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CHAPTER 7

Walking-Beam Reheat Furnace Simulator for Slab Tracking and Level 2 Setpoint Control

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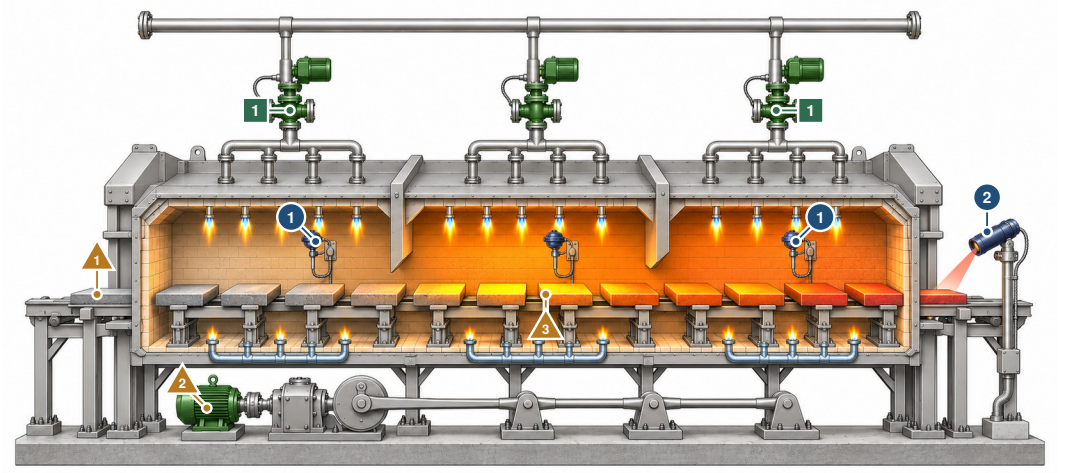
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CHAPTER 7

Walking-Beam Reheat Furnace Simulator for Slab Tracking and Level 2 Setpoint Control



The controller moves 1 fuel and air valves of the three zones

The controller reads 1 zone thermocouples 2 pyrometer at the discharge door

What disturbs it 1 temperature of the charged slabs 2 mill pace and mill delays, through the walking-beam drive 3 a fall in heat transfer to the slabs

Slabs walk from the charge door at the left to the mill at the right while each zone fires from above and below. Notice that the sensors read the zone gas and the slab surface, never the inside of a slab. Illustration, not to scale.

IN PLAIN TERMS **Heating Steel That Nobody Can See Inside**

The main idea. A reheat furnace heats thick slabs of steel for a rolling mill, and each slab must leave hot all the way through. A computer model follows every slab through three fired zones and sets how hot each zone runs.

The challenge. Heat soaks into a slab slowly, so a slab that leaves sooner leaves colder even when every zone holds its heat. The only instrument aimed at a slab sees its skin, never its middle, and that reading must keep the model honest.

Why it matters. A cold slab rolls badly, and extra heat wastes fuel in a furnace that burns around the clock.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	The first page, the history boxes of Section 7.2 and Section 7.4, the fact box of the Introduction, the fact and try-it boxes of Section 7.5, and the key points
Study	40 min	The whole chapter with its pause points and the twelve exercises
Practice	15 min	The first page, Section 7.5, Section 7.6, Section 7.7 with its two open challenges

The control question A reheat furnace must deliver every slab at a mean temperature that no instrument reads, while the mill changes its pace, stops for a roll change and sends hot slabs. Which source of zone setpoints puts the slabs on target, and what keeps a slab-tracking model honest when its heat transfer is wrong?

Learning objectives

- Compute the conduction time, Biot number, residence time and throughput of the furnace from its parameters.
- Explain why zone loops on setpoint and a loop on the slab surface both discharge cold slabs after a pace change.
- Describe how a slab-tracking model turns each slab's predicted discharge mean into zone setpoints and uses the charge temperature as feedforward.
- Calculate a correction of the exchange factor from a pyrometer residual, and weigh the correction gain against the pyrometer noise.
- Compare the slab model with a joint predictive profile on accuracy, fuel and a mill delay.

Prerequisites Sections 1.4.2 (slab conduction and the three clocks), 1.4.5 (material tracking), 1.6.2 (velocity form) and 1.6.4 (scenarios and data). Section 1.6.3 is needed only for the predictive option.

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

See also Volume 5, Chapter 11 for a multi-zone kiln whose brick core is never measured, and Volume 5, Chapter 5 for a moving ribbon that carries its temperature through the half thickness. Volume 9, Chapter 4 for an offset-free predictive controller whose estimator carries a bias.

7.1 Introduction

Feedback acts on the variable it measures. When the measured variable and the product quality are the same thing, that is enough, but on many plants the quality lives inside the product and the sensors see only its surroundings or its skin. A kiln measures its gas and not the clinker, a dryer its air and not the moisture at the center of the web, and a batch reactor its jacket and not the conversion. The multi-zone kiln of Volume 5, Chapter 11 has the same difficulty with the core of a brick. The general answer is a model that runs alongside the plant, driven by the measured inputs and corrected by whatever the plant does measure, which is the structure formalized in the linear filtering problem [1] and extended to unknown model parameters by treating them as additional states [2].

The slab reheat furnace in front of a hot strip or plate mill, such as the mill of Chapter 8, is an unusually clear case. Slabs are charged cold or warm, walked through several fired zones for a couple of hours, and discharged to the mill at a mean temperature that decides whether they roll well, and neither the mean nor the core is measured on line. The furnace is fired around the clock, so every degree of overheating has a price in fuel, and the energy consumption of reheating furnaces under different charging conditions and heating patterns remains an active research subject [3, 4]. A transfer function from zone setpoint to slab temperature hides the part that matters, because the slab response depends on how long each slab stays and where it is when a change occurs, and those quantities move with the mill schedule.

> ✦ **DID YOU KNOW? A Tenth of a Steelworks' Energy**
>
> In Japan around 1980, reheating furnaces burned nearly 10 percent of the total energy of an integrated steelworks and 30 to 70 percent at works without ironmaking [5]. Continuous slab reheating furnaces then ran at about 350 thousand kilocalories per tonne of steel.

Three misconceptions shaped the simulator. One is that zone temperatures held on setpoint deliver slabs on target, when a faster mill shortens every slab's stay. A second treats the surface temperature read by the discharge pyrometer as a measure of the slab, when a hotter furnace widens the gap between surface and center. A third holds that an estimator which agrees with itself is right, when

a change in radiant exchange leaves a slab-tracking model confident and wrong. The same pitfalls appear wherever a moving product carries an internal state, and the answer is the general state and parameter estimator [1, 2].

This chapter works with a walking-beam furnace simulator in which the zone setpoints come from the operator, from a pyrometer trim loop, from a slab-tracking model that can be corrected from the pyrometer, or from a joint predictive profile, with each choice judged on the discharged slabs and the fuel. Slab tracking, model-based setpoint calculation and exchange factor correction are established methods, cited below, and the chapter specifies the furnace model, the tracking model with its sensitivity shadow and the setpoint calculation in enough detail to be rebuilt. The scenarios separate what Level 1 holds, what a proxy measurement can steer, what a model can plan and what only the measurement can correct. Section 7.2 traces furnace control from zone loops to slab tracking. Section 7.3 gives the furnace and slab model, and Section 7.4 the two control levels, the tracking model, its correction and the predictive option. Section 7.5 reports what each scenario measured, Section 7.6 describes the real instruments and control platforms, Section 7.7 states the limitations, and Section 7.8 concludes.

7.2 From Zone Loops to Slab Tracking

A continuous reheating furnace is a long refractory chamber through which slabs move from a charging door to a discharging door. In a walking-beam furnace movable beams lift the slabs, carry them one step and set them down on fixed beams, which allows heating from below as well as above. Burners are grouped into zones along the length, conventionally a preheating zone near the charge door, one or more heating zones, and a soaking zone near the discharge door in which the surface is held while the center catches up. Detailed heat transfer models of reheating furnaces resolve the radiative exchange inside the chamber and the transient conduction inside each slab [6, 7].

> ⧖ HISTORY **The Walking Beam Replaces the Pusher (1967)**
>
> Until the mid-1960s the furnaces that heated large steel for hot rolling were, with few exceptions, multi-zone pusher furnaces, and walking hearths served only special or small furnaces [8]. A large pusher needs a strong pushing mechanism to drive the slabs along the skids. The slabs sliding on skids and hearth were scored on their undersides, the deeper scores survived as defects in the rolled product, and piling and buckling of slabs limited the length of the furnace. In June 1967 a Japanese steelworks began to run four large walking-beam furnaces. With no soaking hearth, each slab was heated over its whole surface from charge to discharge, and a walking-beam furnace was said to need three quarters of the length of a pusher of the same capacity.

The zone temperature loop is an ordinary loop from a thermocouple to the fuel and air of one zone, and it leaves open the question of what temperature each zone should hold. By 1970 that question was being posed as an optimization of the heating of a slab through a reheating furnace [9]. Two decades later integrated control systems for the reheating furnace of a hot strip mill were being reported [10], and the optimal heating of slabs was formulated for control purposes [11]. Because the quantity to be optimized is the unmeasured slab temperature, estimation arrived with it, and the extended Kalman filter was applied to the average slab temperatures of a simulated reheat furnace by 1990 [12].

Model predictive control followed the same path from zone temperatures to slab temperatures. Identification and predictive control of a slab reheating furnace were reported in 2002 [13], a nonlinear predictive controller was developed for a continuous slab reheating furnace [14], and a nonlinear predictive controller based on a numerical model was applied to a walking-beam furnace [15]. The operating events that such controllers exist to handle have their own literature. Mixed loading and mill delays are treated as a rolling-horizon optimization in walking-beam furnaces [16], and the effect of charging conditions on energy consumption and slab heating quality has been assessed on an industrial-scale furnace [4].

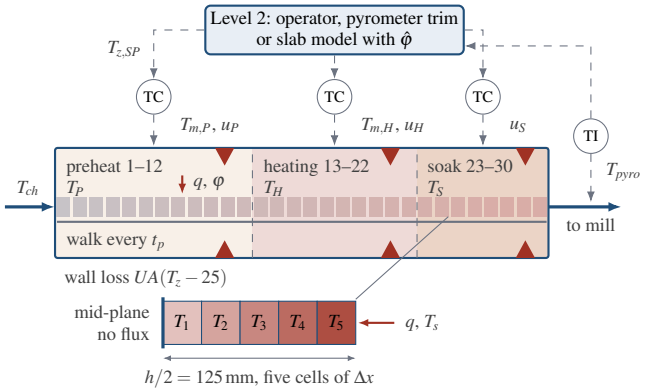


Figure 7.1 Walking-beam reheat furnace as modeled. Thirty slabs charged at T_{ch} walk one position every t_p through the preheat, heating and soak zones at temperatures T_P, T_H and T_S, fired from above and below at u_z percent of capacity and losing heat through the walls. Each slab receives the radiant flux q with exchange factor φ, and half of its thickness is five conduction cells T_1 to T_5 from the mid-plane to the surface temperature T_s (inset). The zone controllers TC read the filtered thermocouples $T_{m,z}$ and follow setpoints $T_{z,SP}$ from Level 2, which also receives the pyrometer reading T_{pyro} of each discharged slab.

Table 7.1 Variables, Their Roles and Default Values

Symbol	Role	Default	Range
$\bar{T}_{dis}$	CV, discharge mean, unmeasured	1200 °C	SP 1150–1260
T_z	CV (Level 1), zone temperature	1150, 1320, 1230	SP 900–1380
$T_{m,z}$	measured, zone thermocouple	T_z	noise 2 °C
T_{pyro}	measured, discharge surface	—	noise 5 °C
u_z	MV, zone firing	holding	0–100 %
$T_{z,SP}$	MV of Level 2, zone setpoint	nominal	800–1350
$T_{i,j}$	states, slab cells (30×5)	periodic	—
E	state, fuel fired	0	—
t_p	DV, mill pace	300 s	180–600
T_{ch}	DV, charge temperature	25 °C	25–800
$\Delta\varphi$	DV, exchange factor change	0 %	±30
—	DV, mill delay length	60 min	5–120

The weakest number in any of these models is the radiant exchange between the furnace and the slab. It is commonly lumped into a total heat exchange factor and estimated, either by solving an inverse heat conduction problem from measured temperatures [17] or from trials in which a slab instrumented with thermocouples travels through the furnace [18]. A recent review of reheating furnaces covers the mathematical models, heating patterns, control systems and energy analysis together [3]. The simulator follows that lineage in miniature, with a one-dimensional slab, one exchange factor, a tracking model and a correction from the discharge pyrometer.

7.3 Furnace and Slab Model

Thirty slab positions pass through three fired zones, preheat (positions 1 to 12), heating (13 to 22) and soak (23 to 30), as drawn in Figure 7.1. Every slab is 10 m long, 1.5 m wide and 250 mm thick, 29.25 t of steel, heated over 30 m^2 of top and bottom faces. At the nominal pace of one walk every $t_p = 300$ s the furnace discharges 351 t an hour and each slab stays 2.5 h, 60 min in preheat, 50 min in heating and 40 min in soak. The mill wants a discharge mean of 1200 °C.

Table 7.1 gives the role and range of each variable. The plant carries 154 states, five cell temperatures for each of the thirty positions, three zone temperatures and a fuel accumulator. The walking

beam, the instruments and the two tracking models run in the controller at every step.

7.3.1 Conduction Through the Slab

Each slab is heated alike from above and below, so half of its thickness h is modeled with $N_c = 5$ cells of width $\Delta x = h/(2N_c) = 25\,\mathrm{mm}$. Cell j exchanges heat with its neighbors by conduction, as shown in Equation (7.1).

$$\rho c_p \Delta x \frac{\mathrm{d}T_j}{\mathrm{d}t} = \frac{k}{\Delta x}\left(T_{j-1} - T_j\right) + \frac{k}{\Delta x}\left(T_{j+1} - T_j\right) \tag{7.1}$$

where $k = 30\,\mathrm{W/(m\,K)}$ and $\rho c_p = 5.07\,\mathrm{MJ/(m^3\,K)}$. The first term is zero for the cell at the mid-plane ($j = 1$), by symmetry, and for the surface cell ($j = 5$) the second term is replaced by the radiant flux q of Equation (7.2).

$$\begin{aligned} q &= \varphi\sigma\left[(T_z + 273.15)^4 - (T_s + 273.15)^4\right] \\ T_s &= T_5 + \frac{q\,\Delta x}{2k} \end{aligned} \tag{7.2}$$

where $\sigma = 5.670 \times 10^{-8}\,\mathrm{W/(m^2\,K^4)}$, T_z is the temperature of the zone over the slab and φ is the overall exchange factor, 0.6 by default. The surface lies half a cell outside the center of cell 5, and the implicit pair is solved by five fixed-point iterations starting from $T_s = T_5$. The slab mean is the average of the five cells and the core is T_1.

Two dimensionless numbers set the character of the slab. The radiant heat transfer coefficient $4\varphi\sigma T^3$ of Equation (1.2), where Chapter 1 writes σ_{SB} for σ and ℓ for $h/2$, is about $460\,\mathrm{W/(m^2\,K)}$ at 1230 °C, so the Biot number on the half thickness is about 1.9 and the surface runs well ahead of the center. The conduction time $(h/2)^2\rho c_p/k$ is about 44 min, comparable to the time a slab spends in any one zone, so a slab moves on well before it equilibrates with any zone.

7.3.2 Zone Heat Balance and Fuel

Each zone is a single lumped temperature, fired at u_z percent of its burner capacity P_z and loaded by the slabs under it, as shown in Equation (7.3).

$$C_z \frac{\mathrm{d}T_z}{\mathrm{d}t} = \eta(T_z)\,P_z \frac{u_z}{100} - A\sum_{i \in z} q_i - UA\,(T_z - 25) \tag{7.3}$$

with $C_z = 100\,\mathrm{MJ/K}$ for every zone, $P_z = 100$, 90 and 30 MW for preheat, heating and soak, $A = 30\,\mathrm{m^2}$ per slab, $UA = 0.003\,\mathrm{MW/K}$ and the flux sum converted to megawatts. The available-heat fraction of Equation (7.4) falls linearly as the zone runs hotter, standing in for the larger flue gas loss of a hotter zone.

$$\eta(T_z) = \mathrm{clamp}\left[0.85 - 0.0004\,(T_z - 900),\ 0.4,\ 0.9\right] \tag{7.4}$$

The fuel accumulator integrates the gross firing, $\dot{E} = \sum_z P_z u_z/100$, and the fuel per tonne is E divided by the tonnes discharged. Linearizing Equation (7.3) about the nominal state with the slabs frozen gives zone time constants of 10.1, 10.0 and 16.5 min for preheat, heating and soak. At that state the zones fire 61.5, 46.9 and 9.6 MW, 117.9 MW in all or about 1.21 GJ/t, while heating steel from 25 to 1199 °C takes 0.763 GJ/t at the model's heat capacity, a thermal efficiency of about 63 %.

7.3.3 Walking Beam, Instruments and Events

A walk clock advances by the integration step except during a mill delay. When it reaches t_p, the slab in position 30 is discharged and recorded (mean, core, true surface and pyrometer reading), every slab moves one position, and a new slab enters position 1 with all five cells at T_{ch}. The pyrometer reads $T_{pyro} = T_s + \sigma_p\varepsilon$ with $\sigma_p = 5\,^\circ\mathrm{C}$ and ε a standard normal deviate. The zone thermocouples add noise of $\sigma_{tc} = 2\,^\circ\mathrm{C}$ and are smoothed by a first-order lag with $\tau_{tc} = 30\,\mathrm{s}$, updated as $T_{m,z} \leftarrow T_{m,z} + (T_z + \sigma_{tc}\varepsilon - T_{m,z})\,\Delta t/(\tau_{tc} + \Delta t)$. The true exchange factor is $\varphi(1 + \Delta\varphi/100)$, and $\Delta\varphi$ is the

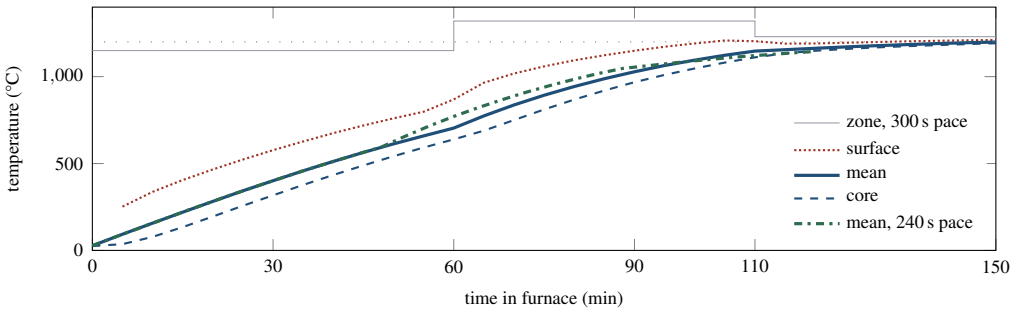


Figure 7.2 Slab heating curves at the operator setpoints of 1150, 1320 and 1230 °C, from the true furnace at its periodic steady state with thermocouple noise off: zone temperature (thin gray steps), surface (dotted), mean (thick solid) and core (dashed) at the 300 s pace, and the mean at the 240 s pace (dash-dotted), with the target as a thin loosely dotted line. At the 300 s pace the slab leaves with a mean of 1199 °C, a core of 1192 °C and a surface of 1211 °C. At 240 s the same zones deliver a mean of 1145 °C after 2 h.

Table 7.2 Furnace and Slab Parameters. Visible Parameters Have Sliders in the Show Model Dialog, Hidden Ones Are Kept From the Student, and Fixed Ones Are Built Into the Source

Symbol	Meaning	Value	Access
φ	exchange factor, true	0.6	visible
k	steel conductivity	30 W/(m K)	hidden
ρc_p	steel heat capacity	5.07 MJ/(m^3 K)	hidden
h	slab thickness	250 mm	visible
N_c	cells per half thickness	5	fixed
A	heated area per slab	30 m^2	fixed
—	slab mass	29.25 t	fixed
C_z	zone heat capacity	100 MJ/K	visible
P_P, P_H, P_S	burner capacity	100, 90, 30 MW	visible
UA	zone wall loss	0.003 MW/K	hidden
T_{max}	zone setpoint limit	1350 °C	visible
η	available heat, Eq. (7.4)	0.85 at 900 °C	fixed
τ_{tc}	thermocouple filter	30 s	fixed
σ_{tc}, σ_p	thermocouple, pyrometer noise	2, 5 °C	slider
N	slab positions (12, 10, 8)	30	fixed

disturbance the tracking model does not know. The events available to the scenarios are a mill delay that stops the walk clock for the delay length, a pace change to 240 s, hot charge at 450 °C and a 15 % fall in φ.

At reset, including a restart that keeps the learner's settings (Section 1.6.1), the true furnace and both tracking models are filled with the periodic steady state of the operator setpoints, held below T_{max}, and the pace and charge temperature then in force, found by marching one slab through the thirty positions with 10 s explicit Euler steps. The zones start at those setpoints. In automatic each zone loop starts from the firing that holds its zone, computed from Equation (7.3) with the derivative set to zero, and in manual from the firing stations, which default to 62.5, 55 and 31.5 %, close to that firing at the nominal state. A 10 s fourth-order Runge-Kutta step advances the plant, and the controller executes at that period too.

The consequence of the conduction time is drawn in Figure 7.2. The surface climbs to about 1208 °C late in the heating zone, falls as the slab enters the cooler soak zone and then holds while the core closes on it, so the surface-to-core gap shrinks from 127 °C at 105 min to 19 °C at discharge. At the faster pace the same zone temperatures act for 30 min less and the mean reaches only 1145 °C.

Table 7.2 collects the parameters.

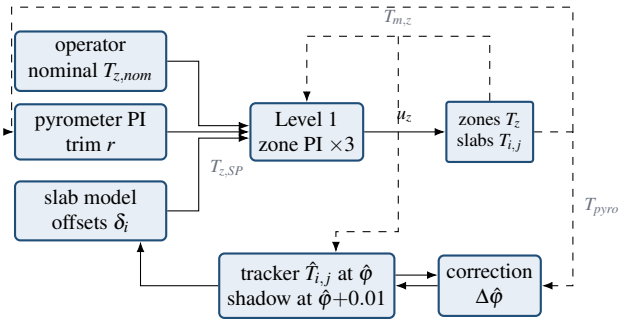


Figure 7.3 The two control levels. One of three Level 2 sources supplies the zone setpoints $T_{z,SP}$ to three Level 1 PI loops. The slab model plans from a tracker driven by the measured zone temperatures, and the correction compares each pyrometer reading with the tracker's predicted surface, using the shadow tracker for sensitivities, and updates $\hat{\varphi}$ and every tracked slab.

7.3.4 Assumptions

Heat flows through the thickness only. Real slabs are colder where they rest on the water-cooled beams and at their edges, effects that a one-dimensional slab cannot represent.

Each zone has one temperature and one exchange factor applies to every slab. The gas and wall temperatures of a real zone vary along its length and differ from the thermocouple, and the total heat exchange factor of a real furnace is estimated from measured temperatures rather than assumed [17, 18].

Steel properties are constant. The heat capacity of carbon steel peaks at its phase transformation and its conductivity changes with temperature, so the mid-furnace temperatures are the least accurate part of the heating curve.

Every slab has the same size, grade and target, and the burners respond instantly to the firing command. The available-heat fraction is a linear function of zone temperature standing in for the combustion and flue gas balance, and scale growth is not modeled.

7.4 Two Levels of Control

The control system is hierarchical, as drawn in Figure 7.3. Level 1 holds the zones. Level 2 decides what they hold, recomputing the three setpoints every 120 s and at reset.

7.4.1 Level 1: Zone Loops

Each zone loop is the velocity-form PID of Section 1.6.2, here without derivative action and with no output bias, executed every $\Delta t = 10$ s on the filtered thermocouple. In the symbols of Equations (1.13) to (1.16), the setpoint is $T_{z,SP}$, the measurement is $T_{m,z}$ and the output u_z is limited to 0 to 100 %. The integral I is seeded with the holding firing at reset and is the only term the limit acts on, by back-calculation with a tracking time equal to τ_I. The loops are reverse acting in the convention of Section 1.6.2, with action $a = +1$, since the zone temperature rises with the firing and a zone below its setpoint raises its firing. The defaults are $K_c = 0.6$ percent per °C for all three zones and $\tau_I = 10$, 10 and 15 min. There is no rate limit on the firing and no feedforward from the slab load. In manual mode each loop tracks the operator's firing so that the transfer to automatic is bumpless.

The loops are fast next to the slabs. With noise off, a 50 °C step in the operator's soak setpoint, which reaches the loop at the next Level 2 calculation, brings the soak zone within 10 °C in 16.0 min and first within 2 °C in 22.8 min, after which it rises to a peak 5.5 °C above the new setpoint at 43 min. This separation is what allows Level 2 to treat a zone setpoint as though it were the zone temperature.

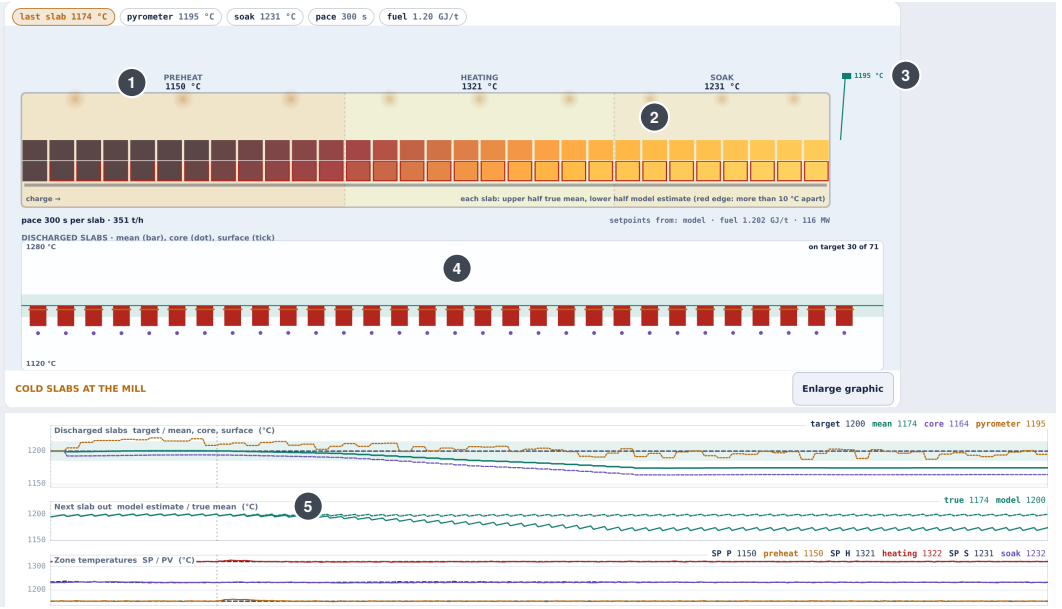


Figure 7.4 A model that is wrong, case 7, six hours into the run with the slab model setting the zones and correction off, cropped to the furnace view and the first three trends. The furnace section shows the zones at 1150, 1321 and 1231 °C, and each slab drawn in two halves, the upper colored by its true mean and the lower by the model's estimate, with a red outline around the lower half wherever the two differ by more than 10 °C. The discharged-slab strip below it shows every recent mean below the target band and 30 of 71 slabs on target, with the status reporting cold slabs at the mill. In the trends the discharged mean falls from 1200 °C to 1174 °C after the fall in heat transfer at 1 h, the pyrometer reads 1195 °C, the model's estimate of the slab about to leave is 1200 °C while its true mean is 1174 °C, and the zone setpoints barely move. Callouts: (1) the zones and their temperatures, (2) the slabs in two halves with the red outlines, (3) the pyrometer reading at the door, (4) the discharged-slab strip with its target band, (5) the trend of the model's estimate against the true mean of the next slab out.

7.4.2 Level 2: Operator and Pyrometer Trim

With operator setpoints the zones hold the nominal values $T_{z,nom}$ of 1150, 1320 and 1230 °C, limited to T_{max}. The pyrometer strategy adds a trim r to the heating and soak setpoints, $T_{H,SP} = \mathrm{clamp}(1320 + r, 800, T_{max})$ and likewise for soak, while preheat stays at nominal. The trim comes from a second velocity-form PI of the same algorithm, also reverse acting, executed once per discharged slab with $\Delta t = t_p$, on the error $e = (\bar{T}_{SP} + 12) - T_{pyro}$. The offset of 12 °C is the assumed surface excess over the mean at the nominal pace. The defaults are $K_c = 0.5$ and $\tau_I = 30$ min, and the trim is limited to ± 120 °C. The T_{max} clamp on the heating setpoint acts after the trim and is not seen by its back-calculation, so a trim above 30 °C leaves the heating zone at 1350 °C while the integral keeps raising the soak setpoint. When another strategy is active the trim loop tracks its last output.

7.4.3 Level 2: The Slab-Tracking Model

The tracker holds its own copy $\hat{T}_{i,j}$ of every slab, integrated by explicit Euler at 10 s from Equations (7.1) and (7.2) with the measured zone temperatures $T_{m,z}$ in place of T_z and its own exchange factor $\hat{\phi}$, which starts at 0.6. It shifts and charges with the true furnace at every walk, so it knows each slab's position, charge temperature and elapsed time exactly. With $\hat{\phi}$ correct its estimate of the

next slab out differs from the truth by at most 0.34 °C over the eight hours of case 4, pace change included.

Every 120 s each tracked slab i asks for the uniform offset δ_i on the nominal profile that brings its predicted discharge mean to the target, Equation (7.5).

$$\bar{\hat{T}}_i(t_{dis};\ \mathrm{clamp}\,[T_{z,nom}+\delta_i,\ 800,\ T_{max}]) = \bar{T}_{SP} \tag{7.5}$$

The prediction marches the slab's cells forward in explicit Euler steps of at most 40 s, or 0.8 of the stability limit $\rho c_p \Delta x^2/2k$ where that is shorter (52.8 s at 250 mm), through the time left at its present position and then t_p at each later position, under the offset zone temperatures and at the present pace. Equation (7.5) is solved for $\delta_i \in [-250, 150]$ by a bracketed secant (false position) iteration of at most seven steps, stopping when the predicted mean is within 0.3 °C of target. A slab that cannot reach the target at the upper bound, or overshoots it at the lower one, returns that bound. The zone setpoint is the nominal plus the average offset of the slabs under it, Equation (7.6).

$$T_{z,SP} = \mathrm{clamp}\left[T_{z,nom} + \frac{1}{n_z}\sum_{i\in z}\delta_i,\ 800,\ T_{max}\right] \tag{7.6}$$

Each δ_i is computed as if it applied to every zone the slab has yet to cross, while the zones receive averages, so the calculation is a heuristic rather than an optimization. The prediction assumes the present pace continues. During a mill delay the walk clock is frozen, the time left at the present position stays constant, and the model responds to the delay through the extra heating it sees in the tracked slabs rather than through knowledge of the delay length. A stopped door slab is not an imminent discharge. At each two-minute Level 2 update during a stop, the soak setpoint is held at the product mean-temperature target, while the preheat and heating zones retain their model calculations. Model planning resumes when the beam moves. The controller uses the current stopped state without forecasting the end of the delay.

> ⧖ HISTORY **Computers Plan the Heating (1985 to 1987)**
>
> By the mid-1980s computer control of a reheating furnace was built around a calculation of the temperature inside the steel, and because it ran on line it had to be fast [19]. Most systems then solved difference equations, since the thermal properties of steel are nonlinear, and a 1985 paper proposed an analytical solution to cut the computing time. A system reported in 1987 computed an optimum temperature profile for the steel in real time to minimize fuel, predicted the temperature of each piece along the furnace with a difference equation, and set each zone's temperature as a weighted average of that profile [20]. In commercial operation it saved at least 10 percent of energy against manual operation and held the discharge temperature within 15 °C of its aim.

7.4.4 Correcting the Model From the Pyrometer

When correction is on, each discharged slab gives one residual, the pyrometer reading minus the surface $\hat{T}_s$ the tracker predicts for that slab from its cells, the measured soak temperature and $\hat{\varphi}$. A shadow tracker runs the same equations at $\hat{\varphi}+\varepsilon$ with $\varepsilon = 0.01$, so the sensitivity of every tracked cell to the exchange factor is a finite difference, $S_k = (\hat{T}'_k - \hat{T}_k)/\varepsilon$. The update is a damped Gauss-Newton step on the scalar $\hat{\varphi}$, Equation (7.7).

$$\Delta\hat{\varphi} = \frac{g\,\mathrm{clamp}\left(T_{pyro}-\hat{T}_s,\ -60,\ 60\right)}{\max\left(20,\ \partial\hat{T}_s/\partial\hat{\varphi}\right)} \tag{7.7}$$

with gain $g = 0.3$ by default and $\hat{\varphi}$ limited to $[0.3, 1.0]$. The same step is then applied to every tracked cell and its shadow, $\hat{T}_k \leftarrow \hat{T}_k + S_k\Delta\hat{\varphi}$, so that the slabs still in the furnace take on the history they would have had under the new exchange factor at once. In the wrong-model scenario the surface sensitivity is about 135 °C per unit of φ, so a 1 °C residual moves $\hat{\varphi}$ by about 0.002 at the default gain.

7.4.5 A Joint Predictive Zone Profile

A receding-horizon alternative jointly chooses the three zone setpoints, rather than averaging independently requested offsets. It is the app's predictive option of Section 1.6.3, built here on a slab model of its own. Predictive reheating formulations motivate this comparison [14, 16, 21]. Its separate 150-cell tracker uses the conduction and radiation balances of Equations (7.1) and (7.2) at declared nominal values: 250 mm, $k = 30\,\mathrm{W/(m\,K)}$, $\rho c_p = 5.07\,\mathrm{MJ/(m^3\,K)}$ and $\varphi = 0.6$. Measured zone temperatures drive ten-second observer steps. The measured charge temperature and current walking pace determine slab entry and shifts. Neither true slab cells, changed thermal coefficients nor a future event schedule is supplied.

When correction is enabled, each discharged pyrometer reading updates a surface-output bias as $b^+ = \mathrm{clip}[b + 0.2(T_{pyro} - \hat{T}_s - b), -40, 40]$. The same bias corrects predicted mean and core outputs. This approximation does not identify the exchange factor or its influence on the internal profile. Its restrictions differ from the parameter correction of the slab model, and no general offset-free guarantee is assigned to it [22]. Volume 9, Chapter 4 treats an offset-free predictive controller whose estimator carries a disturbance bias.

Every 120 s, six cohorts at positions 5, 10, 15, 20, 25 and 30 are predicted to discharge at the present pace. At 300 s per slab, the longest remaining interval is at most 130 min. There is one constant future zone profile, replanned each decision, rather than a time-varying sequence of future setpoints. Prediction uses 20 s Euler cell steps and approximates future zone tracking as instantaneous, as the slab model's predictor does. During a stop, only the two soak cohorts constrain a stationary 30 min forecast. No stop-end time is read.

Central perturbations of $\pm 5\,\mathrm{K}$ produce a local 12-output, three-input map $\hat{y} \simeq c + Hu$, whose outputs are six discharge means and six cores. For u the zone setpoints and u^- their previous values, the five-variable quadratic program minimizes

$$J = \sum_i \frac{(\hat{\bar{T}}_{i,dis} - T_{SP})^2}{225} + 0.0003\|u - u^-\|^2 + 0.0001\sum_z u_z + 0.1\sigma_m^2 + \sigma_c^2. \tag{7.8}$$

Each predicted mean has band $T_{SP} \pm 15$ K enlarged by shared slack $\sigma_m \geq 0$, and each core has floor $T_{SP} - 40 - \sigma_c$ K. Setpoints satisfy $800 \leq u_z \leq T_{max}$ and move at most 30 K from the previous profile clipped into this box. A 10^{-8} ridge is added to the three setpoint diagonals. The linear temperature price is a proxy, not a calculation of fuel cost. In a stop, the objective and output bands apply only to the two soak cohorts.

Independent implicit-surface calculations differ from the five-substitution surface routine by at most 0.002 95 K at three temperatures. Repeating the map with $\pm 2.5\,\mathrm{K}$ changes sensitivities by at most 3.08×10^{-6} K/K. Across the measured runs, the largest nonlinear versus local-map output error at the chosen profile is 0.552 K. A failed or invalid solve retains the last valid profile under the zone PIs, clamped to the current setpoint ceiling even on failed startup. The next valid profile resumes planning. The other three strategies do not change when this option is present.

7.5 Results

Table 7.3 lists the eleven scenarios, and Table 7.4 gives what each one measured. Every value was measured on the application's engine at its default seed, which the application uses on every run (Section 1.6.1), and the spread over other noise seeds is stated where it matters. A slab is on target when its discharge mean is within 15 °C of the target, and the rms error is over every slab discharged in the run. An alternative setting such as the operator setpoints in case 5 is chosen before the run starts, and the application gives one run whether it is chosen then or carried through a restart. Figure 7.5 draws the main outcomes as a chart.

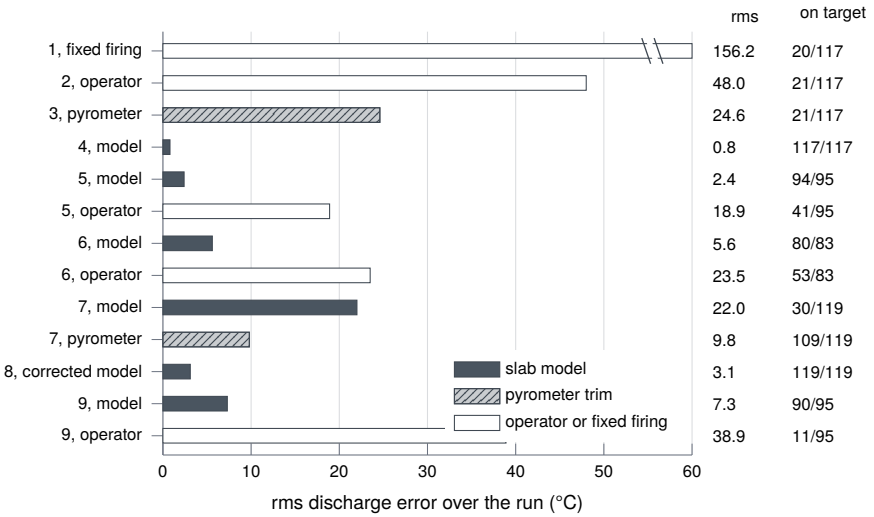


Figure 7.5 The scenario outcomes of Table 7.4 as a chart: the rms discharge error of each case and setpoint source (bars and first column, in °C) and the slabs on target (second column). The case 1 bar is cut at 60 °C. Notice that wherever a case is run with two setpoint sources, the solid bar of the slab model is the shorter, except in case 7, where the model is wrong and uncorrected and the hatched pyrometer bar beats it.

Table 7.3 Scenario Sequence. Events at 1 h Unless Stated

#	Scenario	Setpoints	Event
1	fixed firing (manual)	—	pace 240 s
2	holding the zones	operator	pace 240 s
3	pyrometer trim	pyrometer	pace 240 s
4	slab tracking	model	pace 240 s
5	hot charge	model	$T_{ch} = 450\,°C$
6	mill delay	model	60 min at 2 h
7	a wrong model	model	φ −15 %
8	model corrected	model, $g = 0.3$	φ −15 %
9	harder grade	model	target 1240 °C
10	predictive profile	MPC, bias correction	pace 240 s
11	challenge, 12 h	operator	all four

7.5.1 Holding the Firing and Holding the Zones

In case 1 the firing stays at 61, 52 and 33 % when the mill speeds up from 300 to 240 s per slab. The faster slabs arrive colder and draw more heat, the zones sag to 1131, 1226 and 1073 °C after eight hours, and the last slabs leave at about 1004 °C. The zones are not fast in open loop either. Raising the soak firing from 33 to 43 % at the start of case 1 lifts the soak zone above an otherwise identical run by 22.7 °C in 30 min, 32.5 °C in 1 h and 37.4 °C in 2 h, still rising because the slabs beneath it warm and take less heat.

Case 2 closes the zone loops at the operator setpoints. The zones stay within 7 °C of their setpoints, the largest excursion being a 6.8 °C dip of the soak zone at two hours as the faster slabs reach it. The slabs leave at a mean of about 1145 °C with a core of 1128 °C, the heating curve of Figure 7.2 at the faster pace. Only 21 of 117 slabs are on target, all of them discharged in the first 1.6 h. Level 1 has done its job and the product is 55 °C cold.

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

Table 7.4 Measured Scenario Outcomes. Cases 1 to 6 and 9 Over 8 h, 7 and 8 Over 10 h. Late Mean Is the Average of the Last Ten Slabs

Case and setpoints	on target	rms (°C)	late mean	GJ/t
1, fixed firing	20/117	156.2	1004	0.991
2, operator	21/117	48.0	1145	1.134
3, pyrometer	21/117	24.6	1177	1.169
4, model	117/117	0.8	1200	1.214
5, model	94/95	2.4	1200	0.923
5, operator	41/95	18.9	1224	0.955
6, model	80/83	5.6	1200	1.246
6, operator	53/83	23.5	1199	1.260
7, model	30/119	22.0	1174	1.199
7, pyrometer	109/119	9.8	1192	1.218
8, corrected model	119/119	3.1	1203	1.235
9, model	90/95	7.3	1240	1.299
9, operator	11/95	38.9	1199	1.227

Table 7.5 Tuning Studies. Pyrometer Trim Gain in Case 3 Over 8 h, and Correction Gain and Pyrometer Noise in Case 8 Over 10 h

Case	Setting	on target	rms (°C)	late mean
3	$K_c = 0.2$	21/117	30.3	1174
3	$K_c = 0.5$ (default)	21/117	24.6	1177
3	$K_c = 1.0$	21/117	22.4	1177
8	$g = 0.1$, $\sigma_p = 5$	119/119	4.4	1202
8	$g = 0.3$, $\sigma_p = 5$ (default)	119/119	3.1	1203
8	$g = 1.0$, $\sigma_p = 5$	119/119	3.5	1205
8	$g = 0.1$, $\sigma_p = 15$	115/119	6.9	1206
8	$g = 0.3$, $\sigma_p = 15$	113/119	7.8	1209
8	$g = 1.0$, $\sigma_p = 15$	102/119	9.6	1214

TRY IT IN THE APP **2 · Holding the Zones, Not the Slabs**

Load scenario 2 and press Run. Watch the discharged-slab strip under the furnace after the mill speeds up at one hour. The zones stay within 7 °C of their setpoints, yet the slabs drop below the target band and stay there, about 55 °C cold. Only the slabs that left in the first 1.6 h are on target.

7.5.2 A Loop on the Surface

Case 3 trims the heating and soak setpoints to hold the pyrometer at 1212 °C. The loop succeeds, and the last ten slabs have a surface of 1212 °C (1210 °C as read by the noisy pyrometer) with a mean of 1177 °C and a core of 1159 °C. The heating setpoint reaches its 1350 °C limit at 4.3 h. At the faster pace the surface-to-core gap widens to about 53 °C against 19 °C at the nominal pace. The shorter stay causes most of the widening, since the operator setpoints of case 2 leave nearly the same gap at the same pace, and the hotter zones add little to it. The fixed 12 °C offset therefore no longer relates the surface to the mean, and 96 of 117 slabs still leave more than 15 °C cold. The rms error halves, from 48.0 to 24.6 °C.

No tuning of the trim loop repairs this, as reported in Table 7.5. A gain of 0.2 settles the mean at about 1174 °C and a gain of 1.0 at about 1177 °C, the same as the default, and all three put the same 21 slabs on target. The loop is controlling the wrong variable, and a faster loop only reaches the wrong answer sooner.

Pause. Try Exercise 7.2 before reading on.

7.5.3 Planning With the Slab Model

Case 4 takes the setpoints from the slab model. At the pace change every tracked slab has less time left, and the Level 2 calculation on the scan of the change raises the setpoints from nominal to 1192, 1347 and 1244 °C. They end at about 1195, 1350 and 1277 °C, with the heating zone on its limit from 1.1 h. All 117 slabs leave within 15 °C of target, 0.8 °C rms. The surface-to-core gap still reaches 53 °C, about as much as under the operator setpoints at the same pace, and the calculation does not constrain it. The price is 1.214 GJ/t of fuel against 1.134 GJ/t for the operator setpoints, which deliver cold slabs.

The charge temperature enters the tracker as a known initial condition, so hot charging acts as feedforward. In case 5, slabs charged at 450 °C lower each zone's setpoint as they reach it, to minima of 1126, 1294 and 1161 °C, and the soak setpoint first falls 110 min after the first hot slab enters, when that slab reaches the soak zone. Of 95 slabs, 94 are on target at 0.923 GJ/t. With the operator setpoints the hot slabs leave at about 1224 °C, 54 of 95 are more than 15 °C hot, and the fuel is 0.955 GJ/t, about 3.5 % more.

In case 6 the mill stops for an hour at two hours, on the scan at which a walk falls due, so the slab at the door waits out the delay. The tracked slabs keep heating while the beams stand still, and the model cuts the preheat and heating setpoints to 1117 and 1264 °C by the end of the delay. The soak setpoint holds 1200 °C during the delay and falls to 1133 °C at 3.6 h as the slabs that waited under the heating zone reach it. The furnace burns 249 GJ during the delay against 295 GJ with the operator setpoints, and the first fourteen slabs after the restart leave at 1194 to 1216 °C against 1227 to 1257 °C. Over the run 80 of 83 slabs are on target with the model and 53 with the operator setpoints.

> **DID YOU KNOW? Better and Cheaper With Hot Slabs**
>
> From the simulator: with slabs charged at 450 °C in case 5, the slab model puts 94 of 95 on target at 0.923 GJ/t, while the operator setpoints put 41 of 95 on target at 0.955 GJ/t (Table 7.4). Here accuracy and fuel do not trade against each other: using the charge temperature wins both.

Case 9 raises the target to 1240 °C. The soak setpoint rises to about 1334 °C, but the slabs near the door have too little time left, and the five discharged from the change to 20 min after it leave at 1200 to 1225 °C. From 25 min on every slab is within 15 °C of the new target, and 90 of 95 are on target over eight hours. The operator setpoints, unchanged, put 11 of 95 on target.

7.5.4 A Wrong Model and Its Correction

Case 7 lowers the true exchange factor by 15 % at one hour. The tracker still computes with 0.6, so every tracked slab heats faster in the model than in the furnace. From four hours on, its estimate of the next slab out reads 1196 to 1200 °C while the true mean is 1167 to 1174 °C, the setpoints stay within 6.2 °C of nominal, and the slabs leave at about 1174 °C, as shown in Figure 7.4. Only 30 of 119 are on target. Over the last ten slabs the pyrometer reads 17.0 °C below the predicted surface while the true mean is 25.8 °C below the predicted mean, so the residual is available and nothing uses it. The pyrometer strategy on the same furnace puts 109 of 119 on target, because it at least sees the disturbance.

Pause. Try Exercise 7.3 before reading on.

> **TRY IT IN THE APP 7 · A Model That Is Wrong**
>
> Load scenario 7 and run past four hours. Each slab is drawn in two halves, the upper colored by its true mean and the lower by the model's estimate, with a red edge where they differ by more than 10 °C. The model's next slab out reads 1196 to 1200 °C while its true mean is 1167 to 1174 °C.

Case 8 switches the correction on. The exchange factor estimate first falls below 0.53 at 3.2 h, and between four and ten hours it averages 0.508 with a standard deviation of 0.008 and a range of 0.491

Table 7.6 Challenge Outcomes Over 12 h. Worst Is the Largest Discharge Error in the Last 4 h

Setpoints from	on target	rms (°C)	worst (°C)	GJ/t
operator (as loaded)	22/159	59.7	97.8	1.011
pyrometer	59/159	35.9	46.5	1.040
model	66/159	23.2	50.7	1.040
model, corrected	150/159	8.6	37.0	1.066
same, $K_{c,S} = 1.2$	151/159	7.7	33.1	1.066

to 0.535, against a true value of 0.51. All 119 slabs are on target, 3.1 °C rms, with means between 1192 and 1205 °C. With the pyrometer noise set to zero the estimate stays within 0.507 to 0.510 over the same interval and the error falls to 1.5 °C rms, so the residual scatter of $\hat{\varphi}$ is the pyrometer noise passed through Equation (7.7).

The correction gain trades speed against that noise, as reported in Table 7.5. At 5 °C noise a gain of 1.0 brings $\hat{\varphi}$ below 0.53 by 1.6 h but spreads it over 0.462 to 0.565, while a gain of 0.1 takes until 3.5 h and holds it within 0.499 to 0.518. At 15 °C noise every gain loses slabs, and the largest gain loses the most, 17 of 119 off target against 4 at a gain of 0.1. That ranking holds on average over ten noise seeds (14.9 against 6.4 slabs off target) but not at every seed.

7.5.5 The Graded Challenge

The twelve-hour challenge opens with a one-hour mill delay at one hour, the pace change at three, the fall in exchange factor at five and hot charge at seven, starting on the operator setpoints. It is met when at least 90 % of slabs are on target and none is more than 40 °C off in the last four hours. The outcomes appear in Table 7.6.

As loaded, 22 of 159 slabs (13.8 %) are on target, the worst late error is 97.8 °C, both criteria fail, and slabs leave between 1101 and 1257 °C. The uncorrected model answers the delay, the pace and the hot charge, and the pyrometer the change in heat transfer, but each alone puts fewer than half the slabs on target. Only the corrected model meets both criteria, with 150 of 159 slabs on target and a worst late error of 37.0 °C. That worst slab is the first hot-charged slab to reach the door, 37.0 °C hot at 9.05 h, while the cold-charged slab ahead of it leaves 16.5 °C cold, because the soak zone receives the average offset of both kinds. The corrected model also burns the most fuel, 1.066 GJ/t, because the other configurations discharge 73 to 109 slabs cold. Its margins are narrow, six slabs and 3.0 °C, and on sixty additional noise seeds (1 through 60) it passes at 47. The suggested settings therefore also raise the soak loop gain from 0.6 to 1.2, so the soak zone follows its fast-moving setpoint more closely (17.3 °C rms deviation at logged samples against 22.7 °C). They put 151 slabs on target (95.0 %) with a worst late error of 33.1 °C, again the first hot-charged slab, passing by seven slabs and 6.9 °C, and pass at 58 of those 60 additional seeds. The run is the same whether the settings are chosen before Run or carried through a restart. Changing a model parameter or a disturbance voids the attempt.

7.5.6 Joint Planning and Its Counterfactuals

Case 10 runs the predictive profile with both corrections on, the same seed, sensors and pace step at 1 h as case 4. Table 7.7 measures 8 h, except 10 h for the wrong-model/correction pair and 12 h for the challenge. In case 10 the rms error falls from 3.15 to 1.52 °C, with all 117 slabs on target, while fuel rises from 1.215 to 1.221 GJ/t. Setpoint travel falls from 2236 to 520 °C, as shown in Figure 7.6.

This nominal gain is not evidence that joint optimization is required. With correction off under both methods, the slab model achieves 0.756 °C rms against MPC's 1.348 °C. The smoother bias avoids part of the noise-driven parameter adjustment. A six-setting hindsight slab-model grid has best rms 2.83 °C with correction on, and establishes no optimum over all classical tunings. Half-step integration preserves the paired result, 3.153 versus 1.520 °C.

Table 7.7 Matched Slab-Model and Predictive Profiles

Case, law	On target	rms (°C)	GJ/t
Case 10, Slab	117/117	3.15	1.215
Case 10, MPC	117/117	1.52	1.221
Pace, no bias, Slab	117/117	0.76	1.214
Pace, no bias, MPC	117/117	1.35	1.222
Hot charge, Slab	94/95	2.43	0.923
Hot charge, MPC	94/95	3.14	0.871
Mill delay, Slab	80/83	5.55	1.246
Mill delay, MPC	61/83	13.91	1.387
Wrong model, Slab	30/119	21.99	1.199
Wrong model, MPC	29/119	22.67	1.194
Correction on, Slab	119/119	3.14	1.235
Correction on, MPC	114/119	8.67	1.208
Grade step, Slab	90/95	7.27	1.299
Grade step, MPC	90/95	7.91	1.255
Challenge, Slab	151/159	7.66	1.066
Challenge, MPC	125/159	13.15	1.074

On hot charge, MPC uses 0.871 versus 0.923 GJ/t, with 94 of 95 slabs on target under each law. The final slab-plus-zone stored heat is 830.6 rather than 896.2 GJ, against 2421.5 rather than 2564.4 GJ of firing. The 65.6 GJ lower inventory qualifies the 142.9 GJ firing reduction, so GJ/t alone is not a steady-operation saving. On the mill delay it loses, 61 rather than 80 of 83 slabs, with 13.91 rather than 5.55 °C rms and higher fuel. A stationary half-hour forecast and one constant profile do not reproduce the slab model's delay rule. Output bias also corrects changed heat transfer less effectively than parameter adaptation, 114 versus 119 of 119 slabs on target. With the challenge's suggested settings the MPC fails at 125 of 159 slabs, while the slab model passes at 151 of 159. Its worst late error is 32.96 °C, so the failed criterion is the fraction of on-target slabs.

Core prediction is not core measurement. On the grade step, four MPC slabs rather than three under the slab model have true cores below their target minus 40 K. Actual zone temperatures can also overshoot bounded setpoints: in the challenge with the suggested settings the heating zone peaks at 1354.5 °C under MPC and 1357.6 °C under the slab model. Soft output bands and hard setpoint boxes are consequently not physical temperature guarantees. Chrome mean solve times are 1.60–1.76 ms over six 60-plan captures, at most 0.0880 % core at 60 s/s playback and 5.28 % at the top 3600 s/s setting. Ordinary comparisons have no rejected plans. Eight injected invalid solver results are rejected, and two independent measurement rows reproduce exactly.

7.6 Technology in Practice

What Measures It

The variable the mill cares about, the discharge mean, has no sensor. Two instruments stand in for it. Each zone loop reads a thermocouple through the furnace wall, and a radiation pyrometer reads the surface of each slab as it leaves. The furnace temperature is thus a reading at one place. A 1973 study noted that steelmakers did not define the representative gas temperature of a furnace in the same way, and examined how the position of the reading changes the exchange factor estimated from it [23].

> **TECHNOLOGY Sensor: The Radiation Pyrometer**
>
> A radiation pyrometer concentrates the infrared light from a hot surface onto a small sensing element with a lens or a mirror, and the radiant energy grows with the fourth power of absolute temperature [24]. That steep law limits a pyrometer to a narrow range wherever good accuracy is needed. Its calibration does not depend on distance, because a pyrometer farther away sees a larger patch of the same surface. It reads only the surface, never the temperature inside an object. Its main weakness is emittance, which depends on the material, the finish and the shape and is known for certain only by testing the object at a known temperature.

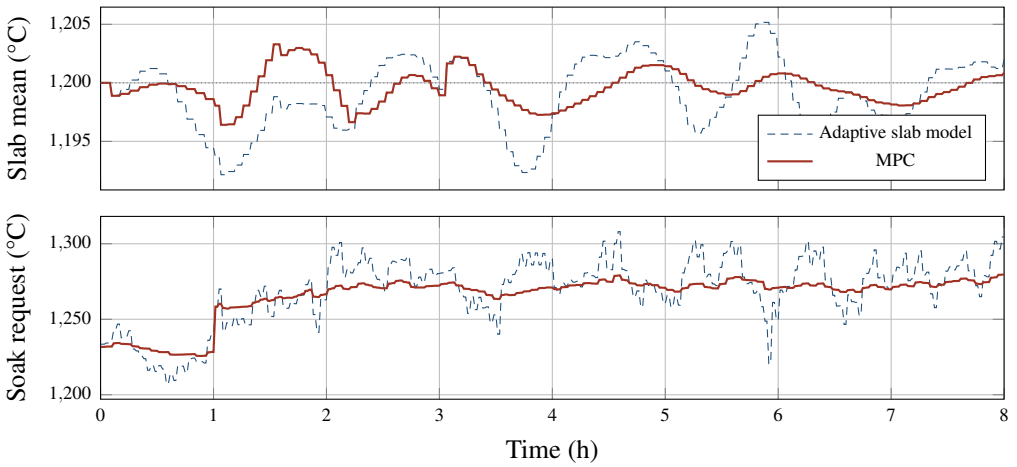


Figure 7.6 Discharged means and soak setpoints in case 10 with both corrections enabled, under the adaptive slab model (dashed) and the MPC (thick solid), with the 1200 °C target dotted. The pace changes after one hour.

In the model of Section 7.3 the thermocouple is the 2 °C noise and the 30 s filter, and the pyrometer is the true surface plus 5 °C of noise. A real pyrometer also carries the error of an uncertain emittance, which the model does not represent.

What Moves It

The zone loop's output u_z is a firing command in percent of burner capacity. On a real furnace it becomes setpoints for the fuel and air flows of the zone's burners, fired from above and below the slabs.

> **TECHNOLOGY** **Final Element: Cross-Limited Fuel and Air**
>
> A zone's firing command is carried out by two flow loops, one on the fuel and one on the combustion air of its burners [24]. With a plain ratio, a step in the command can put fuel ahead of air for a moment, a rich and dangerous mixture. Cross-limiting prevents it with two selectors. The air controller takes the greater of the command and the measured fuel flow, and the fuel controller the lesser of the command and the measured air flow, so air leads on a rise, fuel leads on a fall, and every transient runs lean. A rate limiter on the command keeps a lean transient from blowing the flame out, and a multiplier sets the air to fuel ratio.

The simulated burners respond instantly to the command, with no flow loops, no air ratio and no rate limit, as Section 7.3 states. Figure 7.7 draws the loops with the real devices in place.

Where the Controller Runs

The chapter's two levels map onto the control hierarchy of a plant. In a distributed control system a supervisory controller sends set points to the distributed field controllers and requests data from them, and the field controllers move their actuators on those commands and on sensor feedback [25]. Supervisory loops and lower loops run with cycle times from milliseconds to minutes. The three zone PI blocks of Level 1 would run in such a field controller, and the simulator executes them every 10 s. The slab-tracking model, its correction and the predictive option belong to the supervisory Level 2 computer, which in the simulator recomputes the setpoints every 120 s.

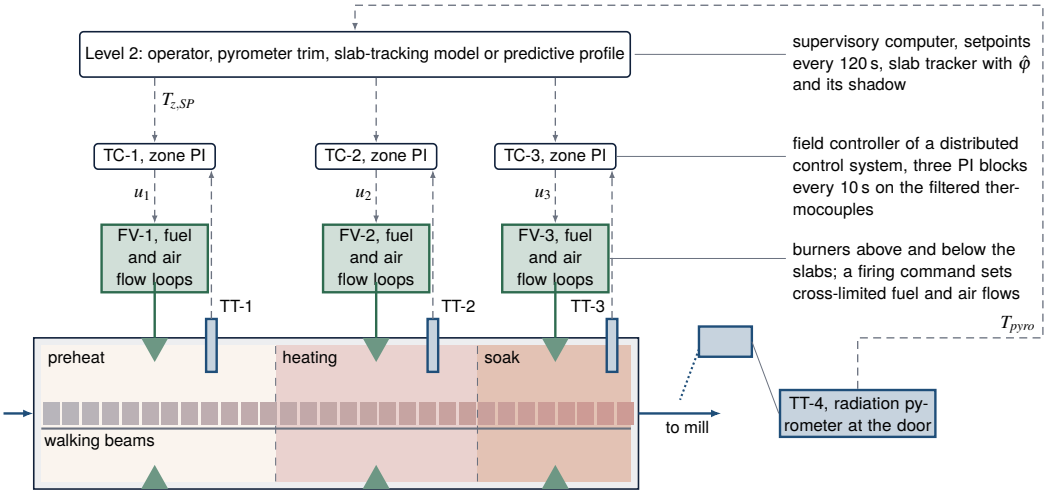


Figure 7.7 The reheat furnace loops drawn with their hardware. Each zone controller TC-1 to TC-3 reads a thermocouple through the roof, TT-1 to TT-3, and sends a firing command to the fuel and air flow loops FV-1 to FV-3 of its burners. The radiation pyrometer TT-4 reads each slab's surface at the door and reports only to Level 2. Notice that no device reads the slab mean: Level 2 turns the pyrometer and the zone readings into the three setpoints.

> **IN PRACTICE** **Decide Which Way a Thermocouple Fails**
>
> The most common failure of a thermocouple is to fail open, known as burning out [24]. An open input lets electrical noise from power lines, motors and drives reach the instrument, where it reads as a wildly varying temperature. Instruments therefore carry a burnout mode that sends the reading to a set end of the scale, and the choice is a safety decision. For a furnace in which too high a temperature is the greater danger, the field text advises high burnout: a burnt-out thermocouple then reports a false high temperature, and the controller lowers the firing. In the reverse-acting zone loops of this chapter, a reading pinned high would cut the firing of that zone.

What Is Modernizing It

Predictive control is reaching the events that the slab model of this chapter handles by rule. A strategy for mixed loading and delays in a walking-beam furnace solves its optimization by a rolling horizon with weights adjusted in real time, and in simulation it raised the control accuracy from 74.79 to 99.17 percent over three typical delay cases [16], the direction taken by the predictive option of Section 7.4.5.

Hot charging changes the furnace's work. Slabs charged directly from the caster need less reheating than slabs cooled to air temperature, which take longer and use more energy [26], as case 5 shows when the model lowers its setpoints for slabs charged at 450 °C.

Combustion itself is changing. A United States energy study lists a next-generation system for scale-free reheating, which uses preheated or oxygen-enriched air to control the flue gas, improves the quality and yield of the steel, and is estimated to save 0.2 GJ/t during reheating [26]. Electric heating, which would remove the flame altogether, is still an open challenge.

7.7 Limitations

The slab is one-dimensional with constant properties, so skid marks, edge effects and the heat capacity peak at the phase transformation are absent.

One exchange factor applies to the whole furnace and changes as a step. In a real furnace it varies by zone and drifts with scale and atmosphere, and a single pyrometer residual per slab cannot separate the zones.

> **OPEN CHALLENGE** **An Exchange Factor That Will Not Stay Put**
>
> Every slab-tracking model rests on a total heat exchange factor, and the factor belongs to the operation as much as to the furnace. A 1973 study estimated it at 0.64 for heavy oil firing and 0.3 for gas firing, both with the gas temperature read by a thermocouple through the furnace wall [23]. A 2021 model of a regenerative furnace found that it rises as fuel consumption or the hot charging temperature falls, and as productivity rises [18]. Its authors offer the result for dynamic compensation of the factor in on-line control models. Progress would be a factor estimated zone by zone, while the furnace runs, from measurements a plant already has.

The slab-model calculation is a per-slab offset averaged by zone, not an optimization over the schedule. It has no fuel term, no bound on the surface-to-core gap, no knowledge of the delay length and no look-ahead to announced grade or pace changes. Predictive formulations that optimize the zone temperatures over a horizon, including through delay operations, are the established answer to these omissions [14, 16].

The predictive option adds soft core and mean bands for six cohorts, but uses one future profile, nominal properties and a scalar surface bias. These restrictions explain the delay and changed-transfer losses. Its temperature price is not a fuel objective.

The fuel per tonne does not credit the heat stored in the slabs still in the furnace, so it compares fairly only runs that end with similar furnace contents.

> **OPEN CHALLENGE** **Heating Slabs With Electricity**
>
> Slabs are reheated to about 1250 °C for rolling, and 1 to 3 percent of the steel is lost to oxidation on the way [27]. Electric resistance heating needs no combustion atmosphere, so it could remove that loss and cut carbon dioxide emissions, and it offers more control of zone temperature than gas burners. For large slabs it is not yet possible. They need many heating elements close to the slab surface, which means elements across the roof, and the usual molybdenum silicide element creeps badly: it serves hung on the side walls, but mounted across the roof it must run well below its maximum temperature. Progress would be an element that keeps its shape when mounted horizontally at furnace temperature.

7.8 Conclusion

This chapter studied a reheat furnace, which heats a moving product whose one important temperature is never measured. In the simulator, zone loops that hold their setpoints through a pace change deliver slabs 55 °C cold, and a pyrometer loop that holds the surface leaves the mean between 1174 and 1177 °C for every trim gain tried. A slab-tracking model that plans the zone setpoints puts all 117 slabs on target through the same pace change, uses the charge temperature of hot slabs as feedforward, and cuts the fuel burned in a one-hour delay from 295 to 249 GJ. When the exchange factor falls 15 % the same model discharges 30 of 119 slabs on target while reading on target, and a Gauss-Newton correction from the pyrometer restores all 119 with $\hat{\varphi}$ averaging 0.508 against a true 0.51. The Level 2 calculation is a heuristic without fuel or gap terms, and the slab is one-dimensional. The joint predictive option saves hot-charge fuel, but loses to the slab model's delay rule and fails the challenge with the suggested settings. A fuller model would add per-zone exchange factors, mixed slab sizes and announced delays. The furnace is an accessible case of estimating, planning with and correcting the state of a product nobody measures.

KEY POINTS

- The furnace must deliver slabs hot all the way through, and no instrument reads the inside of a slab.
- Zone loops that hold their setpoints through a pace change deliver slabs 55 °C cold, and a pyrometer loop on the surface leaves the mean between 1174 and 1177 °C for every trim gain tried.
- A slab-tracking model that plans the zone setpoints puts all 117 slabs on target through the same pace change and uses the charge temperature of hot slabs as feedforward.
- When the exchange factor falls 15 % the model reads on target while 30 of 119 slabs are, and a correction from the pyrometer restores all 119.

Where else this applies. A brick core that is never measured in Volume 5, Chapter 11 and a moving ribbon in Volume 5, Chapter 5 call for the same model run beside the plant.

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7.9 Exercises

7.1 ⌕ Concept check · 2 min

In case 2 the mill pace rises from 300 to 240 s per slab at 1 h. The three zone loops then hold their zones within 7 °C of the operator setpoints, yet the slabs leave about 55 °C cold. Which explanation is right?

(a) Each slab now stays 2 h instead of 2.5 h, so the same zones put less heat into it

(b) The zone loops are too slow for the pace change, so the zones sag below their setpoints for hours

(c) The faster slabs reach the soak zone hotter, so the soak loop cuts its firing and the mean falls

(d) The soak loop winds up against its lower firing limit after the pace change and stays there

7.2 ⌕ Concept check · 2 min

In case 3 a PI loop trims the heating and soak setpoints until the pyrometer reads the target plus 12 °C, 1212 °C. It succeeds, yet after the pace change the mean of the last ten slabs is 1177 °C. Which explanation is right?

(a) The 5 °C pyrometer noise biases the trim integral toward a surface that is too low

(b) At the faster pace the surface runs further ahead of the mean, so the fixed offset no longer fits

(c) The heating setpoint sits at its 1350 °C limit, and a higher trim gain would reach target

(d) The trim leaves the preheat zone at nominal, and that cold zone sets the mean the slabs reach

7.3 ⌕ Concept check · 1 min

In case 7 the true exchange factor falls by 15 % and the slab model is not corrected. Its estimate of the next slab out reads about 1200 °C while the true mean is about 1174 °C. Which signal shows that the model is wrong?

(a) The zone thermocouples, which read lower than the model expects them to read
(b) The model's estimate of the next slab out, which drifts below the target
(c) The pyrometer reading minus the surface the model predicts for the same slab
(d) The fuel per tonne, which climbs above its value with the right exchange factor

7.4 Theory and calculation · 6 min

The slab is 250 mm thick with $k = 30\,\mathrm{W/(m\,K)}$, $\rho c_p = 5.07\,\mathrm{MJ/(m^3\,K)}$, $N_c = 5$ cells per half thickness and an exchange factor $\varphi = 0.6$.

(a) Find the cell width Δx and the conduction time $(h/2)^2 \rho c_p / k$. *Checkpoint:* 25 mm and 44.0 min.

(b) Find the radiant coefficient $4\varphi\sigma T^3$ at 1230 °C and the Biot number on the half thickness. *Checkpoint:* 462 W/(m^2 K) and 1.93.

(c) The predictor of the slab model takes explicit Euler steps of 40 s, shortened to 0.8 of the stability limit $\rho c_p \Delta x^2 / 2k$ where that is shorter. Find the step at 250 mm and at the 180 mm minimum of the thickness slider. *Checkpoint:* 40 s (limit 52.8 s) and 21.9 s (limit 27.4 s).

7.5 Theory and calculation · 6 min

Each slab is 10 m long, 1.5 m wide and 250 mm thick and weighs 29.25 t. The furnace holds thirty slabs, twelve in preheat, ten in heating and eight in soak, and the model's steel has $\rho c_p = 5.07\,\mathrm{MJ/(m^3\,K)}$.

(a) Find the throughput and the residence time at the nominal pace of 300 s and at 240 s, and the time spent in the soak zone at each pace. *Checkpoint:* 351 t/h, 2.5 h, 40 min. 438.75 t/h, 2.0 h, 32 min.

(b) Find the density implied by the slab mass, the specific heat of the model's steel and the heat needed per tonne to raise the steel from 25 to 1199 °C. *Checkpoint:* 7800 kg/m^3, 650 J/(kg K), 0.763 GJ/t.

(c) At the nominal state the zones fire 117.9 MW in all. Find the gross fuel per tonne and the thermal efficiency. *Checkpoint:* 1.21 GJ/t and 63 %.

7.6 Theory and calculation · 6 min

The correction of Equation (7.7) moves $\hat{\varphi}$ by $g\,(T_{pyro} - \hat{T}_s)$ divided by the surface sensitivity. In the wrong-model case the sensitivity is about 135 °C per unit of φ and the default gain is $g = 0.3$.

(a) The true exchange factor falls by 15 % from 0.6. Find its new value. *Checkpoint:* 0.51.

(b) Over the last ten slabs of case 7 the pyrometer reads 17.0 °C below the predicted surface. Find the step in $\hat{\varphi}$ that one such residual gives at the default gain. *Checkpoint:* -0.038.

(c) A single reading carries pyrometer noise with a standard deviation of 5 °C. Find the step that this alone gives at $g = 0.3$ and at $g = 1.0$, and say what the difference means for the estimate. *Checkpoint:* 0.011 and 0.037.

7.7 App challenge · 8 min

Load scenario 2, Holding the zones, not the slabs, and change no setting. The mill speeds up to a slab every 240 s at 1 h. Run 8 h at the default seed, at the 3600 speed setting.

(a) Read the On target, Discharge error rms, Fuel and Worst surface-core gap tiles of the scorecard. *Checkpoint:* 21 of 117, 48.0 °C, 1.134 GJ/t, 53 °C.

(b) Set Zone setpoints from to Slab model, press Reset and run 8 h again. Read the same four tiles. *Checkpoint:* 117 of 117, 0.8 °C, 1.214 GJ/t, 53 °C.

(c) Find the extra fuel per tonne of the second run as a percentage of the first, and say what the two gap tiles show about the cause of the wide gap. Accept the tile values exactly, and the percentage within 0.2 points. *Checkpoint:* 7.1 %.

7.8 App challenge · 9 min

The true exchange factor falls by 15 % at 1 h in both scenarios below. Use the default seed and the 3600 speed setting, and run each for 10 h.

(a) Load scenario 7, A model that is wrong, and run it as given. Read the On target, Discharge error rms and Model exchange factor tiles. *Checkpoint:* 30 of 119, 22.0 °C, 0.600.

(b) Load scenario 8, Correcting the model from the pyrometer, and run it as given. Read the same tiles, then export the CSV file and find the first row after 1 h at which the column `phi_hat` is below 0.53. The time column is in hours. Accept a time within 0.05 h. *Checkpoint:* 119 of 119, 3.1 °C, 0.535, and 3.18 h.

(c) The tile of part (b) reads 0.535 against a true 0.51. Is that evidence of a bias in the estimate? Say how the file answers the question.

7.9 App challenge · 8 min

Load scenario 6, A mill delay. The mill stops for 60 min at 2 h. Use the default seed and the 3600 speed setting.

(a) Run 8 h as given, with the Slab model. Export the CSV file and read the column `fuel_GJ` in the rows at 2.0 and 3.0 h, and the soak setpoint `SP_S_C` during the delay. Read the On target tile at 8 h. *Checkpoint:* 854.2 and 1103.6 GJ, a soak setpoint of 1200 °C, and 80 of 83.

(b) Press Reset, set Zone setpoints from to Operator before Run, and run 8 h again. Read the same rows of `fuel_GJ` and the On target tile. *Checkpoint:* 852.3 and 1147.6 GJ, and 53 of 83.

(c) Find the fuel burned during the delay in each run. Accept each within 1 GJ. *Checkpoint:* 249.4 GJ and 295.2 GJ.

7.10 Application area · 4 min

Case 5 charges slabs at 450 °C from 1 h at the nominal pace of 300 s. Over 8 h the slab model uses 0.923 GJ/t and the operator setpoints 0.955 GJ/t.

(a) Find the fuel the model saves per hour and per day of operation at this pace, taking the run's average per tonne as representative. *Checkpoint:* 11.2 GJ/h and 270 GJ per day.

(b) The predictive profile of case 10 fires 142.9 GJ less than the slab model over the same hot-charge run, but ends with 65.6 GJ less heat stored in the slabs and zones. Bound the saving that steady operation could keep, and say why the bound is not reached. *Checkpoint:* Less than 77.3 GJ over the run.

7.11 Application area · 3 min

In a real walking-beam furnace scale grows mostly on slabs in the preheat zone, so the exchange factor there falls while the soak zone changes little. The app's model has one exchange factor for the whole furnace and one pyrometer at the door.

(a) What does the correction of case 8 do with the residuals such a furnace produces, and what is still wrong afterward?

(b) Name one measurement that would let a plant estimate a factor for each zone.

7.12 Review the agent · 5 min

An AI assistant reviews case 10 and writes: "With both corrections on, the joint predictive profile cuts the rms discharge error from 3.15 to 1.52 °C with all 117 slabs on target, for only 0.5 % more

fuel. Joint optimization of the three zones is clearly better than averaging per-slab offsets. Replace the slab model with the MPC for every shift, including the twelve-hour challenge.” Find the flaw and say how you would check it.