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CHAPTER 4

Basic Oxygen Furnace Simulator for Endpoint Control With One Late Measurement

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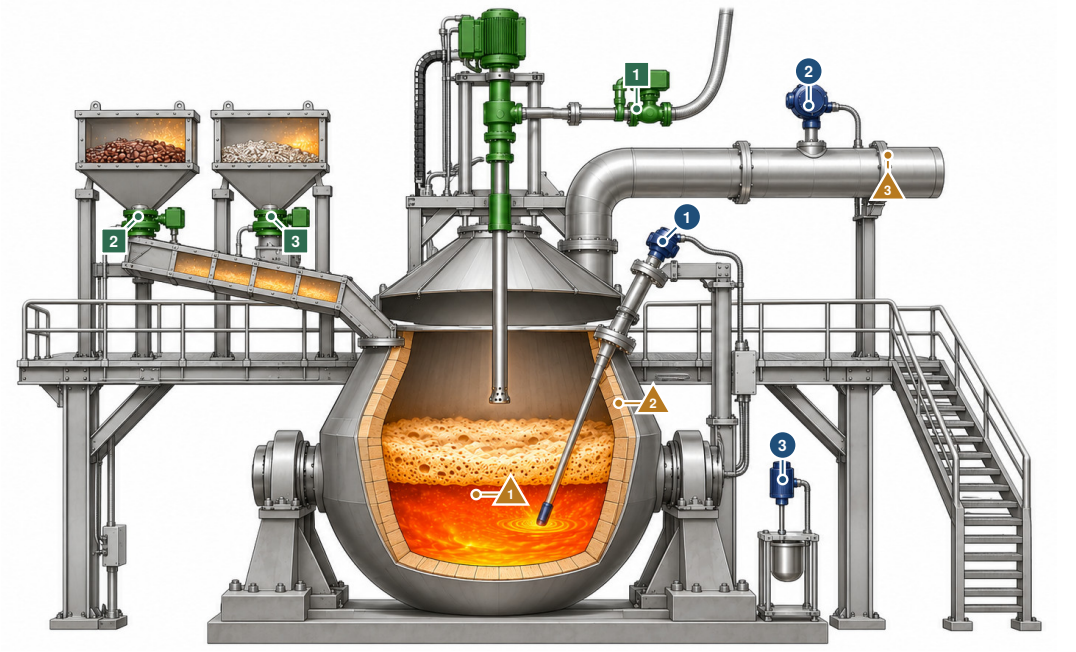
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CHAPTER 4

Basic Oxygen Furnace Simulator for Endpoint Control With One Late Measurement



The controller moves 1 oxygen blown through the lance 2 iron ore added to cool the bath 3 ferrosilicon added to warm a heat that would end cold

The controller reads 1 sublance probe: carbon and temperature late in the blow 2 off-gas analyzer: how fast carbon leaves as gas 3 carbon and temperature tested at turndown

What disturbs it 1 hot metal and scrap that vary from heat to heat 2 a lining that loses more heat each heat 3 an error in the off-gas flow reading

Notice that the lance blows oxygen from above the bath while the sublance dips into it once, late in the blow, after which ore can cool the heat but only more oxygen, burning the carbon below its aim, can warm it. Illustration, not to scale.

IN PLAIN TERMS **One Blow, Judged at the End**

The main idea. A converter makes steel by blowing pure oxygen onto liquid iron. The oxygen burns out the extra carbon, and the burning heats each batch, called a heat, to the temperature the steel needs.

The challenge. Oxygen once blown cannot be taken back, and a probe checks the bath only once, near the end. After that the heat can be cooled with iron ore, but warming it would burn out too much carbon.

Why it matters. A heat that misses must be blown again, or it wastes good iron in the slag on top.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	The first page, the fact box of Section 4.1, the history box of Section 4.2, the try-it boxes and the history box of Section 4.4, the fact box of Section 4.5, and the key points
Study	35 min	The whole chapter with its pause points and the twelve exercises
Practice	10 min	The first page, Section 4.5, Section 4.6, Section 4.7 and the open challenge after it

The control question A converter heat is blown once and judged at its end, and neither the carbon nor the temperature can be taken back. What can a charge model plan, what can one late measurement correct when the only correction left can cool but not heat, and what can only learning between heats follow?

Learning objectives

- Derive the decarburization rate, its time constant below the critical carbon and the iron burned per kilogram of carbon.
- Explain why a static charge model hits the carbon more often than the temperature.
- Size a hot margin for a one-way correction after the sublance.
- Compare the error of an integrated off-gas estimate with that of the same signal read as a rate.
- Compute the lag of run-to-run learning on a drifting heat loss and choose its weight.

Prerequisites Section 1.4.4 (charge model, rate endpoint, one-way correction and EWMA lag), 1.6.1 and 1.6.4 (engine, scenarios and the scorecard).

The app https://apmonitor.com/apps/bof-converter/

See also Volume 8, Chapter 9 for EWMA run-to-run correction from late results, Volume 8, Chapter 10 for learning between repetitions and Volume 8, Chapter 4 for a batch graded only at its end. Volume 5, Chapter 13 for an integrated estimate reset by late fixes and Volume 5, Chapter 4 for acting ahead of a late analyzer.

4.1 Introduction

A batch has no steady state to regulate around. What it delivers is decided by the state it reaches at the end, so batch control is largely a matter of planning the batch from what is known of its start, correcting the plan once or twice on the way, and using the result of each batch to improve the plan for the next. Run-to-run and batch-to-batch control formalize the last of these steps, and surveys have tied them to iterative learning and repetitive control as one family of methods for processes that repeat [1, 2]. Learning between the layers of a build in Volume 8, Chapter 10 is a member of the same family.

The basic oxygen furnace, or converter, is an unforgiving example. The steel sector is responsible for about 7 % of anthropogenic carbon dioxide emissions, and the blast furnace route that dominates its iron production [3] makes its steel in the converter. Each heat is charged with hot metal and scrap and blown with oxygen until the carbon falls to its aim, and the heat of oxidation brings the bath to tapping temperature on the way. One actuator, the oxygen volume, sets both endpoints. Too little oxygen leaves carbon that must be removed by a reblow, and too much oxidizes iron, because below a critical carbon the reaction becomes limited by carbon transport in the bath rather than by oxygen supply [4, 5]. A block diagram with one input and two outputs hides what makes the problem hard, namely that oxygen once blown cannot be withdrawn, that the two endpoints are coupled through the heat of oxidation, and that the only in-blow measurement arrives with 15 % of the blow left.

DID YOU KNOW? Twenty-Eight Percent of American Steel

The United States made about 81 million metric tons of raw steel in 2024, 28 % of it in basic oxygen furnaces and the rest in electric arc furnaces [6], the subject of Chapter 5. A modern converter can make steel at 500 tons an hour [7]. The simulated heat of this chapter is 300 t, blown in about 21 min.

The cases of this chapter are built around the belief that a continuous measurement is always worth more than a single sample, and show where it fails. An off-gas analyzer reports the decarburization rate every second of the blow, while a sublance probe measures the bath once, at 85 % of the planned oxygen. Integrated from the start of the heat, the continuous signal accumulates every percent of flow meter error into the carbon estimate, and the single late sample does not. The broader class is batch endpoint control under a terminal specification, which appears in plasma etch, batch polymerization, fermentation, heat treatment and others, wherever a recipe must be fixed before the batch and

corrected from few measurements during it [2, 8]. The shape of the problem is the same in all of them. A model maps the measured initial state to a recipe, a late measurement re-plans the remainder, the correction available after that measurement is usually one-directional, and slow drift in the equipment is visible only across batches.

This chapter works with a converter simulator in which the static charge model, the sublance re-plan, the off-gas integral, the rate-based endpoint, the temperature margin and run-to-run learning can be switched on one at a time and compared over the same campaign of heats. All of these strategies are established practice. What is particular to this plant is a heat and mass balance of one heat, with the charge variation, instrument errors and controller logic written out completely enough to rebuild. The ten scenarios separate what feedforward from the charge can decide, what one late measurement can correct, and what only learning between heats can follow. Section 1.4.4 introduces these ideas on a smaller converter, and this chapter measures them on a full one. Section 4.2 reviews converter control and Section 4.3 gives the model of one heat, its oxygen distribution, heat balance and heat-to-heat variation. Section 4.4 describes the strategies as implemented, from the static charge model through the sublance re-plan and the two uses of the off-gas signal to reblowing and run-to-run learning. Section 4.5 reports the measured campaigns, from the fixed recipe through the late measurement, the integral against the rate, drift and learning and the low carbon aim to the graded challenge. Section 4.6 describes the real instruments, final elements and control platforms, Section 4.7 states the limitations, Section 4.8 concludes, and Section 4.9 holds the exercises.

4.2 Endpoint Control in Oxygen Steelmaking

Blowing pure oxygen onto a bath of hot metal became an industrial steelmaking process in the early 1950s, and the oxygen converter marked its fiftieth year of production in 2002 [9]. Without a model or an in-blow measurement, the decision to stop rests on a sample taken after turndown and a reblow when the sample is wrong.

> ⧖ HISTORY **From Open Hearth to Oxygen (1954 to the 1980s)**
>
> The basic oxygen furnace was introduced in North America in 1954. The basic open hearth it displaced had made steel there since well before 1900, but it consumed huge tonnages of refractories, needed many hours of labor per ton and was slow, and as labor and energy costs rose the change became inevitable. By 1969 the two processes each made 60 million tons a year. The oxygen process runs on its own heat with 70 percent or more hot metal in the charge. Static and dynamic models and sensors for the turndown have occupied steelmaking technologists since the 1960s. The ladle furnaces of the 1980s eased the temperature problem, because they allowed the temperature to be adjusted after tapping [7].

Computer control of the basic oxygen process was reported by 1964 [10]. The static part of such control is the charge calculation, a heat and mass balance run before the blow that turns the measured hot metal weight, composition and temperature and the scrap weight into an oxygen volume and a coolant addition. These models inherit every error in the charge data and in their own constants. Dynamic control, which corrects the blow from information gathered while it is in progress, was in operation within a few years [11], and by 1983 the control of oxygen steelmaking was treated as a subject of its own in reviews of iron and steelmaking control [12].

The in-blow information comes from two sources. A sublance lowers a disposable probe into the bath near the end of the blow and returns a carbon and a temperature, which the model uses to re-plan the remaining oxygen and coolant. Off-gas analysis measures the flow and composition of the gas leaving the vessel, from which the decarburization rate follows continuously. Model-based estimation of the carbon content from that rate was developed toward closed-loop control in the late 1990s [13, 14], and the gradient of the relative decarburization rate has been used more recently to predict the endpoint [15]. Static models are still refined, for example by combining heat and mass balances with neural networks trained on tens of thousands of heats [16].

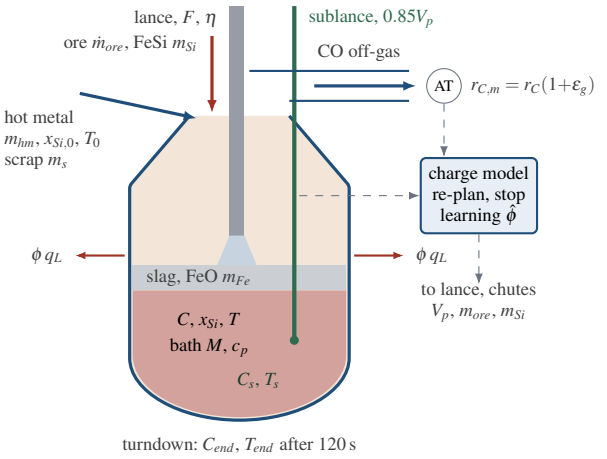


Figure 4.1 Basic oxygen furnace heat as modeled. Hot metal of mass m_{hm}, silicon $x_{Si,0}$ and temperature T_0 and scrap of mass m_s form a bath of mass M with carbon C, silicon x_{Si} and temperature T. The lance blows oxygen at flow F with efficiency η, iron ore and ferrosilicon are added as coolant and fuel, iron oxidized to FeO collects in the slag, and the vessel loses heat ϕq_L. The sublance measures C_s and T_s at 85 % of the planned oxygen V_p, the off-gas analyzer AT reports the decarburization rate with a flow error ε_g, and carbon and temperature are measured again at turndown.

The physics underneath has been modeled in detail. Multi-zone kinetic models treat the jet impact zone, the emulsion of metal droplets in slag and the bulk bath separately [5, 17], reaction models based on Gibbs free energy minimization follow slag and metal chemistry through the blow [18], and the change in decarburization mechanism at a critical carbon content has a theoretical interpretation of its own [4]. Learning between heats, the third element of the simulator, comes from a different industry. The exponentially weighted moving average (EWMA) controller of semiconductor manufacturing updates a model offset from each run's error, and its stability and its sensitivity to drift are well characterized [1, 8].

4.3 Model of One Heat

A nominal heat is charged with 250 t of hot metal at 1350 °C carrying 4.5 % carbon and 0.40 % silicon, and 50 t of scrap. Oxygen is blown at 750 $\mathrm{Nm^3/min}$ and the blow lasts about 21 min. The aim is 0.05 % carbon and 1650 °C, within ±0.01 % and ±10 °C. The vessel and its measurements are shown in Figure 4.1.

Table 4.1 classifies the variables. During a heat the model carries six states: carbon C and silicon x_{Si} in mass percent of the bath, temperature T, the iron oxidized into the slag m_{Fe}, the oxygen blown V and the blowing time t_b. The model heat-loss factor $\hat{\phi}$ changes only between heats.

4.3.1 Oxygen Distribution

Silicon burns first. Its oxidation is first order with time constant τ_{Si}, and it takes the oxygen it needs before carbon does, as shown in Equation (4.1).

$$r_{Si} = \min\left(\frac{x_{Si} M}{100\,\tau_{Si}},\, k_{Si} F\right), \qquad F_r = F - \frac{r_{Si}}{k_{Si}} \tag{4.1}$$

where r_{Si} is in kg/s, $M = m_{hm} + m_s$ is the bath mass in kilograms, F is the oxygen flow in $\mathrm{Nm^3/s}$, F_r is the oxygen left for carbon and $k_{Si} = 28/22.4 = 1.25\,\mathrm{kg/Nm^3}$ for $\mathrm{Si + O_2 \rightarrow SiO_2}$. At the nominal charge the silicon initially takes about 8 $\mathrm{Nm^3/s}$ of the 12.5 $\mathrm{Nm^3/s}$ supplied.

Table 4.1 Variables of One Heat and of the Campaign

Symbol	Role	Nominal	Range
C_{end}	CV, turndown carbon	0.05 %	±0.01 %
T_{end}	CV, turndown temperature	1650 °C	±10 °C
V_p	MV, planned oxygen	15 500 Nm^3	12 000–19 000
m_{ore}	MV, iron ore coolant	2.7 t	0–15
m_{Si}	MV, ferrosilicon silicon	0 kg	≥ 0
C, x_{Si}	states, bath carbon, silicon	4.5, 0.40 %	0.02–4.8
T	state, bath temperature	1350 °C	1250–1900
m_{Fe}	state, iron to slag	0	0–20 t
V	state, oxygen blown	0	0–19 000 Nm^3
t_b	state, blowing time	0	0–1500 s
$\hat{\phi}$	per heat, model loss factor	1	0.5–2
s	DV, charge variation scale	1	0–2
g	DV, off-gas error (1σ)	3 %	0–8
d	DV, heat loss growth	0	0–5 %/heat

Carbon takes the remaining oxygen with efficiency η while it is plentiful. Below the critical carbon C^* the rate is limited by carbon transport to the reaction zone and falls in proportion to the carbon left above the equilibrium value C_{eq}, Equation (4.2), the first form of Equation (1.4) in this chapter's symbols.

$$\begin{aligned} r_C &= \eta F_r k_C f(C) \\ f(C) &= \min\left(1,\ \max\left(0, \frac{C - C_{eq}}{C^* - C_{eq}}\right)\right) \end{aligned} \tag{4.2}$$

with $k_C = 24/22.4 = 1.071\,\mathrm{kg/Nm^3}$ for $\mathrm{C} + \frac{1}{2}\mathrm{O_2} \rightarrow \mathrm{CO}$. The share $1-\eta$ is taken to burn CO to CO_2 in the vessel and is not counted further. The oxygen that carbon could have taken below C^* and cannot oxidizes iron, Equation (4.3).

$$r_{Fe} = \eta F_r k_{Fe} \left(1 - f(C)\right) \tag{4.3}$$

where the iron oxidized per unit of oxygen for $2\mathrm{Fe} + \mathrm{O_2} \rightarrow 2\mathrm{FeO}$ is $k_{Fe} = 2(55.85)/22.4$, which is 4.99 kg/Nm^3. The composition and inventory states then follow from the rates, as shown in Equation (4.4).

$$\begin{aligned} \frac{\mathrm{d}C}{\mathrm{d}t} &= -\frac{100\, r_C}{M}, & \frac{\mathrm{d}x_{Si}}{\mathrm{d}t} &= -\frac{100\, r_{Si}}{M} \\ \frac{\mathrm{d}m_{Fe}}{\mathrm{d}t} &= r_{Fe}, & \frac{\mathrm{d}V}{\mathrm{d}t} &= F \end{aligned} \tag{4.4}$$

and the blowing time t_b advances at one second per second while oxygen is on.

The two regimes are drawn in Figure 4.2. Above C^* the plateau rate is $\eta F k_C = 12.7\,\mathrm{kg/s}$, about 0.25 % of the bath per minute. Below it, carbon decays exponentially with time constant $M(C^* - C_{eq})/(100\,\eta F k_C) \approx 78\,\mathrm{s}$, and the iron burned per kilogram of carbon removed is $(k_{Fe}/k_C)(1-f)/f$, about 47 kg at the 0.05 % aim and about 150 kg at 0.03 %. This is the reason the endpoint must be hit rather than overshot.

4.3.2 Heat Balance

The bath is one well-mixed volume whose temperature follows the heats of oxidation, less the scrap, the ore and the vessel losses, Equation (4.5).

$$\begin{aligned} M c_p \frac{\mathrm{d}T}{\mathrm{d}t} &= h_C r_C + h_{Si} r_{Si} + h_{Fe} r_{Fe} \\ &\quad - q_s - h_{ore} \dot{m}_{ore} - \phi\, q_L \end{aligned} \tag{4.5}$$

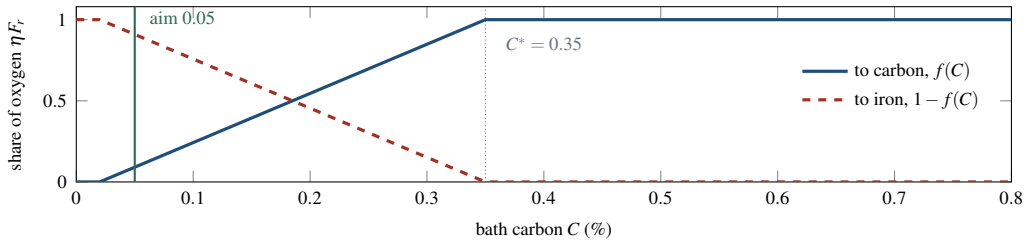


Figure 4.2 Division of the oxygen left after silicon between carbon and iron, from Equations (4.2) and (4.3), the share to carbon solid and the share to iron dashed. Above the critical carbon (dotted) all of it reaches carbon. Below it the share taken by carbon falls linearly to zero at $C_{eq} = 0.02\,\%$, and at the aim about 91 % of it oxidizes iron.

Table 4.2 Measurements Available to the Controller, With Their Errors (1σ)

Measurement	When	Error
bath mass M, scrap m_s	charge	$1.0s$, $0.7s$ t
hot metal silicon $x_{Si,0}$	charge	$0.03s$ %
hot metal temperature T_0	charge	$5s$ K
hot metal carbon C_0	—	assumed 4.5 %
sublance C_s, T_s	$V = 0.85V_p$	3 % of C, 4 °C
off-gas rate $r_{C,m}$	every second	ε_g, fixed per heat
turndown C_{end}, T_{end}	120 s after stop	2 % of C, 3 °C

in MJ/s, with Mc_p in MJ/K (about 246 MJ/K for 300 t), $h_C = 10$, $h_{Si} = 30$ and $h_{Fe} = 4.8\,\mathrm{MJ/kg}$. The scrap absorbs $h_s = 1.3\,\mathrm{MJ/kg}$ at a constant rate $q_s = m_s h_s/600$ over the first 600 s of blowing, the ore absorbs $h_{ore} = 4.0\,\mathrm{MJ/kg}$ as it is added, and the vessel loses $q_L = 42\,\mathrm{MJ/s}$ times the heat's loss factor ϕ while blowing. Temperature is frozen when there is neither blowing nor ore addition. One tonne of ore is worth about 16 °C, and one percent of heat loss over a 21 min blow about 2 °C. Below C^* the iron term dominates, because at the aim the iron burns at about 54 kg/s and heats the bath by about 1 K/s, so an overblown heat is also a hot one.

4.3.3 Heat-to-Heat Variation and Instruments

Every heat $k = 0, 1, \ldots$ draws its true charge and constants from independent standard normal deviates ξ, scaled by the charge variation s, Equation (4.6).

$$\begin{aligned} m_{hm} &= 250 + 2s\xi, \quad m_s = 50 + 1.5s\xi \quad \text{(t)} \\ C_0 &= 4.5 + 0.08s\xi, \quad x_{Si,0} = \max(0.1,\ 0.40 + 0.08s\xi) \\ T_0 &= 1350 + 12s\xi, \quad \varepsilon_g = g\xi/100 \\ \eta &= \mathrm{clamp}(0.95 + 0.012s\xi,\ 0.85,\ 1) \\ \phi &= 1 + dk/100 + 0.04s\xi \end{aligned} \tag{4.6}$$

The lining drift d is the growth of the heat loss in percent per heat. The charge model is told a measured charge rather than the true one, and the instrument errors are listed in Table 4.2. The hot metal carbon is not measured and is taken as 4.5 % on every heat.

The parameters are collected in Table 4.3. The heat starts at C_0, $x_{Si,0}$ plus any ferrosilicon silicon, and T_0, with the iron, oxygen and time states at zero. Physics advances in 1 s steps of the engine's classical fourth-order Runge-Kutta method (Section 1.6.1).

Table 4.3 Heat Model Parameters and Their Status in the Interface, Where Visible Means Adjustable

Symbol	Meaning	Value	Class
F	oxygen flow	750 Nm^3/min	visible
η	oxygen efficiency, nominal	0.95	visible
C^*	critical carbon	0.35 %	visible
C_{eq}	equilibrium carbon	0.02 %	hidden
τ_{Si}	silicon oxidation time	120 s	visible
c_p	bath heat capacity	0.82 kJ/(kg K)	hidden
q_L	heat loss, nominal	42 MJ/s	visible
h_{ore}	ore cooling	4.0 MJ/kg	visible
h_s	scrap melting heat	1.30 MJ/kg	visible
h_C, h_{Si}, h_{Fe}	heats of oxidation	10, 30, 4.8 MJ/kg	fixed
C_{aim}, T_{aim}	aim carbon, temperature	0.05 %, 1650 °C	visible
—	windows	±0.01 %, ±10 °C	visible

4.3.4 Assumptions

The bath is one well-mixed volume, and the scrap and hot metal are mixed into it from the start for composition. Real converters carry gradients of carbon and temperature, and the sublance samples one point in them [5].

Decarburization has two regimes separated by a fixed critical carbon. In practice the critical carbon depends on the blowing and stirring practice, and droplets ejected into the slag emulsion contribute a separate reaction zone [4, 17].

Slag chemistry, phosphorus, manganese and the burning of CO to CO_2 enter only through the fixed oxygen efficiency, and the iron oxidized does not reduce the bath mass. Following the slag and metal chemistry in full takes an equilibrium or kinetic reaction model [18].

Heat loss is proportional to blowing time. The vessel does not cool during turndown or between heats, and the scrap melts at a fixed rate regardless of its size or of the bath temperature.

The off-gas analyzer returns the true decarburization rate multiplied by one flow error per heat, without delay, dilution by air ingress or composition noise.

4.4 Endpoint Strategies as Implemented

The controller runs every 1 s of simulated time, the same step as the physics, and holds no proportional, integral or derivative terms. There is no continuous feedback loop, so the velocity-form algorithm of Section 1.6.2, with its anti-windup, derivative filtering and rate limits, does not apply. The manipulated variables are decided at discrete events: before the blow, at the sublance, at the stop, at turndown and between heats. More oxygen lowers the carbon and raises the temperature, and more ore lowers the temperature without changing the carbon. In the convention of Section 1.3, a loop of carbon on oxygen or of temperature on ore would be direct acting and a loop of temperature on oxygen reverse acting, although no such loop runs here.

4.4.1 Static Charge Model

The charge model simulates the heat from the measured charge with nominal constants, $\eta = 0.95$ and loss factor $\hat{\phi}$, using an explicit Euler step of 2 s. Forty bisection steps on the final oxygen volume over $[V, V + 30000]$ Nm^3 find the volume at which the simulated carbon reaches C_{aim}, which gives the end temperature with no coolant, $\hat{T}^0_{end}$. The temperature target is raised by the margin ΔT_h in automatic, and the ore follows from Equation (4.7).

$$m_{ore} = \max\left(0,\ \frac{\hat{M} c_p \left(\hat{T}^0_{end} - T_{aim} - \Delta T_h\right)}{h_{ore}}\right) \tag{4.7}$$

where $\hat{M}$ is the measured bath mass. The ore is added at a constant rate over the first 180 s, and the oxygen is bisected again with that ore schedule. A heat that would finish below target even with no ore is given ferrosilicon with the charge instead. A secant search of up to six steps, started from $(T_{aim} + \Delta T_h - \hat{T}^0_{end})\hat{M}c_p/h_{Si}$, finds the silicon that lands on target within 0.05 °C. In manual mode the operator's oxygen volume and ore mass replace the plan on every heat and no ferrosilicon is used.

4.4.2 Sublance Re-plan

When V first reaches $0.85V_p$ the sublance returns C_s and T_s. The model re-plans from these readings and the silicon it simulates for the oxygen blown, by bisection with no further ore, obtaining a new V_p and an end temperature $\hat{T}_{end}$, and if $\hat{T}_{end}$ exceeds T_{aim} it adds $\hat{M}c_p(\hat{T}_{end} - T_{aim})/h_{ore}$ of ore over the next 60 s. The re-plan aims at T_{aim} itself, without the margin. At 85 % of the plan the bath carbon is near C^*, between 0.26 and 0.49 % in case 3, and the re-plan leaves 1970 to 2770 Nm^3 of oxygen to blow. Ore after the sublance can remove heat, but the only way to add heat is more oxygen, which would take the carbon below its aim. This is the one-way correction of Equation (1.5), in which the margin ΔT_h plays the part of m.

> **TRY IT IN THE APP** **3 · The Sublance at 85 % of the Blow**
>
> Load the scenario and press Run, then watch the Oxygen, planned and blown trend: when the sublance measures the bath at 85 % of the blow, the planned oxygen changes. After ten heats all ten carbons are in the window and seven temperatures are, and the three misses all finish cold, between 1612 and 1628 °C.

4.4.3 Off-Gas Integral and Rate Endpoint

The measured rate $r_{C,m} = r_C(1 + \varepsilon_g)$ is integrated from the assumed charge carbon, Equation (4.8).

$$\hat{C}_g(t) = 4.5 - \frac{100}{\hat{M}} \int_0^t r_{C,m}\,\mathrm{d}t \tag{4.8}$$

The off-gas strategy stops when $\hat{C}_g \le C_{aim}$, or at 115 % of the static plan if the estimate never gets there. The integral inherits both the flow error and the unmeasured charge carbon. A 3 % error on the 4.45 % of carbon removed is 0.13 %, and the charge carbon scatters by 0.08 %, both larger than the whole ±0.01 % window. An integrated estimate that only a fresh measurement can reset is also the problem of dead reckoning in Volume 5, Chapter 13.

The rate strategy re-plans at the sublance and then inverts Equation (4.2) below C^*, Equation (4.9).

$$\hat{C}_r = C_{eq} + (C^* - C_{eq})\,\frac{r_{C,m}}{0.95\,F\,k_C} \tag{4.9}$$

The estimate is formed only when $r_{C,m}$ is below 97 % of the nominal plateau rate, and the blow stops when $\hat{C}_r \le C_{aim}$ or at 110 % of the re-planned V_p. A relative error in the rate is now a relative error in $C - C_{eq}$, which is 0.03 % at the aim, so a 3 % meter error costs about 0.001 % of carbon. Equation (4.9) is the second form of Equation (1.4) with the nominal plateau rate in place of r_{max}. The same signal that fails as an integral succeeds as an instantaneous measurement. The static and sublance strategies stop when V reaches V_p.

> **TRY IT IN THE APP** **6 · The Sublance and the Decarburization Rate**
>
> After the sublance, watch the Carbon near the end trend: the blow stops when the carbon read from the rate reaches the aim, not when the planned oxygen is in. Over ten heats the case gives nine hits, all ten carbons in the window and no reblows, at 7.2 °C rms. Then load scenario 4, which integrates the same signal, and count its reblows.

4.4.4 Turndown, Reblow and Scoring

After the stop the vessel is turned down for 120 s and C_{end} and T_{end} are measured. A heat measured above $C_{aim} + 0.01\,\%$ is reblown in automatic, up to three times, with the oxygen re-planned from the turndown measurement and the model's silicon, and no further ore. A heat is a hit when its final measured carbon and temperature are both inside their windows, after any reblows. The scorecard reports hits, carbon and temperature hits separately, reblows, the root mean square (rms) end temperature error, the iron to slag per heat and the ferrosilicon silicon per heat.

4.4.5 Run-to-Run Learning of the Heat Loss

After each heat the controller re-simulates it from the measured charge with the oxygen and ore actually used and its current $\hat{\phi}$, obtaining the end temperature $\hat{T}_{end,k}$ it would have predicted. The factor is moved by a fraction λ of the correction that explains the measured error, Equation (4.10).

$$\hat{\phi}_{k+1} = \hat{\phi}_k - \lambda \, \frac{\hat{M} c_p \, (T_{end,k} - \hat{T}_{end,k})}{q_L \, t_{b,k}} \tag{4.10}$$

where $t_{b,k}$ is the blowing time of heat k, the result is clamped to the range 0.5 to 2, and the default weight is $\lambda = 0.5$. This is an EWMA update of one model constant [8], and every unmodeled source of temperature error, including the scatter in η and T_0, is attributed to the heat loss. For a factor that grows by δ per heat the EWMA estimate settles at a lag of δ/λ behind the heat it plans, as Equation (1.6) states, 0.06 for $\delta = 0.03$ and $\lambda = 0.5$, which is worth about 13 °C and is one reason the temperature margin is kept when learning is on. The same EWMA structure corrects each head of a vial filler from late checkweigher results in Volume 8, Chapter 9.

> ⧖ HISTORY **A Shop Model That Learned (1994 to 2006)**
>
> One converter shop ran its own static-dynamic model from 1994 to 2006. A charge calculation set the hot metal, scrap, lime and oxygen for a first blow to an intermediate stop near 0.22 % carbon, chosen because the critical carbon there was about 0.20 to 0.30 %. The dynamic part took the carbon to fall exponentially and the temperature to rise linearly with the oxygen blown. After each heat the errors of the heat and oxygen balances corrected the next heat, weighting the last three heats by 10, 30 and 60 %, the most recent most. Heats tapped without a reblow and within 15 °C of target rose from about 40 to 65 % of the total to about 85 % [19].

4.5 Results

The ten scenarios are listed in Table 4.4 with the teaching point of each and what completes it. Each case is credited when the learner performs the listed actions and the simulated campaign reaches the listed state, as Section 1.6.4 describes. Every value in Table 4.5 and in the text was measured on the simulation engine at the application's default seed, over ten heats unless stated, with the case selected and any setting changed before the first oxygen of the campaign. A control or disturbance changed at that point applies from the first heat, and the application gives the same campaign when the change is carried through Reset. Cases 5 and 8 therefore compare two margins or two learning weights on the same sequence of heats.

> ✦ DID YOU KNOW? **Two Hundredths of a Percent, Five Tonnes of Iron**
>
> From the simulator: in Table 4.5, lowering the carbon aim from 0.05 to 0.03 % on the rate endpoint still gives eight hits, but the iron burned into the slag rises from 6.85 to 11.64 t per heat. Near the aim most of the oxygen burns iron instead of carbon.

Figure 4.3 draws the hits, reblows and rms errors of Table 4.5 as a chart.

Table 4.4 Scenarios and Completion Requirements

#	Scenario, teaching point and kind	Required to complete
1	A fixed recipe (manual) *open loop on a varying batch* (demonstration)	Blow the first heat to turndown in manual, then finish the ten heats with the recipe held at 15 350 Nm^3 of oxygen and 1.9 t of ore.
2	The static charge model *feedforward from the charge* (experiment)	Blow one heat on the static plan in automatic and compare its oxygen with the fixed recipe, then finish ten heats and compare the carbon hits with the temperature hits.
3	The sublance at 85 % *one late measurement* (experiment)	Reach the sublance re-plan at 85 % of the planned oxygen, then finish ten heats and identify the heats that still miss.
4	Integrating the off-gas *an integral that drifts* (demonstration)	Blow one heat stopped on the off-gas integral, then finish ten heats and count the reblows and the heats blown past the aim.
5	Aim hot, trim cold *a one-way correction* (experiment)	Finish ten heats with the sublance and a 25 °C hot aim, then Reset, set the margin to 10 °C before the first oxygen and finish ten more.
6	Sublance and rate *a rate read as a level* (experiment)	Blow one heat to a stop on the decarburization rate after the sublance, then finish ten heats and compare hits, reblows and rms error with cases 4 and 5.
7	A lining that wears *drift across batches* (demonstration)	With the heat loss growing 3 % per heat, reach the sublance of heat 8 or later, then finish the ten heats on the rate endpoint.
8	Learning the heat loss *run-to-run control* (experiment)	Finish ten heats on the wearing lining with learning at $\lambda = 0.5$, then Reset, move λ by at least 0.1 (to 0.3 or 1.0) within the first 1300 s and finish ten more.
9	Aiming lower on carbon *the iron yield cost* (experiment)	With the carbon aim at 0.03 %, blow one heat to turndown, then finish ten heats and compare the iron to slag per heat with case 6.
10	Challenge, twelve heats *graded campaign* (challenge)	Finish twelve heats with at least eight hits in both windows, no reblows and an end temperature error of 15 °C rms or less, with the model parameters and disturbances as given.[a]

[a] With the shipped settings (static model, no margin, no learning) the campaign gives 2 hits, 4 reblows and 38.6 °C rms and fails all three criteria. With the suggested settings (sublance and rate, 30 °C margin, learning) it gives 8 hits, no reblows and 12.6 °C rms, a pass with no hit to spare and 2.4 °C of rms margin.

Table 4.5 Measured Campaigns. Hits Count Both Windows, C and T Count Each Window Alone, rms Is the End Temperature Error

Case and setting	Hits	C	T	Reblows	rms (°C)	Fe (t)
1, manual recipe	1	6	2	0	25.2	6.62
2, static	2	9	2	1	19.0	7.18
3, sublance	7	10	7	0	18.2	6.79
4, off-gas integral	3	8	3	9	65.0	8.79
5, sublance, $\Delta T_h = 10$	6	10	6	0	13.3	6.79
5, sublance, $\Delta T_h = 25$	7	10	7	0	7.2	6.79
6, rate, $\Delta T_h = 25$	9	10	9	0	7.2	6.85
7, as 6, $d = 3$	5	10	5	0	23.7	6.85
8, as 7, $\lambda = 0.3$	8	10	8	0	12.5	6.85
8, as 7, $\lambda = 0.5$	7	10	7	0	12.2	6.85
8, as 7, $\lambda = 1.0$	7	10	7	0	14.5	6.85
9, as 6, $C_{aim} = 0.03$	8	10	8	0	7.6	11.64

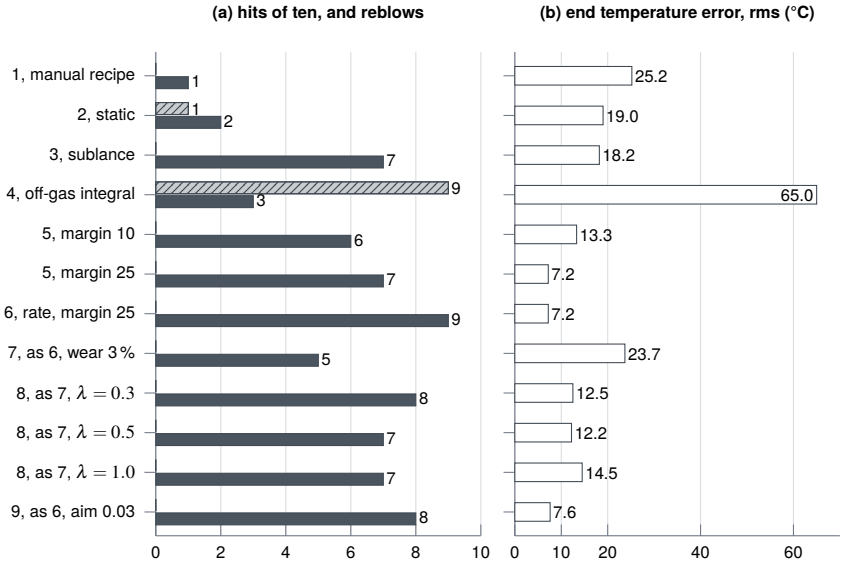


Figure 4.3 The measured campaigns of Table 4.5 as a chart: hits of ten solid and reblows hatched in (a), the rms end temperature error as open bars in (b). Notice that the off-gas integral (case 4) stands out with nine reblows and a 65.0 °C error, that the same signal read as a rate (case 6) gives the most hits, and that a wearing lining (case 7) undoes it until learning (case 8) recovers part of the loss.

4.5.1 Open Loop and the Static Model

A fixed recipe of 15 350 Nm^3 and 1.9 t of ore hits one heat in ten, with the end carbon spread from 0.036 to 0.081 % and the end temperature from 1615 to 1690 °C. The recipe is right for an average heat and no heat is average. The static charge model lands nine of ten carbons but only two temperatures, with an rms error of 19.0 °C. Carbon depends mostly on the oxygen blown, which the model controls. Temperature integrates every heat source and sink the model does not see, namely the efficiency, the heat loss and the errors in the charge measurements. With the charge variation and the meter error set to zero, so that every heat is nominal, the static model hits all ten heats at 3.4 °C rms (3.3 °C in the application's built-in test of the same condition, which draws other turndown errors), so the misses are due to what the model is not told rather than to the model structure.

🕮 **Pause.** Try Exercise 4.1 before reading on.

4.5.2 One Late Measurement

The sublance re-plan puts all ten carbons in the window with no reblows and raises the temperature hits to seven. All three misses are cold, at 1612, 1615 and 1628 °C, while no heat finishes above 1655 °C. Ore after the sublance can take heat out, and nothing can put it back without burning carbon below its aim. Aiming the charge model 25 °C hot moves the static error to the side the sublance can correct, and the rms error falls from 18.2 to 7.2 °C. A 10 °C margin gives 13.3 °C. The hit count stays at seven with the larger margin because two heats still finish at 1637 °C, just outside the window, and the re-planned remainder of a third heat, trimmed with ore at the sublance, ends just above it.

🕮 **Pause.** Try Exercise 4.2 before reading on.

4.5.3 An Integral That Drifts, a Rate That Does Not

Stopping on the integrated off-gas estimate gives three hits and nine reblows. Heats whose estimate falls too fast, because the meter reads high or the charge carbon exceeds the assumed 4.5 %, stop early and are reblown, and heats whose estimate never reaches the aim blow on to the 115 % limit.

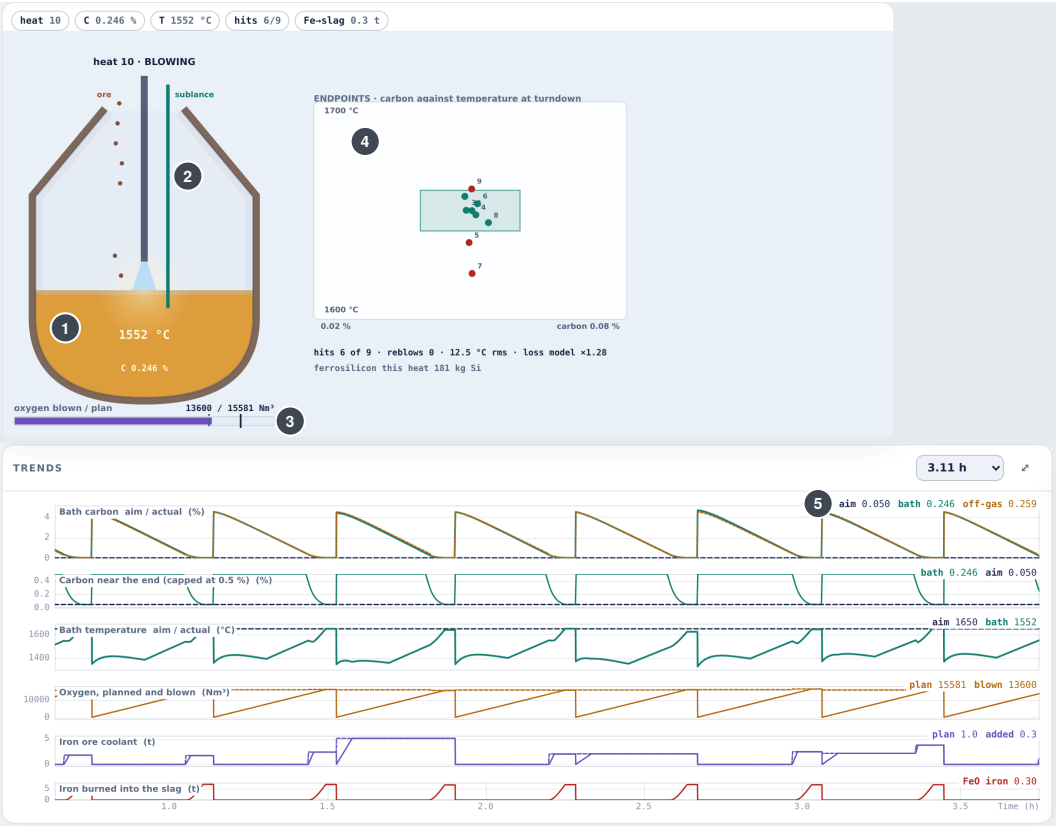


Figure 4.4 Scenario 8, learning the heat loss on a wearing lining with the sublance and rate endpoint and a 25 °C margin, at $t = 3.75$ h, cropped to the plant view and the trends. Heat 10 is blowing at 0.246 % carbon and 1552 °C (1), with 13 600 of a planned 15 581 Nm^3 blown (3), the sublance in the bath (2) and ore falling from the chute. The endpoint map (4) shows heats 1 to 9 against the target window, six inside it, heats 5 and 7 cold and heat 9 hot, with the model's loss factor at 1.28 and 181 kg of ferrosilicon silicon charged to this heat. The trends over 3.11 h show the carbon sawtooth of each heat with the off-gas estimate dashed (5), the bath temperature against its aim, the oxygen plan and volume blown, the ore planned and added, and the iron burned into the slag near the end of every blow.

Two heats end at 0.024 and 0.023 % carbon and at 1792 and 1794 °C, heated by the iron they burned, and the iron to slag averages 8.79 t per heat against 7.18 t for the static model. Setting the meter error to zero for the whole campaign does not rescue the integral, which then gives one hit with five reblows, because the scatter of the unmeasured charge carbon, 0.08 % (1σ), is by itself eight times the half-width of the window.

🕮 **Pause.** Try Exercise 4.3 before reading on.

The rate endpoint uses the same signal after the sublance. With the 25 °C margin it hits nine heats, all ten carbons, with no reblows and 7.2 °C rms. Raising the meter error to 8 % still leaves all ten carbons in the window, with seven hits and 8.1 °C rms.

4.5.4 Drift and Learning

A lining whose heat loss grows 3 % per heat defeats the fixed margin. The first four heats still hit, the last four finish between 1601 and 1633 °C, and the campaign gives five hits at 23.7 °C rms. Carbon

Table 4.6 Challenge: Twelve Heats, Charge Variation 1.2, Drift 3 %/Heat

Configuration	Hits	Reblows	rms (°C)
as loaded, static	2	4	38.6
rate, $\Delta T_h = 30$, no learning	5	0	29.2
rate, $\Delta T_h = 50$, no learning	8	0	17.4
rate, $\Delta T_h = 30$, learning	8	0	12.6

is still right on every heat, because the sublance and the rate endpoint do not depend on the heat balance. With learning at $\lambda = 0.5$ the model factor climbs to 1.24 after the tenth heat, against a true value of 1.27 plus that heat's scatter, and the model charges ferrosilicon to the heats it now expects to be short, 122 kg of silicon per heat on average. The hits return to seven and the rms error to 12.2 °C over the campaign. During the tenth heat the model factor reads 1.28 with six hits in nine, as shown in Figure 4.4. A weight of 0.3 gives eight hits at 12.5 °C, and a weight of 1.0 gives seven at 14.5 °C, because each update then copies more of one heat's random error into the next plan [8].

4.5.5 The Iron Cost of a Low Carbon Aim

Lowering the aim from 0.05 to 0.03 % with the rate endpoint still gives eight hits, but the oxygen per heat rises from 15 643 to 16 695 Nm^3 and the iron to slag from 6.85 to 11.64 t. Both agree with the transport-limited regime of Equation (4.2). Taking $C - C_{eq}$ from 0.03 to 0.01 % at a time constant of 78 s takes $78 \ln 3 \approx 86$ s of blowing, about 1070 Nm^3, while the iron burns at 54 to 58 kg/s, about 4.8 t in total for 60 kg of carbon.

4.5.6 The Graded Challenge

The challenge runs twelve heats with the charge variation at 1.2 and a lining drift of 3 % per heat, starting from the static model with no margin and no learning. It is met with at least eight hits, no reblows and an rms error of 15 °C or less. The challenge is judged on the case as given, and a change to a model parameter, the charge variation, the meter error or the lining drift voids the attempt. Table 4.6 lists the measured outcomes.

As loaded the campaign gives two hits, four reblows and 38.6 °C rms, with one late heat at 1563 °C. The rate endpoint with a 30 °C margin fixes the carbon and the reblows but leaves five hits at 29.2 °C, because the drift eats the margin. A 50 °C margin buys eight hits at 17.4 °C, still outside the rms limit, because the late heats still finish cold, down to 1605 °C. Learning with the 30 °C margin meets all three targets, eight hits, no reblows and 12.6 °C, a pass with no hit to spare and 2.4 °C of rms margin, and charges 235 kg of ferrosilicon silicon per heat on average against 86 kg without learning. The rate endpoint, the margin and the learning each answer one of the campaign's three problems, the charge variation, the one-way correction and the drift.

4.6 Technology in Practice

Figure 4.5 draws the decisions of Section 4.4 with the hardware that measures and carries them out.

What Measures It

A shop measures the bath in the blow at a fixed share of the oxygen, by sublance, by a drop sensor or after turning the vessel down [19]. The temperature comes from a thermocouple, which is less accurate than a resistance thermometer but more rugged and with a wider span. It most often fails open, which reads as wild noise unless the instrument has a burnout mode that drives it high or low [20]. The model's sublance at 85 % of the planned oxygen, with a scatter of 3 % of the carbon and 4 °C, stands for this in-blow measurement, and the turndown reading 120 s after the stop for the test made by hand.

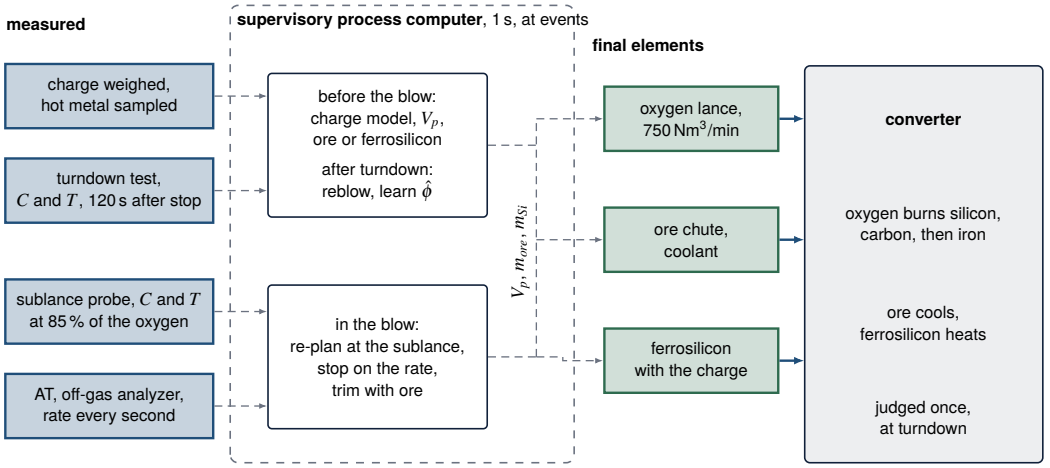


Figure 4.5 The decisions of the simulated converter drawn with their hardware. The charge model plans the oxygen volume V_p and the ore or ferrosilicon from the measured charge, the sublance and the off-gas analyzer AT correct and end the blow, and the turndown test decides a reblow and updates the heat-loss factor $\hat{\phi}$ for the next heat. Notice that every decision reaches the same three final elements, and that no continuous loop runs from a sensor to the lance.

> **TECHNOLOGY** **Sensor: The Off-Gas Analyzer**
>
> The gas leaving the converter carries the carbon removed from the bath as carbon monoxide, which makes up a steady 80 to 90 % of the gas until decarburization slows near the end of the blow. Plants commonly analyze it with infrared or mass spectrometric instruments, which need a clean sample at room temperature drawn from the duct far downstream of the furnace. The delay this causes, and the change in composition from continued reaction and air drawn into the gas, make the signal very difficult to use for dynamic control [21]. An infrared analyzer works because most gases of interest absorb infrared light at their own wavelengths [20].

The model's analyzer has neither the delay nor the air drawn in. It returns the true rate times one flow error per heat.

What Moves It

The lance delivers the one actuator that sets both endpoints.

TECHNOLOGY Final Element: The Oxygen Lance

The oxygen reaches the bath through a top-blown lance whose tip carries Laval nozzles, convergent and divergent passages that turn the pressure of the supply into the speed of a jet. Each nozzle has a design Mach number, pressure and flow rate and is usually run near them. Away from that point, shock or expansion waves form and the jet loses energy. Lances with several nozzles soften the blow to reduce spitting, dust and skull, but jets that merge before they reach the bath strike almost as hard as one, and lance design has been settled almost empirically [22].

The model blows a fixed 750 Nm^3/min with an efficiency η drawn for each heat, so the planned volume V_p is the decision and the blowing time follows from it. Iron ore is added through a chute at a constant rate over the first 180 s and over 60 s after the sublance, and ferrosilicon goes in with the charge.

Where the Controller Runs

Control loops in a plant are often nested, with cycle times from milliseconds to minutes, and a distributed control system uses a supervisory loop to mediate a group of localized controllers [23]. One shop's endpoint model ran its calculations for three adjacent heats at once: the heat in preparation, the heat in progress and the heat just finished [19]. The app executes its controller every 1 s, the step of the physics, but decides only at events. On a plant platform the charge model, the sublance re-plan, the stop rule and the learning are calculations of the supervisory process computer, which writes the oxygen volume and the additions to the oxygen flow loop and the feeders of the basic layer.

IN PRACTICE How a Shop Measures the Endpoint

Standard practice measures the temperature and carbon after about 90 % of the oxygen has been blown, and the temperature and dissolved oxygen at the end of the blow, taking a metal sample each time. The readings are taken by hand after turning the converter down, or with the vessel upright by a sublance or an in-blow drop sensor. In an industry association's 2020 data, 47 of 71 member shops, close to 70 %, used sublances or drop sensors, 37 used off-gas analysis, and only five relied on turndown tests alone [19].

What Is Modernizing It

The first development is optical sensing of the gas at the mouth. A mid-infrared tunable diode laser beam sent through the gas directly above the vessel was tested in four long-term field trials, and the infrared emission of the dusty gas correlated with the turndown carbon from below 0.03 to at least 0.15 % with a precision of ±0.007 %. The same emission signal predicted slopping of the foaming slag for 90 % of 100 heats, over 80 % with at least 30 s of warning [21]. The second is prediction from the records of past heats. A case-based model retrieves the stored heats most similar to a new one, learns as new heats are added and predicted the end temperature of a 120 t converter within 10 °C [24].

4.7 Limitations

The bath is treated as one perfectly mixed volume, and its critical carbon is fixed. Real decarburization runs in several zones whose share changes through the blow [5, 17].

The slag is a tally of oxidized iron, without phosphorus and manganese removal, lime dissolution, foaming or post-combustion [18].

The vessel loses heat only while blowing, so the waiting time between heats, during which a real vessel cools, is absent.

The off-gas analyzer has one flow error per heat and no transport delay or dilution by air drawn in at the hood [14].

The learning adapts one constant and blames every unmodeled heat error on the heat loss, which would mislead it if, for example, the oxygen efficiency drifted instead.

OPEN CHALLENGE **A Complete Model of the Converter**

The transport phenomena in a converter are complex and hard to observe directly, no complete intelligent model of the process had been published in open sources by 2022, and most models predict a single quantity such as the end temperature [24]. Rapid, accurate sensors for the hostile vessel are lacking, and gas analyzed downstream arrives late and altered [21]. A data-driven predictor for a 260 t converter put 90 % of carbons within 0.005 % and 94 % of temperatures within 10 °C, 84 % both, on one plant's records [25]. Progress would be a model of carbon, temperature and slag together that carries from one shop to another.

4.8 Conclusion

The converter combines in one batch the four elements of endpoint control, namely planning from the measured initial state, one late measurement, a correction that works in one direction and learning between batches. A fixed recipe hits one heat in ten, and the static charge model hits nine carbons but only two temperatures at 19.0 °C rms. The sublance at 85 % of the blow fixes every carbon and leaves only cold misses, and a 25 °C hot aim takes the rms error to 7.2 °C. The off-gas signal integrated from the charge gives nine reblows, while the same signal read as a rate below the critical carbon gives nine hits with none. A lining that loses 3 % more heat per heat brings that strategy down to five hits, and learning the heat loss brings it back to seven at 12.2 °C. Lowering the carbon aim by 0.02 % costs 4.8 t of iron per heat. A fuller model would add slag chemistry, the time between heats and lance height as a second actuator. The simulator is a compact case of controlling a batch that is blown once and judged at its end.

KEY POINTS

- A converter heat is blown once and judged at its end, and oxygen once blown cannot be taken back.
- The static charge model hits nine carbons but only two temperatures.
- The sublance fixes every carbon and leaves only cold misses, and a 25 °C hot aim takes the rms error to 7.2 °C.
- The off-gas signal integrated from the charge gives nine reblows, and read as a rate below the critical carbon it gives nine hits with none.
- Learning the heat loss brings a wearing lining back from five hits to seven.

Where else this applies. Volume 8, Chapter 9 applies the same EWMA correction from late results, and Volume 5, Chapter 13 resets an integrated estimate with late fixes.

References

[1] E. Del Castillo and A. M. Hurwitz, "Run-to-Run Process Control: Literature Review and Extensions," *Journal of Quality Technology*, vol. 29, no. 2, pp. 184–196, 1997.

[2] Y. Wang, F. Gao, and F. J. Doyle, "Survey on iterative learning control, repetitive control, and run-to-run control," *Journal of Process Control*, vol. 19, no. 10, pp. 1589–1600, 2009.

[3] L. Holappa, "A General Vision for Reduction of Energy Consumption and CO2 Emissions from the Steel Industry," *Metals*, vol. 10, no. 9, p. 1117, 2020.

[4] J. H. Zong and J. K. Yoon, "Theoretical interpretation of the decarburization mechanism in convective oxygen steelmaking," *Metallurgical Transactions B*, vol. 21, no. 1, pp. 49–57, 1990.

[5] N. Dogan, G. A. Brooks, and M. A. Rhamdhani, "Comprehensive Model of Oxygen Steelmaking Part 1: Model Development and Validation," *ISIJ International*, vol. 51, no. 7, pp. 1086–1092, 2011.

[6] U.S. Geological Survey, "Mineral commodity summaries 2025: Iron and steel," U.S. Geological Survey, Reston, VA, Tech. Rep., 2025.

[7] J. Stubbles, "Energy use in the U.S. steel industry: A historical perspective and future opportunities," U.S. Department of Energy, Office of Industrial Technologies, Tech. Rep., 2000.

[8] A. Ingolfsson and E. Sachs, "Stability and Sensitivity of an EWMA Controller," *Journal of Quality Technology*, vol. 25, no. 4, pp. 271–287, 1993.

[9] F. Wallner and E. Fritz, “Fifty years of oxygen-converter steelmaking,” *Revue de Métallurgie*, vol. 99, no. 10, pp. 825–837, 2002.

[10] K. Katsura, K. Isobe, and T. Itaoka, “Computer control of the basic oxygen process,” *JOM*, vol. 16, no. 4, pp. 340–345, 1964.

[11] J. A. Glasgow, W. F. Porter, and J. Morrill, “Development and operation of BOF dynamic control,” *JOM*, vol. 19, no. 8, pp. 81–87, 1967.

[12] R. Williams, “Control of oxygen steelmaking,” in *Control and Analysis in Iron and Steelmaking*. Elsevier, 1983, pp. 147–176.

[13] D. Widlund, A. Medvedev, and R. Gyllenram, “Towards Model-Based Closed-Loop Control of the Basic Oxygen Steelmaking Process,” *IFAC Proceedings Volumes*, vol. 31, no. 23, pp. 69–74, 1998.

[14] A. Johansson, A. Medvedev, and D. Widlund, “Model-based estimation of decarburization rate and carbon content in the basic oxygen steelmaking process,” in *Conference Record of the 2000 IEEE Industry Applications Conference. Thirty-Fifth IAS Annual Meeting and World Conference on Industrial Applications of Electrical Energy (Cat. No.00CH37129)*, vol. 4, 2000, pp. 2578–2583.

[15] J. Terpak, M. Laciak, J. Kacur, M. Durdan, P. Flegner, and G. Trefa, “Endpoint Prediction of Basic Oxygen Furnace Steelmaking Based on Gradient of Relative Decarburization Rate,” in *2020 21th International Carpathian Control Conference (ICCC)*, 2020, pp. 1–4.

[16] R. Wang, I. Mohanty, A. Srivastava, T. K. Roy, P. Gupta, and K. Chattopadhyay, “Hybrid Method for Endpoint Prediction in a Basic Oxygen Furnace,” *Metals*, vol. 12, no. 5, p. 801, 2022.

[17] B. K. Rout, G. Brooks, M. Akbar Rhamdhani, Z. Li, F. N. H. Schrama, and A. Overbosch, “Dynamic Model of Basic Oxygen Steelmaking Process Based on Multizone Reaction Kinetics: Modeling of Decarburization,” *Metallurgical and Materials Transactions B*, vol. 49, no. 3, pp. 1022–1033, 2018.

[18] R. Sarkar, P. Gupta, S. Basu, and N. B. Ballal, “Dynamic Modeling of LD Converter Steelmaking: Reaction Modeling Using Gibbs’ Free Energy Minimization,” *Metallurgical and Materials Transactions B*, vol. 46, no. 2, pp. 961–976, 2015.

[19] T. D. Bradarić, Z. M. Slović, G. J. Stepanoski, and S. Kosanović, “Static-dynamic model for endpoint control used in Smederevo’s BOF shop,” *Metallurgical and Materials Engineering*, vol. 27, no. 4, pp. 449–456, 2021.

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

[21] S. Allendorf, D. Ottesen, and D. Hardesty, “AISI/DOE advanced process control program vol. 1 of 6: Optical sensors and controls for improved basic oxygen furnace operations,” American Iron and Steel Institute, Tech. Rep. DOE/ID/13205, 2002.

[22] K.-i. Naito, Y. Ogawa, T. Inomoto, S.-y. Kitamura, and M. Yano, “Characteristics of jets from top-blown lance in converter,” *ISIJ International*, vol. 40, no. 1, pp. 23–30, 2000.

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

[24] S.-y. Song, J. Li, and W. Yan, “Intelligent case-based hybrid model for process and endpoint prediction of converter via data mining technique,” *ISIJ International*, vol. 62, no. 8, pp. 1639–1648, 2022.

[25] M. Wang, C. Gao, X. Ai, B. Zhai, and S. Li, “Whale optimization end-point control model for 260 tons BOF steelmaking,” *ISIJ International*, vol. 62, no. 8, pp. 1684–1693, 2022.

4.9 Exercises

4.1 ○ Concept check · 2 min

In scenario 2, The static charge model, the model plans every heat from its measured charge. Over ten heats it lands nine carbons in the window but only two temperatures. Which explanation is right?

(a) The bisection searches the oxygen for the carbon aim, while the ore is set by a cruder formula

(b) The turndown temperature reading is less accurate than the carbon analysis, so hits are scored as misses

(c) Carbon follows the oxygen the model controls, while temperature sums heat terms the model is not told

(d) The temperature window is narrower relative to its aim, so the same model error misses it more often

4.2 ○ Concept check · 1 min

In scenario 3, The sublance at 85 % of the blow, every carbon lands in the window and seven temperatures do. The three misses finish at 1612, 1615 and 1628 °C. Why are all three cold?

(a) The sublance temperature reads high on average, so the re-plan removes heat the bath needed

(b) The vessel heat loss grows from heat to heat, and one reading per heat cannot see that drift

(c) The sublance measures before the scrap has melted, so its temperature misses the scrap's cooling

(d) Ore can take heat out after the sublance, but heat can be added only by blowing the carbon too low

4.3 ○ Concept check · 2 min

In scenario 4, Integrating the off-gas, the off-gas flow meter error is set to zero before Run, so the rate is measured exactly on every heat. What does the chapter report for the ten heats, and why?

(a) One hit and five reblows, because the integral starts from an assumed charge carbon that scatters widely

(b) Ten hits, because with an exact rate the integral equals the carbon removed and the estimate is exact

(c) Nine hits and no reblows, because the integral and the rate endpoint now read the same exact signal

(d) Three hits and nine reblows, as before, because the meter error was never a source of the misses

4.4 ▭ Theory and calculation · 5 min

A nominal heat has a bath of $M = 300\,\mathrm{t}$ with 0.40 % silicon. Oxygen is blown at $750\,\mathrm{Nm^3/min}$ with $\eta = 0.95$, $k_C = 24/22.4$ and $k_{Si} = 28/22.4$ in $\mathrm{kg/Nm^3}$, $\tau_{Si} = 120\,\mathrm{s}$, $C^* = 0.35\,\%$ and $C_{eq} = 0.02\,\%$.

(a) Find the plateau decarburization rate above C^* once the silicon is gone, in kg/s and in percent of the bath per minute. *Checkpoint:* 12.7 kg/s and 0.25 % per minute.

(b) Find the oxygen the silicon takes at the start of the blow. *Checkpoint:* $8.0\,\mathrm{Nm^3/s}$ of the $12.5\,\mathrm{Nm^3/s}$ supplied.

(c) Find the time constant with which the carbon decays below C^*. *Checkpoint:* About 78 s.

4.5 ▭ Theory and calculation · 8 min

Scenario 9 lowers the carbon aim from 0.05 to 0.03 %. Use the constants of the previous exercise, $k_{Fe} = 2(55.85)/22.4$ in $\mathrm{kg/Nm^3}$ and a time constant of 78 s below C^*.

(a) At each aim, find the share of the oxygen left after silicon that oxidizes iron and the iron burned per kilogram of carbon removed. *Checkpoint:* 0.909 and 47 kg at 0.05 %; 0.970 and 149 kg at 0.03 %.

(b) Find the blowing time and the oxygen needed to go from the higher aim to the lower one. *Checkpoint:* About 86 s and $1070\,\mathrm{Nm^3}$.

(c) Estimate the iron burned in that interval, within 0.2 t, and compare it with the measured rise in iron to slag between scenarios 6 and 9. *Checkpoint:* About 4.8 t, against 6.85 to 11.64 t measured.

4.6 Theory and calculation · 5 min

The bath has $\hat{M}c_p = 246\,\mathrm{MJ/K}$, ore cools by $h_{ore} = 4.0\,\mathrm{MJ/kg}$ and the vessel loses $q_L = 42\,\mathrm{MJ/s}$ times the loss factor while blowing.

(a) Find the change in end temperature worth one tonne of ore. *Checkpoint:* 16.3 °C.

(b) For a nominal heat the charge model plans 2.72 t of ore with no margin. Find the ore it plans with $\Delta T_h = 25\,^{\circ}\mathrm{C}$. *Checkpoint:* 1.18 t.

(c) The loss factor grows by 0.03 per heat and is learned with $\lambda = 0.5$. Find the steady lag of the estimate and the end temperature error it causes over a blow of 21 min. Repeat for $\lambda = 0.3$. *Checkpoint:* 0.06 and about 13 °C; 0.10 and about 22 °C.

4.7 App challenge · 8 min

Load scenario 2, The static charge model, change no setting, and run the ten heats at speed 300 with the default seed (the run stops itself at the end). Then load scenario 3, The sublance at 85 % of the blow, and do the same. Export the CSV file of the second run.

(a) For each run, read the Carbon hits, Temperature hits, Reblows and End T error, rms tiles of the scorecard. *Checkpoint:* Scenario 2: 9, 2, 1 and 19.0 °C. Scenario 3: 10, 7, 0 and 18.2 °C.

(b) In the file of scenario 3, read the column `end_T_C` in the rows where `metric_heats` steps up, and list the heats that miss the temperature window with their end temperatures, within 0.1 °C. *Checkpoint:* Heats 1, 5 and 7, at 1627.6, 1615.1 and 1611.5 °C.

Explain why the temperature hits rise from two to seven while the rms error barely moves.

4.8 App challenge · 9 min

Load scenario 5, Aim hot, trim cold, with Aim hot by at its shipped 25 °C. Use the default seed and speed 300, and let each campaign of ten heats run to its end.

(a) Run the scenario as shipped. Read Hit rate and End T error, rms, and find the end temperature of heat 5 in column `end_T_C` of the exported file. *Checkpoint:* 7 of 10, 7.2 °C, heat 5 at 1637.3 °C.

(b) Press Reset, set Aim hot by to 10 °C before Run, and read the same two tiles. *Checkpoint:* 6 of 10, 13.3 °C.

(c) Press Reset, set Aim hot by to 40 °C before Run, and read the same two tiles and the end temperature of heat 5. *Checkpoint:* 8 of 10, 6.4 °C, heat 5 at 1637.3 °C.

Read the end temperatures within 0.1 °C. Use Equation (1.5) to explain why heat 5 does not change between the last two runs.

4.9 App challenge · 8 min

Use the default seed and speed 300, and let each campaign of ten heats run to its end.

(a) Load scenario 7, A lining that wears, change no setting, and read Hit rate and End T error, rms. *Checkpoint:* 5 of 10, 23.7 °C.

(b) Load scenario 8, Learning the heat loss from heat to heat, change no setting, and read the same two tiles, the Ferrosilicon tile and the loss model factor on the learning card at the end. *Checkpoint:* 7 of 10, 12.2 °C, 122 kg of silicon per heat, $\times 1.24$.

(c) Press Reset, set Learning weight to 1.00 before Run, and read the same tiles and the factor. *Checkpoint:* 7 of 10, 14.5 °C, 178 kg, $\times 1.21$.

Explain why the weight of 1.00 ends with a lower factor than the weight of 0.50, although its lag behind a steady drift is smaller.

4.10 Application area · 4 min

The model's off-gas analyzer reports the decarburization rate without delay. Suppose a real analyzer reports it 10 s late, and the rate endpoint stops the blow when the delayed reading gives 0.05 % through Equation (4.9). Below C^* the carbon decays with the time constant of 78 s.

(a) Find the true carbon at the stop, and say whether it is inside the window. *Checkpoint:* 0.046 %, inside the window.

(b) Estimate the extra iron burned and the extra heating in the 10 s, and state the stopping reading that would compensate. *Checkpoint:* About 0.5 t and 10 °C; stop at a reading of 0.054 %.

4.11 Application area · 3 min

At the sublance of scenario 3 the bath carbon lies between 0.26 and 0.49 %, and the re-plan leaves 1970 to 2770 Nm^3 of oxygen to blow at 750 Nm^3/min.

(a) Find the blowing time left after the sublance. *Checkpoint:* 2.6 to 3.7 min.

(b) Give one reason against taking the probe much later in the blow and one against taking it much earlier. *Checkpoint:* No numeric answer.

4.12 Review the agent · 5 min

An AI assistant is asked to pass scenario 10, the challenge, and replies as follows. "Use Sublance + rate for the carbon and raise Aim hot by to 50 °C. Leave learning off. The lining drift adds at most 33 % to the heat loss by heat 12, and a fixed margin covers it without the risk of a model fooled by noise. Expect at least eight hits, no reblows and an rms error well under 15 °C." Find the flaw in the proposal and say how it could be checked.