INTERACTIVE CONTROL ENGINEERING
Principles and Applications

Volume 15 Control in Mining and Mineral Processing

CHAPTER 11

Rotary Cement Kiln Simulator for Ratio Feedforward and Dead-Time-Limited Quality Control

Pages 232–258

Edited by John D. Hedengren

How to cite this chapter. "Rotary Cement Kiln Simulator for Ratio Feedforward and Dead-Time-Limited Quality Control," in *Control in Mining and Mineral Processing*, John D. Hedengren, Ed., vol. 15 of *Interactive Control Engineering: Principles and Applications*. Advanced Process Solutions, LLC, 2026, ch. 11, pp. 232–258.

The page numbers in this file are those of the printed volume.

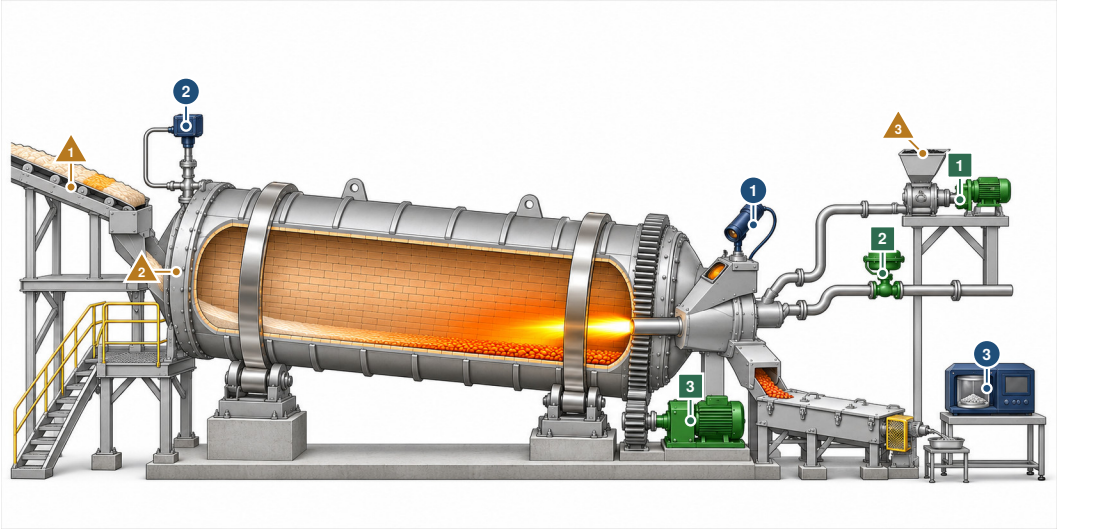
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CHAPTER 11

Rotary Cement Kiln Simulator for Ratio Feedforward and Dead-Time-Limited Quality Control



The controller moves 1 the coal feeder, set by the temperature loop 2 the combustion air, set in ratio to the coal 3 the kiln drive, which sets the speed

The controller reads 1 the burning zone pyrometer 2 the oxygen analyzer at the feed end 3 the free lime test in the laboratory, about twenty minutes late

What disturbs it 1 the raw meal and how hard it burns 2 false air leaking in at the inlet seal 3 the heating value of the coal

Notice that the coal and the air enter together at the burner while the oxygen is read at the far end and the free lime only in the laboratory, which is why the air must follow the coal command rather than the oxygen reading. Illustration, not to scale.

IN PLAIN TERMS A Fast Flame and a Late Lab Test

The main idea. A cement kiln is a long, slowly turning steel tube. It bakes ground limestone and clay into hard lumps called clinker. Its flame answers a change in coal within seconds, but the lab test of the clinker comes back about twenty minutes late.

The challenge. If the coal goes up before the air does, the flame runs short of air and spoils the clinker. Setting the air from the coal order fixes that, but no setting makes a controller that waits for the lab test fast.

Why it matters. The kiln is where cement making burns its fuel, and clinker burned in a flame short of air cannot be repaired later.

THREE WAYS TO READ THIS CHAPTER

⊘	**Explore**	12 min	The first page, the fact box of Section 11.1, the history box of Section 11.2, the fact box and the two try-it boxes of Section 11.5, and the key points
🕮	**Study**	55 min	The whole chapter with its pause points and the twelve exercises
⌓	**Practice**	20 min	The first page, Section 11.5, Section 11.6, Section 11.7 and the open challenge in it

The control question A cement kiln's flame answers the coal in seconds while its free lime assay reports about twenty minutes late. Which control structure keeps the flame oxidizing through a firing move, and how fast can a loop closed on the late assay usefully be?

Learning objectives

- Explain why oxygen feedback alone cannot prevent the carbon monoxide excursion of a firing move, and why ratioing the air to the coal command removes it.
- Compute the excess air, the oxygen reading and the analyzer's error under false air from the combustion laws.
- Assemble the free lime loop's dead time budget and tune the loop by SIMC for its upper end.
- Judge a kiln configuration by its constraint tiles as well as its specific heat, using the graded challenge.
- Separate what a predictive controller gains from its optimization and what it gains from the information and limits it carries.

Prerequisites Sections 1.6.2 (velocity form and loop action), 1.6.4 (scenarios, tiles and exports), 1.4.5 (sampled assays) and 1.4.6 (ratio control). Chapter 7 meets the late assay first, and Chapter 10 the rotary kiln.

The app https://apmonitor.com/apps/cement-kiln/

See also Volume 3, Chapter 4 for cross-limiting and oxygen trim on a fired heater. Volume 5, Chapter 3 and Volume 5, Chapter 11 for a loop through a slow analyzer and an unmeasured kiln product. Volume 9, Chapter 4 for an offset-free predictive controller with a fuel bias estimate.

11.1 Introduction

A rotary kiln converts ground limestone and clay into cement clinker by carrying the material slowly down a rotating steel tube against a coal flame. Two time constants dominate its control. Raw meal takes 22.2 min to travel the kiln at 3.5 rpm, while the flame responds within seconds.

> ✦ DID YOU KNOW? **Four Billion Tonnes a Year**
>
> The world made an estimated 4.0 billion metric tons of cement in 2024, and the United States made its share at 99 plants [1]. Breaking down the limestone alone released 1.48 billion tonnes of carbon dioxide in 2017, about 4 % of the emissions from fossil fuels, before any kiln fuel is counted [2].

The solids transit and the laboratory delay are distinct: the meal takes about 22 min to travel the kiln, and the assay reports about 20 min after clinker leaves. The two time scales must be handled simultaneously. At the fast end, a change in coal rate reaches the burner tip after 0.4 min of transport and a 0.5 min feeder lag, and the resulting oxygen change reaches the back-end analyzer after a further 0.8 min of gas travel and a 0.3 min analyzer lag. Raising the burning zone setpoint by 15 °C gives the temperature controller a proportional step, so the coal command moves within a single 3 s scan while the combustion air is held by an oxygen controller that has not yet observed the change. The excess air ratio falls to 0.964, the carbon monoxide peaks at 611 ppm and spends 0.78 min above the 500 ppm alarm, and 899 ppm min of carbon monoxide leaves the back end. Clinker produced during the excursion is burned under a reducing atmosphere, and the quality loss is not recovered by subsequent operation.

No retuning removes the excursion, because the limit is the transport of gas from the burner to the analyzer rather than the controller settings. Quadrupling the oxygen loop gain and halving its integral time lowers the peak only to 528 ppm, while the oxygen loop's integrated error rises from 11.9 to 17.0 % min over the first hour. The disturbance, however, is the control system's own output, known exactly in the scan it is computed. Ratioing the air to the fuel command and assigning the oxygen controller to trim the ratio leaves the carbon monoxide at its 20 ppm floor and the minimum excess air at 1.085 through the identical move.

At the slow end the proportions reverse. Free lime, the residual uncombined calcium oxide on which clinker quality is judged, is a property of the clinker leaving the burning zone, sampled on a 10 min cycle and reported 15 min after sampling. The effective dead time of a loop closed on the assay is between 15.9 min and 25.9 min depending on where in the sampling cycle the disturbance lands, against a burning zone thermal time constant of 13.0 min. The 22.2 min solids transit is not part of that loop, because it delays only changes that enter at the feed end. A loop closed on the assay acts as a slow trim rather than a regulator, and the application quantifies the cost of tuning it aggressively.

Between the two extremes sits a combustion constraint. The carbon monoxide response to excess air is strongly asymmetric, with 20 ppm at $\lambda = 1.02$, 147 ppm at 1.00, 853 ppm at 0.95 and 1443 ppm at 0.92, while the oxygen falls smoothly and almost linearly across the same range. A penalty of that shape moves the operating point away from the thermodynamic optimum, and it is the reason a kiln runs with more excess air than combustion requires. The asymmetry also makes the oxygen measurement conditional on where the air enters. False air leaking through the kiln inlet seal carries oxygen that bypasses the flame, and at 4.5 kg/s of leakage the analyzer reads 4.06 % instead of 1.91 % while the true excess air is unchanged at 1.100.

The model rests on standard process fundamentals. Each zone carries an energy balance on the charge with counter-current gas exchange, the chemistry enters as two lumped conversions with Arrhenius rates, and the separation between a gas residence of seconds and a solids transit of tens of minutes justifies a quasi-steady gas phase [3, 4]. The model and its scenarios teach ratio and feedforward control, dead-time dominant loops, sampled and delayed measurements, anti-windup with bumpless transfer, and the identification of unmeasured disturbances [4, 5]. Industry runs fired equipment on the ratio-with-trim structure studied here, and kiln quality control operates against assay delays of the magnitude modeled [6, 7].

This chapter works with a rotary kiln simulator described in enough detail to be rebuilt. It compares ratio feedforward with pure oxygen feedback on the same firing move and the same false air leak, and it measures the effect of roughly twenty minutes of assay dead time on a quality loop closed around a burning zone whose own thermal time constant is thirteen minutes. Two measured outcomes carry the argument. The ratio structure removes the entire carbon monoxide excursion from a 15 °C firing move rather than reducing it, and a graded five hour run goes from 88.7 min of reducing flame to none when the structure is assembled correctly. The heat balance, the combustion arithmetic and the ratio structure are standard. What the application adds is an eighteen-state model, twelve graded scenarios and a dead time budget assembled from four separate contributions before any tuning is attempted. A model predictive controller of the coal and the air is offered beside the loops and measured against them on the same cases.

Section 11.2 reviews the background of cement kiln control. Section 11.3 sets out the five-zone model, its combustion and analyzer laws and its kinetics. Section 11.4 describes the burning zone loop, the ratio with oxygen trim, the free lime loop with its dead time budget and the predictive controller. Section 11.5 measures the combustion characteristic, the firing move under both air structures, false air, kiln speed and burnability, the graded challenge and the predictive controller against the loops. Section 11.6 sets the loops in their real hardware, and Sections 11.7 to 11.9 give the limitations, the discussion and the conclusion.

11.2 Background

Portland cement is made by heating a finely ground mixture of limestone and clay to roughly 1450 °C, at which temperature the lime combines with silica, alumina and iron oxide into the calcium silicate phases that give cement its strength. The chemistry proceeds as a sequence of steps. Water leaves, then the carbonate decomposes, then belite forms, then belite and the remaining free lime combine into alite in the presence of a melt whose quantity is fixed by the alumina and iron content of the raw mix [8]. Uncombined lime left in the clinker makes the cement unsound, so the residual free

lime is the number the product is graded on, and it is measured by chemical assay rather than by an instrument.

> ⧖ HISTORY **The Rotating Kiln Takes Over (About 1895 to 1910)**
>
> By 1910 the fixed kilns that had burned Portland cement were giving way to the rotary process. A chamber kiln needed about a week for one run and gave about 30 tons of clinker. A rotating steel cylinder 60 to 150 ft long, lined with refractory brick and carried on rollers at a slight angle, turned out 200 to 400 tons a week. Producer gas had fired the early cylinders with little success, petroleum served in the United States from about 1895, and by 1910 finely powdered coal blown in by air was almost universal. The hot clinker was cooled by a current of cold air, which went on, warmed, to the burner. Underburnt clinker held free lime that could slake slowly in the finished cement and expand enough to destroy the work [9].

The kiln is where the energy and most of the carbon dioxide are spent. Cement manufacture accounts for a large and growing share of global industrial carbon dioxide emissions, with the process emissions from calcination and the combustion emissions from firing contributing separately, and the historical accounting shows both rising with production through the twentieth century [2]. Specific thermal energy consumption is therefore the number the plant is judged on over a year, and the technical routes to improving it are well cataloged and largely exhausted [10]. The remaining margin is operational, and recovering it is a control problem.

Kiln control has an unusual place in the history of the field. The first industrial application of fuzzy logic control was a cement kiln, chosen precisely because the plant was too nonlinear, too slow and too poorly instrumented for the classical methods available at the time [11]. The choice reflected the process. A kiln has strong interaction between fuel, air, feed and speed, a quality measurement that arrives tens of minutes late, and an operator whose expertise consists largely of pattern recognition on a burning zone image. Rule-based and expert-system controllers dominated for two decades for that reason.

Model predictive control eventually displaced them, and reported industrial implementations handle the kiln together with the calciner and the cooler, using the free lime assay as an infrequent correction to an inferred quality rather than as a controlled variable [7]. On the modeling side, one-dimensional axial models of the bed and gas with the reaction sequence resolved have been developed and validated against plant data [12], and extended to the integrated preheater, calciner, kiln and cooler so that the recycles between them can be represented [13]. Those models are the reference against which a reduced model such as the one of this chapter should be read.

However, textbook presentations of feedforward begin from a measured external disturbance and a disturbance transfer function to invert [4]. That presentation does not cover the case where the disturbance is the control system's own output, where the feedback measurement is downstream of the actuator by a fixed transport time, and where the penalty for a late correction is asymmetric and permanent. The application is built to demonstrate that a well-tuned feedback loop is not the remedy for this class of fast disturbance. A refinery fired heater meets the same problem with a slow forced-draft fan and answers it with cross-limiting and oxygen trim in Volume 3, Chapter 4.

11.3 Process Model

The kiln is a 60 m tube of 4.2 m diameter inclined at 3.5 % and rotating at 3.5 rpm. Raw meal enters the high end at 860 °C and 90 % calcined, having already passed through a preheater tower and a precalciner that are boundary conditions here. Coal is fired at the low end into secondary air returning from the clinker cooler at 950 °C. The combustion gas travels counter-current to the meal and leaves the feed end at 1049 °C. The arrangement is drawn in Figure 11.1.

11.3.1 Units and Design Point

The clock runs in minutes. Solids and air are in t/h, energy in kJ, temperature in °C and oxygen in percent by volume dry. At the design condition the kiln takes 258 t/h of raw meal at 860 °C and 90 %

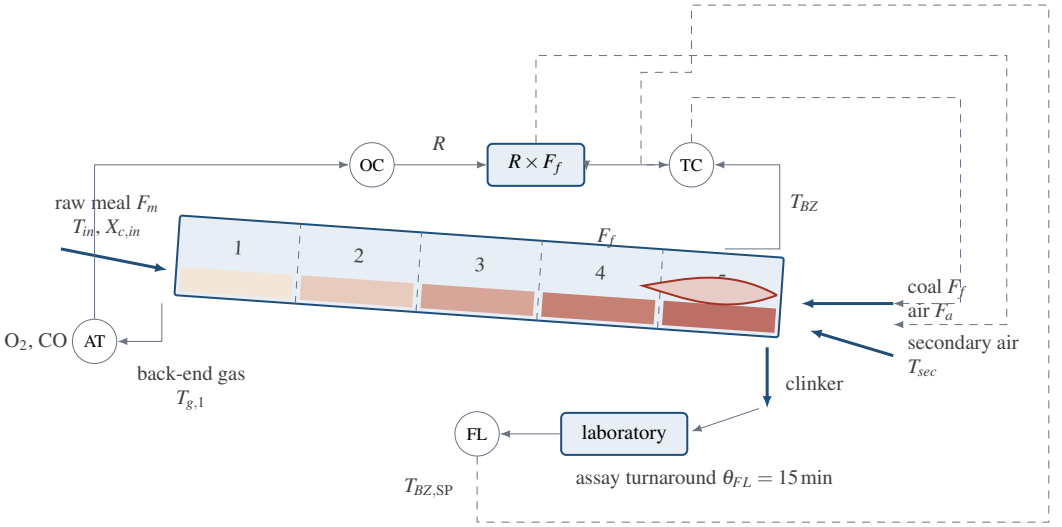


Figure 11.1 Rotary kiln as implemented, drawn on its incline with the five zones numbered from the feed end. Charge shading follows temperature. The temperature controller TC writes the coal rate F_f, which is multiplied by the ratio R to give the combustion air F_a in the same scan, while the oxygen controller OC moves R slowly from the back-end analyzer AT. The free lime assay FL arrives θ_{FL} after clinker leaves zone 5 and writes the burning zone setpoint $T_{BZ,\mathrm{SP}}$.

calcined, fires 11.033 t/h of coal with 127.434 t/h of air for an excess air ratio of 1.100, and turns at 3.5 rpm for a transit of 22.16 min. The charge profile is 826.3 °C, 838.3 °C, 891.5 °C, 1007.8 °C and 1429.8 °C and the gas profile is 1049 °C, 1135 °C, 1260 °C, 1440 °C and 1711 °C. Calcination is complete by zone 3 at $X_c = 0.995$ and clinkerization reaches $X_k = 0.982$ only in zone 5, giving 1.200 % free lime. The back end reads 1.910 % oxygen and 20 ppm carbon monoxide.

11.3.2 Transport

Residence time follows the standard rotary kiln correlation, and it is the only quantity in the model that kiln speed touches directly:

$$\tau = \frac{k_r L}{N D S}, \qquad \tau_z = \frac{\tau}{5}, \qquad M_z = \frac{F_m \tau}{300}, \tag{11.1}$$

where M_z is the charge hold-up per zone in tonnes. At design, $\tau_z = 4.43$ min and $M_z = 19.06$ t.

11.3.3 Charge Energy Balance

Each zone is a well-mixed lump whose effective thermal mass includes the refractory lining:

$$\left(M_z 10^3 C_{p,s}(1+f_{ref})\right)\frac{\mathrm{d}T_{s,i}}{\mathrm{d}t} = 60\Big[\dot{W}_s\left(T_{s,i-1}-T_{s,i}\right) + UA_i\left(T_{g,i}-T_{s,i}\right) + Q_{rad,i} - \Delta H_{cal}\, r_{cal,i} - \Delta H_{clk}\, r_{clk,i}\Big], \tag{11.2}$$

with $\dot{W}_s = F_m 10^3 C_{p,s}/3600$ the heat capacity flow of the solids in kW/K, and $r_{cal,i}$ and $r_{clk,i}$ the mass rates of calcination and clinkerization in zone i in kg/s, obtained from the kinetics of (11.10) and (11.11) applied to the zone hold-up. The factor $f_{ref} = 3.2$ is the ratio of refractory thermal mass to charge thermal mass, and it sets the burning zone time constant. Evaluating $M_z 10^3 C_{p,s}(1+f_{ref})/[60(\dot{W}_s + UA_5)]$ at the design point gives 13.0 min. The charge alone would respond in 3.1 min.

Table 11.1 Controlled, Manipulated and Disturbance Variables

Symbol	Meaning	Unit	Range
Controlled variables			
T_{BZ}	burning zone charge temperature	°C	1330–1520
O_2	back-end oxygen	%	0–8
FL	free lime in the clinker	%	0–5
Manipulated variables			
F_f	coal feed	t/h	4–18
F_a	combustion air	t/h	55–230
R	air to fuel ratio	t/t	8–16
$T_{BZ,\mathrm{SP}}$	burning zone setpoint (outer)	°C	1330–1520
N	kiln speed	rpm	1.5–5.5
Disturbance variables			
F_m	raw meal feed	t/h	180–340
β	raw mix burnability	—	0.55–1.40
c_f	coal calorific value	—	0.80–1.15
$X_{c,in}$	calcination degree from the precalciner	—	0.70–0.97
$\dot{m}_{fa}$	false air at the inlet seal	kg/s	0–8
T_{sec}	secondary air temperature	°C	700–1100
States			
$T_{s,i}$	charge temperature, zones 1–5	°C	—
$X_{c,i}$	calcination conversion, zones 1–5	—	—
$X_{k,i}$	clinkerization conversion, zones 1–5	—	—
F_f, F_a, N	actuator positions	—	—

The conductance profile rises steeply toward the discharge end, because radiation rather than convection is doing the work there:

$$UA_i = UA_0\, w_i, \qquad w = \{0.55,\ 0.70,\ 0.90,\ 1.25,\ 1.90\}. \tag{11.3}$$

11.3.4 Quasi-Steady Gas Profile

Gas residence in the kiln is seconds against a charge transit of 22 min, so the gas is treated as quasi-steady. Marching counter-current from the burning zone toward the feed end,

$$T_{g,i} = \frac{\dot{W}_g T_{g,i+1} + UA_i T_{s,i} + UA_{sh} T_a}{\dot{W}_g + UA_i + UA_{sh}}, \tag{11.4}$$

where $\dot{W}_g = (F_a + F_f)10^3 C_{p,g}/3600$ is the heat capacity flow of the combustion gas in kW/K and $T_a = 25\,^{\circ}\mathrm{C}$ is the ambient temperature behind the shell loss. The march starts from the flame temperature

$$T_{flame} = T_{sec} + \frac{f_g\, \eta(\lambda)\, Q_f}{\dot{W}_g}, \qquad Q_f = \frac{c_f\, \Delta H_f F_f\, 10^3}{3600}, \tag{11.5}$$

where Q_f is the firing heat release in kW and c_f is the calorific value multiplier of Table 11.1. The fraction $f_g = 0.6$ of the combustion heat is carried by the gas and the remainder is radiated directly to the charge in zone 5,

$$Q_{rad,5} = (1 - f_g)\, \eta(\lambda)\, Q_f. \tag{11.6}$$

Because the combustion air scales with the fuel, (11.5) makes the flame temperature nearly independent of firing rate. The coal rate changes the quantity of heat delivered rather than the flame temperature.

11.3.5 Combustion

Excess air, combustion efficiency and carbon monoxide are

$$\lambda = \frac{F_a}{\mathrm{AFR}\, F_f}, \qquad \eta(\lambda) = \min(1,\ \lambda) \tag{11.7}$$

$$\mathrm{CO} = 20 + k_{co}\,(\lambda_{ok} - \lambda)_+^{3/2} \tag{11.8}$$

with $\lambda_{ok} = 1.02$ and $k_{co} = 45\,000$ ppm. Below stoichiometric the combustion efficiency η equals λ, and the unburned fraction leaves as carbon monoxide. The three-halves power in (11.8) concentrates the carbon monoxide response in a narrow band below λ_{ok}, and (11.7) through (11.6) together make a reducing flame a cooler flame, because unburned fuel carries away part of the heat release.

The analyzer does not measure λ directly. False air entering at the inlet seal carries oxygen that bypasses the flame, and the instrument cannot distinguish where the oxygen entered:

$$\hat{\lambda} = \frac{F_a + 3.6\,\dot{m}_{fa}}{\mathrm{AFR}\, F_f}, \qquad \mathrm{O_2} = 21\left(1 - \frac{1}{\hat{\lambda}}\right)\%. \tag{11.9}$$

The leak joins the gas after the last zone, so $\dot{m}_{fa}$ enters (11.9) but neither (11.4) nor (11.5).

11.3.6 Reaction Kinetics

Calcination and clinkerization are first order in the unconverted fraction with Arrhenius rates:

$$\frac{\mathrm{d}X_{c,i}}{\mathrm{d}t} = \frac{X_{c,i-1} - X_{c,i}}{\tau_z} + k_{cal}(T_{s,i})(1 - X_{c,i}) \tag{11.10}$$

$$\frac{\mathrm{d}X_{k,i}}{\mathrm{d}t} = \frac{X_{k,i-1} - X_{k,i}}{\tau_z} + k_{clk}(T_{s,i})\,\beta\,(1 - X_{k,i}) \tag{11.11}$$

$$\mathrm{FL} = \mathrm{CaO}_{free}\left(1 - X_{k,5}\right). \tag{11.12}$$

The clinkerization activation temperature is 45 000 K, which gives (11.11) a threshold character. At the design zone residence the free lime of (11.12) is 9.3 % with zone 5 at 1300 °C, 4.2 % at 1350 °C and 1.4 % at 1420 °C, and it falls below the 2.0 % soundness limit only above about 1397 °C. The zone 5 conversion follows its temperature with a time constant $1/(1/\tau_z + k_{clk}\beta)$ of 0.083 min at design, so the free lime moves with the burning zone temperature within seconds. The burnability multiplier β stands for the raw mix chemistry, fineness and mineralogy together, and no continuous instrument on the kiln measures it.

11.3.7 Initialization

At reset the application solves (11.2) through (11.11) for their simultaneous steady state by damped substitution, sweeping the five zones and re-solving the gas profile on every pass until no charge temperature moves by more than 1×10^{-11} °C. The result is the profile quoted in Section 11.3.1 and the relative residual on every charge temperature and conversion derivative at $t = 0$ is below 1×10^{-13}. Actuator states start at the design point values of Section 11.3.1, the coal transport delay starts filled with the coal value, so a command at $t = 0$ reaches the burner 0.4 min later, and a setting chosen before a run equals the same setting carried through a reset. The automatic scenarios hold 1430 °C, 0.20 °C above the initialized burning zone, so the first scan adds 0.02 t/h of coal.

Table 11.2 Model Parameters, All Adjustable in the Application

Symbol	Meaning	Value	Unit
L	kiln length	60	m
D	kiln diameter	4.2	m
S	kiln slope	0.035	m/m
k_r	residence time coefficient	0.19	—
$C_{p,s}$	solids heat capacity	1.1	kJ/(kg K)
$C_{p,g}$	gas heat capacity	1.15	kJ/(kg K)
f_{ref}	refractory thermal mass	3.2	× charge
UA_0	conductance scale	18	kW/K
UA_{sh}	shell loss per zone	1.6	kW/K
T_a	ambient temperature	25	°C
f_g	flame heat carried by the gas	0.6	—
ΔH_f	coal calorific value	25000	kJ/kg
AFR	stoichiometric air-fuel ratio	10.5	kg/kg
λ_{ok}	excess air clearing CO	1.02	—
k_{co}	carbon monoxide scale	45000	ppm
CO_{lim}	carbon monoxide alarm	500	ppm
y_{CaCO_3}	carbonate fraction of the meal	0.78	—
ΔH_{cal}	calcination enthalpy	1780	kJ/kg
ΔH_{clk}	clinkerization enthalpy	100	kJ/kg
$k_{cal,0}$	calcination rate at 900 °C	0.9	1/min
E_{cal}/R	calcination activation temperature	25000	K
$k_{clk,0}$	clinkerization rate at 1450 °C	16.199	1/min
E_{clk}/R	clinkerization activation temperature	45000	K
CaO_{free}	lime available to combine	65	%
FL_{max}	free lime that makes cement unsound	2.0	%
T_{ring}	burning zone temperature starting a ring	1520	°C
τ_f	coal feeder lag	0.50	min
θ_f	coal transport dead time	0.40	min
τ_a	air damper lag	0.25	min
τ_N	kiln drive ramp	0.80	min
θ_{O_2}	oxygen analyzer transport delay	0.80	min
τ_{O_2}	oxygen analyzer response	0.30	min
τ_{BZ}	pyrometer filter	0.60	min
θ_{FL}	free lime analyzer turnaround	15	min
Δt_{FL}	free lime sample interval	10	min

11.3.8 Assumptions

1. **Five well-mixed zones.** The transport delay is produced by the staged geometry rather than by an explicit dead-time element, at the cost of a coarse temperature profile. Axial models resolve the bed and gas continuously [12], and a real kiln also has a bed depth and a refractory coating whose thickness changes over a campaign.

2. **The gas is quasi-steady.** No flame model, no gas composition, no radiation view factors, and no separation of convective from radiative transfer. The split between gas-borne and directly radiated heat is the single fitted fraction f_g and UA_i is a fitted profile.

3. **Two lumped reactions.** Real clinker chemistry is the belite and alite sequence in a melt whose quantity depends on the alumina and iron moduli [8]. Burnability is one multiplier standing in for all of it.

4. **The rest of the line is a boundary condition.** Preheater tower, precalciner and clinker cooler enter only as the inlet temperature, the inlet calcination degree and the secondary air temperature. The alkali and sulfur recycles that cause build-ups and blockages cannot appear, and integrated models exist precisely to capture them [13].

5. **No reducing-atmosphere chemistry.** Carbon monoxide is algebraic and the damage a reducing flame does to clinker quality is reported in the notes rather than modeled. Nitrogen oxides, which push the operating point the other way, are absent, so the application understates how narrow the acceptable combustion window is.

6. **Ring formation is an alarm.** Nothing builds up, restricts the kiln or changes the residence time. On a real kiln that feedback is among the most disruptive events in operation.

7. **Fixed-step integration.** Classical fourth-order Runge–Kutta at 0.01 min with a 3 s controller scan, so repeated runs reproduce exactly (Section 1.6.1). A physical kiln shows run-to-run variability.

11.4 Controller Design

Four feedback controllers are implemented, and Section 11.4.5 describes a model predictive controller that can take the coal and the air from them. The burning zone temperature drives the coal feeder, the back-end oxygen drives either the air damper or the air-fuel ratio, the free lime writes the burning zone setpoint, and the kiln speed is an operator setpoint with a first-order drive ramp. All use the same incremental, or velocity, form on a 3 s scan, computing an increment to the output each scan rather than the output itself.

11.4.1 Discrete PID Algorithm

Every loop runs the velocity-form PID of Section 1.6.2, Equations (1.10) to (1.13), with the error $e_k = a(\mathrm{SP}_k - \mathrm{PV}_k)$ and the action $a = \pm 1$. The derivative acts on the measurement passed through a 0.5 min first-order filter, and $\tau_D = 0$ in every scenario. Anti-windup is back-calculation with tracking time $T_t = \tau_I$, so the integral alone is corrected and the running sum of proportional and derivative increments is never truncated [14]. Each 3 s scan removes $\Delta t/\tau_I$ of the clipped excess, $1/180$ for the 9 min temperature loop. No run reported here reaches a coal, air, ratio or setpoint limit, so the anti-windup term is inactive in every result.

In manual mode, for the air loop that is not selected and for an advisory free lime loop, the algorithm runs the tracking step of Section 1.6.2, which sets the integral so that the output equals the value actually applied. In automatic mode the manual coal, air and burning zone stations are set to the controller outputs after every controller execution, so the transfer is bumpless in both directions. The temperature, oxygen and ratio trim loops are reverse acting with $a = +1$, because more coal heats the burning zone and more air, or a higher ratio, raises the oxygen. The free lime loop is direct acting with $a = -1$, because a hotter burning zone gives less free lime. The application labels it the same way.

11.4.2 Burning Zone Temperature Loop

Perturbing (11.2) through (11.6) about the design point gives 52.1 °C of burning zone temperature per t/h of coal. The path from the coal command passes a 0.5 min feeder lag, a 0.4 min coal transport delay, the 13.0 min thermal time constant of the zone itself and a 0.6 min pyrometer filter, so the zone alone would present roughly 13 min of lag with about a minute of apparent dead time. The zone does not answer alone, because the hotter gas also warms the four zones upstream, which pass warmer charge into it. With the air ratioed the true burning zone covers 63 % of a coal step after 30 min and 90 % after 77 min, while a copy of the model with zones 1 to 4 held at their design state covers 63 % after 15.8 min at 32.3 instead of 52.0 °C per t/h. Scenarios 3 to 10 use $K_c = 0.11\,\mathrm{t/h/^\circ C}$ and $\tau_I = 9\,\mathrm{min}$, which is the SIMC result [15] for the zone alone with a closed-loop time constant of about 1.3 min. With that tuning the burning zone covers 63 % of a 25 °C setpoint step in 3.7 min and overshoots by 3.9 °C.

11.4.3 Ratio Control with Oxygen Trim

The combustion air is governed by one of two selectable structures:

$$\text{feedback:}\quad F_a = \mathrm{PI}_{O_2}\left(\mathrm{O}_2^{\mathrm{SP}} - \hat{\mathrm{O}}_2\right) \tag{11.13}$$

$$\text{ratio:}\quad R = \mathrm{PI}_R\left(\mathrm{O}_2^{\mathrm{SP}} - \hat{\mathrm{O}}_2\right), \quad F_a = R\,F_{f,k} \tag{11.14}$$

In (11.14) the air is computed from the fuel command of the *same* scan, so it moves in the same 3 s the coal does, and the oxygen controller moves only the one parameter of the feedforward model. The loop that is not selected runs the tracking step continuously, so switching between them is bumpless. The product $R\,F_{f,k}$ is clipped to the air range of Table 11.1 after the trim, whose own limits apply to R, so a clipped air command would not reach the trim's integral. Scenarios 3 to 10 use $K_c = 1.5\,\mathrm{t/h/\%}$ with $\tau_I = 1.2\,\mathrm{min}$ for feedback air and $K_c = 0.15$ per percent with $\tau_I = 6\,\mathrm{min}$ for the ratio trim. The trim is deliberately five times slower than the loop it replaces, because it corrects a slowly drifting model parameter rather than a disturbance.

The structure of (11.14) is the standard industrial arrangement for fired equipment [6], and the reason it is standard is the timing argument rather than any property of the tuning. Ratio stations on other plants of this volume are compared in Section 1.4.6.

11.4.4 Free Lime Loop and Dead-Time Budget

The outer loop writes the burning zone setpoint from the laboratory result. The free lime of (11.12) belongs to the clinker leaving zone 5 and follows the burning zone temperature within seconds, so the 22.2 min transit of (11.1) lies outside this loop and delays only disturbances that enter at the feed end. The loop's effective dead time is the sum of four contributions, the sampled assay age of Section 1.4.5 plus the coal path:

$$\theta_{eff} = \underbrace{\theta_{FL}}_{15} + \underbrace{[0, \Delta t_{FL}]}_{0-10} + \underbrace{\theta_f}_{0.4} + \underbrace{\tau_f}_{0.5} = 15.9 - 25.9\,\mathrm{min}. \tag{11.15}$$

Against the 13.0 min zone time constant the ratio of dead time to lag is between 1.2 and 2.0, which places the loop in the dead-time dominant regime [4]. The free lime controller drives the closed temperature loop rather than the open zone, and that loop reaches 63 % of a setpoint step in 3.7 min, so the ratio for the loop as built is between four and seven. The delay panel of the application adds half a sample interval to the turnaround and reports 20 min at design, the age of the reported value against the clinker leaving the kiln, and shows the transit separately. Dead-time compensation such as the Smith predictor removes the delay from the characteristic equation only to the accuracy of the delay model [16], and the sampling contribution in (11.15) varies by 10 min from one disturbance to the next. Volume 5, Chapter 3 tunes a composition loop through a slow analyzer with the same budget. Scenarios 7 and 10 close the loop with $K_c = 15\,^\circ\mathrm{C/\%}$ and $\tau_I = 13\,\mathrm{min}$. SIMC on the 13.0 min zone,

with the upper end of (11.15) as the dead time and τ_c equal to it, gives the same integral time and a gain of 14 °C/% to 17 °C/% for the steady-state process gain of 0.015 %/°C to 0.018 %/°C between 1430 °C and 1455 °C and at the design point.

11.4.5 Model Predictive Control of Coal and Air

A fifth structure hands the coal and the combustion air to one model predictive controller, the receding-horizon calculation behind most industrial advanced control [17] and the option that Section 1.6.3 describes, and only scenario 11 loads with it selected. Every $\Delta t_m = 0.5$ min, or ten scans, a quadratic program plans both commands over $N_p = 120$ steps (60 min) in twelve move blocks with 24 decisions, and the kiln receives the first move alone. The plan holds the operator's burning zone setpoint, or with the free lime loop closed the temperature its own free lime model needs, and the air structure only names the loops that take over a rejected plan. The raw meal feed stays a disturbance and the kiln speed an operator setpoint, because the declared steady state reaches 1.20 % free lime with 10.018 t/h of coal at 1.5 rpm against 11.033 t/h at 3.5 rpm, and a plan free to slow the kiln would take that saving at a cost in bed depth and coating that the model does not contain.

The controller's model is not the five-zone kiln. Its burning zone is two first-order modes ($i = 1, 2$) driven by the coal at the burner and the applied air, as shown in Equation (11.16),

$$\begin{aligned} \tau_i \frac{\mathrm{d}x_i}{\mathrm{d}t} &= g_{F,i}\left(\hat{F}_f - F_f^0 + d\right) + g_{A,i}\left(\hat{F}_a - F_a^0\right) - x_i \\ \hat{T}_{BZ} &= T_{BZ}^0 + x_1 + x_2 \end{aligned} \tag{11.16}$$

where $\hat{F}_f$ is the coal command passed through the declared delay θ_f and lag τ_f, $\hat{F}_a$ is the air command passed through the damper lag τ_a, F_f^0 and F_a^0 are the design stations of Section 11.3.1, T_{BZ}^0 is the offset fixed when the estimate starts, and d is an input disturbance in t/h of coal. Manual step tests at the design point with the noise off, ± 0.25 t/h of coal and ± 4 t/h of air, give $\tau_1 = 17.0$ min and $\tau_2 = 42.3$ min with coal gains $g_{F,i}$ of 37.86 and 26.15 and air gains $g_{A,i}$ of −1.364 and 0.336 °C per t/h, leaving 0.27 % RMS of each response. An independent fit gives 16.3 and 41.5 min with steady gains of 64.02 and −1.030, against the plant's 64.02 and −1.037. The two modes are a reduction of a kiln whose linearization has a slowest real mode of 33.4 min and three complex pairs.

The oxygen and the free lime come from the declared laws. The analyzer's reading is Equation (11.9) without false air, linearized at every plan about the coal and air the model holds, and the declared delay θ_{O_2} and lag τ_{O_2} enter where the reading is compared with the model. A fourth output is the flame's own oxygen, $\mathrm{O}_{2,f} = 21(1 - \mathrm{AFR}\,\hat{F}_f/\hat{F}_a)$, computed from the plan's commands and the declared AFR. The free lime is Equation (11.11) for zone 5 alone at design burnability, taken in logarithms so that a change of burnability becomes an additive bias b_L, as shown in Equation (11.17),

$$\ln \widehat{\mathrm{FL}} = \ln \frac{\mathrm{CaO}_{free}}{1 + k_{clk}(\hat{T}_{BZ})\,\tau_z(N)} + b_L \tag{11.17}$$

where $\tau_z(N)$ is the zone residence of Equation (11.1) at the speed command. Against the kiln's steady state between 1367 and 1494 °C the law is within 1.72 % of the free lime. Every constant is fixed at load time, so a learner's change to the kiln's parameters acts on the plan as plant-model mismatch.

Three estimators keep the plan offset-free, each giving the model a disturbance of the kind the kiln receives [18], as in the offset-free controller of Volume 9, Chapter 4. A steady-state Kalman filter on the modes, the pyrometer filter and d, with variances of 2×10^{-5} (t/h)^2 per scan for d and 1 °C^2 for the pyrometer, reads any feed, calcination, coal or cooler change as a heat input and estimates 63 % of a 0.1 t/h step in d within 4.05 min. The oxygen bias b_{O_2} is the analyzer's reading less the model's prediction of it through that delay and lag, filtered over 2 min. At each assay b_L moves by $w_L = 0.6$ of the residual, taken against the model's free lime when the sample was cut, θ_{FL} before the report, which is the alignment of a slow, delayed quality measurement that multi-rate inferential control requires [19]. It is the bias update of Section 1.4.5, compared at the sampling instant, which Chapter 7

uses on a tailings assay. Compared at the report time instead, the free lime IAE of scenario 11 rises from 20.93 to 29.46 % min.

Each plan minimizes Equation (11.18),

$$J = \sum_{k=1}^{N_p} \left[\left(\hat{T}_{BZ,k} - T^* \right)^2 + q_O \left(\hat{\mathrm{O}}_{2,k} - \mathrm{O}_2^* \right)^2 \right] + \mu \sum_{j=1}^{12} \left(s_F \, \Delta F_{f,j}^2 + s_A \, \Delta F_{a,j}^2 \right) + \sum_{\ell=1}^{4} \left(\rho_\ell \, \varepsilon_\ell^2 + \sigma_\ell \, \varepsilon_\ell \right) \tag{11.18}$$

where $\hat{T}_{BZ,k}$ and $\hat{\mathrm{O}}_{2,k}$ are the predictions at step k, Δ is the change of a command from one block to the next, the first measured from the commands applied now, $q_O = 400$ per %^{2} against 1 per °C^2, $s_F = 4000$ and $s_A = 2$ per (t/h)^2, $\mu = 1$ is the move price, and $\varepsilon_\ell \geq 0$ are the slacks of four soft limits with prices ρ_ℓ and σ_ℓ. The target T^* is the operator's setpoint with the free lime loop advisory and, with it closed, the solution of Equation (11.17) for the free lime target, clipped to 1330 °C and to 5 °C under the ring limit. The oxygen target is $\mathrm{O}_2^* = \max\left[\mathrm{O}_2^{SP},\ \mathrm{O}_{2,min} + \max(0, b_{O_2})\right]$ with the floor $\mathrm{O}_{2,min} = 1\,\%$, which is $\lambda = 1.05$. The plan prices no coal, because two handles and two tracked outputs leave no steady degree of freedom, and a price of 640 per t/h per step saves 0.56 t of coal over scenario 11 while the free lime IAE rises to 40.86 % min.

The coal stays within 4 and 18 t/h and the air within 55 and 230 t/h on every block, the clamps of the loops, as hard bounds. Four limits are soft, and the shared solver allots each a single slack for the entire horizon rather than one per step: the analyzer's and the flame's oxygen above $\mathrm{O}_{2,min}$ at 1×10^6 per %^{2} and 1×10^5 per %, the free lime under the 2.0 % soundness limit with the loop closed at 1×10^5 and 1×10^4 in logarithmic units, and the burning zone between 1330 °C and the lower of 1520 °C and the ring limit at 1×10^4 and 1×10^3.

The raised target is what holds the flame under false air, as Section 11.5.6 measures. When the analyzer reads more than the plan's coal and air explain, b_{O_2} grows and O_2^* rises with it, so the analyzer is aimed at the floor plus the leak's share of the reading. At 150 min of scenario 11 the analyzer reads 3.47 % while the flame has 0.99 % ($\lambda = 1.050$), with $b_{O_2} = 2.31\,\%$ and a target of 3.29 %. The flame row cannot see a wrong stoichiometric ratio, because its excess air is computed from the commands, and it equals the true λ at every scan only because the simulated actuators do exactly what they are told. With the plant's AFR at 11.0 it reads 0.053 high and the flame reaches $\lambda = 0.995$ with 193 ppm of carbon monoxide.

A plan is kept only when the solver's own status is optimal, checked even when the solve reports success, every returned array has its shape and finite entries, every planned command lies inside its bounds and the first equals the applied move. Otherwise the loops take over with the learner's air structure and free lime loop until a later plan passes, starting from the applied coal, air and burning zone setpoint that they follow at every scan without preload. With the noise off, rejections forced at 60, 140 and 185.5 min of scenario 11 move the coal 0.002 to 0.009 t/h on the hand-over scan, and 0.134 t/h at 80 min, where the free lime loop answers an assay arriving on that scan. No run reported here rejected a plan.

The kiln model is integrated with the run's parameters, each instrument applies its own delay, lag and noise, and the plan's equations hold the declared values, which keeps plant, instruments and controller model separate. A replay test feeds the measurements of 150 min of scenario 11, logged with a different hidden kiln, to a fresh controller state and obtains all 3000 commands bit for bit, and at 23 captured decisions the Karush-Kuhn-Tucker conditions hold. A plan takes 0.85 to 0.96 ms on average in Chrome in the runs behind this chapter, 10.2 to 11.5 % of one core at the top speed of 60 min of kiln time per second.

Table 11.3 Combustion Air Swept at 11.033 t/h of Coal, Steady State

λ	F_a t/h	O_2 %	CO ppm	T_{BZ} °C	FL %
0.92	106.6	0.00	1443	1392.3	2.155
0.95	110.1	0.00	853	1411.1	1.606
1.00	115.8	0.00	147	1442.0	0.997
1.02	118.2	0.41	20	1439.6	1.035
1.05	121.6	1.00	20	1435.9	1.095
1.10	127.4	1.91	20	1429.8	1.200
1.20	139.0	3.50	20	1418.0	1.437
1.35	156.4	5.44	20	1401.4	1.861

11.5 Results

The application offers twelve scenarios in its selector, each isolating one mechanism: the kiln as a conveyor, the flame and the carbon monoxide cliff, the burning zone loop, oxygen feedback alone and the ratio against the same firing move, false air, the free lime loop, kiln speed, coal calorific value, raw meal chemistry, the predictive controller against the loops on one shift, and the graded challenge. Section 1.6.4 describes how a case is briefed, credited and exported. A case is credited when the learner performs its 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 all twelve cases accumulates toward certificates of progress and completion. Reset restarts a run from $t = 0$ and keeps every setting the learner changed, which is how scenarios 6 and 7 compare two configurations on the same disturbance, while reloading a scenario restores its own settings.

11.5.1 Steady-State Combustion Characteristic

Table 11.3 sweeps the combustion air at fixed coal. Oxygen falls smoothly and carbon monoxide does not. Between $\lambda = 1.02$ and $\lambda = 0.92$ the oxygen reading moves by 0.41 % and the carbon monoxide by 1423 ppm.

The burning zone column shows a second effect. The maximum lies near $\lambda = 1.00$ and the temperature falls on both sides. Above it, excess air is heated and carried up the kiln to the stack. Below it, part of the fuel leaves as carbon monoxide instead of releasing its heat, so a reducing flame is also a cooler flame. The kiln is nevertheless run at $\lambda = 1.10$, giving up 12.2 °C of burning zone temperature and 0.20 % of free lime, because of the carbon monoxide penalty on the fuel-rich side in the third column.

> **+ DID YOU KNOW? An Oxygen Reading That Stops at Zero**
>
> From the simulator: in Table 11.3 the oxygen reads 0.00 % at every excess air ratio from 1.00 down to 0.92, while the carbon monoxide climbs from 147 to 1443 ppm. Once the flame is short of air, the oxygen reading says so but cannot say by how much.

11.5.2 Ratio Feedforward Against a Firing Move

Scenarios 4 and 5 raise the burning zone setpoint by 15 °C at $t = 10$ min, which corresponds to the correction issued after a high free lime assay. Table 11.4 reports the identical move under the two air structures, feedback air in scenario 4 and the ratio in scenario 5. Peaks and times come from the 0.6 s integration step and the integrated errors from the application's scorecard.

The ratio structure removes the carbon monoxide excursion rather than reducing it, and the mechanism is timing rather than tuning. Under feedback the air cannot begin to move until the coal

Table 11.4 Burning Zone Setpoint Raised 15 °C at $t = 10$ min, Measured Over 60 min

Quantity	feedback air	ratio with trim
Peak carbon monoxide (ppm)	611	**20**
Minimum excess air λ	0.964	**1.085**
Time above 500 ppm (min)	0.78	**0.00**
Integrated CO above floor (ppm min)	899	**0**
Oxygen loop IAE (% min)	11.86	**3.25**
Burning zone IAE (°C min)	68.7	81.7

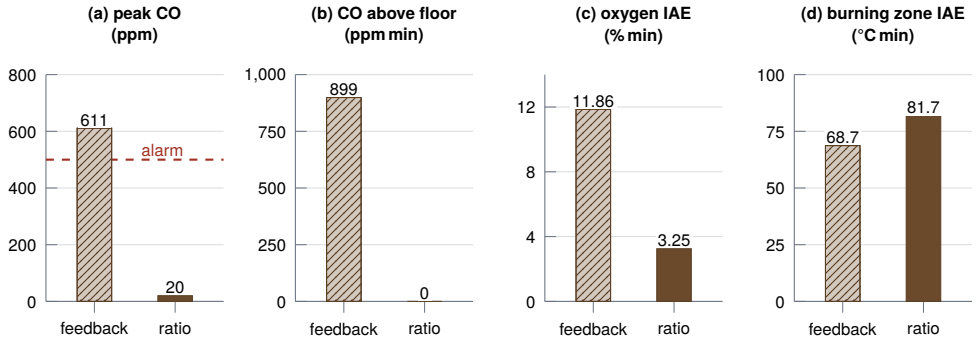


Figure 11.2 The firing move of Table 11.4 as a chart, feedback air hatched and the ratio with trim solid; the dashed line in (a) is the 500 ppm alarm. Notice that the ratio does not shrink the carbon monoxide bars, it removes them, and cuts the oxygen error too. The one bar that grows is the burning zone error in (d), the small price the text explains.

has finished its 0.4 min of transport and the gas has carried the change 0.8 min to the analyzer, so the air command first moves at 11.26 min, 1.26 min after the step, and the 0.3 min analyzer lag slows it further. The 0.5 min feeder lag keeps the extra coal arriving meanwhile, and the flame runs short of air, with λ below λ_{ok}, from 10.77 min to 13.66 min, 2.9 min in all. Under the ratio the air moves in the same 3 s scan.

The one column that degrades is the burning zone integrated error, by 19 %. Under feedback the lagging air leaves the extra coal burning with less excess air, a hotter flame that speeds the burning zone's rise. Under the ratio the air follows the coal command in the same scan, while the extra coal is still in transport and in the feeder lag, so the flame briefly runs with more excess air than at design, up to $\lambda = 1.235$, and the temperature loop carries slightly more of the correction. That cost is small against the 899 ppm min carbon monoxide excursion the structure eliminates. Figure 11.2 draws four rows of the table as bars.

Table 11.5 Kiln Speed Swept at Fixed Firing, Steady State

N (rpm)	τ (min)	T_{BZ} (°C)	FL (%)
2.5	31.0	1430.5	0.850
3.0	25.9	1430.1	1.025
3.5	22.2	1429.8	1.200
4.2	18.5	1429.5	1.445
5.0	15.5	1429.2	1.723

TRY IT IN THE APP 4 · Oxygen Feedback Alone, Against a Firing Move

Load the scenario and press Run. At minute 10 the burning zone setpoint rises 15 °C. Watch the Carbon monoxide and excess air trend: the coal moves at once, the air waits for the analyzer, and the carbon monoxide peaks near 611 ppm. Then load scenario 5, Ratio the air to the fuel, and watch the same trend stay at its 20 ppm floor.

Pause. Try Exercise 11.1 before reading on.

11.5.3 False Air and Analyzer Bias

Scenario 6 opens a false air leak of 4.5 kg/s at the kiln inlet seal at $t = 12$ min and repairs it at $t = 80$ min. At steady state the leak raises the analyzer from 1.910 % to 4.063 % oxygen with the true excess air unchanged at 1.100, because the oxygen entered downstream of the flame.

TRY IT IN THE APP 6 · False Air: The Analyzer Lies

Run the scenario with Air control on O_2 feedback. The leak opens at minute 12, the controller closes the air, and the carbon monoxide peaks at 1146 ppm. Press Reset, switch Air control to Ratio + trim and run past the repair at minute 80: the flame drifts only to an excess air of 0.971, with a peak of 504 ppm just after the repair.

Under feedback the controller acts on the biased reading, closes the damper, and drives the flame to a minimum excess air of 0.934 with a carbon monoxide peak of 1146 ppm at 35 min, above 500 ppm from 14 min after the leak for 39.9 min in all. Under the ratio the same bias enters through the trim, which moves five times more slowly, and the flame drifts to 0.971 with a peak of 504 ppm 0.8 min after the repair, when the analyzer registers it, crossing the alarm only for that last 0.8 min. The ratio structure does not protect the kiln against a biased analyzer. Left unrepaired, the leak takes both structures to the same state after 300 min, $\lambda = 0.963$ and about 635 ppm, because both obey the same analyzer. What the ratio changes is the speed of the failure. It converts an immediate loss of control into a slow drift of one model parameter, which is a more manageable failure, and it is the second reason the structure is standard.

Pause. Try Exercise 11.3 before reading on.

11.5.4 Kiln Speed, Burnability and the Free Lime Loop

Table 11.5 compares the two ways of moving free lime. Kiln speed changes the residence time of (11.1) and therefore the conversion of (11.11), and it does so without moving the burning zone at all.

Over the range, the free lime moves by 0.872 % while the burning zone moves by 1.3 °C. Speed is therefore an almost pure quality handle, and a fast one. In scenario 8 the free lime covers 63 % of its change 0.9 min after the speed step, against 3.6 min for the setpoint step of scenario 3. Kiln speed also sets throughput, so in practice it is committed to production rate rather than to quality.

Table 11.6 Challenge Scenario Over 300 min, Shipped Configuration Against the Suggested One

Quantity	shipped	suggested
Burning zone IAE (°C min)	6096.5	**674.5**
Oxygen IAE (% min)	338.5	**69.1**
Free lime IAE (% min)	242.7	**22.7**
Final free lime (%)	2.73	**1.20**
Final carbon monoxide (ppm)	3242	**20**
Final excess air λ	0.848	**1.035**
Time with a reducing flame (min)	88.7	**0.0**
Final specific heat (kJ/kg)	1600	1721

Burnability demonstrates why the assay loop is still required. Reducing β from 1.00 to 0.72 raises the free lime from 1.200 % to 1.646 % at unchanged firing, and the coal required to hold the burning zone at 1429.8 °C with the air fixed changes from 11.033 t/h to 11.024 t/h, a difference of 0.08 %. A burning zone controller is blind to it, and only the assay can see it.

🕮 **Pause.** Try Exercise 11.2 before reading on.

Scenario 7 closes the free lime loop with the budget of (11.15) in the path. The burnability step to 0.72 at 20 min reaches the controller with the result reported at 40 min, a dead time of 20 min in the middle of the budget. Over 6 h the loop accumulates 18.6 % min of free lime error with a burning zone error of 62.1 °C min, returns within 0.1 % of target 39 min after the step and stays within 0.02 % from 118 min after it. Raising K_c to 45 °C/% with $\tau_I = 12$ min produces an oscillation with a period of 57 min, close to three times that dead time, and in the sixth hour the free lime is still swinging between 0.92 % and 1.51 % while the burning zone setpoint has ranged over 1426 °C to 1485 °C. The loop therefore functions as a trim. The burning zone temperature holds the kiln, because it is fast and continuously measured, although it is not itself a product specification.

11.5.5 Challenge Scenario

The challenge, scenario 12, runs five hours with the raw meal stepped to 295 t/h at 20 min, burnability to 0.80 at 70 min, false air to 3 kg/s at 130 min and coal calorific value to 0.91 at 200 min. It opens with the air on feedback, the free lime loop open and the cautious tunings of scenario 1, which include $K_c = 0.025\,\mathrm{t/h/°C}$ and $\tau_I = 40$ min on the temperature loop. The pyrometer, the oxygen analyzer and the assay carry noise with standard deviations of 3 °C, 0.12 % and 0.05 %. Table 11.6 compares the shipped configuration with the suggested one, the ratio with trim, a closed free lime loop and the tunings of Section 11.4. The reducing flame time is the application's Reducing time tile, the minutes with carbon monoxide above the 500 ppm alarm.

The challenge passes when the burning zone stays within ±15 °C of setpoint, the carbon monoxide stays below 500 ppm throughout, the free lime returns below 2.0 % after each of the four upsets and the burning zone stays below the 1520 °C ring limit. The shipped configuration fails on three of the four limits. Its worst burning zone error is 44.1 °C, the carbon monoxide peaks at 3309 ppm and the free lime is still 2.7 % at 300 min after the calorific value drop at 200 min. The suggested configuration passes. Its worst error is 12.6 °C, the carbon monoxide peaks at 144 ppm, the free lime returns below 2.0 % after all four upsets with a peak of 1.48 %, and the burning zone peaks at 1449.6 °C, which leaves 2.4 °C and 356 ppm to spare.

The last two rows are related. The shipped configuration ends with the *better* specific heat consumption, 1600 kJ/kg against 1721 kJ/kg, and it achieves that by supplying insufficient combustion air for 88.7 min and producing clinker at 2.73 % free lime. Its cumulative coal is also lower, 68.7 kg per tonne of clinker against 71.4 kg. A scorecard reporting fuel per tonne alone would rank the

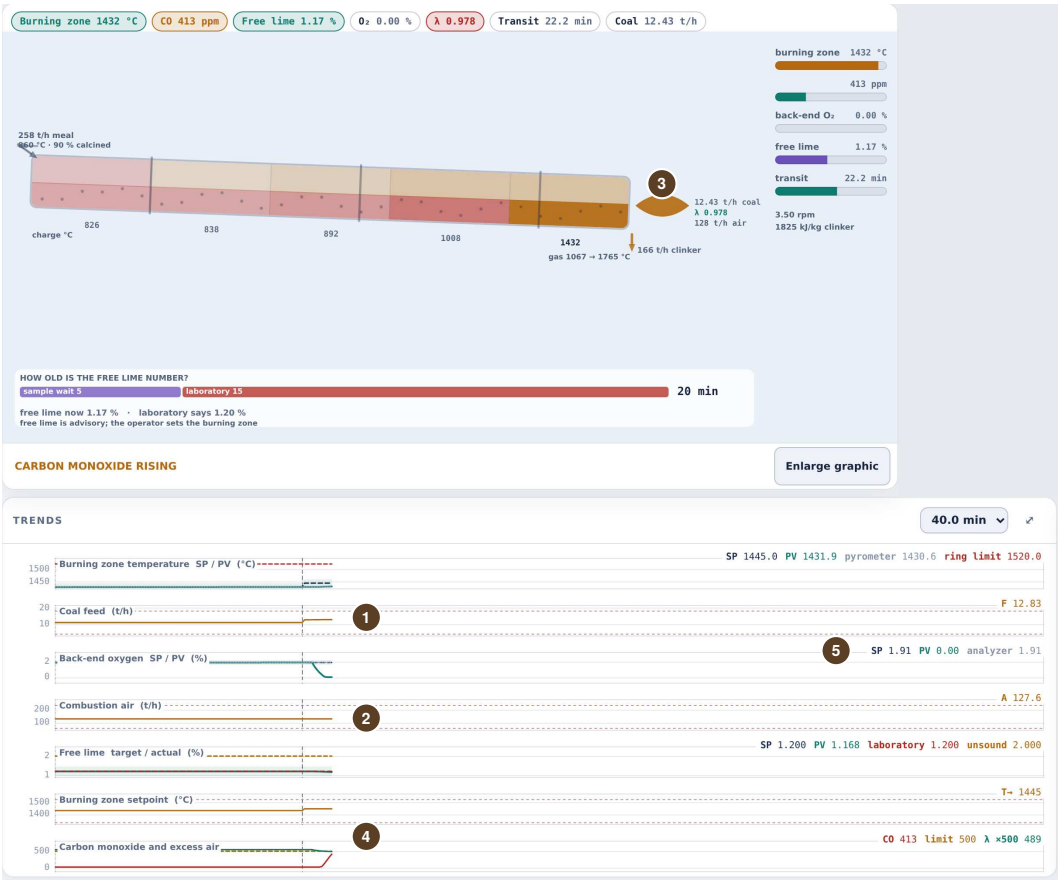


Figure 11.3 Scenario 4 at $t = 11.2$ min, cropped to the plant view and the trends, 1.2 min after the burning zone setpoint stepped from 1430 °C to 1445 °C, with the air on oxygen feedback alone. The coal command (1) rose from 11.05 t/h to 12.70 t/h within one scan and now stands at 12.83 t/h, with 12.43 t/h reaching the burner, while the combustion air (2) is still 127.6 t/h. The flame (3) is at $\lambda = 0.978$ with 413 ppm of carbon monoxide (4) and the back-end oxygen is 0.00 %, but the analyzer (5), 0.8 min of gas travel downstream, still reads 1.91 %.

shipped configuration higher. The application therefore reports carbon monoxide time and free lime beside the energy number, because a single figure of merit is blind to the constraint violations that reduce it.

Of the two structural choices, the air structure decides the outcome. The suggested tunings with feedback air still fail, with a carbon monoxide peak of 1329 ppm and 11.0 min of reducing flame, while the ratio with an advisory free lime loop passes, at a free lime error of 72.4 % min against 22.7 % min with the loop closed.

Figure 11.3 shows the kiln during scenario 4 at 11.2 min, after the coal has moved and before the air has.

11.5.6 Predictive Controller Against the Loops

The MPC is compared with the loops in Table 11.7. Every run lasts 300 min, or 360 min for scenario 10, at the case's own seed with its instruments, noise and events. The loops are the ratio with trim and the closed free lime loop at the case's tunings, or the challenge's suggested settings, while

Table 11.7 The MPC Against the Ratio With Trim and a Closed Free Lime Loop, With the Information and Limits It Carries Handed to the Loops

Case	Structure	FL IAE (% min)	λ_{min}	Under floor min (% min)	CO ppm (min)	Travel (t/h)
11	loops	22.48	0.948	191.5 (178.73)	891 (26.9)	100.5
	MPC	20.93	1.043	101.3 (1.48)	20 (0)	29.1
	MPC, no raised target	21.05	1.026	186.1 (10.82)	20 (0)	29.9
	MPC, assays at report	29.46	1.043	93.6 (1.58)	20 (0)	29.5
	loops, T*	19.70	0.941	190.8 (178.79)	1014 (26.4)	103.8
	loops, floor + cross	22.94	1.049	9.3 (0.05)	20 (0)	100.5
	loops, T*, floor + cross	19.60	1.049	9.2 (0.05)	20 (0)	103.5
	loops, hindsight	20.33	0.940	157.0 (106.75)	1040 (5.0)	188.5
6	loops	2.04	0.971	81.0 (58.91)	502 (0.3)	1.7
	MPC	0.39	1.050	8.5 (0.00)	20 (0)	0.6
	loops, floor + cross	0.87	1.050	0.3 (0.00)	20 (0)	0.6
7	loops	18.54	1.081	0	20 (0)	3.0
	MPC	15.12	1.096	0	20 (0)	1.7
	loops, T*	12.54	1.087	0	20 (0)	4.8
	loops, hindsight	13.24	0.998	0.9 (0.50)	169 (0)	10.9
8	loops	29.21	1.060	0	20 (0)	4.4
	MPC	4.70	1.094	0	20 (0)	3.7
	loops, T*	2.76	0.945	1.1 (0.83)	939 (0.3)	8.6
	loops, T*, floor + cross	2.68	1.082	0	20 (0)	8.3
9	loops	11.98	1.071	0	20 (0)	9.1
	MPC	8.40	1.093	0	20 (0)	7.3
	loops, T*	7.38	1.076	0	20 (0)	6.4
	loops, hindsight	3.13	1.057	0	20 (0)	10.5
10	loops	15.59	1.088	0	20 (0)	3.8
	MPC	13.75	1.096	0	20 (0)	2.7
	loops, T*	11.19	1.091	0	20 (0)	5.1
	loops, hindsight	10.82	1.021	0.7 (0.22)	20 (0)	13.5
12[a]	loops, met	22.67	1.000	142.3 (53.04)	144 (0)	100.6
	MPC, not met	23.58	1.044	82.1 (1.30)	20 (0)	29.7
	MPC, $\mu = 0.1$, met	20.94	1.046	85.6 (1.25)	20 (0)	56.9
	loops, T*, met	21.02	0.998	141.2 (53.34)	169 (0)	102.5
	loops, hindsight, met	19.08	0.983	104.0 (41.75)	339 (0)	185.7

FL IAE integrates the true free lime error, under floor is the time and depth of the flame's oxygen, $21(1 - 1/\lambda)$, below 1 %, CO is the peak with its minutes over the 500 ppm alarm, and travel is the summed movement of the coal command. Cases 6 to 10 carry no noise. Every MPC run made 600 plans (720 on case 10) and rejected none, at 0.79 to 0.84 ms per plan in Node.
[a]The challenge with its suggested settings, judged by its rule. The MPC with $\mu = 0.1$ is not shipped.

the MPC carries the settings shipped in scenario 11 into every case unchanged. Neither structure measures the feed, the meal or the coal. Three rows hand the loops what the plan carries. T* gives them the plan's burning zone target. Floor and cross-limit hold the trim's ratio above 1.05 AFR and ratio the air to the larger of the coal command and the modeled coal at the burner, so the air leads the coal up and lags it down, the cross-limited arrangement of fired equipment [6]. Hindsight is the best of 38 tunings of the three loops searched on that case after the fact. The measures come from the logged columns at 0.1 min, the sampling of the scorecard.

Scenario 11 hardens the raw meal to a burnability of 0.75 at 20 min, opens 4.5 kg/s of false air at 100 min and cuts the coal calorific value by 12 % at 180 min, with the challenge's instrument noise. The free lime peaks alike, at 1.629 and 1.631 %, and the IAE from 20 to 100 min is 11.77 under the MPC against 12.32 under the loops, as shown in Figure 11.4. The structures part at the leak. The trim believes the analyzer and takes the flame to $\lambda = 0.948$ at 165.5 min with 891 ppm of carbon monoxide, and the run ends at $\lambda = 0.990$ with 255 ppm, while the plan holds 1.043 or above and ends at 1.050. The plan burns 60.48 against 60.67 t of coal and moves it 29.1 against 100.5 t/h.

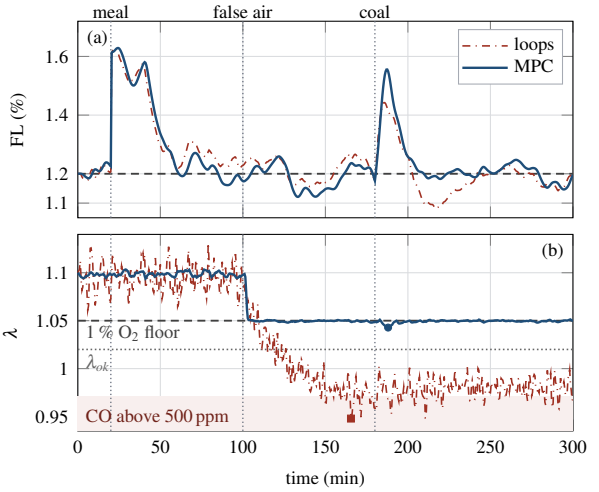


Figure 11.4 Scenario 11, the MPC against the ratio with trim and a closed free lime loop at the case's own seed, the MPC solid and the loops dash-dotted. (a) True free lime against its 1.20 % target, dashed. (b) The flame's lowest excess air per half minute against the MPC's floor at $\lambda = 1.05$, dashed, and λ_{ok}, dotted, with carbon monoxide above the alarm in the shaded band. The meal hardens at 20 min, false air enters at 100 min and the coal weakens at 180 min, at the dotted verticals. The lowest points, $\lambda = 1.043$ at 188.0 min (circle) and 0.948 at 165.5 min (square), are marked.

Removing one mechanism at a time places both gains outside the optimization. Without the raised oxygen target the plan's flame falls to $\lambda = 1.026$ with 186.1 min under the floor, while without the flame row it stays at 1.043 with 105.3 min, and the analyzer row never binds. A classical floor and cross-limit hold $\lambda = 1.049$ with 9.3 min under the floor against the plan's 101.3 min, since the plan rides a target placed exactly at the floor and is more than 0.05 % under it for only 4.1 min. The free lime gain is information. The loops handed T* reach 19.70 % min, and with the floor and cross-limit as well 19.60 % min at $\lambda = 1.049$, which beats the plan on free lime and on the flame together. What stays with the plan is calm, 29.1 against 103.5 t/h of coal travel.

The other cases repeat the pattern. Under the false air of scenario 6 the plan holds $\lambda = 1.050$ where the loops reach 0.971 and 502 ppm, and the floor and cross-limit hold 1.050 as well. On scenarios 7 to 10 the plan improves on the loops' free lime, the loops handed T* improve on the plan, and scenario 8 gives the plan its largest lead because the speed command enters its free lime law. There T* alone brings 939 ppm after the speed returns at 110 min, which the floor and cross-limit remove.

The losses are reported as measured. On free lime the plan loses to the loops handed T* on every case from 7 to 11 and in the challenge, and to the loops retuned in hindsight on scenarios 7, 9, 10, 11 and the challenge. The best of 360 settings on scenario 11 reaches 19.31 % min, with $\lambda = 0.920$ and 48.8 min over the alarm. On scenario 9 its free lime peaks at 1.562 against 1.468 %, because the move price that keeps the coal calm makes the plan slower than the PI on a heat load it cannot measure, and at a move price of 0.1 the peak is 1.495 %. At three further seeds of scenario 11 the plan reaches 21.13, 23.48 and 24.64 against the loops' 26.13, 27.54 and 22.32 % min, so its free lime lead holds on three of four seeds, while its flame stays at 1.043 or above on all four, and a halved integration step changes no ranking.

The same calm fails the challenge. With the suggested settings the plan's burning zone falls to 1414.3 °C against a target of 1431.3 °C at 26.1 min on the raw meal step, an error of 17.0 °C against the rule's 15 °C, while the loops' PI meets the rule at 12.6 °C. The feed step is a heat load that the plan sees only through its disturbance estimate and answers at the move price chosen on scenario 11. A move price of 0.1 would meet the rule at 14.8 °C with 56.9 against 29.7 t/h of coal travel, and

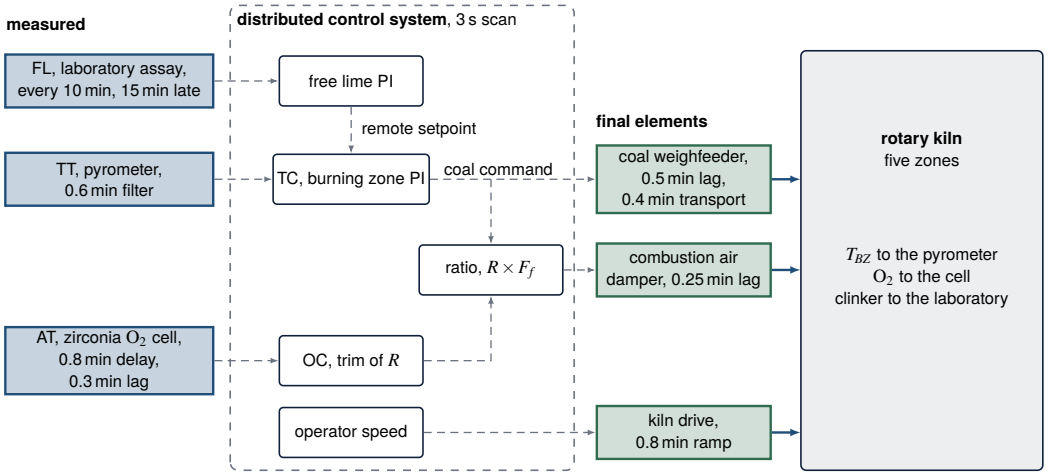


Figure 11.5 The loops of the simulated kiln drawn with their hardware. The temperature controller TC sets the coal weighfeeder, and the same coal command, multiplied by the ratio R, sets the combustion air in the same scan, while the oxygen controller OC only trims R. The free lime result writes the burning zone setpoint each time an assay arrives, and the kiln speed stays with the operator.

at the three further seeds the shipped plan misses at 15.9 and 15.7 °C and meets it at 14.0 °C. The limits the challenge does not score fall the other way, with the plan's flame 82.1 min and 1.30 % min under its floor and never below λ_{ok}, and the loops' flame 142.3 min and 53.04 % min under it, down to $\lambda = 1.000$ and below λ_{ok} for 19.9 min.

11.6 Technology in Practice

Figure 11.5 draws the loops of Section 11.4 with their hardware.

What Measures It

The burning zone is read by a pyrometer that looks at the hot charge from the burner end. The model's 0.6 min pyrometer filter stands for the smoothing such a reading gets. The oxygen at the back end can be read by a high-temperature zirconium oxide cell with platinum electrodes, one side in the gas and the other in heated reference air, drawn in Figure 11.6. The oxygen in the exhaust of an efficiently controlled burner sits near 2 %, and it matters for fuel efficiency and for nitrogen oxides alike [20]. The cell reads whatever oxygen reaches it, which is why the false air of Equation (11.9) biases it. The model's 0.8 min delay and 0.3 min lag stand for the gas travel and the cell's response. Free lime has no instrument at all: it is a laboratory assay.

> **TECHNOLOGY Sensor: The Burning Zone Pyrometer**
>
> A pyrometer reads temperature from the thermal radiation a hot body emits, which suits a burning zone no probe would survive. The instrument sees only a surface, and its main weakness is inaccuracy: the emittance of the target has to be found once against a contact reading and set in the instrument. Radiation reflected from other bodies taints the reading, and an instrument aimed through a gas may report the solid behind it [20]. A wrong emittance shifts every reading, and the loop then holds the wrong temperature.

What Moves It

The coal reaches the burner through a feeder that the temperature controller sets.

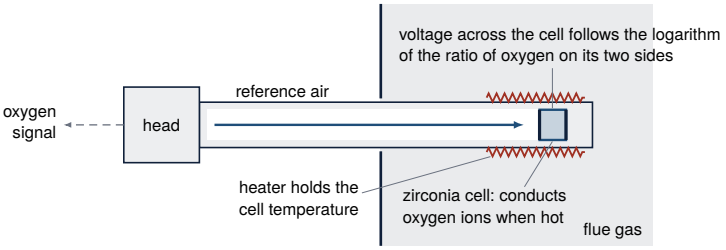


Figure 11.6 The zirconia oxygen cell. Notice that the voltage compares the oxygen in the gas at the probe with the reference air. Nothing in the cell knows whether that oxygen passed through the flame, so air leaking in at the inlet seal reads as excess air, the bias of scenario 6.

TECHNOLOGY Final Element: The Coal Weighfeeder

A weighfeeder carries the solid on a short conveyor belt whose middle section rests on rollers coupled to load cells. The load cells give the weight per length of belt, a speed sensor gives the belt speed, and their product is the mass flow, which the feeder's controller holds at a setpoint in tons per hour. The belt loading fluctuates in normal operation and the flow calculation lags the weighing, so the flow trend is noisy and slightly late [20]. The model's 0.5 min feeder lag and 0.4 min of transport to the burner stand for this path.

The combustion air is moved by a damper or fan with a 0.25 min lag in the model, and in the ratio structure its setpoint is the coal command times R. The kiln drive follows the operator's speed with a 0.8 min ramp. The model has no dead band or stiction.

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 [21]. In the app every loop acts on a 3 s scan against a burning zone time constant of 13.0 min, and the predictive controller plans every 0.5 min. On such a platform the temperature, oxygen trim and free lime loops are PID function blocks of the regulatory layer. The ratio is a multiplying block between the coal command and the air setpoint, and the free lime loop writes the temperature loop's remote setpoint each time an assay arrives.

IN PRACTICE Cross-Limiting the Air and the Fuel

Burner control in practice adds two selectors to the ratio. The air setpoint is the larger of the firing command and the measured fuel flow, and the fuel setpoint is the smaller of the firing command and the measured air flow. The air therefore leads when firing rises and the fuel leads when it falls, so the mixture runs lean, which is safe, rather than rich, which is dangerous. A rate limit on the firing command keeps a lean transient from blowing the flame out, and a multiplying function sets the air to fuel ratio [20]. The floor and cross-limit rows of Table 11.7 hand the kiln's loops a version of this.

What Is Modernizing It

The first development is supervisory control above these loops. Rule-based, fuzzy logic and expert systems try to act as the best human operator. One such system, first installed at a cement works in 1985, cut fuel use by nearly 8 %. Model predictive control with dynamic models of the kiln followed, and a kiln fitted in 1999 needed 4 % less energy. Typical savings of such systems are put at 2.5 to 5 % [22]. The second is measurement of the feed. Online analyzers give the chemical composition of the raw materials at once, so the blend can be corrected before it reaches the kiln [22], which meets the burnability disturbance of scenario 7 at its source. The third is the dynamic kiln model. One-dimensional models that track the individual clinker and fuel compounds are offered as

a stepping stone for developing process control on existing plants [23], the role the eighteen-state model of Section 11.3 plays here at a coarser scale.

11.7 Limitations

The reaction scheme is the largest simplification. Two lumped reactions with Arrhenius rates reproduce the shape of the conversion profile and the switch-like behavior of clinkerization, and they cannot represent the phase sequence, the melt or the effect of the alumina and iron moduli that decide burnability in practice [8]. The burnability multiplier β is a stand-in for all of it, which is adequate for a control argument about an unmeasured disturbance and inadequate for any statement about a particular raw mix.

The rest of the pyroprocessing line is a boundary condition. A real line recirculates alkalis and sulfur between the kiln and the preheater, and those cycles produce the build-ups, blockages and coating changes that dominate real kiln operation. Integrated simulators exist to capture exactly those recycles [13], and nothing in this application can substitute for one. Ring formation is an alarm here rather than a mechanism, so the kiln never restricts and the residence time never changes as a result.

Carbon monoxide is algebraic, and the clinker damage a reducing flame causes is asserted rather than computed. Nitrogen oxides are absent, which matters because they constrain the operating point from the opposite side and make the acceptable combustion window narrower than this application shows. The gas phase carries no composition at all, so the model can describe an oxygen reading and cannot describe a gas analysis.

The predictive controller's model leaves out what its estimators have to absorb. Its two modes have gains fixed at the design feed and firing, so a change of feed rate or operating point is model error. The kiln speed enters only the free lime law, although a speed step moves the burning zone by −1.80 °C per rpm at about 57 min before it settles at −0.74. Burnability reaches the plan only through the assays, false air only through the oxygen bias, and the true air-fuel ratio not at all, because the excess air the plan protects is computed from its commands with the declared stoichiometry. The raised target sits exactly at the floor rather than a margin above it, and the plan prices no fuel.

Finally, the free lime measurement is a clean delayed sample with optional noise. Real assays carry sampling error from a clinker stream that is not homogeneous, and disagreement between the laboratory result and the kiln condition is a routine operational problem that the application does not represent.

> ⚠ **OPEN CHALLENGE** **Clinker Quality That Holds Still**
>
> Ordinary Portland cement is about 90 % clinker, and its strength depends on the clinker's composition. Large swings in that composition limit how much supplementary material can replace clinker, because more clinker is needed to cover the spread in strength. Reducing the variation of clinker quality has been called a must for a more sustainable cement, through better quality predictions and through control [23]. The free lime loop shows why it is hard: the quality number arrives 15.9 to 25.9 min late. Progress would be a quality estimate at every scan that the burning zone loop could trust.

11.8 Discussion

The two ends of the kiln lead to opposite control conclusions, and the application presents both in one plant.

At the fast end the remedy is structural and complete. The disturbance is the control system's own output, it is known exactly and immediately, and using it removes the excursion rather than reducing it. The general form is that feedforward is built from whatever signal arrives with the disturbance, and feedback then corrects the model rather than the plant. The ratio is the model and 11.55 tonnes of air per tonne of coal is its one parameter. The same structure also degrades gracefully against a corrupted measurement, as Section 11.5.3 shows, which is a second argument that is usually absent from the textbook presentation.

At the slow end no structural remedy exists. Up to 26 min of assay dead time on a 13 min zone, driven through a temperature loop that answers in a few minutes, gives a loop that cannot be made fast, and (11.15) establishes that limit before any tuning is attempted. What follows is a division of roles. The burning zone temperature becomes the controlled variable because it is fast and measured, the free lime becomes a slow trim on its setpoint, and kiln speed becomes available as a faster quality handle. Industrial model predictive implementations arrive at the same division, using the assay to correct an inferred quality rather than to close a loop [7].

The model of Section 11.3 also supports control methods beyond the PID, ratio and trim loops and the linear predictive controller of Section 11.4.5 that the application implements. The eighteen differential states, algebraic gas profile and actuator limits match the problem form solved by nonlinear model predictive control, which would coordinate coal, air and kiln speed in one constrained calculation and could run an economic objective on the specific heat consumption of Table 11.6 while holding the carbon monoxide limit as a hard constraint rather than a scorecard entry [24]. Moving horizon estimation over the same equations would reconstruct burnability and false air from the temperature and oxygen histories, converting the two unmeasured disturbances of scenarios 6 and 10 into soft-sensed quantities, and Kalman filtering of the sampled assay would supply a continuous free lime estimate between laboratory results. The Gekko Optimization Suite implements these methods in Python from model statements close to (11.2) through (11.12) [25].

The third conclusion concerns performance metrics. Table 11.6 shows a configuration that wins on specific heat consumption and loses on every other measure, by supplying insufficient combustion air. Any single figure of merit on this plant can be improved by actuator action that the figure does not observe, which is the general reason that operating limits belong on the scorecard beside the objective rather than only in an alarm list [5].

11.9 Conclusion

A rotary kiln combines a combustion excursion lasting about three minutes and a quality loop carrying up to 26 min of dead time in one vessel. The fast problem has a complete structural remedy, because the air can be computed from a fuel command that is known in the scan it is issued, and the application measures that remedy as the difference between a 611 ppm carbon monoxide peak and none at all through the same firing move. The slow problem has no such remedy, and the dead-time budget of (11.15) establishes that limit before tuning is attempted rather than after a shift of oscillation. Between the two sits a combustion penalty so asymmetric that the kiln gives up 12.2 °C of burning zone temperature to stay clear of it, and an oxygen measurement that false air biases without any change in the flame’s excess air. A graded five hour run assembled correctly removes 88.7 min of reducing flame and pays 121.6 kJ per kilogram of clinker for it, which is the trade-off the plant faces. The added predictive controller holds the flame at an excess air of 1.043 or more through false air where the ratio with trim falls to 0.948, mostly through its raised oxygen target, while the loops handed its burning zone target, a ratio floor and a cross-limit reach 19.60 against its 20.93 % min of free lime error.

KEY POINTS

- The air should follow the coal command, not the oxygen reading, which arrives only after the gas has traveled: a 15 °C firing move then leaves no carbon monoxide peak, against 611 ppm.
- False air biases the oxygen analyzer, and the ratio turns that failure into a slow drift.
- With 15.9 to 25.9 min of dead time on a 13.0 min zone, the free lime loop is a slow trim on the burning zone setpoint.
- A configuration can win on specific heat by running a reducing flame, so limits belong on the scorecard.

Where else this applies. Volume 3, Chapter 4 adds cross-limiting to the same ratio, and Volume 5, Chapter 3 tunes a loop through a slow analyzer.

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11.10 Exercises

11.1 Concept check · 2 min

The burning zone setpoint steps up 15 °C and the temperature controller raises the coal command within one scan. Why does ratioing the combustion air to that command keep the carbon monoxide at its floor when no tuning of an oxygen feedback loop can?

(a) The coal command is known in the scan it is computed, so the air moves before any gas reaches the analyzer

(b) The ratio trim is tuned five times faster than the oxygen feedback loop it replaces

(c) The ratio structure raises the oxygen setpoint for the duration of every firing move

(d) The ratio removes the coal transport delay between the feeder and the burner

11.2 Concept check · 1 min

The raw meal becomes harder to burn, its burnability falling from 1.00 to 0.72, while the burning zone loop holds 1430 °C. Which reading is the first to show the change?

(a) The pyrometer, as the burning zone cools by about 10 °C

(b) The laboratory free lime, once a report covers clinker made after the change

(c) The oxygen analyzer, because a harder meal needs more combustion air

(d) The coal feed, which the temperature loop raises by about a tenth

11.3 Concept check · 2 min

A worn inlet seal admits 4.5 kg/s of false air while the air is on oxygen feedback. What does the controller do?

(a) It opens the damper further, because the leak dilutes the flame and cools it

(b) It does nothing, because the analyzer's 0.3 min lag filters the leak out

(c) It closes the damper and drives the flame's own excess air below stoichiometric

(d) It leaves the air alone and the burning zone loop cuts the coal instead

11.4 Theory and calculation · 6 min

Use Equation (11.1) and the parameters of Table 11.2 at the design feed of 258 t/h.

(a) Compute the transit τ, the zone residence τ_z and the zone hold-up M_z at 3.5 rpm, to two decimals. *Checkpoint:* 22.16 min; 4.43 min; 19.06 t

(b) Evaluate the burning zone time constant $M_z 10^3 C_{p,s}(1+f_{ref})/[60(\dot{W}_s + UA_5)]$ with $UA_5 = UA_0 w_5$ from Equation (11.3), and the same expression without the refractory, to one decimal. *Checkpoint:* 13.0 min; 3.1 min

(c) Scenario 8 raises the speed to 4.6 rpm. Compute the new transit to one decimal, and say why it does not enter the free lime loop's dead time. *Checkpoint:* 16.9 min

11.5 Theory and calculation · 7 min

Use Equations (11.7) to (11.9) with AFR $= 10.5$ at the design coal rate of 11.033 t/h.

(a) Compute λ and the oxygen reading at 127.434 t/h of air, and the carbon monoxide at $\lambda = 0.95$. *Checkpoint:* 1.100; 1.91 %; 853 ppm

(b) False air of 4.5 kg/s enters at the inlet seal. Compute $\hat{\lambda}$ and the analyzer reading with the air unchanged. *Checkpoint:* 1.240; 4.06 %

(c) An oxygen feedback loop drives the analyzer back to 1.91 % with the coal held at 11.033 t/h. Compute the air, the flame's λ and the carbon monoxide at steady state, and compare with the run in Section 11.5.3, which ends at $\lambda = 0.963$ and about 635 ppm. *Checkpoint:* 111.2 t/h; 0.960; 678 ppm

11.6 Theory and calculation · 7 min

The free lime loop's dead time is the budget of Equation (11.15). Use the SIMC rules $K_c = \tau_p/(K_p(\tau_c+\theta_p))$ and $\tau_I = \min(\tau_p, 4(\tau_c+\theta_p))$.

(a) Give the shortest and longest effective dead time and their ratios to the 13.0 min zone constant and to the 3.7 min the closed temperature loop takes to cover 63 % of a setpoint step, to one decimal. *Checkpoint:* 15.9 and 25.9 min; 1.2 and 2.0; 4.3 and 7.0

(b) Tune the loop on the 13.0 min zone with $\theta_p = \tau_c = 25.9$ min, for process gain magnitudes of 0.015 and 0.018 %/°C. Give K_c to one decimal and τ_I. *Checkpoint:* 16.7 and 13.9 °C/%; 13 min

(c) Which sign does the controller action take, and why? *Checkpoint:* $a = -1$

11.7 App challenge · 8 min

Run scenario 4, "Oxygen feedback alone, against a firing move", as shipped at the default seed, to 60 min at 5 min per second; pause within a minute of 60 min. Repeat with scenario 5, "Ratio the air to the fuel".

(a) For each run read the Reducing time tile and the burning zone IAE in the Learn panel, to ±0.5 °C min. *Checkpoint:* 0.8 and 0.0 min; 68.7 and 81.7 °C min

(b) Export each run's CSV and give the minimum of the `lambda` column to three decimals. *Checkpoint:* 0.964; 1.085

(c) By how many percent of scenario 4's value is the burning zone IAE higher under the ratio, to the nearest percent? Explain the increase from the excess air of the two runs during the rise. *Checkpoint:* 19 %

11.8 App challenge · 9 min

Load scenario 7, "Close the loop on free lime", at the default seed. Before Run, set Free lime gain to 45 and Free lime integral time to 12 min. Run to 360 min at 60 min per second and export the CSV, whose time column is in hours.

(a) From the `lime_pct` column after 120 min, estimate the oscillation period from successive highest peaks, to ±5 min. *Checkpoint:* about 57 min

(b) Give the lowest and highest `lime_pct` in the sixth hour, 300 to 360 min, to ±0.02, and the range of the burning zone setpoint `bz_sp_C` over the whole run, to ±1 °C. *Checkpoint:* 0.92 to 1.51 %; 1426 to 1485 °C

(c) The burnability step at 20 min first moves the setpoint at 40 min. Compare the period with that dead time and say what the shipped tuning of 15 and 13 min achieves instead. *Checkpoint:* about three dead times

11.9 App challenge · 9 min

Load the challenge at its default seed and run it as shipped to 300 min at 60 min per second. Then reload it, press Reveal suggested tuning before Run and run it again.

(a) For each run read the Reducing time, Specific heat, Coal per tonne and Free lime tiles at 300 min. *Checkpoint:* 88.7, 1600, 68.7, 2.73; 0.0, 1721, 71.4, 1.20

(b) A plant manager ranks configurations by specific heat alone. Which run wins, and what does the ranking hide? *Checkpoint:* the shipped run

(c) Keep the suggested tuning but set Air control back to O_2 feedback before Run. Read the Reducing time tile and say which of the two structural choices decides the challenge. *Checkpoint:* 11.0 min; the air structure

11.10 Application area · 3 min

Table 11.3 shows the burning zone hottest near $\lambda = 1.00$, yet the kiln runs at $\lambda = 1.10$.

(a) What does the operating point give up in burning zone temperature and free lime against $\lambda = 1.00$? *Checkpoint:* 12.2 °C; 0.20 %

(b) Give the reason a plant accepts that cost, and name one constraint the model leaves out that would narrow the window further. *Checkpoint:* carbon monoxide; nitrogen oxides

11.11 Application area · 4 min

Table 11.5 sweeps the kiln speed at fixed firing.

(a) From 3.5 to 4.2 rpm, how much does the free lime rise? Using the chapter's steady gain of 0.015 to 0.018 %/°C and 52.1 °C per t/h, how much hotter would the burning zone have to run, and how much more coal would that take? *Checkpoint:* 0.245 %; 14 to 16 °C; 0.26 to 0.31 t/h

(b) Speed moves the free lime faster than the burning zone setpoint does. Why is it rarely used as a quality handle in practice? *Checkpoint:* throughput, bed depth, coating

11.12 Review the agent · 5 min

An AI assistant tunes the free lime loop: "The dead time is the 22.2 min kiln transit plus the 15 min turnaround, half a 10 min sample interval and 0.9 min of coal path, about 43 min. SIMC with $\tau_c = \theta_p$ on the 13 min zone and a gain of 0.016 %/°C gives $K_c \approx 9.4$ and $\tau_I = 13$ min. Expect a hot tuning to ring with a period of about two hours." Find the flaw and say how you would check it in the app.