INTERACTIVE CONTROL ENGINEERING
Principles and Applications

Volume 16 Control in Iron, Steel, and Metals Production

CHAPTER 2

Iron Blast Furnace Simulator for Mid-Ranging Coal and Coke on a Sampled Hearth

Pages 23–47

Edited by John D. Hedengren

How to cite this chapter. "Iron Blast Furnace Simulator for Mid-Ranging Coal and Coke on a Sampled Hearth," in *Control in Iron, Steel, and Metals Production*, John D. Hedengren, Ed., vol. 16 of *Interactive Control Engineering: Principles and Applications*. Advanced Process Solutions, LLC, 2026, ch. 2, pp. 23–47.

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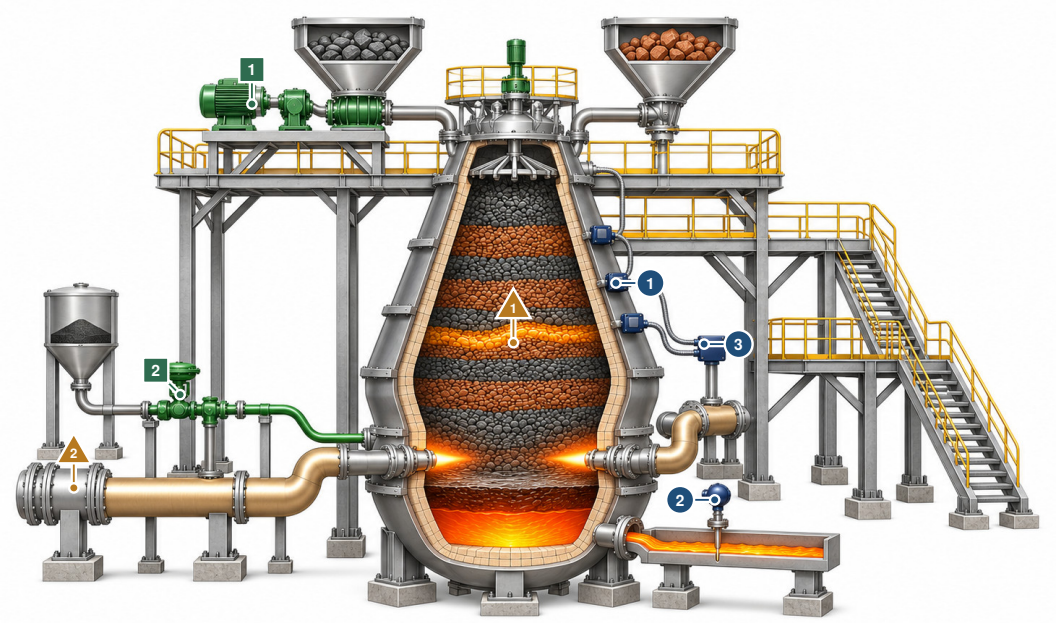
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CHAPTER 2

Iron Blast Furnace Simulator for Mid-Ranging Coal and Coke on a Sampled Hearth



The controller moves 1 coke rate, charged at the top 2 coal injected at the tuyeres

The controller reads 1 wall stave heat, feeding the thermal index 2 temperature dip and sample at each cast 3 hot blast temperature

What disturbs it 1 harder ore in the burden 2 a hot stove fault that cools the blast

Notice that the coal enters just above the hearth while the coke must ride the layers down from the top, and that the hearth is read only at the runner when the furnace is cast. Illustration, not to scale.

IN PLAIN TERMS **Two Fuels That Arrive at Different Times**

The main idea. A blast furnace melts iron ore with burning coke. The liquid iron collects in a pool at the bottom called the hearth. Its temperature is checked only when the furnace is drained, about every two hours.

The challenge. Coal blown in near the bottom acts within hours but first cools the hearth a little. Coke added at the top takes five hours to arrive. The controller makes quick fixes with coal, hands lasting changes to coke, and checks any estimate it uses in between against each reading.

Why it matters. A hearth that runs cold drains poorly and can freeze, and one that runs hot wastes costly coke.

THREE WAYS TO READ THIS CHAPTER

⊘	**Explore**	12 min	The first page, the fact box of Section 2.1, the two history boxes of Section 2.2, the try-it boxes and the fact box of Section 2.5, and the key points
🕮	**Study**	50 min	The whole chapter with its pause points and the twelve exercises
⛰	**Practice**	20 min	The first page, Section 2.5, Section 2.6, Section 2.7 and the open challenge in it

The control question A blast furnace hearth is dipped once a cast and answers coal within the hour but coke only after five hours of burden descent. How should the coal loop be tuned for the cast, kept honest by a drifting soft sensor and relieved by the coke when the coal runs out of room?

Learning objectives

- Derive the net gain and inverse response of the coal path and the worth of coal against coke.
- Tune the coal loop by SIMC with the dead time a held cast adds.
- Compute the lag of a soft sensor's bias update against a drift.
- Decide from the capacity balance when the coal saturates and where mid-ranging on coke settles.
- Compare mid-ranging with a predictive controller that plans the coke on its delay.

Prerequisites Sections 1.4.3 (two actuators on two clocks), 1.6.2 (velocity form and loop action), 1.4.4 (the EWMA lag) and 1.4.6 (soft sensors). Section 1.6.3 only for the predictive controller.

The app https://apmonitor.com/apps/blast-furnace/

See also Volume 4, Chapter 10 and Volume 4, Chapter 9 for mid-ranging and valve-position control. Volume 5, Chapter 3 for a loop tuned through a slow analyzer, Volume 5, Chapter 10 and Volume 5, Chapter 4 for inferred qualities corrected by late samples.

2.1 Introduction

The loops in a first control course have one actuator and a measurement that arrives continuously. Many industrial loops have neither. A fast actuator with a narrow range often works beside a slow actuator with a wide one, and the standard way to coordinate them, mid-ranging or valve position control, returns the fast actuator to the middle of its range while the slow one carries the sustained load [1, 2]. Quality variables are often known only from laboratory samples, and continuous inferential estimates stand in between the samples on the condition that they are corrected against them [3, 4].

The iron blast furnace combines both problems in one loop. The thermal state of its hearth, the hot metal temperature and the silicon content that follows it, is measured when the furnace is tapped, and the prediction of silicon from routine process data has a literature of its own because the sample arrives so seldom [5]. Coal injected at the tuyeres changes the heat supply within hours, but it first lowers the raceway flame temperature [6], while coke reaches the hearth only after the burden has descended from the top. Coal is the cheaper fuel, and raising the injection rate toward what the raceway can burn has long been an aim of furnace operation [7]. The steel industry's carbon dioxide emissions also make each kilogram of coke per tonne a matter of policy as well as cost [8].

DID YOU KNOW? 1.3 Billion Tonnes of Pig Iron

The world made an estimated 1.3 billion metric tons of pig iron in 2024, beside 1.9 billion tons of raw steel [9]. A furnace blown in in 1974, with a hearth 9.6 m across, made 3800 t of pig iron a day [10]. The simulated furnace of this chapter makes 10 000 t.

The cases of this chapter are built around three misconceptions. The first is that a loop can be tuned without regard to how often it sees the plant, when a correction held for two hours adds about an hour of dead time [11]. The second is that integral action removes any offset, when an actuator on its limit leaves the loop open. The third treats a soft sensor as though it were a measurement, when it is a model whose error grows until something checks it. The class of problem is general. Any plant with a cheap, fast and bounded input beside an expensive, slow and wide one, such as a trim valve beside a large valve, a letdown beside a boiler, or a fine reagent valve beside a coarse one, needs the same division of labor, and the saturation and windup that follow when it is missing have been studied in their own right [12, 13]. Volume 4, Chapter 9 returns a cooling load to an absorption chiller with a valve-position controller, and Volume 4, Chapter 10 adds a mid-ranging layer above a fast turbine bypass and a slow firing rate.

This chapter works with a blast furnace thermal simulator in which the coal loop can run on cast dips or on a soft sensor, the soft sensor can be corrected or left to drift, and a mid-ranging loop on coke can be switched in, with each choice priced in hearth temperature and fuel cost. Sampled PI control, bias updating and mid-ranging are established methods, and so is the model predictive controller (MPC) that the application also offers, which plans both fuels over a twelve-hour horizon in the receding-horizon manner of industrial practice [14]. What is particular to this plant is the thermal model of the hearth, with an inverse response on the coal path and a burden-descent delay on the coke path, written out completely enough to be rebuilt. The scenarios first isolate the measurement problem and the actuator problem and then pose them together. Section 2.2 traces the history of furnace thermal control and Section 2.3 gives the model. Section 2.4 describes the coal loop, the mid-ranging loop on coke and the MPC. Section 2.5 reports the measured results case by case, from the two response times through the sampled loop, the soft sensor, saturation and mid-ranging, the coal target and a stove fault to the graded challenge and the comparison with the MPC in Section 2.5.7. Section 2.6 sets the loops in their hardware, Section 2.7 states the limitations, Section 2.8 concludes, and Section 2.9 holds the exercises.

2.2 Thermal Control of the Iron Blast Furnace

A blast furnace is a countercurrent shaft reactor. Coke and iron ore are charged in alternating layers at the top, hot air is blown in at the tuyeres near the bottom, and the gas from the burning coke rises through the burden, reducing and melting the ore on its way. Liquid iron and slag collect in the hearth and are drained through a taphole at intervals, and every drainage is a cast. The phenomena inside the shaft, from burden descent and gas flow to heat exchange and reduction, have been the subject of mathematical models of increasing detail for several decades [15].

Operators judge the furnace by its thermal level. A hearth that runs cold drains poorly and in the extreme chills, and a hearth that runs hot wastes coke and raises the silicon in the iron. Because the thermal level is known directly only from the temperature and silicon of each cast, the historical practice was to read the recent casts, compare them with experience, and adjust the fuel rate, the blast temperature or the blast moisture. Expert systems that encoded that practice were applied to furnace operation by the late 1980s, with rules that diagnosed the thermal trend and proposed actions [16]. Statistical and neural predictors followed, trained on routine process data to forecast the silicon or the hot metal temperature of the next casts [17, 18], and the data-driven silicon models have been reviewed in detail, including the long and variable delays between the inputs and the cast [5].

> ⧖ HISTORY **The Hearth Under Computer Control (1975 to 1977)**
>
> In the 1970s one furnace that held its hot metal temperature by the rate of injected heavy oil put that rate under a computer. Its model was updated against the measured top gas composition and hot metal temperature, predicted the temperature ahead by simulating the furnace forward, and moved the oil by an integral law on the predicted error. Automatic control began in November 1977. Over a week of 78 casts, 92 % of the temperatures fell within 15 °C of the aim, against about 70 % by hand, and the steadier furnace was run 15 °C cooler, which cut the fuel rate by about 4 kg per tonne [10].

Tuyere injection changed the actuator set. Pulverized coal blown in with the hot blast replaces part of the coke as a fuel and reductant, and its combustion in the short residence time of the raceway was studied extensively as injection rates rose [7]. Injected coal lowers the raceway flame temperature, which is why a step in coal first cools the lower furnace before its extra reducing gas warms the hearth [6]. With coal at the tuyeres and coke at the top, the furnace acquired exactly the pair of actuators that mid-ranging is designed for. Mid-ranging structures were analyzed as a design problem [1], tuning rules for the valve position loop were developed and applied industrially [2], anti-windup was added for the case in which the fast actuator saturates before the slow one has taken over [12], and a feedforward formulation has since been proposed [13].

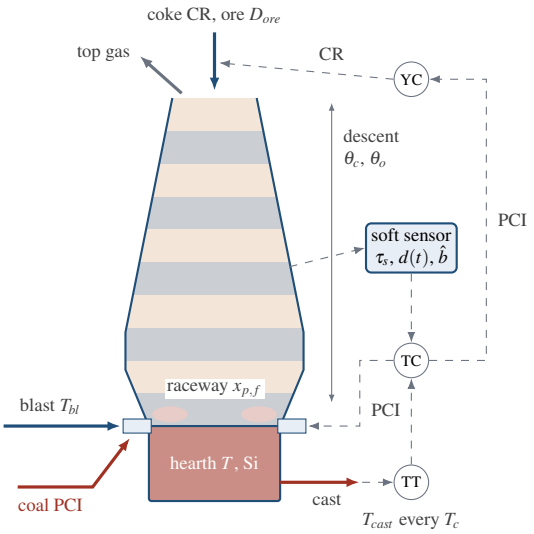


Figure 2.1 Iron blast furnace and its thermal control loops. Coke at rate CR and ore of thermal demand D_{ore} are charged at the top and reach the tuyeres after the burden descent times θ_c and θ_o. Hot blast at T_{bl} and pulverized coal at rate PCI enter at the tuyeres, where the coal first cools the raceway ($x_{p,f}$). The hearth temperature T and silicon are dipped at every cast, once every T_c, by TT, and a soft sensor built from stave heat loads lags the hearth by τ_s, drifts by $d(t)$ and is corrected by the bias estimate $\hat{b}$. The controller TC sets the coal rate and the mid-ranging controller YC moves the coke rate to return the coal to its target.

> ⧖ HISTORY **Fuel at the Tuyeres (1840 to the 1980s)**
>
> Fuel injection through blast furnace tuyeres dates back to coal experiments in France in 1840. Trials in the United Kingdom in 1962 blew coarsely ground coal in pneumatically at up to 360 pounds per ton of hot metal, and the coal replaced coke about pound for pound, but the trials stopped when oil became cheaper [19]. Oil had been the preferred injectant in the 1950s. When fuel oil grew scarce and costly around 1979, coal was taken up again, and injection spread quickly in Europe and Japan during the 1980s [20]. A demonstration proposed in the United States in 1990 fed each of 28 tuyeres per furnace from pressurized storage through metering equipment [19].

The soft sensor has its own lineage. Inferential control, in which a secondary measurement estimates an unmeasured output for use in feedback, was formalized in the late 1970s [3]. Data-driven soft sensors are now common in the process industries, and the review literature treats their drift as a maintenance problem, answered by adaptation mechanisms of which the simplest is a bias update against each laboratory result [4, 21]. Volume 5, Chapter 10 keeps a psychrometric soft sensor in service the same way, against a sampled and delayed laboratory moisture.

2.3 Process Model

The simulated furnace makes 10 000 tHM/d of hot metal on 350 kg/tHM of coke and 150 kg/tHM of injected coal with a 1180 °C blast. At these base rates the hearth sits at 1500 °C with 0.45 % silicon, and at $400 per tonne of coke and $150 per tonne of coal the fuel costs $162.5 per tonne of hot metal, or $1.625 million a day. The furnace and its two loops are drawn in Figure 2.1.

Table 2.1 lists the variables. The model integrates five thermal states, one for coke, two for coal, one for the blast and one for the burden, together with three accumulators for the fuel cost and the tonnes of coke and coal consumed. Every thermal state is a deviation from the base operation and

Table 2.1 Variables, Their Roles and Ranges Around the Base Operation

Symbol	Role	Base	Range
T	CV, hot metal temperature	1500 °C	SP 1460–1540
Si	hot metal silicon	0.45 %	≥ 0.05
T_{cast}	measured, cast dip	1500 °C	held 1 cast
$\hat{T}_s$	measured, soft sensor	1500 °C	—
PCI	MV, coal injection	150 kg/tHM	80–200
CR	MV, coke rate	350 kg/tHM	300–420
x_c, $x_{p,f}$, $x_{p,s}$, x_b, x_o	states, thermal	0	—
D_{ore}	DV, burden demand	0 °C	−90 to 30
T_{bl}	DV, blast temperature	1180 °C	1050–1250
σ_w	DV, furnace wander (1σ)	6 °C	0–15
r_d	DV, soft sensor drift	0 °C/h	±10
σ_s	DV, soft sensor noise	3 °C	0–10

starts at its steady value for the coke rate, coal rate, blast and burden in force, zero in every case as loaded. Each scenario therefore begins at a true steady state, and a rate chosen before the run starts is a starting condition rather than a step.

2.3.1 The Thermal State as a Sum of Delayed Responses

The hearth temperature is the base temperature plus five deviations and a slow wander, as shown in Equation (2.1).

$$T = 1500 + x_c + x_{p,f} + x_{p,s} + x_b + x_o + w(t) \tag{2.1}$$

Each deviation is a first-order lag behind a dead time, driven by the deviation of one input from its base value. Coke must descend with the burden, Equation (2.2).

$$\tau_c \frac{\mathrm{d}x_c}{\mathrm{d}t} = G_k \,\Delta\mathrm{CR}(t - \theta_c) - x_c \tag{2.2}$$

where $\Delta\mathrm{CR} = \mathrm{CR} - 350$ is the coke rate deviation in kg/tHM, $G_k = 2.0\,^\circ\mathrm{C}$ per kg/tHM is the thermal gain of coke, $\theta_c = 5\,\mathrm{h}$ is the burden descent time and $\tau_c = 3\,\mathrm{h}$ is the lag. A coke change therefore does nothing at the hearth for five hours.

2.3.2 Coal and the Inverse Response

Coal acts through two parallel paths with opposite signs, as shown in Equations (2.3) and (2.4).

$$\tau_r \frac{\mathrm{d}x_{p,f}}{\mathrm{d}t} = -G_r \,\Delta\mathrm{PCI}(t) - x_{p,f} \tag{2.3}$$

$$\tau_p \frac{\mathrm{d}x_{p,s}}{\mathrm{d}t} = G_p \,\Delta\mathrm{PCI}(t - \theta_p) - x_{p,s} \tag{2.4}$$

The fast path, with $G_r = 0.4$ and $\tau_r = 0.4\,\mathrm{h}$, has no dead time and represents the cold coal cooling the raceway flame. The slow path, with $G_p = 1.6$, $\theta_p = 1\,\mathrm{h}$ and $\tau_p = 1.5\,\mathrm{h}$, represents the extra reducing gas reaching the hearth. The steady-state gain is $G_p - G_r = 1.2\,^\circ\mathrm{C}$ per kg/tHM, positive, but the first response to a coal increase is a fall, an inverse response. In the resulting transfer function, Equation (2.5),

$$\frac{T(s)}{\Delta\mathrm{PCI}(s)} = -\frac{G_r}{\tau_r s + 1} + \frac{G_p\,\mathrm{e}^{-\theta_p s}}{\tau_p s + 1} \tag{2.5}$$

the fast negative term dominates until the delayed positive term arrives. In the notation of Section 1.4.3, coal is the fast actuator with $K_f = G_p - G_r$ and coke the slow one with $K_s = G_k$. Thermally, one kilogram of coal is worth $1.2/2.0 = 0.6$ kg of coke, so a degree of hearth temperature costs \$0.125 per tonne of hot metal from coal and \$0.20 from coke at the default prices.

🕮 **Pause.** Try Exercise 2.1 before reading on.

2.3.3 Blast, Burden and Wander

The blast temperature and the burden act as Equations (2.6) and (2.7).

$$\tau_b \frac{\mathrm{d}x_b}{\mathrm{d}t} = G_b \,\Delta T_{bl}(t-\theta_b) - x_b \tag{2.6}$$

$$\tau_o \frac{\mathrm{d}x_o}{\mathrm{d}t} = D_{ore}(t-\theta_o) - x_o \tag{2.7}$$

with $G_b = 0.25$, $\theta_b = 0.3\,\mathrm{h}$, $\tau_b = 0.5\,\mathrm{h}$, $\theta_o = 4\,\mathrm{h}$ and $\tau_o = 2\,\mathrm{h}$. The burden demand D_{ore} is expressed directly in degrees of hearth temperature, so a harder ore that needs 30 °C more heat is $D_{ore} = -30$. The wander $w(t) = \sigma_w\, n(t)$ is first-order colored noise n of unit standard deviation and a 6 h time constant, standing in for coke quality, permeability and moisture. Silicon follows the temperature linearly, Equation (2.8).

$$\mathrm{Si} = \max\left[0.05,\; 0.45 + 0.008\,(T - 1500)\right] \;\%\tag{2.8}$$

The engine is that of Section 1.6.1. The dead times are realized by a ring buffer of the four input deviations, written at every 5 min controller scan and read with linear interpolation. The inputs are held between scans, and the states are integrated by fourth-order Runge-Kutta with a 60 s step. The fuel cost accumulates at $\dot{C} = (P/86400)(\mathrm{CR}\,p_k + \mathrm{PCI}\,p_p)/1000$ dollars per second, with the production P in tHM/d and the prices p_k and p_p in dollars per tonne.

2.3.4 The Cast and the Soft Sensor

The furnace is cast every $T_c = 2\,\mathrm{h}$, first at $t = T_c$. At cast k the dip reads $T_{cast,k} = T(kT_c) + \sigma_d\,\varepsilon_k$ with $\sigma_d = 6\,^\circ\mathrm{C}$ and ε_k a standard normal deviate, and the laboratory silicon reads $\mathrm{Si} + 0.03\,\varepsilon'_k$. Both are held until the next cast. The soft sensor is the hearth temperature through a first-order filter, plus a drift and colored noise, Equation (2.9).

$$T_s = \mathscr{F}_{\tau_s}[T] + d(t) + \sigma_s\,\nu(t), \qquad \frac{\mathrm{d}d}{\mathrm{d}t} = r_d \tag{2.9}$$

with $\tau_s = 0.5\,\mathrm{h}$ and ν of unit standard deviation and a 10 min time constant. When correction is on, the corrected reading is $\hat{T}_s = T_s - \hat{b}$, and at every cast the bias estimate moves a fraction α of the way toward the observed discrepancy, Equation (2.10).

$$\hat{b} \leftarrow \hat{b} + \alpha\left(T_s - \hat{b} - T_{cast,k}\right) \tag{2.10}$$

The default weight is $\alpha = 0.5$. A hearth below 1450 °C raises the cold-hearth alarm and one below 1420 °C the chilled-hearth alarm, each cleared with a hysteresis of 5 and 10 °C.

The parameters are listed in Table 2.2. The base rates and temperatures that define the deviations, 350 and 150 kg/tHM, 1180 °C and 1500 °C, are written in the code.

2.3.5 Assumptions

The thermal state is linear in the fuel rates with fixed dead times and lags. On a real furnace the descent time changes with the production rate, and the replacement of coke by coal becomes less effective at high injection rates [7], so the gains and delays here hold only near the base operation.

The hearth is one lumped temperature. Radial and circumferential differences, the deadman and the drainage behavior of the hearth are outside the model, as are burden distribution and gas flow [15].

Silicon is locked to the temperature by Equation (2.8). In practice the two are correlated but not locked, and many furnaces control from the laboratory silicon rather than from the temperature [5].

Casts are instantaneous samples on a fixed schedule. A real cast lasts an hour or more, the temperature is dipped partway through it, and its timing varies with taphole practice.

The soft sensor is a lagged copy of the truth with a drift and noise. It stands in for estimators built from stave heat loads, top gas analysis and burden descent rate, whose errors are structured rather than additive.

Table 2.2 Model Parameters. Visible Ones Can Be Changed in the Application, Hidden Ones Are Not Shown, and Fixed Ones Are Constants in the Code

Symbol	Meaning	Value	Access
G_k	thermal gain of coke	2.0 °C per kg/tHM	visible
θ_c, τ_c	burden descent, coke lag	5, 3 h	visible
G_p	coal gain, reducing gas	1.6 °C per kg/tHM	visible
θ_p, τ_p	coal dead time, lag	1, 1.5 h	visible
G_r	raceway cooling by coal	0.4 °C per kg/tHM	visible
τ_r	raceway cooling lag	0.4 h	hidden
G_b	thermal gain of blast	0.25	visible
θ_b, τ_b	blast dead time, lag	0.3, 0.5 h	fixed
θ_o, τ_o	burden demand delay, lag	4, 2 h	fixed
—	wander time constant	6 h	fixed
T_c	time between casts	2 h	visible
σ_d	cast dip noise (1σ)	6 °C	visible
—	laboratory silicon noise	0.03 %	fixed
τ_s	soft sensor lag	0.5 h	visible
—	soft sensor noise time constant	10 min	fixed
p_k, p_p	coke, coal price	400, $150/t	visible
P	production	10 000 tHM/d	visible
—	cold, chilled hearth	1450, 1420 °C	visible

2.4 Implemented Control System

2.4.1 Coal Loop on the Hot Metal Temperature

The coal controller TC is the framework's velocity-form PID with no derivative term, executed as Equations (2.11) to (2.14).

$$e_k = T_{SP} - T_{m,k}, \qquad P_k = K_c\, e_k \tag{2.11}$$

$$s_k = s_{k-1} + (P_k - P_{k-1}), \qquad c_k = s_k + I_{k-1} \tag{2.12}$$

$$u_k = \mathrm{clamp}\,(c_k, 80, 200) \tag{2.13}$$

$$I_k = I_{k-1} + \left[\frac{K_c}{\tau_I}\, e_k + \frac{u_k - c_k}{\tau_t}\right] \Delta t_k \tag{2.14}$$

where T_m is either the cast dip T_{cast} or the corrected soft sensor $\hat{T}_s$, c_k is the coal rate the algorithm demands, u_k the coal rate applied in kg/tHM and $\tau_t = \tau_I$ the tracking time. These are Equations (1.13) to (1.16) of Section 1.6.2 with no derivative and no output bias, with s_k for S_k and c_k for v_k. The sum is never clamped, the integral starts from the initial coal rate and so carries the bias, and only the integral is corrected for clipping, by back-calculation against the coal rate actually applied. The loop is reverse acting, with the action $a = +1$ of Section 1.6.2: a cold hearth raises the coal, because the steady-state gain of Equation (2.5) is positive even though the first response is not.

The execution depends on the measurement. On the soft sensor the loop runs at every 5 min scan with $\Delta t_k = 300$ s. On cast dips it runs only when a new cast arrives, with Δt_k equal to the time since its last execution, normally $T_c = 2$ h, and its output is held in between. Each cast therefore adds $(K_c/\tau_I) e_k T_c$ to the integral in one step. The defaults are $K_c = 0.30$ kg/tHM per °C and $\tau_I = 2$ h, with sliders from 0 to 3 and from 0.25 to 48 h, where 48 h removes integral action and with it the back-calculation. In manual mode the integral tracks the operator's coal rate at every scan and each cast still counts as an execution, so transfer to automatic is bumpless. After six hours of manual operation in case 2, the first cast in automatic adds 2.4 kg/tHM to the integral, one cast interval's worth at its 8 °C error.

The default tuning is close to the SIMC rule once the hold is counted as dead time [11]. Treating the raceway lag as effective delay because it produces the inverse response, and adding half the sample interval for the zero-order hold, the coal path has $\theta_e \approx \theta_p + \tau_r + T_c/2 = 2.4$ h, a lag $\tau_p = 1.5$ h

and a gain of 1.2. With the closed-loop time constant $\tau_{cl} = \theta_e$ the rule gives Equation (2.15).

$$\begin{aligned} K_c &= \frac{\tau_p}{1.2\,(\tau_{cl} + \theta_e)} \approx 0.26 \\ \tau_I &= \min\left[\tau_p,\, 4(\tau_{cl} + \theta_e)\right] = 1.5\,\mathrm{h} \end{aligned} \tag{2.15}$$

Without the hold term the same rule gives $K_c \approx 0.45$, so the two-hour sample alone should cut the gain by about a factor of 1.7.

2.4.2 Mid-Ranging on Coke

The mid-ranging controller YC is a second velocity-form PI, direct acting with $a = -1$ in the convention of Section 1.6.2, as the app's Show Model note also calls it. Its measurement is the coal command and its setpoint is the coal target PCI_{SP}, Equation (2.16).

$$\mathrm{CR}_k^{*} = \mathrm{clamp}[\mathrm{PI}_{K_v,\tau_V}\left(\mathrm{PCI}_k - \mathrm{PCI}_{SP}\right),\, 300,\, 420] \tag{2.16}$$

A coal rate above its target raises the coke rate, which warms the hearth five hours later, which in turn lets the coal loop take coal back out. The loop runs at every 5 min scan, so on cast dips it sees a coal command that changes once per cast. The scenarios use $K_v = 0.2$ kg of coke per kg of coal and $\tau_V = 12\,\mathrm{h}$. The applied coke rate follows the command at no more than 5 kg/tHM per hour, a limit on how fast the burden recipe may change. That rate limit acts after the controller and is not fed back to its integral. When mid-ranging is off the coke rate is set by hand and the controller tracks it.

The structure is the standard one of Section 1.4.3, and its two tuning choices are the ones the literature emphasizes [1, 2]. The coal loop must be the faster of the two, and the mid-ranging loop must be slow enough that the coke's five-hour delay does not make the two fight. There is no feedforward from the blast temperature or the burden, and no anti-windup coupling between the loops of the kind proposed for a saturating fast actuator [12].

🕮 **Pause.** Try Exercise 2.3 before reading on.

2.4.3 Model Predictive Control of Coal and Coke

A second thermal-control structure, never the default and selected as loaded only by scenario 10, gives both fuels to one model predictive controller. Every $T_{\mathrm{MPC}} = 15\,\mathrm{min}$, which is three controller scans, and again after each cast, a quadratic program plans the coal rate and the coke rate over the next $N = 48$ periods (12 h), in the receding-horizon manner of Section 1.6.3. Predictive control of the silicon content and the slag basicity, the quality indices that follow the thermal state, has been studied on a large industrial furnace whose slow responses take more than eight hours [22]. Here the coal is decided as a rate held over each period and the coke as a ramp v in kg/tHM per hour, bounded by the recipe change limit $r_c = 5\,\mathrm{kg/tHM}$ per hour that already acts after the mid-ranging loop, so the coke the plan counts on is the coke the burden receives. While a plan acts, the coal loop and the mid-ranging loop track the applied rates at every scan with no preload.

The controller's model is Equations (2.2) to (2.4) with the parameter values of Table 2.2, frozen when the application loads, so a parameter changed by the learner becomes model error, as it would on a furnace. Its estimate of the hearth is Equation (2.17),

$$\hat{T} = 1500 + x_c + x_{p,f} + x_{p,s} + \hat{d} \tag{2.17}$$

where the three states are driven by the rates the controller itself applied, kept in its own five-hour record, and $\hat{d}$ is a single output disturbance that carries everything the model leaves out: the blast and burden paths of Equations (2.6) and (2.7), the wander, the soft sensor drift left after correction, and any changed parameter. The balance is linear. Stepped by 10 kg/tHM in manual with the noise off, the simulated hearth follows the model to 4×10^{-8} °C, while a first-order-plus-dead-time fit misses the coal step by 5.2 % RMS of its response and cannot reproduce its inverse response. Sampled at

T_{MPC}, the coke and coal dead times become chains of 20 and 4 periods, and the program's model has 28 states. A plan made at 60 h of scenario 10 with the setpoint raised 20 °C, then applied open loop with the wander and noise off, predicts the true hearth at the end of every period to within 0.005 °C.

On cast dips the disturbance is corrected once per cast, as shown in Equation (2.18),

$$\hat{d} \leftarrow \hat{d} + \alpha \left[T_{cast,k} - T_{mod}(t_k) - \hat{d} \right] \tag{2.18}$$

with the weight α of Equation (2.10) and the model's own hearth $T_{mod} = \hat{T} - \hat{d}$ read from its record at the tap time t_k, when the dip was taken. Between casts $\hat{d}$ is held. On the soft sensor a steady-state Kalman filter acts at every scan on two states, the index's declared 0.5 h lag and $\hat{d}$ as a random walk, and reads the index exactly as the coal loop reads it, bias-corrected at each cast when the correction is on. Its variances come from the declared noise settings rather than from tuning, 1 °C^2 per scan for $\hat{d}$ from the 6 °C, 6 h wander and 36 °C^2 for the index, whose 3 °C colored noise is replaced by white noise of equal low-frequency power, and the resulting gains are 0.115 on the lag state and 0.157 on $\hat{d}$ per scan. One integrating disturbance on the one measured output makes the plan offset-free [23], but on the measurement rather than on the hearth, so an index drift that the cast correction has not yet removed becomes hearth error.

Each plan minimizes Equation (2.19),

$$\begin{aligned} J = \sum_{k=1}^{N} \left[\left(\hat{T}_k - T_{SP} \right)^2 + w_m \left(\mathrm{PCI}_k - \mathrm{PCI}_{SP} \right)^2 + r_v v_k^2 \right] \\ + \sum_{j=1}^{12} \left(\lambda \, \Delta \mathrm{PCI}_j^2 + s_v \, \Delta v_j^2 \right) \end{aligned} \tag{2.19}$$

where $\hat{T}_k$ is the predicted hearth at the end of period k, PCI_{SP} is the coal target of Equation (2.16), Δ is the change from one move block to the next with the first change measured from the rates applied now, $w_m = 0.03$ per (kg/tHM)^2 against 1 per °C^2, $\lambda = 1$ per (kg/tHM)^2, and $s_v = 2$ and $r_v = 0.02$ per (kg/tHM per hour)^2. There is no terminal weight. The moves are held in twelve blocks, four of one period and two of two, then 3, 4, 6, 9 and 15 periods and a final block of 3, which gives 24 decisions. Because the coal target enters as a resting rate for the coal, a sustained load can be carried only by the coke, which is the mid-ranging idea written as a cost instead of a second loop. Every constraint is hard: the coal stays within the 80 to 200 kg/tHM clamps of Equation (2.13), $|v_k| \le r_c$, and the coke stays within 300 to 420 kg/tHM at the end of every block. The coke rate advances by $v_k T_{\mathrm{MPC}}$ over a period, and the staircase the ramp makes at the three scans enters the dead-time chain as its mean. The temperature has no soft band. A cold-hearth band at 1465 °C, carried by the solver's single slack over the whole horizon, raised the IAE of case 6 from 583 to 605 °C h and its coal travel from 399 to 444 kg/tHM, with the coldest hearth at 1457.4 against 1457.2 °C.

The original design asked for a 5 min period and 144 steps. That horizon exceeds the 120 steps the shared solver supports, and with a 5 min period and 120 steps the model needs 76 states and about 66 ms per plan in Node, about three processor cores at the top playback speed of 14400 times real time, for an IAE of 621 instead of 644 °C h on scenario 10 with half again as much coal and coke travel. The weights were chosen once, on scenario 10, from 216 combinations of horizon, λ, w_m and s_v. Of the 43 that moved neither fuel further than the coal loop does, rejected no plan and never held the coal at its limit, the best reached 627 °C h, and among those within 5 % of it the one that kept the coal closest to its target was taken, the shorter horizon breaking ties.

The controller keeps a plan when the solver's own status is optimal, the returned moves, predictions and cost are all finite, each planned coal rate, ramp and coke rate over the horizon respects its bounds, and the first planned move equals the one applied. Otherwise the coal loop and mid-ranging take the fuels from the rates they have been tracking until a later plan passes the same checks. With the wander and noise switched off, forcing a rejection at 20.25 h of scenario 10 moves the coal 0.09 kg/tHM

on the soft sensor, which is the coal loop's own first move, and not at all on cast dips, where the loop holds the coal until the next cast. None of the runs reported here rejected a plan, and each makes 288 plans in three days. A return from manual is a decision rather than a transfer. After three hours of manual operation across the arrival of the first burden change, the first plan raises the coal 16.0 kg/tHM at once.

The plant runs on the run's parameters, the instruments add their own lag, noise and drift, and the controller's model keeps the declared values, so the three models stay separate. Replaying the instrument record of six three-day runs, each over a different hidden plant, reproduces every applied coal and coke rate bit for bit. With no bound active the plans agree with an independently written condensed solution to 6.4×10^{-14}, and Karush-Kuhn-Tucker certificates hold at eight instants that exercise every kind of constraint. A plan takes 4.2 ms on average in Chrome, which is 1.7 % of one core at the default playback of 3600 times real time and 6.8 % at the top speed.

2.5 Results

The ten teaching scenarios and the challenge are listed in Table 2.3 with what each teaches and what a learner must do to complete it, and their measured outcomes are given in Table 2.4. Each case is credited when the learner performs the listed actions and the simulation reaches the listed state. The challenge is judged on the case as given, so changing a model parameter or a disturbance voids the attempt, and the credit from the eleven cases (ten scenarios and the challenge) accumulates toward certificates of progress and of completion, as Section 1.6.4 describes. Every value below comes from the application's engine at its default seed, with each setting changed after the case is loaded and before the run starts, which gives the same run as the setting carried through Reset.

2.5.1 Two Actuators on Two Clocks

Case 1 runs in manual with the wander off. The coke step of 10 kg/tHM reaches about 19 °C fifteen hours later, close to the steady 20 °C of Equation (2.2), and the coal step of the same size dips before it rises, as listed in Table 2.4. The coke step can be fitted by a first-order model with dead time to 0.97 % RMS error, a little later and slower than Equation (2.2) alone because the recipe change limit ramps the step in. The coal step cannot be described by that model, because its first response has the wrong sign.

> **TRY IT IN THE APP** **1 · Step the Coke and the Coal by Hand**
>
> Load the scenario and press Run, then watch the Hot metal temperature trend. The coke step at one hour does nothing for five hours, and fifteen hours later the hearth is up about 19 °C. After the coal step at twenty hours the hearth first falls about 3.6 °C within the hour, then rises about 12 °C.

2.5.2 A Loop That Sees the Hearth Once a Cast

In case 2 a harder ore charged at twelve hours reaches the hearth four hours later. The loop cannot see it earlier and the coal needs an hour to act, so the hearth falls to about 1475 °C before the loop recovers it, and the coal ends the two days about 20 kg/tHM higher. The true temperature at the casts is held to about 10.3 °C RMS. Case 3 raises the gain from 0.3 to 0.8 and halves the integral time, as a loop on a continuous measurement might be tuned, and the hearth swings from about 1439 to 1543 °C, spends 2.9 h below the cold alarm and holds the coal on a limit for 8 h.

The sampling and the coal dynamics each contribute to that ceiling, and Table 2.5 separates them. The continuous measurement is the soft sensor with no lag, no drift, no bias correction and a noise of 10^{-9} °C, which keeps the random sequence of the cast run, so it reads the true hearth every five minutes. At the default tuning the two-hour cast costs 10.3 against 7.8 °C RMS, and the SIMC estimate of Equation (2.15) performs about the same as the default, with 9.9 °C RMS on the casts. At the case 3 tuning the hold decides how cold the hearth goes. The continuous loop stays above the alarm, with a minimum of 1458 °C, while the cast loop falls to 1439 °C and spends 2.9 h below it.

Table 2.3 Scenarios and Completion Requirements

#	Scenario, teaching point and kind	Required to complete
1	Coke and coal stepped by hand *two response times* (experiment)	Run in manual past 16 h, by which time the coke step at 1 h has raised the hearth above 1510 °C, and on past 21.5 h to cover the first 1.5 h after the coal step at 20 h.
2	Coal loop on casts, new ore blend *sampled feedback* (experiment)	Run in automatic through the ore change at 12 h and past 36 h, by which time the coal rate exceeds 165 kg/tHM.
3	Tuned as if continuous *the gain ceiling* (demonstration)	Run past 24 h at $K_c \geq 0.75$ with the hearth falling below 1460 °C, then Reset, return to $K_c = 0.3$ and $\tau_I = 2$ h before 1 h and run past 24 h again.
4	Soft sensor drifting, uncorrected *an unchecked model* (demonstration)	Run on the uncorrected soft sensor through the drift start at 6 h to 24 h, by which time the hearth is more than 15 °C below setpoint.
5	Soft sensor corrected each cast *bias updating* (experiment)	Run to 24 h with the correction weight $\alpha = 0.5$, then Reset, set $\alpha \leq 0.25$ before the drift starts at 6 h and run to 24 h again.
6	Burden change beyond the limit *saturation* (demonstration)	Hold the coal on its 200 kg/tHM limit for 2 h after the second burden change at 36 h, and run the full 72 h.
7	Mid-ranging on coke *the slow actuator* (experiment)	Run 72 h with mid-ranging at $K_v \leq 0.21$ until the coke rate exceeds 365 kg/tHM, then Reset, set $K_v = 0.5$ before the first burden change at 2 h and run 72 h again.
8	A high coal target *economics and margin* (experiment)	Run 72 h with mid-ranging and a coal target of at least 189 kg/tHM, then Reset, set the target to 150 kg/tHM before 1 h and run 72 h again.
9	Hot stove fault *a fast disturbance* (demonstration)	Run past 14 h at the default gain, through the fault at 12 h, then Reset, raise K_c to 1.0 before 1 h and run past 14 h again.
10	Coke planned five hours ahead, MPC *planning on a delay* (experiment)	Run past 36 h in automatic with the MPC, then Reset, select the coal loop before the first burden change at 2 h and run past 36 h again.
11	Challenge *graded run* (challenge)	At 72 h the coldest hearth of the run is at or above 1450 °C and each of the last 12 cast dips, from 48 to 70 h, is within ±15 °C of 1500 °C, with the model parameters and disturbances as given.[a]

[a] With the shipped settings (uncorrected soft sensor, mid-ranging off) the hearth falls to 1337 °C, 113 °C below the alarm, and the worst last-day dip is 162.0 °C off setpoint. With the suggested settings (bias correction at $\alpha = 0.8$, mid-ranging on, $K_c = 0.25$ and $\tau_I = 3$ h) the coldest hearth is 1459.1 °C, 9.1 °C above the alarm, and the worst dip is 12.8 °C off, 2.2 °C inside the band.

Setting the soft sensor noise to exactly zero, as a learner would, removes its draws from the random sequence and so changes the furnace wander, and the continuous loop then just touches the alarm, at 1449 °C for 6 min, with 18.6 °C RMS. Neither loop is stable at that tuning. With the wander and the noise off and a 5 °C burden step, the loop with $\tau_I = 1$ h settles at $K_c = 0.65$ on the continuous measurement but not at 0.70, and on the casts it settles at 0.45 but not at 0.50, so the hold lowers the stable gain by a factor of about 1.4, against the 1.7 of the SIMC estimate. At $K_c = 0.8$, with the case's own ore change and the wander and noise still off, both loops lock into a cycle that the 200 kg/tHM coal limit bounds, between 1464 and 1528 °C on the continuous measurement and between 1446 and 1537 °C on the casts from 24 to 96 h, and only the larger cycle reaches the alarm. A gain of 1.2 swings the hearth to 1400 °C even on the ideal measurement. With the default tuning the cast error is

Table 2.4 Measured Scenario Outcomes. RMS Is of the True Temperature Minus Setpoint at Every Cast

Case and condition	Result
1, coke +10 kg/tHM	no change for 5 h, +19 °C after 15 h
1, coal +10 kg/tHM	−3.6 °C within 1 h, then +12 °C
2, default, ore −30	min 1475 °C, coal +20, 10.3 °C RMS
3, $K_c = 0.8$, $\tau_I = 1$ h	1439–1543 °C, 2.9 h cold, 21.6 °C RMS
4, drift, uncorrected, 24 h	index 1514, hearth 1464 °C, coal 114
4 and 5, cast error	15.1 against 6.5 °C RMS
5, corrected, 24 h	hearth 1492 °C, index 1503 °C
6, two changes, no mid-ranging	coal on limit 26 h, last 12 h 1477 °C
7, mid-ranging	never on limit, last 12 h 1504 °C
7, end of run	coke 382, coal 171 kg/tHM
6 and 7, fuel	$1.68 against $1.73 million per day
6 and 7, first change	min 1448 °C in both, 0.3 h cold
8, targets 190 and 150, no ore change	$1.59 against $1.63 million per day
8, ore −25	coal on limit 2 h, min 1462 against 1464 °C
9, stove −80 °C	min 1473 (loop), 1480 ($K_c = 1$), 1470 (none)
9, stove back	overshoot to 1522 °C

Table 2.5 Case 2 Over 48 h With Cast Dips and With an Ideal Continuous Measurement. Same Random Sequence in Each Pair

		Cast dips		Continuous	
K_c	τ_I (h)	RMS	min	RMS	min
0.30	2.0	10.3	1475	7.8	1479
0.26	1.5	9.9	1475	7.7	1479
0.60	1.5	9.5	1473	7.6	1474
0.80	1.0	21.6	1439	18.1	1458
1.20	1.0	31.1	1387	36.9	1400

Case 3 is the $K_c = 0.8$ row.

7.7, 10.3 and 10.2 °C RMS for casts every 1, 2 and 4 h, and the hearth error over the whole run ranks the three the same way, at 7.6, 11.1 and 10.3 °C RMS. Casts every hour help, while on this seed a four-hour interval costs no more than a two-hour one. Volume 5, Chapter 3 meets the same limit with a composition loop closed through a slow analyzer.

2.5.3 A Soft Sensor Is a Model

Case 4 puts the loop on the soft sensor and starts a drift of 3 °C per hour at six hours. The loop pulls the index toward setpoint by removing coal, and after a day the index reads about 1514 °C while the hearth is at about 1464 °C and the coal has been cut to about 114 kg/tHM. The cast dips show the truth throughout and nothing uses them. In case 5 the same drift is corrected at every cast with $\alpha = 0.5$, the hearth ends the day at about 1492 °C, and the cast error is 6.5 °C RMS against 15.1 °C uncorrected. Over the same day a weight of 0.2 gives 9.6 °C RMS and a weight of 1.0 gives 5.1 °C, so with this drift rate the drift outweighs the 6 °C dip noise that a large weight passes into the estimate.

> **TRY IT IN THE APP** **4 · A Soft Sensor That Drifts, Uncorrected**
>
> Run the scenario for a day. From six hours the soft sensor reads 3 °C per hour high. On the Hot metal temperature trend, compare the soft sensor with the cast dips: at 24 h the index reads about 1514 °C and the hearth about 1464 °C, and the Coal injection trend shows the coal cut to about 114 kg/tHM. Then load scenario 5, where each cast corrects the index.

Pause. Try Exercise 2.2 before reading on.



Figure 2.2 Mid-ranging on coke, case 7, at the end of the three-day run ($t = 72$ h), cropped to the plant view and the trends. The furnace section on the left shows the coke and ore layers with a 5.0 h descent (1), the coal at the tuyeres and the hearth at 1506 °C with 0.49 % silicon (2). Beside it the last twelve casts are plotted as dips and soft sensor readings against the ±15 °C band and the cold-hearth line (3), above gauges for the coal at 171 kg/tHM against its target and limit and the coke at 382 kg/tHM (4). The trends show the hearth dipping after each burden change, the deeper dip near 11 h marked as a cold-hearth event (5), the coal stepping at every cast to a peak of 192 kg/tHM, below its 200 kg/tHM limit, and then easing back toward its target, and the coke climbing from 350 to 382 kg/tHM.

2.5.4 Saturation and Mid-Ranging

Case 6 charges two burden changes a day and a half apart, 45 °C and then 80 °C of extra demand in all. At the net coal gain the two together need about 67 kg/tHM of extra coal against 50 kg/tHM of room, so the capacity test of Equation (1.3) fails and the coal sits on its 200 kg/tHM limit for about 26 h. Over the last 12 h the hearth averages about 1477 °C, and integral action cannot remove that offset because the actuator cannot reach it. Case 7 switches on mid-ranging. The coal peaks at 192 kg/tHM, below its limit, the hearth averages about 1504 °C over the last half day, and at the end the coke has risen to 382 kg/tHM with the coal back to 171 kg/tHM and still returning, as shown in Figure 2.2. The fuel costs about $1.73 million a day against $1.68 million without mid-ranging, which is the price of a hearth that is not cold. Neither case prevents the first dip. The first burden change reaches the hearth at six hours, and the coal, an hour late itself, cannot answer it in time, so in both cases the hearth falls to about 1448 °C and spends 20 min below the cold alarm.

Table 2.6 Mid-Ranging Tuning in Case 7 Over 72 h

K_v	τ_V (h)	RMS	max T	peak CR	time cold (h)
0.2	12	15.9	1519	382	0.33
0.2	4	18.2	1530	393	0.35
0.5	12	19.0	1541	390	0.52
1.0	12	37.6	1563	420	6.97

A faster mid-ranging loop overshoots, as reported in Table 2.6. At $K_v = 0.5$ the hearth overshoots to 1541 °C and the cast error rises from 15.9 to 19.0 °C RMS. At $K_v = 1.0$ the two loops fight through the coke delay, the coke reaches its 420 kg/tHM limit, the coal spends 8 h on a limit and the hearth spends 7.0 h cold. The coke rate limit plays almost no part at the default tuning. It is active for 3.7 h of the run, and raising it to 20 kg/tHM per hour moves the last half-day mean by 0.02 °C, from 1503.78 to 1503.76 °C.

> **+ DID YOU KNOW? A Faster Helper Makes the Hearth Colder**
>
> From the simulator: in Table 2.6, raising the mid-ranging gain from 0.2 to 1.0 at the same 12 h integral time raises the cast error from 15.9 to 37.6 °C RMS and the time below the cold-hearth alarm from 0.33 to 6.97 h. A coke loop that hurries fights the coal loop through the five-hour delay.

2.5.5 The Coal Target and a Fast Disturbance

The coal target is an economic setting. With the burden change removed and the wander left on, over three days a target of 190 kg/tHM runs the furnace on about $1.59 million of fuel a day against $1.63 million at 150 kg/tHM, a saving of about $33,000 a day. It also leaves the coal only 10 kg/tHM of room, while a 25 °C burden change asks for about 21. With that change the coal sits on its 200 kg/tHM limit for one cast, 2 h, and ends the run at about 193 kg/tHM while the coke catches up, and the coldest hearth is about 1462 °C against 1464 °C at the lower target, for $1.62 against $1.65 million of fuel a day. The target is set where the price of fuel meets the size of the disturbances the furnace actually sees.

A stove fault that drops the blast by 80 °C for eight hours shows the limit of feedback on this plant. Before the stove returns the hearth falls to about 1470 °C with no loop, 1473 °C with the default loop and 1480 °C with a gain of 1.0, because the blast reaches the hearth within the hour and the loop sees it only at the next cast. When the stove returns, the coal the loop has added is still arriving and the hearth overshoots to about 1522 °C. The hotter loop overshoots to 1524 °C and then swings down to 1461 °C at 28.75 h, colder than anything the fault itself did. The blast temperature is measured and its effect is known from Equation (2.6), which makes it a candidate for feedforward rather than for tighter feedback.

2.5.6 The Graded Challenge

The challenge runs three days with a 40 °C burden change at six hours, a 3 °C per hour soft sensor drift from twelve hours, and a second change to 75 °C in all at 24 hours. It starts on the uncorrected soft sensor with mid-ranging off. It is met when the hearth never falls below 1450 °C and every cast dip in the last day, the twelve casts from 48 to 70 h, is within 15 °C of setpoint. Table 2.7 reports the outcomes.

As loaded, the drifting index walks the hearth to about 1337 °C, a chilled hearth. Correcting the index alone keeps the hearth above 1453 °C but leaves the coal on its limit for 28.5 h and the last half day 18 °C cold. Mid-ranging alone makes matters slightly worse, because the coke then follows a coal rate that is itself answering a false measurement. The two settings together keep the coldest hearth at 1456 °C, but at a weight of 0.5 the bias estimate trails the drift, the last day runs 7.8 °C cold on average, and the worst last-day dip is 20.6 °C off. The suggested settings raise the weight to 0.8 and

Table 2.7 Challenge Outcomes Over 72 h. Worst Dip Is the Largest Deviation of a Cast Dip From Setpoint in the Last Day, as the Challenge Scores It

Configuration	min T (°C)	on limit (h)	last 12 h (°C)	worst dip (°C)	fuel ($M/d)	met
as loaded	1337	3.7	1353	162.0	1.60	no
bias correction	1453	28.5	1482	25.2	1.68	no
mid-ranging	1328	0	1344	170.7	1.59	no
both	1456	0	1493	20.6	1.71	no
suggested	1459	0	1500	12.8	1.72	yes
cast dips, mid-ranging	1454	0	1502	12.1	1.72	yes

Suggested: bias correction at $\alpha = 0.8$, mid-ranging on, $K_c = 0.25$, $\tau_I = 3$ h. Both: bias correction at $\alpha = 0.5$ and mid-ranging, with the coal loop at its default tuning.

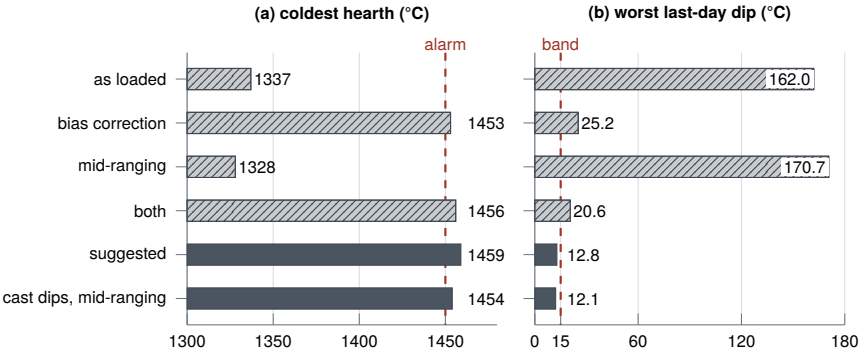


Figure 2.3 The graded challenge of Table 2.7 as a chart, runs that meet the target solid and runs that miss it hatched. The dashed lines are the 1450 °C cold-hearth alarm in (a) and the 15 °C band in (b). Notice that bias correction lifts the coldest hearth above the alarm but leaves the last day outside the band, that mid-ranging alone makes both slightly worse, and that only the suggested settings and the cast dips with mid-ranging clear both lines.

soften the coal loop to $K_c = 0.25$ and $\tau_I = 3$ h, which at the same weight cuts the total coal travel over the run from 611 to 508 kg/tHM, and they meet the target with a minimum of 1459 °C and a worst last-day dip of 12.8 °C. Either refinement alone leaves a worst dip of 15.8 to 16.6 °C. Abandoning the soft sensor for the cast dips, with mid-ranging on, also meets the target at 1454 °C and 12.1 °C, which shows that the corrected index buys margin above the alarm rather than feasibility. The dips carry 6 °C of noise, so the last-day criterion is decided by a few degrees. The true temperature at those casts is never more than 7.3 °C from setpoint with the suggested settings and 8.1 °C with the cast dips. Figure 2.3 draws the coldest hearth and the worst dip of each configuration as bars.

2.5.7 Comparison of the Predictive Controller With Mid-Ranging

The MPC is compared with the coal loop in Table 2.8. Every run lasts 72 h at the default seed with the instruments and noise as the case loads them. The comparator is the challenge's suggested coal loop, $K_c = 0.25$ and $\tau_I = 3$ h, on the soft sensor corrected at $\alpha = 0.8$, with mid-ranging at its default tuning, which is the line-up scenario 10 runs when the coal loop is selected. The MPC runs on the same corrected index with scenario 10's settings and is not retuned for any case, and neither structure is told about the burden. The hindsight row is the best of 768 coal-loop tunings (K_c, τ_I, K_v, τ_V and α) at the case's own coal target, chosen after seeing that case. It bounds what a fixed loop could do instead of offering a design, and a wider search inside the same ranges reaches 494 °C h on scenario 10. IAE

Table 2.8 The MPC Against the Suggested Coal Loop With Mid-Ranging and a Coal Loop Retuned in Hindsight. Each Run 72 h at the Default Seed

Case	Structure	IAE (°C h)	Coldest (°C)	At 200 (h)	Off target (kg h/tHM)	Travel (kg/tHM)	Coke (t)
10	coal loop	1016	1453.5	0.50	2138	506/106	11199
	hindsight	512	1456.6	0	1622	1168/296	11363
	MPC	644	1457.2	0	670	385/104	11594
	MPC, coal only[a]	667	1457.2	5.50	2018	360/94	11184
	MPC, coke delay 15 min[b]	1367	1450.9	0	476	275/294	11612
6, 7	coal loop	699	1458.0	0	1629	504/104	10984
	hindsight	504	1456.6	0	2006	1170/118	10915
	MPC	583	1457.2	0	605	399/103	11292
8	coal loop	648	1463.9	0	948	500/105	10094
	hindsight	385	1470.4	0	1384	1150/116	10331
	MPC	403	1473.0	7.25	534	322/105	10034
5	coal loop	459	1479.5	0	154	504/99	10471
	hindsight	351	1485.3	0	99	312/31	10496
	MPC	467	1472.9	0	267	335/69	10451
2	coal loop	470	1477.4	0	688	496/99	10709
	hindsight	349	1477.7	0	375	1147/295	10875
	MPC	415	1476.5	0	344	327/77	10840
11[c]	coal loop, met	694	1459.1	0	1520	508/103	10941
	hindsight, not met	558	1460.8	0	1338	838/88	11053
	MPC, not met	709	1458.6	0	534	374/94	11229
	MPC on cast dips, met	644	1452.3	0	536	302/87	11267

At 200 is the time with the coal at its injection limit, travel is the summed coal and coke movement, and coke is the tonnage charged. Every MPC run made 288 plans and rejected none. [a]The MPC planning the coal with mid-ranging moving the coke. [b]The MPC's model, free response and record with 15 min of coke dead time instead of 5 h. [c]The challenge with its suggested settings, judged by its own rule.

integrates the absolute error of the true hearth temperature, and the coal's distance from its target is integrated in the same way.

Scenario 10 charges a burden 45 °C harder at 2 h and 90 °C harder in all at 10 h. At the net coal gain the second change asks for about 75 kg/tHM of extra coal against 50 kg/tHM of room below the injection limit, so the coke must take part of the load. Under the MPC the hearth first falls below 1495 °C at 6.18 h, the coke ramp reaches the recipe limit at 8.02 h and stays there for 3.75 h in all, and when the second change reaches the hearth at 14 h the coke is at 375.0 against 357.2 kg/tHM under mid-ranging, as shown in Figure 2.4. The coal peaks at 192.0 kg/tHM at 10.0 h, never reaches its limit, and is back to 157.1 kg/tHM at 24 h and 147.9 kg/tHM at 36 h. Under the coal loop the coal reaches the limit at 21.7 h, still stands at 191.8 kg/tHM at 36 h, and ends the three days at 167.9 against 146.3 kg/tHM under the MPC. The IAE is 644 against 1016 °C h and the coal's distance from its target 670 against 2138 kg h/tHM. The earlier coke costs 395 t more over the three days, $18,532 a day at the default prices.

Removing one mechanism at a time locates these gains. An MPC that plans the coal alone while mid-ranging moves the coke reaches 667 °C h, so most of the temperature gain over the coal loop belongs to the coal plan. What the coke plan buys is room for the coal, because without it the coke reaches 370 kg/tHM at 22.4 h instead of 11.6 h and the coal spends 5.5 h at its limit, and with nobody moving the coke the IAE is 2020 °C h with 56.5 h at the limit. The price on the coal's distance from its target is what hands the load to the coke. With $w_m = 0$ the plan raises the coke less, holds the coal at its limit for 7.25 h and reaches an IAE of 742 °C h. Knowing the delay matters more than the horizon. A model that gives the coke 15 min of dead time instead of five hours roughly doubles the IAE, to 1367 on scenario 10 and 1329 on cases 6 and 7, and nearly triples the coke travel, while horizons of 8, 20 and 30 h all give 644 °C h.

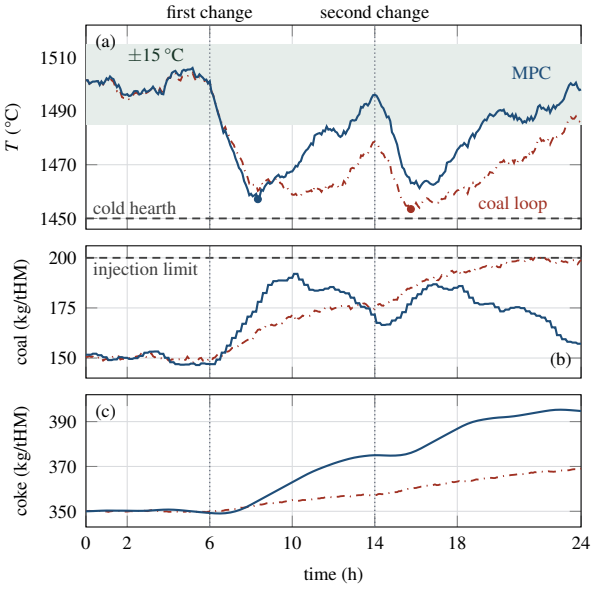


Figure 2.4 Scenario 10 over its first day under the MPC and under the coal loop with mid-ranging, at the default seed. The MPC is the thick solid line and the coal loop the dash-dotted line. The cold-hearth alarm and the injection limit are dashed, and the dotted verticals mark the arrival of each burden change. (a) True hot metal temperature against the ±15 °C band and the cold-hearth alarm, with each coldest point marked. The burden changes charged at 2 and 10 h reach the hearth at 6 and 14 h. (b) Coal rate against the injection limit. (c) Coke rate. At 24 h the MPC holds the coal at 157.1 kg/tHM with the coke at 394.7 kg/tHM, while the coal loop holds it at 198.9 with the coke at 369.1 kg/tHM.

The events of scenario 10 were chosen from nineteen candidate sets built around the same two changes, with second changes of 80 or 90 °C at 10 to 16 h, coal targets of 150 to 180 kg/tHM, and days of three and four changes. On all nineteen the MPC has the lower IAE, by 16 to 49 % with a median of 34 %, and scenario 10's 37 % ranks sixth, so the case is typical of the family rather than its best member. On three further seeds of the wander and the noise the MPC stays ahead on scenario 10, at 665 to 757 against 849 to 1075 °C h, with its coal never at the limit.

The coal loop retuned in hindsight holds the hearth closer than the MPC on every case of Table 2.8, with 2.2 to 3.6 times the MPC's coal travel except in case 5, where it moves the coal less, 312 against 335 kg/tHM, and still wins. Held to the MPC's own coal and coke travel, the best retuned loop still wins cases 2, 5 and 10 and the challenge (399, 351, 620 and 612 °C h), ties case 9 (423 against 420) and loses cases 6 and 7 (666) and case 8 (438), and on scenario 10 it then spends 5.4 h with the coal at its limit. In case 8 the MPC rests the coal at the 190 kg/tHM target it is given, cutting the coke to between 324.5 and 330.6 kg/tHM from 6 to 24 h to do so, which leaves the coal 10 kg/tHM of room, and after the burden change at 24 h the coal spends 7.25 h at its limit where the coal loop spends none, although the MPC's IAE is lower, 403 against 648 °C h. Case 5 is lost narrowly, 467 against 459 °C h, on all four seeds. Both structures act there on an index that reads 6.5 to 6.6 °C above the hearth over 24 to 72 h and so hold the hearth 6.6 to 6.8 °C cold, and the MPC trails by 9 and 14 °C h over 6 to 24 and 24 to 48 h before leading by 15 over the last day. On cases 2 and 9 the order changes with the seed, so neither is counted as a win. After the second change of cases 6 and 7 the MPC's hearth dips to 1464.7 against 1476.9 °C, with window IAEs of 237 and 236, because the coal loop is still running hot from the first change, 14.6 °C above setpoint on average over the four hours before the second one arrives against 9.6 under the MPC.

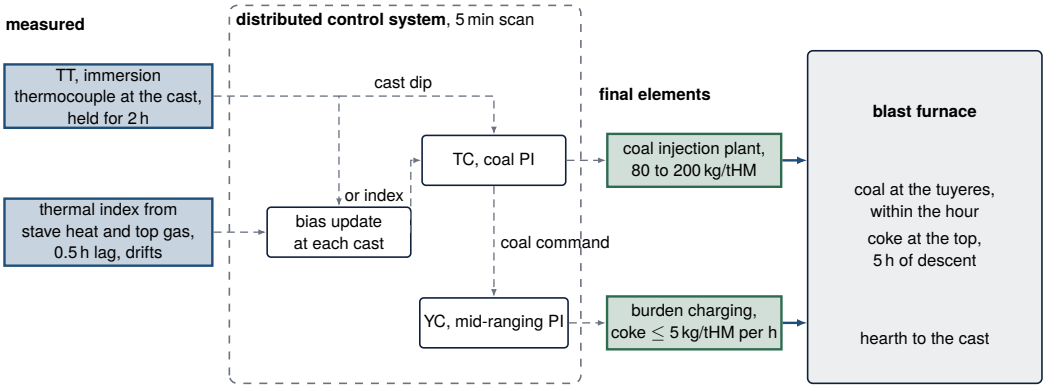


Figure 2.5 The loops of the simulated furnace drawn with their hardware. The coal controller TC reads either the cast dip or the corrected thermal index and sets the coal injection plant. The mid-ranging controller YC takes the coal command as its measurement and moves the coke through the burden recipe, so the coke takes over a lasting load while the coal returns to its target.

Run under the MPC with the suggested settings of the challenge, the furnace misses its target. The coldest hearth is 1458.6 °C and no unscored limit is broken, but the worst last-day dip is 23.7 °C off setpoint. Over the last day the corrected index reads 6.7 °C above the hearth on average, because the drift adds 6 °C between casts and $\alpha = 0.8$ removes 80 % of the error at each, and the MPC holds that index 0.4 °C under setpoint, so the hearth runs 7.1 °C cold. The suggested coal loop meets the target because it is slower. Its index is still 6.0 °C above setpoint over the last day, which leaves the hearth 0.6 °C cold, and continued to 144 h it settles with the index 0.1 °C under setpoint and the hearth 5.4 °C cold, where the MPC ends 0.9 °C under setpoint on the index and 6.2 °C cold. On cast dips, which do not drift, the MPC meets the challenge at the default seed, with a coldest hearth of 1452.3 °C and a worst dip of 12.7 °C, where the suggested coal loop on cast dips misses it at 16.3 °C. The verdicts turn on a few degrees of dip noise, since over four seeds the suggested coal loop meets the target three times, the MPC on the corrected index once and the MPC on cast dips twice. As loaded, on the uncorrected index, the MPC walks the hearth down as the coal loop does, to 1332.6 against 1337.5 °C.

2.6 Technology in Practice

Figure 2.5 draws the two loops of Section 2.4 with their hardware.

What Measures It

A thermocouple generates its own voltage at the junction of two metals. Thermocouples are typically less accurate than resistance thermometers but more rugged, with wider spans, and the types with platinum and rhodium wires are the ones listed for the highest temperatures [24]. The model's dip noise of 6 °C and the reading held until the next cast stand for the scatter of the dips and the stepwise record a plant computer keeps.

> **TECHNOLOGY** **Sensor: The Immersion Thermocouple at the Cast**
>
> The hot metal temperature is read by an immersion thermocouple dipped into the iron runner at the exit of the taphole. Two or three readings are taken in a cast, and the first tends to be low, because the first metal comes from the cold lower hearth near the walls [18]. The trough cools the metal as well. A reading past the skimmer ran about 30 °C low early in a cast, so one furnace took its dip only after a set quantity of metal had passed [10]. A thermocouple fails most often open, which reads as wild noise unless the instrument has a burnout mode [24].

The thermal index of the soft sensor is computed from stave heat loads and top gas analysis. The model represents it as a copy of the hearth temperature with a 0.5 h lag, a drift and noise, and the laboratory silicon arrives with each cast.

What Moves It

The coal is the fast final element, and the controller's command reaches the tuyeres through the injection plant.

> **TECHNOLOGY** **Final Element: The Coal Injection Plant**
>
> Dried and ground coal is conveyed by air to pressurized storage beside the furnace, and metering equipment there sends it pneumatically to each tuyere, 28 per furnace in one demonstration [19]. At the tuyere the coal enters through a lance inserted into the blowpipe that carries the hot blast. Coal that does not burn in its short stay in the raceway leaves char that rises and can block the void spaces of the burden, and a black layer was found inside lances after a period of service [20]. The coal rate a controller sets is delivered only while every line and lance stays clear.

The model applies the commanded coal rate at once, clamped between 80 and 200 kg/tHM. The coke rate is moved through the burden recipe at the top, and the model lets it follow its command at no more than 5 kg/tHM per hour. The hot blast enters as a disturbance.

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 [25]. In the app the coal loop and the mid-ranging loop are scanned every 5 min, the coal loop on cast dips executes once a cast, 2 h apart, and the predictive controller plans every 15 min. On such a platform the two loops are PID function blocks of the regulatory layer, the mid-ranging block taking the coal block's output as its measurement, and the bias update is a calculation block triggered by each cast. The predictive controller sits in the supervisory layer and writes both fuel rates.

> **IN PRACTICE** **Bringing a Hearth Loop Into Service**
>
> The computer control of the 1970s furnace in Section 2.2 went into service in three steps: an operation guide that showed the predicted temperature from September 1975 to January 1977, a test of automatic control from February to October 1977, and practical use from November 1977. The reasons given were that a blast furnace needs a long time to recover once it is in trouble, and that the experienced operators had to gain confidence in the system. The controlled temperature was the average of three consecutive casts, which smoothed the scatter between tapholes and the measurement errors [10].

What Is Modernizing It

The first development is data-driven prediction of the thermal state. Neural network models of the hot metal temperature take the elapsed times of the casting cycle as inputs, so that the irregular dips can be used [18], and a gradient-boosted model predicted the average silicon of the coming cast from the previous shift's operating data with an accuracy of 91 % over 200 predictions [26]. The second is simulation of the injection itself. Three-dimensional flow models of the blowpipe, lance, tuyere and raceway have been built to find how far the coal rate can rise, with long-term targets near 200 kg per tonne, 40 % of the fuel [20], the same figure as the injection limit of this chapter's coal. The third is a look inside the shaft. Muon radiography uses cosmic-ray muons to image the average density of the furnace and is being tested to follow the cohesive zone, where the descending burden softens and melts [27].

2.7 Limitations

The thermal model is linear with fixed delays. The descent time varies with production rate on a real furnace, and the coke replacement ratio of coal is not constant at high injection rates [7].

The coal path is written as two lags, one of them delayed. The raceway physics, including oxygen enrichment and the flame temperature limit that bounds injection in practice, is represented only by the fast negative path and the fixed 200 kg/tHM limit [6].

Silicon is a function of temperature, so the simulator cannot teach the separate prediction and control of silicon that much of the literature addresses [5, 17].

The soft sensor error is a ramp plus noise. A real thermal index errs when the furnace changes in ways its model did not see, and a bias update then corrects some of that error and not the rest [21].

There is no feedforward from the stoves or the burden, and no anti-windup coupling between the coal and coke loops [12].

The MPC's model leaves out what its single output disturbance must absorb. It does not read the burden, which on a real furnace is decided when it is charged, four hours before it reaches the hearth, so like the loops it cannot prevent the first cooling a burden change brings. It plans with the declared gains and delays, so a changed parameter is absorbed only as an offset. On the soft sensor it is offset-free on the index, so the drift that the cast correction leaves between casts becomes hearth error, 7.1 °C on average over the challenge's last day. A coal target near the injection limit leaves the plan no room, as case 8 shows, and the shared solver's single slack over the whole horizon is why the plan carries no soft temperature band.

> ⚠ **OPEN CHALLENGE** **Reading the Hearth From Everything Measured**
>
> Silicon in the hot metal serves as a proxy for the heat in the hearth, because the hostile interior rules out measuring its temperature directly. The furnace answers an operator's move late, and the laboratory analysis adds its own delay, which hampers real-time control. Physical models can be slow or not accurate enough, data-driven predictors mostly use a few hand-picked variables, and each furnace offers a different set [26]. Progress would be a predictor that a new furnace can adopt with little hand work, trusted enough to close the loop on, which the soft sensor of this chapter only stands in for.

2.8 Conclusion

The blast furnace hearth is held by a fast, cheap and bounded fuel and a slow, expensive and wide one, and it is seen once a cast. In the simulator of this chapter a coal step cools the hearth 3.6 °C before warming it 12 °C, and a coke step waits five hours. A coal loop tuned for the two-hour cast holds 10.3 °C RMS, while a gain of 0.8 with a one-hour integral time swings the hearth from 1439 to 1543 °C on the casts, against a minimum of 1458 °C on an ideal continuous measurement, and the hold lowers the stable gain by a factor of about 1.4. An uncorrected soft sensor drifting 3 °C per hour takes the hearth to 1464 °C while reading 1514 °C, and a bias update at each cast holds it at 1492 °C. When burden changes exceed the injection limit the hearth runs 23 °C cold, and a slow mid-ranging loop on coke restores it to about 1504 °C for about $44,000 a day of extra fuel. In the challenge a bias update weighted at 0.8, mid-ranging and a gentler coal loop together lift the coldest hearth from 1337 °C to 1459 °C. The predictive controller of Section 2.4.3, which schedules the coke on its five-hour delay, keeps the coal off its injection limit in scenario 10, with an IAE of 644 against 1016 °C h and no time at the limit against 0.5 h, for 395 t more coke over three days, while a coal loop retuned in hindsight reaches 512 °C h by moving the coal three times as far. The model keeps the delays fixed and locks silicon to temperature. A fuller model would add production-rate dependent delays, a silicon model, stove feedforward and anti-windup between the two loops. The furnace remains a compact case of dividing a load between a fast actuator and a slow one.

KEY POINTS

- The hearth is warmed by a fast, cheap fuel with little room, coal, and a slow, costly one with plenty, coke, and is checked once a cast.
- The two-hour hold of the cast lowers the stable gain of the coal loop by a factor of about 1.4.
- An uncorrected soft sensor drifting 3 °C per hour takes the hearth to 1464 °C while reading 1514 °C, and a bias update at each cast holds it at 1492 °C.
- When burden changes exceed the injection limit, a slow mid-ranging loop on coke restores the hearth to about 1504 °C.

Where else this applies. Volume 4, Chapter 10 and Volume 4, Chapter 9 divide a load the same way, and Volume 5, Chapter 10 corrects a soft sensor against late samples.

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2.9 Exercises

2.1 ○ Concept check · 1 min

In case 1 the coal injection rate is raised by 10 kg/tHM in Manual with the furnace wander off. What does the hearth do in the first hour after the step, and why?

(a) It cools by a few degrees, because the cold coal lowers the raceway flame temperature first

(b) It holds steady for five hours, because the coal must descend with the burden before it acts

(c) It warms at once by about 12 °C, because the coal burns just above the hearth

(d) It cools by a few degrees, because the cast dip is taken before the coal has burned

2.2 ○ Concept check · 2 min

In case 4 the coal loop runs on the soft sensor with no bias correction, and from 6 h the index reads 3 °C per hour high. What does the chapter find a day into the run?

(a) The index and the hearth both return to setpoint, because integral action removes any steady offset

(b) The index stays within about 15 °C of setpoint while the hearth cools far below it

(c) The hearth runs hot, because the loop adds coal to answer an index that keeps rising

(d) The loop sets the index aside once it disagrees with the cast dips and follows the dips

2.3 ○ Concept check · 2 min

Which description of the mid-ranging controller YC is right in the loop-action convention of Chapter 1, where $a = +1$ is reverse acting and $a = -1$ direct acting?

(a) It measures the hearth temperature and moves the coke rate, and it is reverse acting like the coal loop

(b) It measures the coke rate and moves the coal target, and it is direct acting

(c) It measures the coal command and moves the coke rate, and it is direct acting

(d) It measures the coal command and moves the coke rate, and it is reverse acting

2.4 Theory and calculation · 5 min

The soft sensor of case 5 drifts at $r_d = 3\,^{\circ}\mathrm{C}$ per hour and is corrected at every cast, $T_c = 2\,\mathrm{h}$, by Equation (2.10). Ignore the dip noise, the index noise and the index lag, and take the hearth as steady, so the corrected index reads the hearth plus the bias error $\varepsilon = d - \hat{b}$.

(a) Show that ε just before a cast settles at $r_d T_c/\alpha$, and evaluate it at $\alpha = 0.5$ and $\alpha = 0.8$. *Checkpoint:* 12 °C and 7.5 °C.

(b) Find ε just after a cast and its average over a cast interval at both weights. *Checkpoint:* After: 6 and 1.5 °C. Average: 9 and 4.5 °C.

(c) A loop that holds the corrected index at setpoint runs the hearth cold by that average. Over the challenge's last day at $\alpha = 0.8$, under the MPC, the chapter measures the index 6.7 °C above the hearth. Say why the run differs from (b), and what a larger weight trades. *Checkpoint:* 6.7 °C measured against 4.5 °C from (b).

2.5 Theory and calculation · 6 min

The coal path of Equation (2.5) has $G_r = 0.4$, $\tau_r = 0.4\,\mathrm{h}$, $G_p = 1.6$, $\theta_p = 1\,\mathrm{h}$ and $\tau_p = 1.5\,\mathrm{h}$, and the hearth is dipped every $T_c = 2\,\mathrm{h}$.

(a) Approximate the coal path as a first-order lag with dead time. Count the raceway lag as delay because it causes the inverse response, and add half the cast interval for the hold. Give the gain and the effective delay. *Checkpoint:* Gain 1.2, $\theta_e = 2.4\,\mathrm{h}$.

(b) Apply the SIMC rule with $\tau_{cl} = \theta_e$ for K_c and τ_I. *Checkpoint:* $K_c \approx 0.26\,\mathrm{kg/tHM}$ per °C, $\tau_I = 1.5\,\mathrm{h}$.

(c) Repeat (b) without the hold term, give the ratio of the two gains, and compare it with the factor the chapter measures from the stability boundaries. *Checkpoint:* $K_c \approx 0.45$, ratio about 1.7, against about 1.4 measured.

2.6 Theory and calculation · 5 min

Use the steady gains of the model, 1.2 °C per kg/tHM of coal and 2.0 °C per kg/tHM of coke, the coal limit of 200 kg/tHM and the coke range of 300 to 420 kg/tHM. Both fuels start at their base rates of 150 and 350 kg/tHM.

(a) Case 6 adds 80 °C of burden demand in all, with the coke held at 350 kg/tHM. Find the extra coal needed, the room the coal has, and the steady hearth temperature with the coal on its limit. *Checkpoint:* 66.7 kg/tHM against 50 kg/tHM; about 1480 °C.

(b) In case 7 mid-ranging returns the coal to its 150 kg/tHM target. Where must the coke settle, and is that inside its range? *Checkpoint:* 390 kg/tHM, inside the 420 kg/tHM limit.

(c) Case 8 sets the coal target to 190 kg/tHM. How large a burden change can the coal absorb alone, and how much coal does the case's 25 °C change ask for? *Checkpoint:* 12 °C; about 20.8 kg/tHM.

2.7 App challenge · 8 min

Load scenario 1, "Step the coke and the coal by hand (MANUAL)," at the default seed with no changes. The furnace wander is off in this case. Run to 36 h at the default speed of 3600× (one furnace hour per second), and export the CSV file. Read the column `hmt_C` against `Time (h)`. Give temperatures to ±0.1 °C.

(a) Read the hearth at 6.0 h and at 16.0 h. When does the coke step made at 1 h first move the hearth? *Checkpoint:* 1500.0 and 1519.0 °C; not before 6 h.

(b) Find the lowest hearth between 20 and 24 h, its time, and its difference from the value at 20.0 h. *Checkpoint:* 1516.1 °C at 21.0 h, 3.6 °C below the 1519.7 °C at 20 h.

(c) Read the hearth at 36.0 h and estimate the steady gains of coke and coal from your readings. *Checkpoint:* 1532.0 °C; about 2.0 and 1.2 °C per kg/tHM.

2.8 App challenge · 9 min

Load scenario 6, "A burden change beyond the injection limit," at the default seed with no changes, and run the full 72 h, at 14400× if you prefer (about 18 s). Export the CSV file. Then load scenario 7, "Mid-ranging: coke takes the load so the coal can return," and do the same.

(a) For each run, count the rows with `pci_saturated` equal to 1 and convert to hours (one row per 5 min), and average `hmt_C` over the rows from 60 to 72 h. Give hours to ±0.1 h and temperatures to ±0.1 °C. *Checkpoint:* Case 6: 26.0 h and 1477.3 °C. Case 7: 0 h and 1503.8 °C.

(b) Read the scorecard tiles Fuel cost, run average and Coke, coal at 72 h in each run. *Checkpoint:* $1681.6k and $1725.9k a day; coke 350 and 382 kg/tHM, coal 200 and 171 kg/tHM.

(c) Price the steady states the two structures head for, the coal on its limit with the coke at 350 kg/tHM and the coal back at 150 kg/tHM with the coke at 390 kg/tHM, at $400 per tonne of coke, $150 per tonne of coal and 10 000 tHM/d. Compare the difference with the three-day averages of (b). *Checkpoint:* $1.700 and $1.785 million a day, $85,000 apart, against $44,300 measured.

2.9 App challenge · 8 min

Load scenario 10, "Coke takes the load five hours ahead: MPC against mid-ranging," at the default seed. Run to 36 h with Thermal control on MPC as loaded, and export the CSV file. Press Reset, set Thermal control to Coal loop before pressing Run, run to 36 h again and export a second file. Skip any comment lines that start with `#`. Give rates to ±0.2 kg/tHM.

(a) In each file read `coke_kg` at 14.0 h, when the second burden change reaches the hearth, and `pci_kg` at 24.0 h. *Checkpoint:* MPC 375.0 and 157.1 kg/tHM. Coal loop 357.2 and 198.9 kg/tHM.

(b) In each file find the largest `pci_kg` and the first row at the 200 kg/tHM limit, if any. *Checkpoint:* MPC 192.0 kg/tHM, never at the limit. Coal loop at the limit from the 21.75 h row.

(c) Explain why the plan moves the coke earlier than mid-ranging, and what the earlier coke costs over the chapter's three-day run. *Checkpoint:* About 395 t more coke, $18,532 a day.

2.10 Application area · 4 min

The coal target is the rate the mid-ranging loop returns the coal to. At the base operation the furnace burns 350 kg/tHM of coke at $400 per tonne and 150 kg/tHM of coal at $150 per tonne, making 10 000 tHM/d, and one kilogram of coal is worth 0.6 kg of coke.

(a) With no disturbance, find the steady coke rate and fuel cost per tonne of hot metal at targets of 150 and 190 kg/tHM, and the daily saving. *Checkpoint:* Coke 350 and 326 kg/tHM; $162.5 and $158.9 per tonne; $36,000 a day.

(b) The chapter measures a saving of about $33,000 a day over three days. Give the reason for the difference, and say what the higher target costs in disturbance margin. *Checkpoint:* A margin of 12 °C for the coal alone.

2.11 Application area · 5 min

A hot stove fault drops the blast temperature by 80 °C for eight hours, as in case 9. The blast temperature is measured, so the coal could be moved as soon as the stove trips.

(a) From Equation (2.6) find the steady hearth loss and the coal step that offsets it. *Checkpoint:* 20 °C; about 16.7 kg/tHM.

(b) Compare the timing of the blast and coal paths, and say what a static feedforward of that size does in the first hour after the trip and when the stove returns. *Checkpoint:* Blast 0.3 h delay and 0.5 h lag. Coal cooling at once, heating after 1 h and a 1.5 h lag.

(c) The return of a stove is planned. How should the feedforward use that? *Checkpoint:* Compare the coal path's delay and lag with the blast's.

2.12 Review the agent · 5 min

In case 7 the coal takes days to return to its target after the second burden change. An AI assistant proposes: "Raise the mid-ranging gain from 0.2 to 1.0. The coke will then take the load five times faster, the coal will be back at its target within a day, and it will have more room for the next change." Find the flaw, and say how you would check it in the app.