loops of Section 3.5 with their hardware.

What Measures It

The product's metallization has no on-line instrument in this model. It is inferred from the top gas and checked by the laboratory. The model's top-gas analyzer, a lag of two minutes with 0.05 points of noise, stands for an on-line analyzer of hydrogen and steam. One common family of such analyzers, the process gas chromatograph, injects a measured sample into a column at intervals and tells the species apart by the time each takes to leave it, so it answers once per analysis [19]. The model's laboratory, a spot sample every two hours reported half an hour late with 0.3 points of noise, stands for an assay of the kind described below.

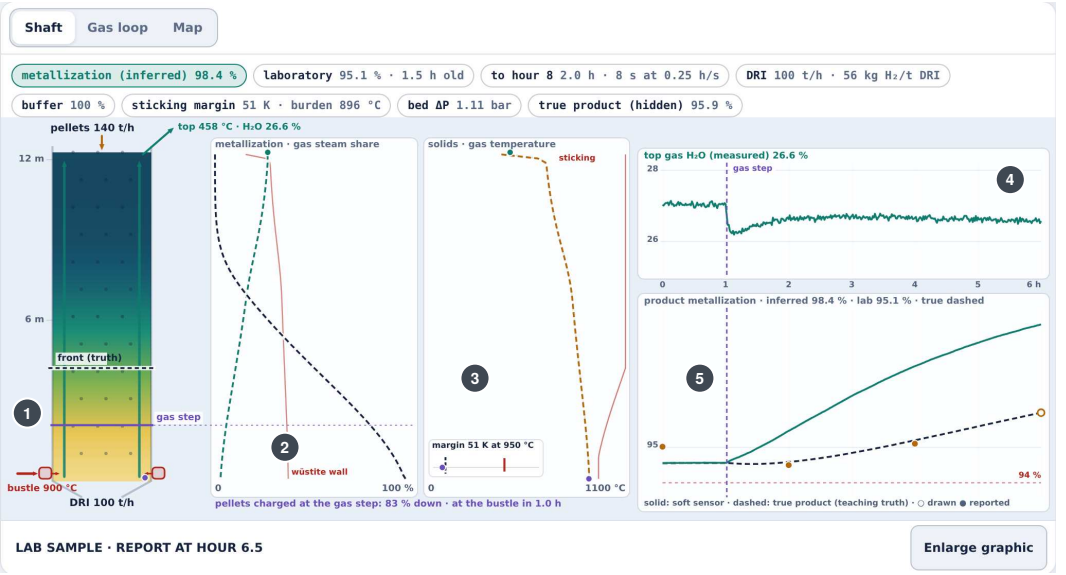


Figure 3.5 Case 1 at hour 6, five hours after the gas ratio was raised from 1690 to 1800 Nm^3/t on the Shaft view in Manual, cropped to the plant view. The bed is shaded by metallization with the reduction front marked as teaching truth and the pellets charged at the step drawn 83 % of the way down, one hour from the bustle (1). Beside it, the gas's steam share against the wüstite wall (2) and the temperatures against the sticking curve with a 51 K margin at the burden thermocouple's 896 °C (3). The top-gas plot has stepped to 26.6 % at the marker (4), while the product plot shows the soft sensor at 98.4 %, the true product at 95.9 % (dashed) and the laboratory's 95.1 % from the sample of hour 4 (5).

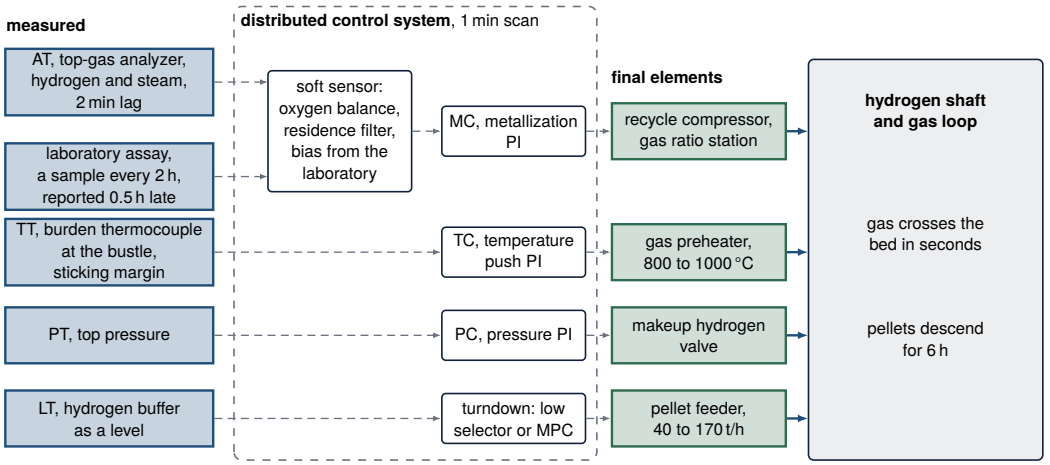


Figure 3.6 The loops of the simulated shaft drawn with their hardware. The metallization controller MC reads the soft sensor, which balances the oxygen on the top-gas analysis and takes its bias from the late laboratory assay, and sets the gas ratio that the recycle compressor delivers. The push TC holds the sticking margin on the gas preheater, PC holds the top pressure on the makeup hydrogen, and the turndown caps the pellet feed (or, at priority Quality, the gas ratio) when the buffer runs low.

TECHNOLOGY Sensor: The Laboratory Assay of Metallization

At the first pilot shaft in the United States run on hydrogen, pellet samples were discharged into sealed metal bins after cooling to room temperature in nitrogen. A sample of one kilogram was crushed and pulverized, and 100 mg of the powder was analyzed, the metallic iron by an iron(III) chloride titration under ISO 16878 and the total iron by a titanium(III) chloride titration under ISO 2597-2. Metallization is the moles of metallic iron over the moles of all the iron in the product [10]. Such an assay describes the pellets that left at the hour of sampling, and it reaches the control room only after the sample has been cooled, ground and titrated.

What Moves It

In the model the compressor delivers the requested bustle gas up to its capacity, the heater and the feeder follow their commands through lags of 0.1 h, and the makeup hydrogen closes the pressure.

TECHNOLOGY Final Element: The Recycle Compressor and the Gas Preheater

In the same pilot, the top gas of hydrogen and steam passed a filter for dust and fines and a condenser for its moisture, a compressor returned the remaining hydrogen to the feed, and excess hydrogen was burned in a thermal oxidizer. A preheater brought the gas to its inlet temperature before a bustle fed it into the shaft. A recycle of 400 liters a minute with 870 °C of external heating gave 91.8 % average metallization, against 67.8 % at 100 liters a minute and 850 °C [10]. A centrifugal compressor surges, violently and possibly destructively, when its flow falls too low against too high a pressure difference, and a recycle valve from discharge to suction prevents it [19].

Where the Controller Runs

Control loops in a plant are often nested or cascaded, with cycle times from milliseconds to minutes, and a distributed control system uses a supervisory loop to mediate a group of localized controllers [20]. In the application the plant is integrated every five seconds and the controllers execute every minute. On such a platform the metallization loop, the temperature push and the pressure loop are PI function blocks of the regulatory layer, the soft sensor is a calculation block whose bias is moved by each accepted laboratory report, and the turndown is a low selector with its reset fed back from the applied value. The buffer MPC, re-solved every half hour on the wind forecast, sits in the supervisory layer and writes a cap on the pellet feed.

IN PRACTICE Keeping a Soft Sensor Honest in Service

A soft sensor in service must be maintained and tuned regularly, because drifts of the process and of its instruments make its performance deteriorate. Most soft sensors have no automated maintenance, so their quality control is manual and a significant cost, and whether a model still works is often judged by an operator's visual comparison of its predictions with the target values. A drift of an instrument calls for recalibration or adaptation of the soft sensor, not for action on the process. Laboratory values arrive far less often than the automatic measurements, and where material takes time to pass through a process, measurements taken at the same moment in different places must be synchronized by that delay [8].

What Is Modernizing It

The first development is the pilot shaft run on hydrogen. A finite element model of the first such pilot in the United States predicted its average metallization and its internal temperatures, and was used extensively in commissioning the pilot and in predicting its startup for given operating parameters [10]. The second is the detailed model of the industrial shaft. A two-dimensional model of the reduction zone with a pellet-scale kinetic model shows that complete metallization can be reached with hydrogen in a reactor smaller than the shafts that now run on gas made from natural gas [1].

3.8 Limitations

The model is a reduction zone without a transition or cooling zone, so its DRI leaves at 899 °C and cannot be compared with a cold product without a model the application does not have. The kinetics are teaching values with a chemical-control shape, the bed is one-dimensional with uniform pellets, and the walls lose no heat, so profiles are plausible rather than predicted for a particular shaft. The bustle composition is declared, which puts the makeup 3 % above an exact species balance. The sticking curve's level has a laboratory source but its shape does not, and the cluster index and the pressure-drop law are teaching relations.

The soft sensor's residence filter is first order while the bed is close to plug flow, and its six-hour gate admits reports before the product has caught up, which leaves a 0.7-point error after case 1's step with a correct analysis. The MPC models only the buffer and plans on a forecast whose error it never sees, the override has no forecast at all, and the electrolyzer has no minimum load. Every limit of the scorecard is a teaching value, and passing a case in simulation qualifies no real plant's controls.

OPEN CHALLENGE **Running a Shaft on Wind Hydrogen**

A steelworks usually asks for hydrogen at a constant rate, while wind and sun deliver power intermittently, and storage must turn the one into the other. Alkaline electrolyzers, the most mature type, must run between 20 and 100 % of their rated power, which limits how closely they can follow the wind [16]. One pilot program designs its shaft to run on hydrogen or on a mixture with natural gas, so that production continues when hydrogen is short [10]. Progress would be a shaft, buffer and electrolyzer run as one plant.

3.9 Conclusion

A hydrogen shaft furnace is a plant whose quality is inferred, delayed and fed from a variable supply, and the simulator of this chapter logs the inference, the laboratory and the true product side by side on a moving bed whose ledgers close to 10^{-9}. Raising the gas moves the top gas within three minutes and the product half its way only after 6.73 h, while the soft sensor gets there in 2.18 h and overstates the product by 2.4 points at hour 8. The heat the hydrogen must carry, not the 36.9 % wüstite ceiling, sets a design flow of four times the hydrogen consumed and a 27.0 % top gas. A laboratory correction recovers a wrong pellet analysis over a day, a temperature push buys rate up to a sticking margin, and a six-hour lull with the shipped buffer cannot keep both full tons and full quality on any of 984 settings and schedules. On the challenge day the suggested settings pass on five of five seeds, and a forecast-based MPC adds tons because it knows the wind. The model omits the cooling zone, carbon and a computed loop composition. A fuller model would add a cooling zone that delivers a cold product, a soft sensor with an inventory state of the bed, measured kinetics and an electrolyzer with a minimum load. The shaft is a compact case for learning that the measurement a controller trusts may describe the plant now while the product describes the plant six hours ago.

KEY POINTS

- The gas crosses the shaft in seconds and the iron takes six hours, so the top gas answers within minutes and the product over hours.
- The soft sensor reads the whole bed, not the discharge, and overstates the product by 2.4 points at hour 8.
- The heat the hydrogen must carry, not the 36.9 % wüstite ceiling, sets a design flow of four times the hydrogen consumed.
- Through a six-hour lull the shipped buffer cannot keep both full tons and full quality.

Where else this applies. Volume 5, Chapter 4 grades a charge that descends for hours, and Volume 5, Chapter 10 corrects a soft sensor against late samples.

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3.10 Exercises

3.1 Concept check · 2 min

In case 1 the gas ratio is raised from 1690 to 1800 $\mathrm{Nm^3/t}$ at hour 1. At hour 8 the corrected soft sensor reads 99.0 % while the true product is 96.6 %. Why does the soft sensor run ahead of the product?

(a) The top-gas analyzer's two-minute lag lets the balance overshoot its final value
(b) The first laboratory reports after the step have raised the bias by 2.4 points
(c) The soft sensor's residence filter is set shorter than the residence of the bed
(d) The balance counts the oxygen the whole bed loses now, not that of the pellets leaving

3.2 Concept check · 1 min

At the design point the top gas leaves with 27.0 % steam against a wüstite ceiling of 36.9 %. What sets the bustle flow at about four times the hydrogen the reduction consumes?

(a) The heat the hydrogen must carry to warm the pellets and drive an endothermic reduction
(b) The wüstite equilibrium, which the top gas would cross at any lower flow
(c) The recycle compressor, whose capacity caps the ratio at the design value
(d) The purge, which removes two percent of the loop gas on every pass

3.3 Concept check · 2 min

The laboratory correction uses a report only if the gas ratio and the feed stayed within 3 % and 3 t/h over the 6 h before the sample was drawn. What is this gate for?

(a) The laboratory's 0.3 points of noise grow too large while the bed is moving
(b) A balance read in a transient counts oxygen the bed stores or releases as a model error
(c) The metallization loop tracks the applied ratio during a feed move and cannot use a new bias
(d) Reports of samples drawn during a transient arrive later than the usual half hour

3.4 Theory and calculation · 6 min

The shaft holds $n_{Fe} = 10\,153$ kmol of iron and is fed 140 t/h of pellets. Take $M_{Fe} = 55.845\,\mathrm{kg/kmol}$.

(a) Compute the iron fed, $\dot{F}_{Fe}$, at 67.5 % Fe and the residence $n_{Fe}/\dot{F}_{Fe}$. *Checkpoint:* 1692.2 kmol/h; 6.000 h.

(b) The lot of cases 2 and 5 carries 68.5 % Fe at the same 140 t/h. Compute the new iron feed and residence, and the change of the residence in percent. *Checkpoint:* 1717.3 kmol/h; 5.912 h, 1.5 % shorter.

(c) The grade feedforward scales the ratio by the analysis. Compute the new ratio from 1690 $\mathrm{Nm^3/t}$, and the pellet feed, to the nearest 1 t/h, that would bring the iron fed back to its design value. *Checkpoint:* 1715 $\mathrm{Nm^3/t}$; 138 t/h.

3.5 Theory and calculation · 6 min

The wüstite step has $K_2 = \mathrm{e}^{A_2 - B_2/T}$ with $A_2 = 1.0836$ and $B_2 = 1899$ K, and the steam share of the reducing gas over wüstite cannot exceed $s_{eq} = K_2/(1+K_2)$.

(a) Compute K_2 and s_{eq} at 800 and 900 °C. Give s_{eq} to ± 0.1 points. *Checkpoint:* 0.504 and 33.5 %; 0.586 and 36.9 %.

(b) The bustle gas is 95 % reducing with $x_W = 0.025$, so the steam share of its reducing gas is $x_W/0.95$. Each mole of reducing gas that leaves at a steam share s_{top} has taken $s_{top} - x_W/0.95$ moles of oxygen. Compute the moles of reducing gas, and of hydrogen, per mole of oxygen at the design top gas of 27.04 %. *Checkpoint:* 4.10 and 3.99.

(c) Repeat (b) with the top gas at the 900 °C ceiling, and say how many times that minimum the design carries. *Checkpoint:* 2.92 and 2.84; about 1.4 times.

3.6 Theory and calculation · 7 min

Case 6 asks whether the shaft can keep 140 t/h and 94 % through the six-hour lull. Use $\dot{F}_{Fe} = 1692.2$ kmol/h, hematite at 1.5 oxygen per iron, a product at $m = 0.94$ whose remaining oxygen is wüstite, $M_{H_2} = 2.016\,\mathrm{kg/kmol}$, the 30 t buffer with its 20 % floor, the 600 MW wind farm at a capacity factor of 0.06 through the lull and $e_{el} = 52\,\mathrm{kWh/kg}$.

(a) Compute the hydrogen consumed by the oxygen alone over the six hours. *Checkpoint:* 29.5 t.

(b) Compute the hydrogen the buffer can give above its floor and what the electrolyzer makes in the lull, and the shortfall. *Checkpoint:* 24.0 t and 4.2 t; 1.3 t short.

(c) At what constant pellet feed would this count balance? Say why the count alone does not prove the lull feasible or infeasible. *Checkpoint:* about 134 t/h.

3.7 App challenge · 8 min

Load scenario 1, "Raise the gas: the top answers now, the product later," at the default seed in Manual. Run at 0.1 h/s and press Pause when the clock reads 1.0 h (anywhere from 0.95 to 1.05 h). Set Gas ratio to 1800 $\mathrm{Nm^3/t}$, press Run again and let the case pause itself at hour 8. Export the CSV file and read the rows against `Time (h)`. Give metallizations to ±0.1 points.

(a) From `top_h2o_pct`, give the average steam share of the top gas over the half hour before the step and over the half hour after it, each to ±0.1 points. *Checkpoint:* about 27.0 %, then about 26.3 %.

(b) At 8.0 h, read the corrected soft sensor `met_inf_pct` and the true product `truth_met_pct`. *Checkpoint:* 99.0 % and 96.6 %.

(c) The product lines out at 98.52 % from 94.54 %. What share of that move has each reading made at hour 8? *Checkpoint:* about 0.52 and 1.12.

3.8 App challenge · 8 min

Load scenario 3, "The soft sensor against the laboratory," at the default seed with no changes, so the header is in Auto and Laboratory correction is On. Run at 1 h/s until the case pauses at hour 30. Then switch Laboratory correction Off, press Reset and run again to hour 30. Read the scorecard's DRI tile after each run, and the CSV columns `truth_met_pct`, `met_bias_pts` and `ratio_applied` at 30.0 h. Give metallizations to ±0.1 points and the ratio to ±2 $\mathrm{Nm^3/t}$.

(a) With the correction on: the true product, the bias and the applied ratio at hour 30, and the samples below 94 % on the tile. *Checkpoint:* 94.4 %, −2.56 points, 1730 $\mathrm{Nm^3/t}$; 10 of 16.

(b) With it off: the true product at hour 30 and the samples below 94 %. *Checkpoint:* 92.6 %; 13 of 16.

(c) Explain why the correction recovers the product so slowly, and name a cheaper remedy the chapter offers for a known change of the pellets. *Checkpoint:* each report describes the product of hours ago; the grade feedforward of case 5.

3.9 App challenge · 9 min

Load the challenge, "a day on the wind forecast," at the default seed. Run at 1 h/s. The day pauses at hour 24 with the verdict held on the Challenge target tile. Report tons to ±2 t, the worst sample to ±0.1 points and the buffer low to ±1 %.

(a) Run as shipped. Read the tons, the worst sample, the samples below 94 % and the buffer low. *Checkpoint:* 2452 t, 74.6 %, 9 of 13, 0 %.

(b) Reveal the suggested settings, press Reset and run the day again. Read the same four values and the verdict. *Checkpoint:* 2096 t, 97.6 %, 0 of 13, 28 %; met.

(c) Keep the suggested settings, set Turndown method to MPC in the Advanced settings of the production card, press Reset and run again. Read the tons and the buffer low, and explain where the extra tons come from. *Checkpoint:* 2128 t, 56 %; the MPC plans the feed on the wind forecast.

3.10 Application area · 3 min

Case 7 trips the recycle compressor for half an hour, and the product stays below 94 % from hour 2.33 to hour 9.33 while the burden keeps moving.

(a) At the design DRI rate of 100.87 t/h, about how much off-specification iron does the trip cost? *Checkpoint:* about 706 t.

(b) The feed may move at most 30 t/h per hour. How long would cutting it from 140 to 40 t/h take, and what do plants do instead when the gas is lost? *Checkpoint:* 3.3 h; they stop the burden.

3.11 Application area · 4 min

The model has no cooling zone, so its DRI leaves at 899 °C. The arc furnace of Chapter 5 declares a cold charge at 25 °C, with about 600 °C for a hot charge. Use the model's solids heat capacity, 65 kJ per kmol of iron per kelvin, and the product's 93.69 % total iron.

(a) How much heat per tonne of DRI must a cooling zone remove to deliver a cold charge? *Checkpoint:* about 953 MJ/t.

(b) How much of it would a hot charge at 600 °C keep, and why might a plant still cool the product? *Checkpoint:* about 627 MJ/t kept; storage and handling.

3.12 Review the agent · 5 min

An AI assistant reviewing the design writes: "The top gas leaves at 27.0 % steam, but the wüstite ceiling at 900 °C is 36.9 %. A quarter of the hydrogen does no work. Cut the gas ratio by the same share, from 1690 to 1235 Nm^3/t. The top gas will then run at the ceiling, the metallization will hold and the plant will save about 27 % of its hydrogen." Find the flaw, and say how you would check it in the app.