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CHAPTER 11

Alumina Feed Control Through a Non-Monotone Resistance in a Smelting Cell Simulator

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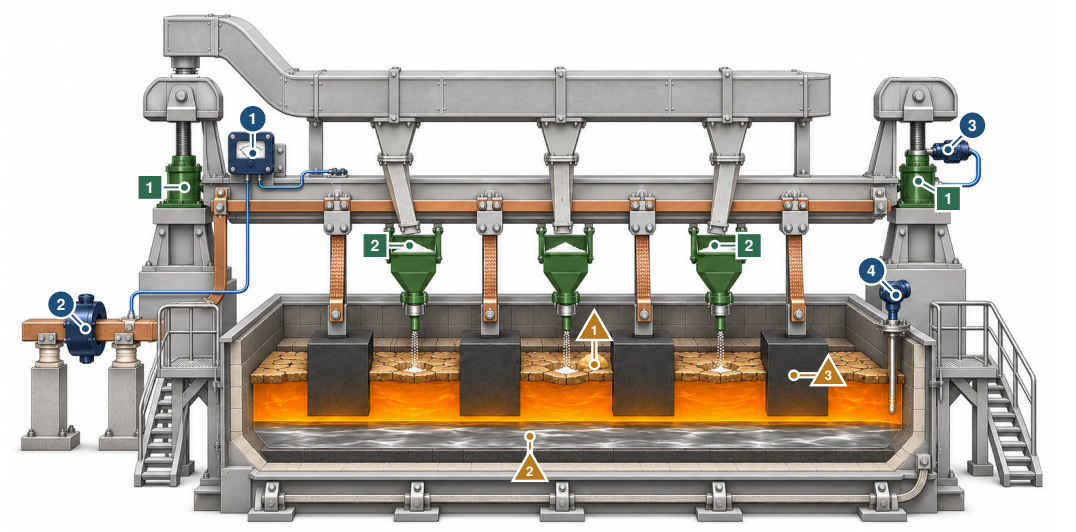
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CHAPTER 11

Alumina Feed Control Through a Non-Monotone Resistance in a Smelting Cell Simulator



The controller moves 1 the jacks that raise and lower the anode beam 2 the feeders that drop alumina into the bath

The controller reads 1 the voltage across the cell 2 the current through the cell 3 the height of the anode beam 4 a daily dip of the bath

What disturbs it 1 a wet lot of alumina that dissolves slowly 2 the rolling of the metal pad 3 an anode change

Notice that no device reads the alumina dissolved in the bath, so the controller judges it from the voltage and the current alone. Illustration, not to scale.

IN PLAIN TERMS **Feeding a Smelting Cell It Cannot See Into**

The main idea. Aluminum is made by sending a huge electric current through hot melted salt that holds a white powder called alumina. Feeders drop small doses of the powder into the bath, and a computer decides when by watching the voltage.

The challenge. The voltage is lowest in the middle, so one reading can mean too little powder or too much. If the powder runs low, the voltage jumps many times higher and the cell gives off strong greenhouse gases.

Why it matters. Feeding well saves power and keeps those gases out of the air.

THREE WAYS TO READ THIS CHAPTER

Explore	11 min	The first page, the fact box of the Introduction, the history box of Section 11.2, the try-it and fact boxes of Section 11.6, and the key points
Study	50 min	The whole chapter with its pause points and the twelve exercises
Practice	15 min	The first page, Section 11.6, Section 11.7, Section 11.8 and its open challenge

The control question A smelting cell is fed through a pseudo-resistance that has a minimum, so one reading cannot say on which side of it the alumina lies. How does a controller keep the alumina on the steep side, a few tenths of a percent from the anode effect, without ever measuring it, and what does each part of the controller buy in alumina, superheat, energy and anode-effect time?

Learning objectives

- Explain why a reading with a minimum cannot close a simple loop, and compute the slope of the curve from its three voltage terms.
- Describe the tracking cycle of demand feeding and show why it absorbs a constant error in the feeders' dose.
- Place a slope threshold and filter window between the pad's noise and the anode-effect wall with the half-window rule.
- Relate the target resistance to the heat balance, the ledge and the sludge, and judge a daily-dip inference for bias.
- Price an anode effect in minutes and CO_2-equivalent, and name the disturbances that only a margin can absorb.

Prerequisites Sections 1.4.6 (soft sensors corrected by a slower measurement), 1.4.4 (an endpoint read from a rate), 1.4.2 (thermal inertia), 1.6.2 and 1.6.4. Chapter 4 and Chapter 8 help but are not required.

The app https://apmonitor.com/apps/aluminum-smelting/

See also Volume 7, Chapter 4 for regulation at the peak of a plant characteristic, where the gain changes sign. Volume 5, Chapter 12 for a sensor that rises on both sides of the right dose and Volume 5, Chapter 3 for a loop closed on a slow analyzer. Volume 9, Chapter 8 for an operating point chosen against a moving optimum and a constraint.

11.1 Introduction

Primary aluminum is made by the Hall–Héroult process, in which alumina dissolved in an electrolyte of molten cryolite and aluminum fluoride is reduced on carbon anodes, and modern potlines run at about 300 to 600 kA [1]. The average alumina concentration is usually kept within 2 to 4 wt%, the most modern smelters need close to 13 kWh for a kilogram of aluminum against a world average near 14, and a cell whose alumina runs too low has an anode effect, a cell voltage of perhaps 30 to 40 V with CF_4 and C_2F_6 in the anode gas [1]. Over 100 years CF_4 carries a global warming potential of 6630 against CO_2 and C_2F_6 one of 11 100 [2]. Cell control feeds the alumina by watching how the cell resistance changes with it [3], through a pseudo-resistance computed from the cell voltage, a quantity easily confused with the cell's true ohmic resistance [4], and measured against bath samples that pseudo-resistance falls to a minimum and climbs again toward the anode effect [5].

DID YOU KNOW? Seventy-Two Million Tons a Year

The world's smelters made about 72 million metric tons of primary aluminum in 2024, an estimate, 43 million of them in China. Their capacity at the end of the year was about 78 million tons [6].

The minimum defeats the obvious ways of feeding a cell. A resistance looks like a measure of alumina, yet in this cell 8.68 µΩ stands for 2.5 % or 5.14 % alumina, and while the alumina falls from 4.1 to 2.7 % the filtered reading wanders only between 8.595 and 8.641 µΩ. Feeding what Faraday's law says the cell consumes looks safe, yet feeders that deliver 2.8 % less than they are counted for take the cell from 3.50 % into the anode effect at 32.5 h, while until then the controller's tally of shots never strays more than 1.8 kg from balance and the true shortfall reaches 165 kg. A lower slope threshold looks like an earlier warning, yet at 0.03 µΩ/h the metal pad's noise ends the underfeeds early, and the alumina climbs past the minimum to 4.03 % and spends 31 min above its band, on the side where an underfeed lowers the resistance. Demand feeding at the default 0.10 µΩ/h keeps the alumina between 2.14 and 3.07 % for two days after its first underfeed, with no anode effect and

no measurement of alumina. A block diagram with one gain from feed to resistance hides all of it, because the sign of that gain flips at the minimum.

The difficulty belongs to a class. Whenever a measured output has an extremum in the variable that matters, a reading cannot say which side of the extremum the plant is on, and the controller has to move the input on purpose to learn the sign of the local slope. Extremum seeking control does this with a deliberate perturbation, and its first stability proof allowed a general nonlinear dynamic plant whose equilibrium map has a maximum [7]. A photovoltaic array's power against its operating voltage has such a maximum, and at least 19 distinct methods have been introduced to track it [8]. A burner whose efficiency peaks at one air ratio has the same shape, and so has a braking tire's force against its slip, which Volume 7, Chapter 4 regulates at the peak. The tailpipe sensor of Volume 5, Chapter 12 rises on both sides of the right urea dose, so that a high reading may mean too little urea or too much. The smelting cell is the sharper teaching case for two reasons. Its useful operating point is not the extremum but a band on the steep side, a few tenths of a percent from a failure, and the plant moves its own measurement for reasons that are not alumina, an anode change, a tap, anodes that burn and metal that rises, which a slope detector must not mistake for an answer.

The curves that make a cell hard to feed were measured on industrial cells by sampling the bath through a feeding cycle [5], and the feeding, resistance regulation and heat-balance control of potlines are documented as practice [3, 9]. A real cell does not let the alumina be watched while the controller cannot see it, an anode effect be provoked on purpose, or the same noise be replayed against another threshold. This chapter does all three on a simulator of one 300 kA prebake cell whose controller cannot invert its only continuous measurement, and it measures how much alumina, superheat, energy and anode-effect time each part of a cell controller is worth. Demand feeding, resistance regulation and a daily correction of the heat balance follow the practice the literature reviews. To them the chapter adds a half-window rule that places the end of an underfeed, from the curve's slope, the drift of the anode–cathode distance and the fit's window, within 0.03 % of alumina of the engine at the default window. The model has 11 states and 17 ledgers, its thresholds are declared teaching values, and its controller sees only the voltage, the current, the beam's encoder, the crew's signals and a sampled bath dip, so that its view and the truth are logged side by side. Nine cases and a challenge separate the curve, the threshold, the anode effect, two crew operations, the heat balance and an infeasible wet lot.

Section 11.2 traces the domain from the first cells to the process computer. Section 11.3 builds the cell: the alumina between a shot and the anode, the voltage and the control room's pseudo-resistance, the bath, ledge and superheat, the beam and the crew, the anode effect and the metal pad's noise. Section 11.4 shows why the curve has a minimum, what slope an underfeed produces, where an underfeed ends and how the beam moves resistance and heat together. Section 11.5 describes the controller loop by loop, and Section 11.6 reports the measured runs of every case and of the challenge. Section 11.7 describes the real sensors, final elements and control platform, and Section 11.8 lists what the model leaves out, and Section 11.9 sums up.

11.2 Pots, Point Feeders and Process Computers

> ⧖ **HISTORY** **Invented Twice in One Year (1886)**
>
> Charles Martin Hall in the United States and Paul Héroult in France were both born in 1863, and each independently electrolyzed alumina dissolved in molten cryolite. Héroult bought a dynamo of 400 A and 30 V for his experiments, and his French patent dates from 23 April 1886. Hall applied for his U.S. patent on 9 July 1886, and his carbon anode was consumed in the overall reaction. The first commercial company started on 18 September 1888 with steel cells lined with baked carbon and cylindrical carbon anodes 3 inches across. The cells were called pots and the electrolyte bath, a terminology that has survived, and apart from scale, hooding and fume recovery a prebake cell is still built the same way. World production grew from 4682 t in 1900 to 49.7 million metric tons in 2013 [10].

The process dates from 1886, as the history box above tells, and the cell has changed since in its anode, its feeding and its control. The anode changed first. The Søderberg anode, a continuous and self-baking anode, has an electrical resistivity about 30 % higher than a prebaked one and makes its baking fumes hard to collect, and Søderberg cells are being replaced by cells whose anodes are baked at 1150 to 1200 °C in a separate furnace [1]. Feeding changed next. Older designs received large and infrequent additions of alumina, while modern cells carry point feeders that dose it automatically, which leaves anode changing as the most labor-intensive manual routine [1]. A cell of 16 to 40 prebaked anodes changes about one anode a day, and the change is the largest operating disturbance a prebake cell sees [1].

Computers came to the cell in the early 1960s, first to set its energy input by moving the anode beam and to feed alumina by watching how the cell resistance changed with the alumina concentration [3]. A paper of 1966 presented computer control of reduction cells as the maximum production for a given power input and, with automatic feeding added, the possibility of a completely automated potline [11]. Point breaking and feeding in prebake cells, combined with alternating overfeeding and underfeeding, then brought the alumina concentration to 2 to 3 %, which has remained an optimum for cell performance, and AlF_3 came under computer control through automatic feeding [3]. A review of automatic cell control lists its objectives as alumina feeding, resistance regulation through the anode–cathode distance (ACD), bath chemistry and the heat balance, with the routine operations on the cells accounted for [9]. Pseudo-resistance curves measured against bath samples on five types of cell put their minimum at 5.0 to 5.5 % alumina and their anode effect at 1.6 to 2.2 %, 100 to 300 mV above the minimum, and showed a fall of about 100 mV within 30 min of a switch from overfeeding to underfeeding, which the study suggested may come from sludge dissolving [5]. Cell voltages fell for 50 years and have leveled off at 4.1 to 4.2 V in cells above 200 kA [12]. For the heat balance, plant data in which the energy disturbance dominated led to a strategy of nearly constant AlF_3 addition with the energy manipulated through the resistance reference [13].

The anode effect became an environmental problem in the 1990s, when the high global warming potential of perfluorocarbons raised public concern and anode effects were held to be their only significant source [2]. By 1994 the industry was voluntarily exploring how to reduce the number and the duration of anode effects [14]. A measurement program sponsored by the U.S. Environmental Protection Agency at seven smelters found a clear trend toward lower emissions with fewer and shorter anode effects, with a scatter that pointed to other operational factors [15]. Anode effects are triggered by low alumina near the anode surface, start on a single anode, spread until the whole cell is on anode effect, and end only when at least part of the anode–cathode gap is short-circuited [16]. The voluntary programs cut perfluorocarbon emissions in ten countries by 31 to 78 % against 1990, 46 % on average [2], prediction and practical elimination of anode effects reduced them to a minimum [3], and a modern prebake cell can run for more than a week, even for months, without one [1]. The simulator puts these pieces into one cell and keeps the true alumina beside every decision its controller makes.

11.3 One Prebake Cell at 300 kA

The simulated cell has 24 prebaked anodes on a line current of 300 kA, modeled as one well-mixed bath over one metal pad, as shown in Figure 11.1. Its 11 integrated states are the dissolved alumina m_a, the alumina dispersing from dry and from wet shots, m_s and m_w, the sludge m_k, the bath solvent m_b, the excess aluminum fluoride m_f, the temperature T shared by bath and metal, the ledge thickness L, the metal pad's depth h_m, the beam position b and the anodes' burn-off z. Seventeen ledgers integrated with them record what was fed, consumed, made, tapped, burned, heated, lost and emitted, so that each balance closes from the state alone. The feeder shots, the start and end of an anode effect, the metal pad's noise and the timed disturbances are applied between integration steps and stay out of the derivative function. Table 11.1 classifies the signals.

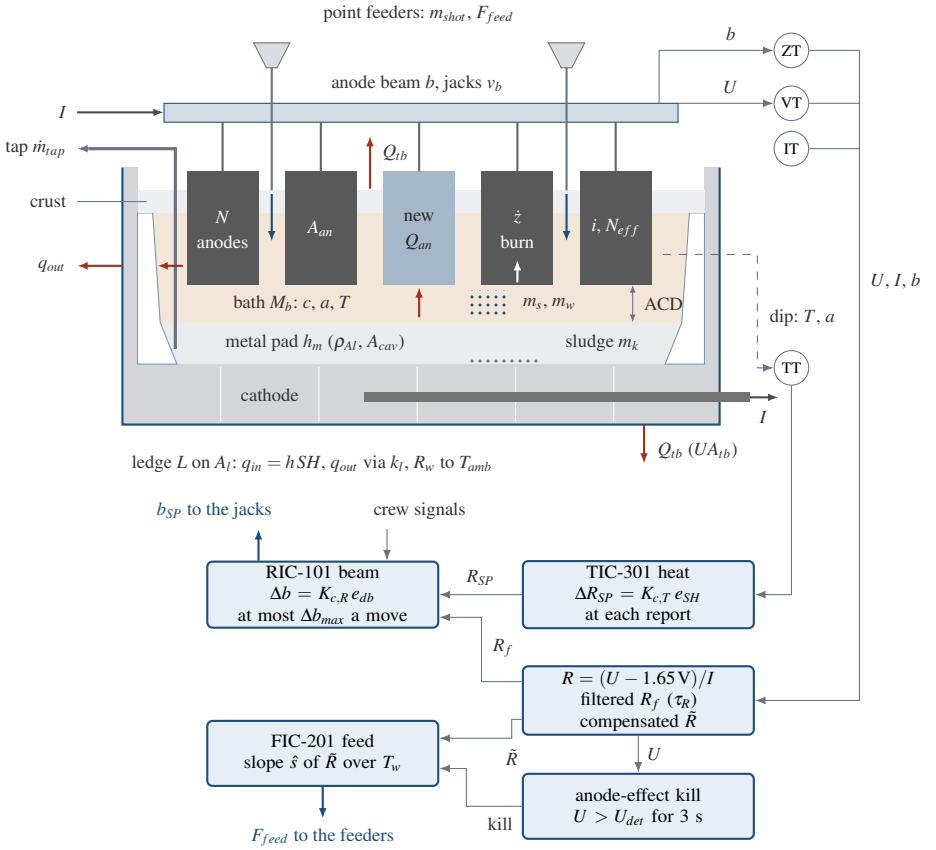


Figure 11.1 One prebake cell in longitudinal section, not to scale, with five of its 24 anodes, and its controller. The beam b, moved by jacks at v_b, carries anodes of area A_{an} that burn upward at $\dot{z}$ over a bath M_b with alumina c, excess AlF_3 a and temperature T, the ACD above a metal pad h_m on A_{cav}, and a ledge L on the sidewall area A_l. Point feeders drop shots m_{shot} at the rate F_{feed} into dispersing pools, m_s for dry alumina and m_w for a wet lot, or into sludge m_k. A new anode draws Q_{an}, so N_{eff} anodes carry I at the density i, and a tap siphons $\dot{m}_{tap}$. The controller reads U (VT), I (IT), b (ZT), the crew's signals and a daily dip of T and a (TT), and moves b_{SP}, F_{feed} and its own target R_{SP}, with e_{db} the error outside the dead band and $e_{SH} = SH_{SP} - SH_{est}$.

11.3.1 Alumina Between a Shot and the Anode

Each shot of a working feeder delivers $m_{shot} = 1.75\,\mathrm{kg}$, while the controller counts 1.80 kg, a declared error of 2.8 %. A share φ of the shot sinks to the metal as sludge and the rest joins a dispersing pool, m_w while a wet lot is on the feeders and m_s otherwise. The pools release alumina to solution as shown in Equation (11.1).

$$\begin{aligned}
&\frac{\mathrm{d}m_s}{\mathrm{d}t} = -\frac{m_s}{\tau_{dis}}, \qquad \frac{\mathrm{d}m_w}{\mathrm{d}t} = -\frac{m_w}{\tau_{wet}}, \qquad \frac{\mathrm{d}m_k}{\mathrm{d}t} = -\frac{m_k}{\tau_k} \\
&\frac{\mathrm{d}m_a}{\mathrm{d}t} = \frac{m_s}{\tau_{dis}} + \frac{m_w}{\tau_{wet}} + \frac{m_k}{\tau_k} - r_{cons} \\
&r_{cons} = \frac{\eta_{CE}\, I\, M_{Al_2O_3}}{6F}, \qquad c = \frac{100\, m_a}{m_a + m_b + m_f}
\end{aligned} \tag{11.1}$$

Table 11.1 Variables of the Smelting Cell, Their Roles and Defaults

Symbol	Role	Default	Range
R_f	CV of RIC-101, filtered pseudo-resistance	8.63 µΩ SP	7.4–10.0
SH	CV of TIC-301, superheat (inferred daily)	10 K SP	3–20
c	truth, alumina, never measured	3.5 % start	band 2–4
b	MV, beam position from its encoder	200 mm	0–400
F_{feed}	MV, alumina feed rate	180.70 kg/h	0–450
R_{SP}	MV of TIC-301, target resistance	8.63 µΩ	7.4–10.0
F_{AlF_3}	MV, AlF_3 addition	1.6 kg/h	0–6
I	DV, line current, measured	300 kA	250–320
w	DV, slower dissolution of a lot	1, wet $\frac{10}{3}$	1–5
μ	DV, pad noise multiplier	1	0–3
—	DVs, events	anode change, tap, feeder stuck	
—	DVs, events	pad instability, current drop	
m_a, m_s, m_w, m_k	states, alumina pools (kg)	315, 8.8, 0, 21.7	—
m_b, m_f	states, bath solvent, excess AlF_3 (kg)	7560, 1125	—
T, L	states, temperature, ledge	959.8 °C, 12.6 cm	—
h_m, b, z	states, pad, beam, burn-off	20, 20, 0 cm	—
U, I	measured every 1 s	4.24 V, 300 kA	—
T_{dip}, a_{dip}	measured daily, 1 h late, ±1.5 K, ±0.2 %	06:00	—

where η_{CE} is the current efficiency, $M_{Al_2O_3}$ the molar mass of alumina, F Faraday's constant and c the alumina in wt%. The excess AlF_3 is $a = 100\,m_f/(m_a+m_b+m_f)$, its mass grows with the addition F_{AlF_3} and falls with a loss r_{AlF_3} to the lining and the fumes, and the crew holds the bath level, so $\mathrm{d}m_b/\mathrm{d}t = 0$. At 300 kA and 95 % the cell consumes 180.70 kg/h of alumina and makes 95.64 kg/h of aluminum, 2.295 t a day, and the base feed is one shot every 36 s. In the 9000 kg bath one percent of alumina is 90 kg, half an hour of consumption. The three times and the sinking share depend on the superheat SH, the lot's factor w and the alumina, as shown in Equation (11.2).

$$\begin{aligned} g &= \frac{13}{\max(0,SH)+3}, \qquad \chi = \mathrm{clip}_{[0.05,2]}\left(\frac{c_{sat}-c}{c_{sat}-3.5}\right) \\ \tau_{dis} &= \frac{\tau_{dis,0}\,g}{\chi}, \qquad \tau_{wet} = w\,\tau_{dis}, \qquad \tau_k = \frac{\tau_{k,0}\,g}{\chi} \\ \varphi &= \mathrm{clip}_{[0,0.9]}\left(\varphi_0 + \varphi_{wet}[w>1] + 0.25\,\mathrm{clip}_{[0,1]}\left(\tfrac{5-SH}{5}\right)\right) \end{aligned} \tag{11.2}$$

where $\mathrm{clip}_{[p,q]}(x) = \min(q,\max(p,x))$, g is 1 at 10 K of superheat and 4.3 at the liquidus, χ slows dissolution toward the solubility c_{sat}, and $[w>1]$ is 1 under a wet lot. The lot of the cases has $w = 10/3$, so its shots disperse in 10 min instead of 3 min and a further 30 % of each sinks. Below 5 K of superheat a growing share of every shot sinks too, which is how a cold bath starves its own solution.

11.3.2 Voltage and the Control Room's Number

The cell voltage is built from a reversible part, two anode overvoltages, a cathode overvoltage and two ohmic drops, as shown in Equation (11.3).

$$\begin{aligned} U &= E_{rev} + \eta_{rxn} + \eta_{conc} + \eta_c + IR_{ext} \\ &\quad + \frac{I\,(ACD + d_{bub})}{\kappa N_{eff} A_{an} f_{fr}} \\ \eta_{rxn} &= \frac{R_g T_K}{\alpha F} \ln \frac{i}{i_0\,(c/3.5)^m} \\ \eta_{conc} &= \frac{R_g T_K}{2F} \ln \frac{c}{\max(c - c_{crit}, 0.01)} \\ i &= \frac{I}{N_{eff} A_{an}}, \qquad c_{crit} = c_{crit,0}\,\frac{i}{i_{nom}} \\ R &= \frac{U - 1.65\,\mathrm{V}}{I} \end{aligned} \tag{11.3}$$

where R_g is the gas constant, T_K the absolute temperature, α the anode's transfer coefficient, i_0 its exchange current density at 3.5 % alumina and m the exponent on alumina, c_{crit} the critical alumina of the moment, which scales with the current density against its design value i_{nom}, d_{bub} the bubble layer counted as the bath it replaces, f_{fr} the fringing of current around the anodes and R_{ext} the anodes, cathode and busbars. The concentration overvoltage has a pole at c_{crit}, the mass-transfer limit where the anode effect starts, and is held at its value 0.01 % above it. The conductivity follows the correlation that the application takes from the moving-electrode measurements of [17], as shown in Equation (11.4), with the alumina, AlF_3 and CaF_2 in wt% and κ in S/cm.

$$\ln \kappa = 1.977 - 0.0200\,c - 0.0131\,a - 0.0060\,w_{CaF_2} - \frac{1204.3}{T_K} \tag{11.4}$$

At the design point, 3.5 % alumina, 959.8 °C, an ACD of 4.0 cm and 0.847 A/cm^2, the 4.237 V across the cell divide into 1.20 V reversible, 0.499 and 0.038 V at the anode, 0.10 V at the cathode, 1.550 V in the bath and 0.850 V in the conductors, with a conductivity of 2.089 S/cm. The control room's pseudo-resistance R subtracts 1.65 V, an intercept of the voltage–current line that lies below the true back electromotive force, so R is not the ohmic resistance of the cell [4]. It reads 8.625 μΩ at the design point, where the cell voltage is a little above the 4.1 to 4.2 V at which cells above 200 kA have settled [12], and one millimeter of ACD moves it 0.117 μΩ.

11.3.3 Bath, Ledge and Superheat

The liquidus is the empirical equation of [18] without its LiF, MgF_2 and KF terms, as shown in Equation (11.5), in °C with a, w_{CaF_2} and c in wt%.

$$\begin{aligned} T_{liq} &= 1011 + 0.50a - 0.13a^{2.2} - \frac{3.45\,w_{CaF_2}}{1 + 0.0173\,w_{CaF_2}} \\ &\quad + 0.124\,w_{CaF_2} a - 0.00542\,(w_{CaF_2} a)^{1.5} \\ &\quad - \frac{7.93\,c}{1 + 0.0936\,c - 0.0017\,c^2 - 0.0023\,a\,c} \end{aligned} \tag{11.5}$$

It is 949.8 °C at the design point and falls 6.0 K for each percent of alumina near 2.6 %, so the superheat $SH = T - T_{liq}$ moves with the feeding cycle. The bath and the metal share one heat capacity

C, and the ledge freezes or melts against the superheat, as shown in Equation (11.6).

$$\begin{aligned} C\frac{\mathrm{d}T}{\mathrm{d}t} &= I\,(U_s - E_{tn}) + \delta_{AE} f_{AE} I\,(U_{AE} - U_s) \\ &\quad - q_A\, r_{dis} - Q_{side} - UA_{tb}(T - T_{amb}) - Q_{an} \\ \rho_l \Delta H_f \frac{\mathrm{d}L}{\mathrm{d}t} &= q_{out} - q_{in}, \qquad q_{in} = h\,SH \\ q_{out} &= \frac{T_{liq} - T_{amb}}{L/k_l + R_w} \end{aligned} \tag{11.6}$$

where U_s is the voltage of Equation (11.3) at the smooth ACD, without the pad's noise, E_{tn} the reaction enthalpy as a voltage with the alumina already hot, δ_{AE} is 1 during an anode effect, f_{AE} the share of its extra power that heats the bath, q_A the heat that warms and dissolves alumina at the rate r_{dis} at which it dissolves, $Q_{side} = A_l\, q_{in}$ the heat into the ledge, ρ_l and ΔH_f the frozen bath's density and latent heat, k_l the ledge's conductivity and R_w the resistance of the sidewall and shell. When the ledge has melted to L_{min} and $q_{in} > q_{out}$, the bath heats a bare wall, $Q_{side} = A_l(T - T_{amb})/(1/h + L_{min}/k_l + R_w)$, and L stops changing. At the design point the 1271 kW the cell draws are 570 kW of reaction, 60 kW for the feed, 112 kW into a ledge 12.6 cm thick and 529 kW through the top and bottom.

11.3.4 Beam, Anodes, Metal and the Crew

The anodes hang from the beam, they burn from below, and the metal rises under them, so the ACD follows Equation (11.7).

$$\begin{aligned} ACD &= ACD_0 + (b - b_0) + z - (h_m - h_{m,0}) \\ \frac{\mathrm{d}z}{\mathrm{d}t} &= \frac{b_C\, \dot{m}_{Al}}{\rho_C N A_{an}}, \qquad \frac{\mathrm{d}h_m}{\mathrm{d}t} = \frac{\dot{m}_{Al} - \dot{m}_{tap}}{\rho_{Al} A_{cav}}, \qquad \frac{\mathrm{d}b}{\mathrm{d}t} = v_b \end{aligned} \tag{11.7}$$

where $\dot{m}_{Al} = \eta_{CE} I M_{Al}/(3F)$ is the aluminum made, b_C the net carbon burned per kilogram of aluminum and ρ_C the anode density. The anodes burn 0.723 mm/h while the metal rises 0.904 mm/h, so the ACD closes 0.181 mm/h unless the beam moves. A tap siphons $m_{tap} = 2300$ kg at 12 000 kg/h, for 11.5 min, and opens the ACD by 21.7 mm. An anode change takes n anodes out for $t_{out} = 10$ min and sets cold ones, so the cell has $N_{eff} = N - n$ anodes carrying current while they are out and $N_{eff} = N - n\,\mathrm{e}^{-\theta/\tau_{pick}}$ at an age θ after their return, when the new anodes draw $Q_{an} = nQ_{ac}\,\mathrm{e}^{-\theta/\tau_{an}}$ from the bath. A cell of 24 anodes that last about 30 days changes one every 30 h or so, close to the one a day that cells of 16 to 40 anodes see [1], so the cases fire changes as events rather than on a schedule.

11.3.5 The Anode Effect and Its Emissions

The anode effect is a hybrid state, as shown in Equation (11.8).

$$\begin{aligned} &\text{starts when } c \le c_{crit} \\ &\text{ends when } c \ge c_{crit} + \Delta c_{self} \\ &\quad \text{or when } ACD \le ACD_{kill} \text{ and } c \ge c_{crit} + \Delta c_{kill} \\ &U = U_{AE} + \sigma_{fl}\, \nu_k, \qquad \dot{m}_{CF_4} = 60\, S_{CF_4} P_{day} \\ &\dot{m}_{C_2F_6} = F_{C_2F_6} \dot{m}_{CF_4} \end{aligned} \tag{11.8}$$

where a new standard normal draw ν_k arrives with every step, $\sigma_{fl} = 2.5$ V a flicker, P_{day} the aluminum made in a day in metric tons, and the emission rates are in kilograms per hour. The second ending is the kill. With the alumina 0.2 % above critical, pumping the anodes down to an ACD of 15 mm sweeps the gas film away, which stands for the short circuit of the anode–cathode gap that a termination requires [16]. The emission coefficients follow the slope method, kilograms of CF_4 per metric ton of

aluminum for each anode-effect minute per cell-day, so every anode-effect minute of this cell vents 0.328 kg of CF_4, which with the GWP-100 values of 6630 and 11 100 [2] is 2.62 t of CO_2-equivalent. During an effect the cell runs at 9.0 MW instead of 1.27 MW.

11.3.6 The Metal Pad's Noise

The ACD the anodes see carries a noise w_{pad} that stands for the metal pad's roll and heave, as shown in Equation (11.9), updated once per step Δt in seconds.

$$\begin{aligned} \dot{x}_{k+1} &= \dot{x}_k - (2\zeta\omega\dot{x}_k + \omega^2 x_k)\,\Delta t + \sigma_x\sqrt{\Delta t}\;\nu_{1,k} \\ x_{k+1} &= x_k + \dot{x}_{k+1}\Delta t \\ y_{k+1} &= \beta y_k + \sqrt{1-\beta^2}\,\sigma_{slow}\nu_{2,k} \\ w_{pad} &= \lambda\,\mu\,(x+y) \end{aligned} \tag{11.9}$$

where x is a lightly damped oscillator of frequency $\omega = 2\pi/T_{pad}$ and damping ratio ζ whose stationary standard deviation is σ_{pad}, with $\sigma_x = \sigma_{pad}\sqrt{4\zeta\omega^3}$, y a first-order heave with $\beta = \mathrm{e}^{-\Delta t/\tau_{slow}}$, μ the multiplier the operator sets and λ is 4 during a pad instability and 1 otherwise. The noise enters the voltage the controller measures and not the heat balance, and it moves the pseudo-resistance by 0.033 μΩ, one standard deviation from second to second.

11.3.7 Start and Numerics

Every case starts at 00:00 in thermal balance. The bath, AlF_3 and alumina masses follow from $M_{b,0}$, a_0 and c_0, the superheat solves $I(U - E_{tn}) - q_A r_{cons} - A_l h SH - UA_{tb}(T - T_{amb}) = 0$ by bisection, the ledge is the thickness at which $q_{out} = q_{in}$, and the pools hold what the base feed would leave in transit, $r_{cons}(1-\varphi)\tau_{dis}$ dispersing and $r_{cons}\varphi\tau_k$ as sludge. At the design point the superheat is 10.01 K, the ledge 12.6 cm and the alumina in transit 30.4 kg. Table 11.2 lists the parameters. The integrator is fourth-order Runge–Kutta with a fixed step of 1 s, the controller scans every second, the historian logs every 10 s, and the speed selector runs from 0.01 to 4 simulated hours per second, so a two-day case takes 192 s at the default 0.25 h per second. The order of work in a step, the Reset that keeps the learner's settings and the reload that restores the case's own are those of every framework app (Section 1.6.1). The pad's noise and the dip's errors draw on one generator seeded at 20 261 011. The ledgers close every balance to a relative 1×10^{-9} through whole runs, and halving the step with the pad's noise off moves the lowest alumina of a day of demand feeding by under 0.01 %, the bath temperature by under 0.05 K and the count of triggers by none, two of the 41 checks the application passes.

11.3.8 Assumptions

One well-mixed bath. Real anode effects are triggered by low alumina near an anode surface and start on a single anode before they spread [16]. Here one concentration stands for the whole bath, so no local anode effect can start while the mean is above the wall.

A teaching curve. The Tafel, mass-transfer and ohmic constants are placed so that the minimum sits at 3.5 % and the anode effect at 1.80 % at the design current density. Measured curves had their minimum at 5.0 to 5.5 % and their anode effect at 1.6 to 2.2 %, 100 to 300 mV above the minimum [5], and this one rises 137 mV from its minimum to 1.85 %, inside that range.

A threshold for the anode effect. The effect is a threshold on the mean alumina, and its 30 V, the share of its power that heats the bath and the kill condition are teaching values, as are the slope coefficients of its emissions. Real alumina feeding and anode-effect prediction belong to each plant's computer control [3, 9], and real emissions are measured on the potlines that make them [15].

A bath level held by the crew. Crushed bath goes in as the ledge grows and is ladled out as it melts, so the ledge moves heat but not the bath's composition. A growing ledge would otherwise concentrate the AlF_3 and the alumina and lower the liquidus.

Table 11.2 Model Parameters, With M for a Show Model Slider and C for a Constant Fixed in the Code

Symbol	Meaning	Value	Class
I_{nom}, N	design current, anodes	300 kA, 24	M
A_{an}	area of one anode, 1.80 m × 0.82 m	1.476 m^2	M
η_{CE}	current efficiency	95 %	M
$M_{b,0}$	liquid bath at the start	9000 kg	M
c_0	alumina at the start (case 1: 5.0)	3.5 %	M
a_0, w_{CaF_2}	excess AlF_3 at the start, CaF_2	12.5, 5 %	M
ACD_0, b_0	ACD and beam at the start	4.0 cm, 200 mm	M, C
E_{rev}	reversible voltage	1.20 V	M
α, m	transfer coefficient, exponent on alumina	1.0, 0.492	M
i_0	exchange current density at 3.5 %	0.0077 A/cm^2	M
$c_{crit,0}$	critical alumina at i_{nom}	1.80 %	M
η_c	cathode overvoltage	0.10 V	M
f_{fr}, d_{bub}	fringing, bubble layer	1.159, 0.43 cm	M
R_{ext}	anodes, cathode and busbars	2.833 μΩ	M
U_{AE}, σ_{fl}	voltage of an anode effect, flicker	30 V, 2.5 V	M, C
—	intercept of R	1.65 V	C
A_{cav}, $h_{m,0}$	metal pad area, depth at the start	46 m^2, 20 cm	M
ρ_{Al}	liquid aluminum density	2300 kg/m^3	M
b_C, ρ_C	net carbon, anode density	0.415, 1550 kg/m^3	M
t_{out}, τ_{pick}	anode out of the cell, current pickup	10 min, 8 h	M
Q_{ac}, τ_{an}	heat a new anode draws, heating time	60 kW, 6 h	M
m_{tap}, $\dot{m}_{tap}$	metal of one tap, siphon rate	2300 kg, 12 000 kg/h	M
t_{dip}	hour of the daily dip	06:00	M
C	heat capacity of bath and metal	55 MJ/K	M
E_{tn}	reaction enthalpy as a voltage	1.90 V	M
q_A	heat to warm and dissolve alumina	1.2 MJ/kg	M
A_l, h	ledge area, bath-ledge coefficient	16 m^2, 700 W/(m^2 K)	M
k_l, R_w	ledge conductivity, wall resistance	1.8 W/(m K), 0.06 m^2 K/W	M
T_{amb}	potroom air at the shell	40 °C	M
ρ_l, ΔH_f	frozen bath density, latent heat	2100 kg/m^3, 530 kJ/kg	M
UA_{tb}	top and bottom loss coefficient	575 W/K	M
L_{min}	thinnest ledge, bare wall below	1.0 cm	M
f_{AE}	anode-effect power to the bath	0.10	M
r_{AlF_3}	AlF_3 lost to lining and fumes	1.6 kg/h	M
m_{shot}	true dose (counted 1.80)	1.75 kg	M
$\tau_{dis,0}$, $\tau_{k,0}$	dispersing, sludge times at 10 K	3 min, 4 h	M
φ_0, φ_{wet}	sinking share, extra from a wet lot	0.03, 0.30	M
c_{sat}	alumina solubility	7.5 %	M
Δc_{kill}, Δc_{self}	above critical to kill, to end alone	0.2, 1.0 %	M
ACD_{kill}	ACD at which a pump sweeps the film	15 mm	M
S_{CF_4}	slope coefficient (per AE-min/day)	0.143	M
$F_{C_2F_6}$	C_2F_6 per kilogram of CF_4	0.121	M
—	GWP-100 of CF_4, C_2F_6	6630, 11 100	M
σ_{pad}, T_{pad}, ζ	pad roll: deviation, period, damping	0.25 mm, 45 s, 0.15	M
σ_{slow}, τ_{slow}	pad heave: deviation, correlation time	0.10 mm, 120 s	M
λ	roll factor in a pad instability	4	C

The constants of Equation (11.2) (13, 3, 0.25, 5 K and the clip limits) and the floors of Equation (11.3) (0.05 % alumina and 0.01 % above critical) are class C. Constants: $F = 96485.33\,\mathrm{C/mol}$, $R_g = 8.314462\,\mathrm{J/(mol\,K)}$, $M_{Al_2O_3} = 0.101961\,\mathrm{kg/mol}$ and $M_{Al} = 0.0269815\,\mathrm{kg/mol}$.

Constants where the cell varies. The current efficiency is a constant 95 %, the pad's noise is a declared spectrum that cannot grow by itself, dissolution is first order in three pools, and the bath, metal and walls are lumped, with one ledge on 16 m^2 and one loss coefficient for the top and bottom.

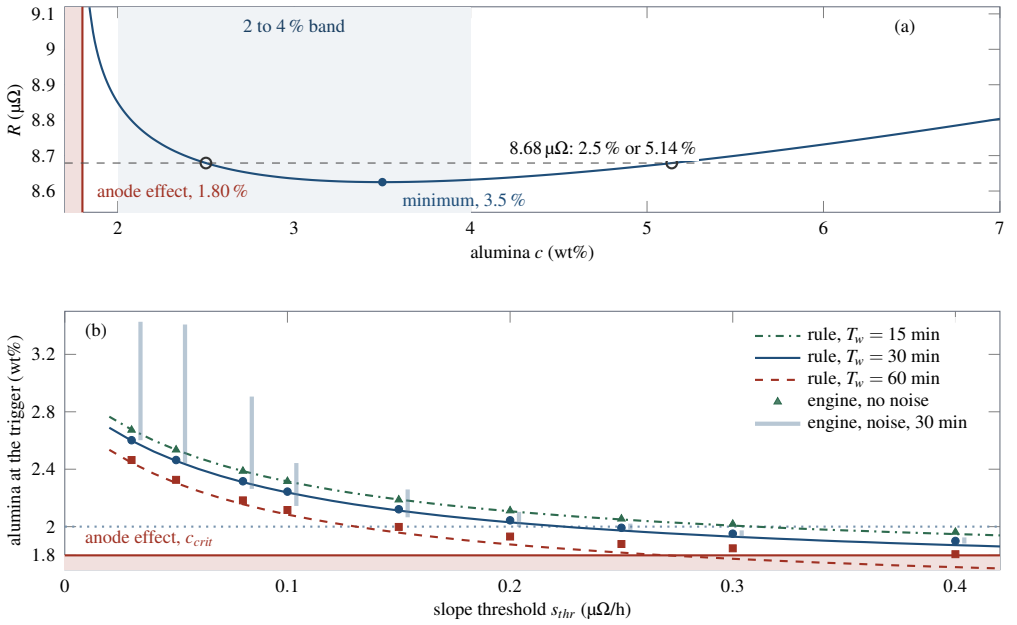


Figure 11.2 The curve the controller reads and where its underfeeds end. (a) The pseudo-resistance against alumina at the design point, 959.8 °C, an ACD of 4.0 cm and 300 kA. (b) The alumina at which an underfeed ends against the slope threshold, from the half-window rule of Equation (11.11) (dash-dotted, solid and dashed lines for windows of 15, 30 and 60 min) and the engine's first trigger in case 3 with the pad noise off (triangles, circles and squares for the same windows), with the spread of every trigger in 24 h at the default noise and the 30 min window (shaded bars).

11.4 A Reading With Two Answers

11.4.1 Why the Curve Has a Minimum

The minimum is where three slopes cancel. Differentiating Equation (11.3) at fixed temperature, ACD and current gives Equation (11.10), per wt% of alumina.

$$I\frac{\partial R}{\partial c} = -\frac{R_g T_K}{\alpha F}\frac{m}{c} + \frac{R_g T_K}{2F}\left(\frac{1}{c} - \frac{1}{c - c_{crit}}\right) + 0.0200\,U_{bath} \tag{11.10}$$

where U_{bath} is the ohmic drop in the bath. At 3.5 % the reaction term is −14.9 mV per percent, the concentration term −16.1 mV and the ohmic term +31.0 mV, 2 % of the 1.550 V drop, and they cancel. At 2.5 % the anode terms grow to −20.9 and −54.6 mV while the ohmic term stays at 30.4 mV, so the curve falls 0.151 μΩ per percent there, 0.341 μΩ at 2.2 % and 0.784 μΩ at 2.0 %. Figure 11.2(a) shows the result. A reading of 8.679 μΩ means 2.5 % or 5.14 %, 2.2 % reads as 6.24 % and 2.0 % as 7.58 %, while above the minimum the curve rises only 0.172 μΩ from 4 to 7 %. A reading says how far the cell is from the minimum and nothing about the side.

🕮 **Pause.** Try Exercise 11.1 before reading on.

11.4.2 The Slope an Underfeed Produces

An underfeed reads the side through a time derivative, as the rate endpoint of Chapter 4 reads a carbon that a level cannot give (Section 1.4.4). During a 70 % underfeed the alumina falls 0.615 %/h in case 3 (0.609 to 0.617 over its 21 underfeeds), faster than the 0.602 %/h of the counted dose because every shot is 2.8 % short, and slower than the 0.641 %/h of the true dose because the dispersing pools drain as the feed drops. The alumina-driven slope $s_c = -\dot{c}\,\partial R/\partial c$ is then 0.027 μΩ/h at 3.0 %, 0.093 at

2.5 %, 0.210 at 2.2 % and 0.482 at 2.0 %. Two things stand between that slope and the controller. The closing ACD lowers every slope by $d = 0.181\,\text{mm/h} \times 0.117\,\mu\Omega/\text{mm} = 0.021\,\mu\Omega/\text{h}$, which the beam corrects only in steps of its own. The pad's noise leaves a standard deviation in the least-squares slope of 0.071 μΩ/h over a 15 min window, 0.027 over 30 min and 0.010 over 60 min, measured at the flat bottom with the beam held, and 0.109 μΩ/h over 30 min in a pad instability. The noise falls about as the window to the power -1.4, near the $-3/2$ of white noise, and the price of a longer window is lag.

11.4.3 Where an Underfeed Ends

A least-squares line through the last T_w of a steady descent estimates the slope near the middle of its window, half a window behind the present alumina, so an underfeed ends near the alumina of Equation (11.11).

$$c_{trig} \approx c^*(s_{thr} + d) - |\dot{c}|\,\frac{T_w}{2}, \qquad s_c\big(c^*(s)\big) = s \tag{11.11}$$

where $c^*(s)$ is the alumina at which the alumina-driven slope equals s and s_{thr} is the threshold. With the noise switched off, the engine's first trigger lies within 0.013 % of the rule at 15 min, 0.028 % at 30 min and 0.090 % at 60 min over thresholds of 0.03 to 0.40 μΩ/h, and above it at the longer windows, where the curve's convexity across the window makes the fit lead its midpoint, as shown in Figure 11.2(b). At the default 0.10 μΩ/h and 30 min the rule gives 2.238 % and the engine 2.244 %. The rule sets the two edges of a usable threshold. The lower edge is the noise. A threshold within two or three standard deviations of the flat-bottom slope ends underfeeds on the roll, and with the default noise the triggers of a day spread over 2.60 to 3.43 % at 0.03 μΩ/h and 2.26 to 2.91 % at 0.08, against 2.14 to 2.44 % at 0.10. The upper edge is the wall, because c_{trig} must stay above c_{crit} with room for the overfeed's alumina to dissolve. At 60 min the rule reaches 1.80 % at 0.27 μΩ/h, and the engine meets the wall at 0.40 with the noise off.

11.4.4 One Handle for Resistance and Heat

The beam moves the resistance and the heat together. One millimeter of ACD is 0.117 μΩ, every 0.1 μΩ of target is 9.0 kW of heat at 300 kA, and a kelvin of superheat drives 11.2 kW into the ledge against 0.575 kW through the top and bottom. Solving the heat balance at 3.5 % for a given target shows the consequence. The steady superheat rises 0.76 K for each 0.1 μΩ, and a target of 7.90 μΩ instead of 8.625 settles at 4.47 K with an ACD of 3.37 cm. The bath alone answers in $C/(A_l h + UA_{tb}) = 1.30\,\text{h}$, while the ledge integrates an imbalance for days, the clocks of thermal inertia in Section 1.4.2. A beam loop that holds the resistance therefore holds the heat as well, unless its target is wrong, and the only measurement of the heat is a dip a day.

11.5 The Cell Controller, Loop by Loop

The controller reads five inputs and nothing else, the cell voltage every second with the pad's noise in it, the line current, the beam's encoder, the crew's signals of an anode change or a tap with their start times, and a daily bath dip. It never reads the alumina, the superheat, the ACD or the ledge. It forms the pseudo-resistance R every scan and filters it with a first-order lag of $\tau_R = 2\,\text{min}$, held while an anode effect is detected. Table 11.3 lists the settings.

11.5.1 Resistance Regulation on the Shared PID

Every $T_{reg} = 5\,\text{min}$ the beam loop forms the error $e = R_{SP} + R_{ac} - R_f$, removes a dead band, $e_{db} = \text{sgn}(e)\max(0, |e| - \delta_R)$ with $\delta_R = 0.08\,\mu\Omega$, and passes e_{db} as the setpoint of the framework's shared PID with a process value of zero and $\Delta t = T_{reg}$. That PID is the velocity form of Section 1.6.2, Equations (1.13) to (1.16), with the action $a = +1$, reverse acting because a higher beam raises the resistance. Its clamp keeps the beam within its 0 to 400 mm of travel, its slew holds a move to $\Delta b_{max} = 3\,\text{mm}$ per interval, it has no derivative action ($\tau_D = 0$), and its integral is back-calculated with a tracking time equal to τ_I. Because τ_I equals the interval, the back-calculation returns the

Table 11.3 Controller Settings and Constants, Defaults and Ranges

Symbol	Setting	Default	Range
RIC-101, resistance to beam			
R_{SP}	target resistance	8.63 µΩ	7.4–10.0
$K_{c,R}$	gain, mm/µΩ	6	0–20
$\tau_{I,R}$, T_{reg}	integral time, interval	5, 5 min	1–60, 1–30
δ_R	dead band	0.08 µΩ	0–0.4
Δb_{max}	move limit	3 mm	0.5–30
τ_R	resistance filter	2 min	0.5–15
—	anode-change, tap compensation	off, off	on
s_R	assumed beam sensitivity	0.12 µΩ/mm	C
ΔR_{an}, $\hat{\tau}_{pick}$	assumed rise per anode, pickup	0.22 µΩ, 8 h	C
FIC-201, alumina feed			
—	feeding	demand	manual, fixed
s_{thr}	slope threshold	0.10 µΩ/h	0.01–0.6
u_{under}	underfeed	70 %	30–100
u_{over}	overfeed	150 %	100–300
t_{over}, t_{base}	overfeed, base period	45, 30 min	5–180, 0–180
t_{arm}	arming time	20 min	2–90
$t_{under,max}$	longest underfeed	4 h	0.5–12
—	slope filter	least squares	two lags
T_w	slope window	30 min	5–120
t_{hold}	hold after an event	1 h	5–240 min
u_{fixed}	fixed feed	100 %	50–150
—	counted dose, $\hat{\eta}_{CE}$	1.80 kg, 0.95	C
—	feeders, shortest gap	4, 20 s	C
Anode-effect detection and kill			
U_{det}	detection, held 3 s	8 V	5–20
m_{kill}	kill burst	36 kg	0–90
Δb_{pump}	pump stroke	30 mm	5–60
—	automatic termination	on	off
t_{crew}	crew response, termination off	8 min	1–60
TIC-301, superheat to target resistance			
—	heat loop mode	manual	auto
SH_{SP}	superheat target	10 K	3–20
$K_{c,T}$	gain, µΩ/K	0.06	0–0.3
$\tau_{I,T}$	integral time	24 h	6–240
c_{as}	alumina the inference assumes	2.6 %	1.5–6
—	step limit, target range	0.3 µΩ, 7.4–10.0	C

integral to the applied output at every call, and each move is exactly $\Delta b = K_{c,R}\, e_{db}$ within $\pm\Delta b_{max}$. With $K_{c,R} = 6\,\mathrm{mm/\mu\Omega}$ a move removes $6 \times 0.117 = 0.70$ of the error outside the band. The jacks run the beam to its setpoint at 10 mm/min, and a resistance above its target lowers the beam, which the application's direction check confirms. Regulation pauses while an anode effect is detected and for 10 min after it.

Two options feed a known cause forward. Tap compensation lowers the beam setpoint with the metal the siphon takes, $\dot{m}_{tap}\Delta t/(\rho_{Al}A_{cav})$ per scan at the controller's assumed density and area, and carries the move in the PID's integral so that the loop owns it. Anode-change compensation adds to the target the resistance the controller expects the missing current to add, $\sum_j \Delta R_{an}\, n_j\, \mathrm{e}^{-\max(0,\,\theta_j - t_{out})/\hat{\tau}_{pick}}$, with $\Delta R_{an} = 0.22\,\mu\Omega$ against the plant's step of 0.25 and $\hat{\tau}_{pick} = 8\,\mathrm{h}$, passed through the same first-order lag τ_R as the reading, so that R_{ac} and R_f step together at a change.

11.5.2 Feeding Modes and the Tracking Cycle

The feed loop's base rate F_b is the consumption r_{cons} of Equation (11.1) at the measured current and an assumed current efficiency $\hat{\eta}_{CE}$ of 95 %, 180.70 kg/h at 300 kA, and the loop turns any rate into shots of 1.80 kg through an accumulator that fires the next of four feeders, each at most every 20 s. Fixed feeding asks for $u_{fixed}F_b$. Demand feeding runs the tracking cycle and decides every 30 s. It underfeeds at $u_{under} = 70\,\%$ of F_b until, after an arming time of 20 min, the slope of

Equation (11.12) passes $s_{thr} = 0.10\,\mu\Omega/\mathrm{h}$, or until the underfeed has lasted 4 h. It then overfeeds at 150 % for $t_{over} = 45\,\mathrm{min}$, feeds F_b for 30 min and underfeeds again.

$$\tilde{R}_j = \bar{R}_j - s_R\,(b_j - b_{ref}), \qquad \hat{s} = \frac{\sum_j (t_j - \bar{t})(\tilde{R}_j - \bar{\tilde{R}})}{\sum_j (t_j - \bar{t})^2} \tag{11.12}$$

where $\bar{R}_j$ are 30-s block means of the unfiltered resistance at block times t_j, $s_R = 0.12\,\mu\Omega/\mathrm{mm}$ is the beam sensitivity the controller assumes against the plant's 0.117, b_{ref} the beam at the start of the underfeed, and the sums run over the blocks of the last $T_w = 30\,\mathrm{min}$. A second estimator, two first-order lags of $T_w/4$ on the resistance and on its block-to-block change, is an option. An anode change, a tap or an anode effect puts a hold on the cycle, because its step in resistance is not alumina. The estimator forgets its blocks, an underfeed in progress drops to the base rate, and a fresh underfeed starts once the hold, $t_{hold} = 1\,\mathrm{h}$ plus a tap's duration, has passed.

11.5.3 Anode-Effect Detection and Kill

The detector declares an anode effect when the voltage stays above $U_{det} = 8\,\mathrm{V}$ for 3 s and releases it after 10 s below. With automatic termination on the kill starts at once, and with it off the crew starts it $t_{crew} = 8\,\mathrm{min}$ later. The kill fires a burst of 36 kg, raises every feeding mode to 200 % of the base rate until the effect is over, and pumps the beam 30 mm down at 30 mm/min, holds it 10 s and returns it, first 30 s after the kill starts and then a minute after each return while the effect lasts. Demand feeding then runs an overfeed, a base period and a fresh underfeed.

11.5.4 The Daily Dip and the Target Resistance

The heat loop runs on the framework's shared sampled analyzer. A dip drawn at 06:00 every 24 h reports the bath temperature with 1.5 K of noise and the excess AlF_3 with 0.2 % an hour later, at 07:00, and the loop infers the superheat as $SH_{est} = T_{dip} - T_{liq}(c_{as}, a_{dip})$ from Equation (11.5) at an assumed alumina $c_{as} = 2.6\,\%$ and 5 % CaF_2. In AUTO each report moves the target through the shared PID with $K_c = 0.06\,\mu\Omega/\mathrm{K}$ and $\tau_I = 24\,\mathrm{h}$, equal to the report interval, so each step is $K_{c,T}(SH_{SP} - SH_{est})$, limited to 0.3 µΩ and to 7.4 to 10.0 µΩ, and a superheat below its target raises the target, so the loop is reverse acting ($a = +1$). In MANUAL the target is the operator's, 8.63 µΩ by default. The inference inherits the liquidus's 6.0 K per percent of alumina, so an error of 0.5 % in c_{as} is 3 K of superheat that no dip reveals. The inference is a soft sensor of the kind Section 1.4.6 describes, exact for what its model contains and biased by the alumina it assumes.

11.5.5 Manual Mode and Three Kinds of Model

The master MANUAL and AUTO switch throws all three stations, and each station has a mode of its own. The transfer is bumpless both ways, as in every framework app (Section 1.6.2). Equations (11.1) to (11.9) are the simulation model. No model is fitted to the plant's data. The controller's internal models are the base rate at 95 % and 1.80 kg, the beam sensitivity s_R, the anode-change term with its pickup, the metal density and pad area of the tap compensation, and the liquidus at an assumed alumina, and each differs from the plant by a declared amount.

11.6 Measured Runs of the Cell

Table 11.4 lists the cases, and Table 11.5 collects their scorecards, which the application keeps on the truth at every step. The engine produced each number below on its own, at the default seed, in the window that its row or sentence names, with a variant's settings changed after the case is chosen and before it runs, the same run that a reset with those settings gives. Each case starts from the reference line of Table 11.3, demand feeding at 0.10 µΩ/h with the heat loop in MANUAL at 8.63 µΩ, and each case alters that line only where its row says so. Figure 11.3 draws the alumina range of every row against the band and the anode-effect wall.

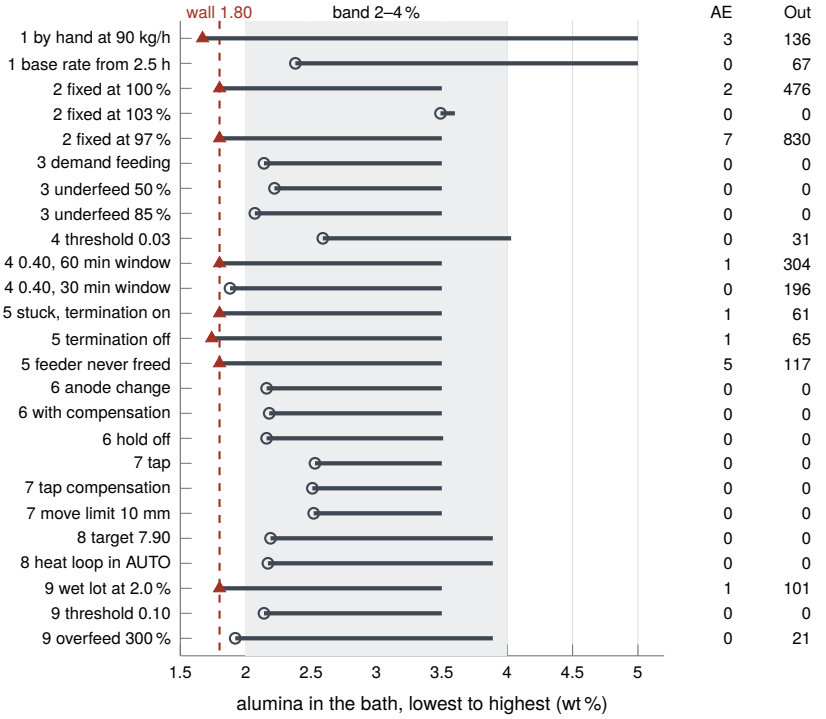


Figure 11.3 The 25 rows of Table 11.5 as a chart: each bar runs from the lowest to the highest alumina of its run, the shaded band is 2 to 4 % and the dashed line is the anode-effect wall at 1.80 %. A filled triangle marks a run with an anode effect, an open circle one without, and the columns at the right give the anode effects (AE) and the minutes outside the band (Out). Notice that every run that reaches the wall is fed on the clock, has a stuck feeder or a wet lot, or ends its underfeeds behind a 60 min window at 0.40 μΩ/h, while the runs of cases 3, 6, 7 and 8 stay inside the band.

Table 11.4 Cases of the Cell and What Each Teaches

#	Change from the reference line	Teaching point
1	$c_0 = 5.0\,\%$, 90 kg/h by hand, beam held, termination off	the curve by hand
2	fixed feeding at 100 % of F_b	open-loop drift
3	none	the tracking cycle
4	$s_{thr} = 0.03\,\mu\Omega/\mathrm{h}$	threshold against noise
5	a feeder stuck from 1 to 5.5 h	anode effect and kill
6	an anode change at 1 h	current redistribution
7	a tap at 1 h	a rate-limited beam
8	$R_{SP} = 7.90\,\mu\Omega$	the heat balance
9	$s_{thr} = 0.25\,\mu\Omega/\mathrm{h}$, a wet lot at 2.0 %	honest infeasibility
10	fixed feeding, $R_{SP} = 8.30\,\mu\Omega$, anode change, tap, wet lot	graded two days

11.6.1 A Reading That Hardly Moves

Case 1 starts the cell at 5.0 % alumina, feeds it 90 kg/h by hand, about half its consumption, holds the beam and leaves anode effects to the crew. The alumina falls 0.98 %/h between 1 and 3 h. The filtered resistance starts at 8.692 μΩ, reaches its lowest, 8.595 μΩ, at 1.37 h and 3.76 %, and stays between 8.595 and 8.641 μΩ while the alumina falls from 4.1 to 2.7 %, a band the size of the pad's noise. It reads 8.703 μΩ at 3 h and 2.15 %, 8.857 μΩ at 3.25 h and 1.90 %, and 9.167 μΩ just before 3.35 h, when the alumina reaches 1.80 % and the anode effect starts. The voltage jumps to about 30 V,

Table 11.5 Truth Scorecard of Each Case and Variant. AE Counts Anode Effects and Out the Minutes Outside 2–4 % Alumina

Case and configuration	Window (h)	AE	Alumina (%)	Out (min)	Superheat (K)	*SE* (kWh/kg)	Other
1 by hand at 90 kg/h (shipped)	5	3	1.67–5.00	136	6.5–29.3	23.43	98.4 t CO_2-eq
1 base rate from 2.5 h	8	0	2.38–5.00	67	7.1–10.9	13.27	
2 fixed at 100 % (shipped)	48	2	1.80–3.50	476	9.0–14.5	13.49	first at 32.53 h
2 fixed at 103 %	48	0	3.49–3.60	0	9.4–10.0	13.23	
2 fixed at 97 %	48	7	1.80–3.50	830	8.8–14.3	14.12	first at 15.82 h
3 demand feeding (shipped)	48	0	2.14–3.50	0	7.9–10.4	13.24	21 triggers
3 underfeed 50 %	48	0	2.22–3.50	0	7.5–10.6	13.24	25 triggers
3 underfeed 85 %	48	0	2.07–3.50	0	8.4–10.5	13.25	14 triggers, 1 timeout
4 threshold 0.03 μΩ/h (shipped)	24	0	2.59–4.03	31	7.6–10.8	13.23	triggers at 2.60–3.43 %
4 0.40 μΩ/h, 60 min window	24	1	1.80–3.50	304	7.8–13.1	13.51	11.65 t CO_2-eq
4 0.40 μΩ/h, 30 min window	24	0	1.88–3.50	196	7.8–10.5	13.27	
5 stuck feeder, termination on (shipped)	12	1	1.80–3.50	61	7.7–13.0	13.76	4.45 min, 11.65 t CO_2-eq
5 termination off	12	1	1.74–3.50	65	7.7–19.3	14.65	12.45 min, 32.58 t CO_2-eq
5 feeder never freed	12	5	1.80–3.50	117	7.7–13.9	15.75	58.6 t CO_2-eq
6 anode change (shipped)	12	0	2.16–3.50	0	5.1–10.0	13.27	ledge to 17.2 cm
6 with compensation	12	0	2.18–3.50	0	6.3–10.0	13.37	ledge to 15.8 cm
6 hold off	12	0	2.16–3.51	0	4.7–10.0	13.27	false trigger at 2.91 %
7 tap (shipped)	3	0	2.53–3.50	0	8.7–11.9	13.52	R to 10.38 μΩ
7 tap compensation	3	0	2.51–3.50	0	8.5–10.0	13.28	R to 8.64 μΩ
7 move limit 10 mm	3	0	2.52–3.50	0	8.7–10.4	13.42	R to 10.02 μΩ
8 target 7.90 μΩ (shipped)	48	0	2.19–3.89	0	2.2–10.0	12.57	sludge to 129 kg
8 heat loop in AUTO	48	0	2.17–3.89	0	2.9–10.0	12.91	sludge to 70 kg
9 wet lot at 2.0 % (shipped)	12	1	1.80–3.50	101	7.6–14.2	14.12	19.9 t CO_2-eq
9 threshold 0.10 μΩ/h	12	0	2.14–3.50	0	7.9–10.4	13.26	the lot never comes
9 overfeed 300 %	12	0	1.92–3.89	21	7.6–12.7	13.26	sludge to 312 kg

38.2 V at its flickering peak, the superheat goes from 6.7 to 18.2 K, and in the 12.5 min before the crew's kill the cell vents 4.11 kg of CF_4, 32.8 t of CO_2-equivalent. With the feed unchanged, effects follow at 4.00 and 4.64 h, and the five hours cost 98.4 t of CO_2-equivalent at 23.4 kWh/kg. Fed the base rate from 2.5 h, when the resistance has barely begun to rise, the cell has no anode effect and settles near 2.38 %.

> **TRY IT IN THE APP** **1 · Feeding by Hand: Find the Minimum, Cross It**
>
> Load scenario 1 and press Run. Watch the resistance R in the badge row while the hidden alumina falls. Between 4.1 and 2.7 % alumina the reading stays between 8.595 and 8.641 µΩ, a band the size of the pad's noise. Near 3.35 h the alumina reaches 1.80 %, and the voltage jumps to about 30 V.

11.6.2 A Tally That Balances While the Bath Runs Down

Case 2 feeds F_b, one shot every 36 s, without looking at the resistance. The shots are 2.8 % short, so the cell loses about 5 kg of alumina an hour while the controller's tally stays within 1.8 kg of balance until the first anode effect. At 12 h the alumina is 2.86 % and the filtered resistance 8.555 µΩ, at 24 h 2.24 % and 8.567 µΩ, because the bottom of the curve is flat and the beam loop holds the resistance to its target. At 32.53 h the alumina reaches the wall with a true shortfall of 165 kg, and the kill ends the effect in 4.4 min. A second effect follows at 42.19 h, and the alumina spends 476 min outside its band. At 103 % of F_b the drift reverses, to 3.60 % after two days, and at 97 % the first effect comes at 15.82 h and six more follow about every 4.7 h. Open-loop feeding would need the dose and the current efficiency to a fraction of a percent, held for days.

> **DID YOU KNOW?** **Three Percent Either Way**
>
> From the simulator: fixed feeding at 103 % of the Faradaic rate keeps the alumina between 3.49 and 3.60 % for two days with no anode effect, while 97 % brings the first anode effect at 15.82 h and seven in the two days (Table 11.5). A feeder can be counted, but its dose cannot be trusted that closely.

11.6.3 Riding the Low Side

Case 3 is the reference line. The first underfeed, from 3.50 %, runs 2.10 h and ends at 2.24 % on a slope of 0.103 µΩ/h. After it the cycle repeats every 2.29 h on average, 21 triggers in two days, each at 2.14 to 2.45 % alumina and a slope of 0.100 to 0.112 µΩ/h. From the first trigger on, the alumina stays between 2.14 and 3.07 %, the superheat between 7.9 and 10.4 K, and no underfeed times out, at 13.24 kWh/kg with 67 beam moves that total 5.9 mm. By 48 h the controller has counted 132 kg more than its base rate, while the cell received 113 kg less than it consumed, having started at the minimum. The cycle absorbs a constant feed error because it ends each underfeed on the curve and not on the clock, as shown in Figure 11.4. A 50 % underfeed triggers 25 times at 2.24 to 2.69 %, every 1.88 h, and an 85 % one 14 times at 2.07 to 2.29 %, every 3.14 h, with one underfeed timing out.

Pause. Try Exercise 11.2 before reading on.

11.6.4 Threshold, Window and Noise

Case 4 lowers the threshold to 0.03 µΩ/h, less than two standard deviations of the noise above the flat-bottom slope of −0.021 µΩ/h. The ten triggers of the day come at 2.60 to 3.43 % alumina, half of them or more where the noise-free resistance rose more slowly than the threshold, as the application's own check confirms, so the roll ends the underfeeds. Each early end still buys a full overfeed, the alumina ratchets past the minimum to 4.03 %, and 31 min are spent above the band. At 0.40 µΩ/h the 30 min fit ends its underfeeds at 1.88 to 1.92 %, a few hundredths of a percent from the wall. Behind a 60 min window every underfeed of the day ends between 1.805 and 1.810 %. After the second, which ends at 5.108 h, the overfeed's alumina dissolves too slowly, and the anode effect starts at 5.123 h, about a minute after the trigger and the only one in 24 h. At 0.10 µΩ/h the alumina stays between 2.14 and 3.50 %, and a pad instability fired at 3.36 h, just after the second underfeed of that run begins, ends it at 3.68 h and 2.68 % instead of at 4.44 h and 2.21 %.

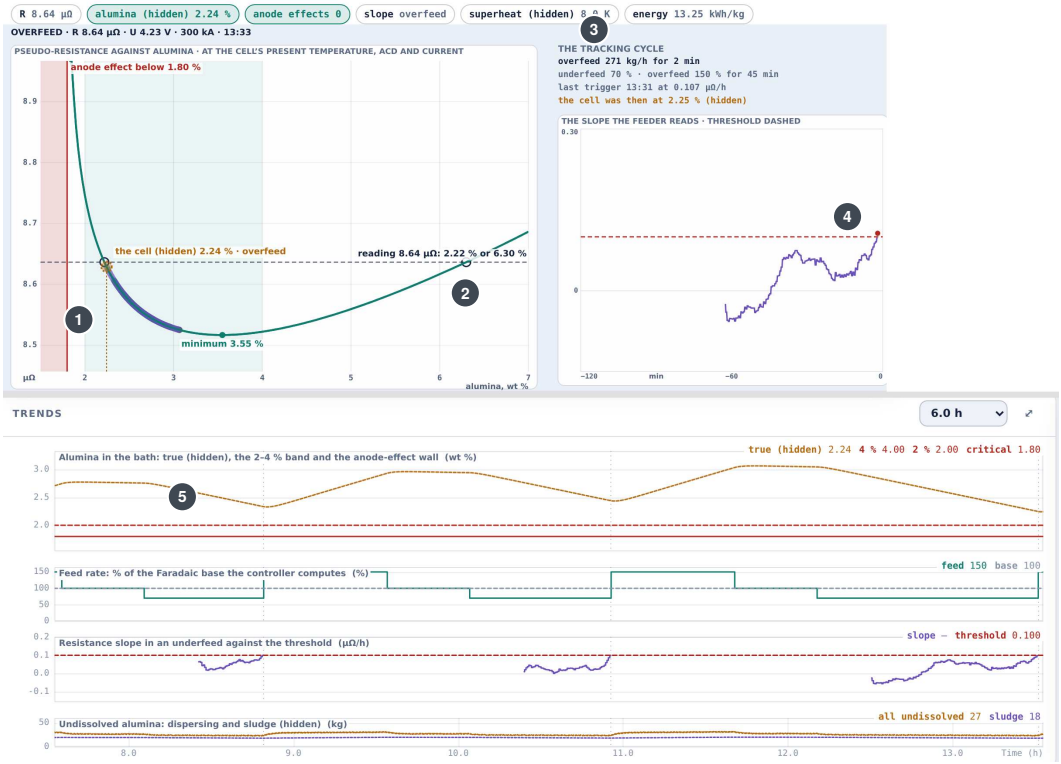


Figure 11.4 The cell in case 3 (Demand feeding rides the slope) at $t = 13.55$ h (13:33) on the Curve view with the 6 h trend window and every control as shipped. The header reads OVERFEED, R 8.64 µΩ, U 4.23 V and 300 kA, and the badges give the hidden alumina at 2.24 %, no anode effect, a hidden superheat of 8.0 K and 13.25 kWh/kg. The curve, drawn at the present 964.3 °C and ACD of 3.91 cm, has its minimum at 3.55 % and its wall at 1.80 %, and the dashed reading of 8.64 µΩ crosses it at 2.22 % and 6.30 %. The tracking panel records the trigger at 13:31 at 0.107 µΩ/h with the cell then at 2.25 %, the sixth of the run, followed by 2 min of overfeed at 271 kg/h, 150 % of 181 kg/h, and the slope panel shows that underfeed's slope climbing to the dashed 0.10 µΩ/h. Over the window the trends show three underfeeds with the alumina between 2.24 and 3.07 %. The callouts mark (1) the hidden alumina where the cell sits on the curve, (2) the reading crossing the curve on both sides of its minimum, (3) the tracking panel, (4) the slope reaching its dashed threshold and (5) the alumina trend above the dashed 2 % line of its band.

11.6.5 A Stuck Feeder and the Kill

Case 5 sticks one of the four feeders from 1 to 5.5 h. It still fires and is still counted, but nothing falls, so the 150 % overfeed delivers 109.8 % of the consumption and the underfeed 50.1 %, and the cycle cannot put back what its underfeeds take. At 4.447 h the alumina reaches 1.80 %. Automatic termination ends the effect in 4.45 min with 1.46 kg of CF_4 and 0.177 kg of C_2F_6, 11.65 t of CO_2-equivalent, while the superheat rises from 8.76 to 12.96 K. Left for the crew, the effect lasts 12.45 min, vents 4.09 kg of CF_4, 32.58 t of CO_2-equivalent, heats the bath to 19.30 K of superheat and raises the 12 h specific energy from 13.76 to 14.65 kWh/kg. Never freed, the feeder brings effects at 4.45, 6.03, 7.60, 9.17 and 10.74 h.

> **TRY IT IN THE APP** **5 · An Anode Effect and Its Termination**
>
> Load scenario 5 and run 12 h. The stuck feeder takes the alumina to 1.80 % at 4.447 h, and automatic termination ends the effect in 4.45 min for 11.65 t of CO_2-equivalent. Turn automatic termination off and run again. The crew's kill comes later, the effect lasts 12.45 min and vents 32.58 t.

11.6.6 Current That Moves Between Anodes

Case 6 changes one anode at 1 h. While it is out the other 23 carry the current, the noise-free resistance steps from 8.619 to 8.868 μΩ and the critical alumina rises from 1.800 to 1.878 %. The new anode draws 52.2 kW an hour after the change, and the cell has 23.38 of its 24 shares at 5 h. The beam loop reads the step as a long ACD and lowers the beam 1.4 mm, taking heat away when the cold anode is drawing it, so the superheat falls from 8.71 to 5.13 K at 5.25 h and the ledge thickens from 12.7 to 17.2 cm. With the compensation the target and the filtered reading step together, the beam setpoint stays within 0.02 mm of where it was until 6 h, and the superheat bottoms at 6.27 K at 5.32 h and the ledge at 15.8 cm. With the hold off, the step reads as a slope, ends an underfeed a minute after the change at 2.91 % alumina and starts an overfeed the cell did not need, and the superheat bottoms at 4.70 K.

Pause. Try Exercise 11.3 before reading on.

11.6.7 A Tap Under a Rate-Limited Beam

Case 7 taps 2300 kg at 1 h, faster than the move limit lets the beam follow. The filtered resistance peaks at 10.38 μΩ at 1.25 h, 1.75 μΩ above target, with the ACD opened to 5.57 cm, and returns to its dead band at 1.78 h, 47 min after the tap began, after 10 moves that total 20.9 mm. The extra voltage heats the bath from 8.7 to 11.9 K of superheat and costs 64 kWh more over the three hours than the same run without a tap. With tap compensation the beam follows the metal, the resistance never exceeds 8.64 μΩ, and the energy stays within 5 kWh of the untapped run. A move limit of 10 mm returns in 32 min for 35 kWh but still peaks at 10.02 μΩ.

11.6.8 A Target That Starves the Bath of Heat

Case 8 sets the target to 7.90 μΩ, 66 kW less heat than the 8.63 μΩ that holds the cell in balance, and the beam loop closes the ACD as told. Its first underfeed ends at the first armed decision, at 0.33 h and 3.32 %, because the beam's 4.9 mm descent is taken out of the slope at the controller's 0.12 μΩ/mm instead of the plant's 0.117 (with 0.117 in a copy of the code it runs to 1.69 h), and the overfeed that follows lifts the alumina to 3.89 % at 1.22 h. The superheat reaches 2.85 K at 3.9 h, where the next underfeed ends, and then swings about 1.6 K either side of a mean of 3.83 K from 6 to 48 h, lowest at the end of each underfeed and 2.22 K at 14.5 h. That mean lies 0.64 K under the 4.47 K of the static balance, as case 3 lies 0.70 K under its own. A cold bath dissolves alumina slowly and sinks more of it, so the undissolved alumina reaches 106 kg at 12 h and 129 kg at its most, against 32 kg in case 3, while the ledge grows from 12.6 to 22.6 cm by 12 h and to 37.4 cm by 48 h. The feed logic reads the dissolved alumina running low as an underfed cell and feeds 109 kg more than case 3 in the two days, most of it into sludge. The energy is cheaper, 12.57 kWh/kg against 13.24, and the ledge and the sludge are the bill. With the heat loop in AUTO the dip of 06:00, reported at 07:00, estimates 1.89 K where the truth was 5.04 K, because the alumina was 3.03 % against the assumed 2.6 and the thermocouple read 0.84 K low. The loop raises the target by its 0.3 μΩ limit to 8.2, and to 8.5 μΩ at the next report, and the superheat bottoms at 2.85 K at 3.9 h, before the first report, recovers to 6.71 K by 12 h and ends at 7.64 K, with 70 kg of sludge at most and 12.91 kWh/kg.

11.6.9 A Wet Lot Below Two Percent

Case 9 raises the threshold to 0.25 μΩ/h, so that underfeeds run deep, and lets a wet lot reach the feeders the moment the alumina falls through 2.0 %, at 2.497 h in the first underfeed. The slope passes the threshold 2.20 min later at 0.257 μΩ/h and the overfeed starts, yet the alumina keeps falling,

Table 11.6 The Two-Day Challenge in Eight Configurations

Configuration	AE	Alumina (%)	Out (min)	Superheat (K)	*SE* (kWh/kg)	
as shipped	5	1.80–3.50	594	3.40–16.21	14.14	fails
demand feeding	0	2.02–3.50	0	2.80–10.01	12.96	fails
+ heat loop	0	1.91–3.50	31.65	4.33–10.72	13.20	fails
+ compensation	0	1.92–3.53	30.1	5.48–11.17	13.23	fails
suggested[a]	0	2.25–3.56	0	5.32–12.50	13.32	passes
no compensation	0	2.26–3.55	0	4.68–12.15	13.29	fails
heat loop manual	0	2.25–3.50	0	3.32–10.12	12.99	fails
fixed feeding	5	1.80–3.50	439	6.61–17.82	14.33	fails

[a] demand feeding at 0.08 μΩ/h with a 60 min overfeed, heat loop in AUTO, anode-change compensation on.

because the lot's shots disperse in 10 min and lose a further 30 % to sludge, so that at 150 % they dissolve about what the cell consumes. The anode effect starts at 2.769 h, 16.4 min after the lot, and vents 19.9 t of CO_2-equivalent. The limit is one of information, not tuning. An oracle that meets the lot at 2.0 % with an immediate 45 min overfeed, on a cell that had been underfeeding at 126 kg/h, still reaches the wall 75.2 min after the lot at 150 %, half an hour after its overfeed ends, and 218 min after it at 200 %. Only 300 % holds the cell, which bottoms at 1.966 %. In case 9 itself a 300 % overfeed bottoms at 1.92 % with 312 kg of sludge, while on dry alumina at the default 0.10 μΩ/h the same overfeed carries the cycle up to 6.60 % in two days. The defense is margin, as it is for the inferred limit of Volume 15, Chapter 8. At thresholds of 0.15 and 0.10 μΩ/h the underfeeds end above 2 %, at 2.06 and 2.14 % at the lowest, and the lot never meets a cell that low.

11.6.10 Two Days at 300 kA

The challenge runs 48 h through an anode change at 8 h, a tap at 20 h and a wet lot from 30 h, and asks for no anode effect, alumina between 2 and 4 % for all but 30 min, superheat between 5 and 15 K and at most 13.5 kWh/kg, scored on the truth. The challenge is judged on the case as given, so that a changed model parameter or disturbance voids the attempt. As shipped the cell is fed F_b with a target of 8.30 μΩ left from an energy drive. Table 11.6 compares the configurations. As shipped the superheat fails first, below 5 K at 8.99 h, an hour after the anode change, and 3.40 K at its lowest. The drifting alumina leaves the band at 27.07 h, the first anode effect starts at 30.08 h, five minutes after the wet lot, four more follow, and the two days end at 14.14 kWh/kg and 107 t of CO_2-equivalent.

Each element repairs one line of the target. Demand feeding alone removes the anode effects and lets the low target cool the bath to 2.80 K. Adding the heat loop lifts the target at the first dip, but the anode change still takes the superheat to 4.33 K and the default cycle dips to 1.91 % on the wet lot. Adding the anode-change compensation keeps the superheat above 5 K, at 5.48 K at its lowest, but leaves the alumina 30.07 min outside the band, four seconds more than allowed, a margin within the noise, since it passes on three of five other seeds and the suggested configuration on all six. The suggested configuration rides higher and keeps the alumina between 2.25 and 3.56 % with no minute out of the band and the superheat between 5.32 and 12.50 K, at 13.32 kWh/kg, margins of 0.32 K on the superheat and 0.18 kWh/kg on the energy. Without its compensation it bottoms at 4.68 K, with the heat loop in MANUAL at 3.32 K, and on fixed feeding it has five anode effects. Its success also leans on an inference error. Both dips read the superheat low, 3.30 against 8.07 K and 5.75 against 10.31 K, because the cell held 3.31 and 3.23 % alumina against the assumed 2.6, so the loop keeps raising the target, to 8.86 μΩ by the end.

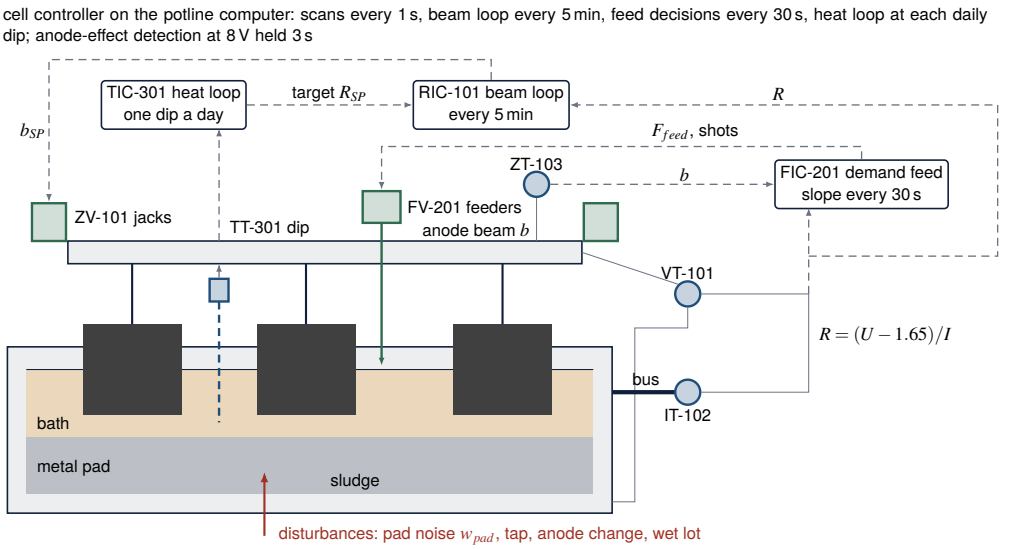


Figure 11.5 The cell's three loops drawn with their hardware. The cell voltage VT-101 and the line current IT-102 give the pseudo-resistance, and the beam encoder ZT-103 lets the controller remove its own beam moves from the slope. The beam loop RIC-101 moves the anode beam on its jacks ZV-101, the demand feed loop FIC-201 fires the point feeders FV-201, and the heat loop TIC-301 turns a daily dip TT-301 into the beam loop's target. Notice that no sensor reaches the alumina in the bath: every loop reads it through the voltage.

11.7 Technology in Practice

The controller of Section 11.5 reads two electrical signals, the beam position and a daily dip, and it moves the beam and the feeders. Figure 11.5 draws its loops with that hardware in place of the schematic's symbols.

What Measures It

The chapter's controller never reads the dissolved alumina. Its pseudo-resistance is computed from the cell voltage VT-101 and the line current IT-102, and the beam encoder ZT-103 lets the slope estimator take the beam's own moves out of the reading. The heat balance is seen once a day, through the dip TT-301 of the bath temperature and the excess aluminum fluoride.

> **TECHNOLOGY** **Sensor: Cell Voltage and Line Current**
>
> Cell control rests on two electrical readings. The voltage of each cell is read directly, and one potline system gathered the voltages of hundreds of pots over a shared cable to a central control computer [19]. A cell normally runs at 4.0 to 4.5 V, and an anode effect raises it to perhaps 30 to 40 V [1]. The line current is the same for every cell in series and is kept constant [1]. It can be read without contact from the magnetic field around the conductor, which Hall-effect sensors resolve even for direct current. A shared cable is a weak point, because a cut loses every reading it carries at once [19]. The chapter's VT and IT are read every second, with the pad's noise on the voltage.

What Moves It

The second handle is the anode beam. The anodes burn away, so the beam has to be lowered step by step to keep the anode–cathode distance, while regular tapping holds the metal surface at about the same height. When the beam reaches its lower stop, a beam-raising machine carried by the overhead

crane lifts it again [1]. The chapter's beam ZV-101 travels 400 mm on jacks that run at 10 mm/min, with a move limit of 3 mm in each interval, and the feeders FV-201 turn a requested rate into shots.

> **TECHNOLOGY** **Final Element: The Point Feeder**
>
> A point feeder keeps a hole open in the crust and drops a measured dose of alumina into the bath. The alumina comes from a bin in the cell's superstructure, and two to six volumetric feeders in turn add about 1 kg every minute or so, doses small enough to dissolve and disperse fast. The holes lie along the center line between the two rows of anodes, and the aluminum fluoride goes in through them too. Too much alumina forms sludge, which settles under the metal and raises the cell's resistance [1]. The chapter's four feeders drop 1.75 kg and count 1.80 kg a shot, and case 5 shows a feeder that fires and is counted while nothing falls.

Where the Controller Runs

The potline current is held constant, and each cell has its own voltage adjustment for its heat balance and its condition [1]. Cell voltages are gathered to a central control computer [19]. Control systems of this kind run a supervisory layer over localized controllers, with cycle times from milliseconds to minutes [20]. The chapter's cell controller scans every second. Its beam loop RIC-101 acts every 5 min through the shared velocity-form PID, the feed loop FIC-201 decides every 30 s, and the heat loop TIC-301 moves the target of RIC-101 once a day, a cascade whose outer loop is the slowest of the three.

> **IN PRACTICE** **Anode Effects Are Counted and Reported**
>
> Across the industry a high-voltage anode effect is typically a cell voltage above 8 V for 3 s, the rule of the chapter's detector. Many point-fed smelters end it automatically by moving the anodes and feeding alumina, mostly with no manual step [21]. In the United States a smelter reports its anode-effect frequency, duration and minutes per cell-day, computed monthly, and the method that measures them. Its slope coefficients must be measured again at least every ten years, or sooner when a change in the control algorithm alters the mix of anode effects or the termination routine [22].

What Is Modernizing It

Three developments touch the loops of this chapter. The first is power modulation. Smelters have tried running at a varying power since the 1970s, and poor control of the heat balance then froze cryolite in the bottom of cells. Recent work optimizes the line current and the anode–cathode distance together under limits on the heat balance, so that a potline can follow a power price or a renewable supply, and offers this as a foundation for online control policies [23]. Case 8 shows what an unwatched heat balance costs. The second is online gas measurement. Instruments at the smelter can measure perfluorocarbons continuously and separate the emissions of high-voltage and low-voltage anode effects, though neither continuous nor sampled measurement is routine in the industry yet [21]. The third is the inert anode, first suggested in 1886. It would give off oxygen instead of carbon dioxide, and an anode that lasted the life of the cell would end the anode change of case 6, but every material dissolves to some extent in the corrosive cryolite [1].

11.8 Limitations

One well-mixed bath stands for a cell whose alumina differs between feeders and far corners, so an anode effect cannot start on one anode while the mean is above the wall, as real ones do [16]. The curve, every threshold, the bands of 2 to 4 % and 5 to 15 K, the emission coefficients and the challenge's energy ceiling are teaching values, and their real counterparts come from each plant's cell control and measurement campaigns [9, 15], as Section 11.3.8 records. Each disturbance arrives as a step, which a potroom would rarely allow, but a step keeps one cause apart from the others. The current efficiency is constant, so a hot, squeezed or unstable cell loses energy here but not metal. The

crew's bath level removes the ledge's effect on the bath's composition, the pad's noise cannot grow by itself, and the bath, metal and walls are lumped. The controller's assumptions differ from the plant only by declared amounts, and a dip a day is its only reading of the heat.

OPEN CHALLENGE Anode Effects the Voltage Does Not Show

Perfluorocarbons can also form without the cell voltage rising. Such low-voltage anode effects have been found since the late 2000s in high-amperage cells with many large anodes, and they come from the same upset on a smaller, local scale. Higher current density, a smaller anode–cathode distance, larger anodes with less bath to dissolve alumina, more anodes for each feeder and longer cells all make them more likely [21], and larger cells with fewer feeders for their current have bath that differs more from place to place [23]. Progress would be a controller that finds a local shortage of alumina before the gas forms, which one voltage across the whole cell cannot.

11.9 Conclusion

Feeding a Hall–Héroult cell means reading a measurement that cannot say on which side of its minimum the alumina lies, and the cases put a price on that blindness and on each remedy. On the cell's curve 8.68 µΩ means 2.5 % or 5.14 %, and the filtered reading moves only 0.046 µΩ while the alumina falls from 4.1 to 2.7 %. Feeding the Faradaic rate with shots 2.8 % short reaches the anode effect at 32.5 h with the controller's tally within 1.8 kg of balance, while demand feeding at 0.10 µΩ/h holds 2.14 to 3.07 % for two days without measuring alumina. A half-window rule places the end of each underfeed within 0.03 % of the engine at the default window and bounds the threshold between the noise, which ends underfeeds early at 0.03 µΩ/h, and the wall, which a 60 min window meets at 0.40. A stuck feeder's anode effect costs 11.65 t of CO_2-equivalent when it is killed at once and 32.58 t when the crew arrives after 8 min, and a target 0.73 µΩ too low runs at 12.57 kWh/kg while the ledge grows to 37.4 cm. Everything rests on one lumped cell and on teaching values. A fuller model would add alumina gradients and local anode effects, a current efficiency that varies, ledge-driven changes of the bath's composition and the neighboring cells of a potline. The cell is a place to learn control through a measurement with an extremum.

KEY POINTS

- The controller reads a resistance that is lowest in the middle, so one reading cannot say whether the alumina is too low or too high.
- Feeding the Faradaic rate with shots 2.8 % short reaches the anode effect at 32.5 h while the controller's tally stays within 1.8 kg of balance.
- Demand feeding at 0.10 µΩ/h holds 2.14 to 3.07 % for two days without measuring alumina, because it ends each underfeed on the curve and not on the clock.
- A stuck feeder's anode effect costs 11.65 t of CO_2-equivalent when it is killed at once and 32.58 t when the crew arrives after 8 min.

Where else this applies. Regulation near the peak of a plant characteristic also governs the braking tire of Volume 7, Chapter 4, and a sensor that rises on both sides of the right dose the urea loop of Volume 5, Chapter 12.

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11.10 Exercises

11.1 Concept check · 2 min

On the curve of Figure 11.2(a), drawn at the design point, the control room reads a pseudo-resistance of 8.68 μΩ. What does that reading alone say about the alumina?

(a) It is near 3.5 %, because the curve is flattest at its minimum
(b) It is near 2.5 or near 5.1 %, and the reading cannot say which
(c) It is near 2.5 %, because only the low side can raise the reading
(d) Nothing at all, because the metal pad's noise hides every reading of R

11.2 Concept check · 1 min

Scenario 2 feeds the Faradaic rate with feeders 2.8 % short and reaches the anode effect at 32.5 h. Scenario 3, Demand feeding rides the slope, has the same feeders and no anode effect in two days. Why does demand feeding not drift?

(a) It reads the alumina in the daily dip and trims the feed rate to it
(b) Its underfeeds and overfeeds average exactly to the Faradaic rate
(c) It ends each underfeed on the slope of the curve, not on the clock
(d) It corrects its count of shots to the true dose of 1.75 kg

11.3 Concept check · 2 min

In scenario 6, The anode change, one of 24 anodes is out of the cell at 1 h. The noise-free resistance steps from 8.619 to 8.868 μΩ while the ACD and the alumina have not moved. With anode-change compensation off, what does the beam loop do?

(a) Holds the beam, because the step lies inside its dead band of 0.08 μΩ
(b) Raises the beam, reading the step as a short ACD, and so heats the bath
(c) Waits out the hold after the event, so the beam stays where it was
(d) Lowers the beam, reading the step as a long ACD, and so cools the bath

11.4 Theory and calculation · 5 min

The cell runs at $I = 300\,\mathrm{kA}$ with a current efficiency of 95 %. Use $F = 96\,485.33\,\mathrm{C/mol}$ and $M_{Al_2O_3} = 0.101\,961\,\mathrm{kg/mol}$ in Equation (11.1).

(a) Find the alumina consumption in kg/h and the time between shots of the counted 1.80 kg. *Checkpoint:* 180.70 kg/h and about 36 s.

(b) Each shot really delivers 1.75 kg. On fixed feeding at 100 %, how much alumina does the cell lose per hour? *Checkpoint:* About 5.0 kg/h.

(c) The bath starts with 315 kg of dissolved alumina in 9000 kg in all, 3.50 %, and the other 8685 kg stay constant. Find the dissolved alumina at the wall of 1.80 % and estimate when the cell reaches it. *Checkpoint:* About 159 kg, a loss of 156 kg, in about 31 h.

11.5 Theory and calculation · 8 min

At the design point, $T = 959.8\,^{\circ}\mathrm{C}$, $\alpha = 1$, $m = 0.492$, $c_{crit} = 1.80\,\%$, the bath's ohmic drop is 1.550 V and $I = 300\,\mathrm{kA}$. Use $R_g = 8.314\,462\,\mathrm{J/(mol\,K)}$ and $F = 96\,485.33\,\mathrm{C/mol}$ in Equation (11.10).

(a) Evaluate the reaction, concentration and ohmic terms at 3.5 % alumina, in mV per percent. *Checkpoint:* -14.9, -16.1 and $+31.0$, a sum near zero.

(b) Repeat the two anode terms at 2.5 %, take the ohmic term there as 30.4 mV per percent, and convert the sum to μΩ per percent. *Checkpoint:* -20.9 and -54.6; about -0.150 μΩ per percent.

(c) A 70 % underfeed lowers the alumina 0.615 % per hour, and the closing ACD lowers R by 0.021 µΩ/h. What slope does the controller see at 2.5 %, and how much alumina does a 30 min least-squares window lag behind? *Checkpoint:* About 0.072 µΩ/h, below the threshold of 0.10; a lag of about 0.15 %.

11.6 Theory and calculation · 5 min

At 300 kA the beam loop holds a target resistance. The ledge area is 16 m^2 with a bath-to-ledge coefficient of 700 W/(m^2 K), the top and bottom lose 575 W/K, and bath and metal hold $C = 55\,\mathrm{MJ/K}$.

(a) How much heat does each 0.1 µΩ of target add? *Checkpoint:* 9.0 kW.

(b) With the liquidus fixed, by how much does the steady superheat rise per 0.1 µΩ? Starting from 10.01 K at 8.625 µΩ, estimate the steady superheat at a target of 7.90 µΩ. *Checkpoint:* 0.76 K, and about 4.47 K.

(c) Find the time constant of the bath alone. *Checkpoint:* 1.30 h.

11.7 App challenge · 8 min

Load scenario 2, Fixed feeding at the Faradaic rate, at the default seed and a speed of 4 h per second. For each run below, let the clock pass 48 h, pause, export the CSV file and read the row at `Time (h)` = 48 and the rows named.

(a) Run as shipped. Find the first row where `ae_count` is 1, and in the row at 32.5 h read `feed_balance_kg` and the difference `fed_true_kg` minus `consumed_kg`. Give times within 0.02 h and masses within 2 kg. *Checkpoint:* 32.53 h; about −1 kg counted against −164 kg real.

(b) Press Reset, set the Fixed feed rate to 97 % before Run, and find the first anode effect and the count at 48 h. *Checkpoint:* 15.82 h; 7 anode effects.

(c) Press Reset, set 103 %, and read `ae_count` and `c_true_pct` at 48 h, the latter within 0.01 %. *Checkpoint:* 0 anode effects; 3.60 %.

11.8 App challenge · 9 min

Load scenario 4, The slope threshold against the noise, at the default seed and a speed of 4 h per second. For each run below, let the clock pass 24 h, pause, export the CSV file and read the row at `Time (h)` = 24.

(a) Run as shipped, with the Slope threshold (low side) at 0.03 µΩ/h. Read `metric_c_min_pct`, `metric_c_max_pct`, `metric_c_out_min` and `triggers`, the alumina within 0.01 %. *Checkpoint:* 2.59 to 4.03 %, 31 min out of the band; 10 triggers.

(b) Press Reset, set the Slope threshold to 0.40 µΩ/h, switch to Advanced and set the Slope filter window to 60 min before Run. Read `ae_count`, `co2e_t`, `metric_c_min_pct` and `SE_kWhkg`, the energy within 0.01 kWh/kg. *Checkpoint:* 1 anode effect, 11.65 t CO_2-eq; 1.80 %; 13.51 kWh/kg.

(c) The slope fitted over 30 min at the flat bottom has a standard deviation of 0.027 µΩ/h, and the closing ACD lowers every slope by 0.021 µΩ/h. How many standard deviations above the flat-bottom slope does a threshold of 0.03 sit? *Checkpoint:* About 1.9.

Explain each run with the two edges of a usable threshold.

11.9 App challenge · 9 min

Load scenario 8, The heat balance: a target set too low, at the default seed and a speed of 4 h per second, with the Target resistance at its shipped 7.90 µΩ.

(a) Run with the Heat loop in Manual until the clock passes 48 h, pause and export the CSV file. In the row at `Time (h)` = 48 read `metric_SH_min_K`, `metric_SH_max_K`, `SE_kWhkg`, `metric_sludge_max_kg` and `ledge_cm`, the ledge within 0.1 cm. *Checkpoint:* 2.2 to 10.0 K; 12.57 kWh/kg; 129 kg at most; 37.4 cm.

(b) Press Reset, set the Heat loop to Auto on the TIC-301 card, and run past 7 h. Read the dip on the TIC-301 card and the target it wrote, and read `SH_true_K` in the row at 6.0 h. *Checkpoint:* Superheat 1.9 K from the dip of 06:00, target 8.20 µΩ; true superheat 5.0 K.

(c) Run on past 48 h, export the file again and read the first four columns of (a) in the row at 48 h. *Checkpoint:* 2.9 to 10.0 K; 12.91 kWh/kg; 70 kg at most.

Explain why the superheat still bottoms below 3 K with the loop in Auto.

11.10 Application area · 4 min

An anode effect vents CF_4 at a slope coefficient of 0.143 kilograms per metric ton of aluminum for each anode-effect minute per cell-day, and C_2F_6 at 0.121 of the CF_4 by mass. The cell makes 2.295 t of aluminum a day, and the GWP-100 values are 6630 for CF_4 and 11 100 for C_2F_6.

(a) Find the CF_4, the C_2F_6 and the CO_2-equivalent of one anode-effect minute. *Checkpoint:* 0.328 kg, 0.040 kg and 2.62 t.

(b) In scenario 5 the automatic kill ends the effect in 4.45 min and the crew, arriving late, in 12.45 min. What does the wait for the crew cost in CO_2-equivalent? *Checkpoint:* About 21 t.

Name one cost of the late kill besides the emissions.

11.11 Application area · 3 min

The model has one well-mixed bath and a constant current efficiency.

(a) Real anode effects start on one anode where the alumina is low. Where in a cell would that be, and what does it mean for the band a plant keeps above the wall? *Checkpoint:* Far from the feeders; a margin above the mean wall.

(b) Scenario 8 runs at 12.57 kWh/kg against 13.24 for the reference line of scenario 3. Why might a real cell not show that saving? *Checkpoint:* A squeezed, cold cell would also lose metal.

11.12 Review the agent · 5 min

A learner runs the challenge with the suggested settings: Demand feeding, Slope threshold 0.08 µΩ/h, Overfeed duration 60 min, Heat loop Auto and Anode-change compensation On. It passes. An AI assistant writes: *The heat loop is what saves the bath. Its dips report a superheat of 3.3 K on day 1 and 5.7 K on day 2, so the bath really was cold, and the loop rightly raised the target to 8.86 µΩ. A more accurate liquidus estimate would only make the run pass with more margin.* Find the flaw, and say how to check it in the app.