INTERACTIVE CONTROL ENGINEERING
Principles and Applications

Volume 6 Multivariable and Plantwide Control

CHAPTER 10

Sealed Orbiting Cabin Simulator Where Added Oxygen Shuts the Nitrogen Valve

Pages 229–252

Edited by John D. Hedengren

How to cite this chapter. "Sealed Orbiting Cabin Simulator Where Added Oxygen Shuts the Nitrogen Valve," in *Multivariable and Plantwide Control*, John D. Hedengren, Ed., vol. 6 of *Interactive Control Engineering: Principles and Applications*. Advanced Process Solutions, LLC, 2026, ch. 10, pp. 229–252.

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

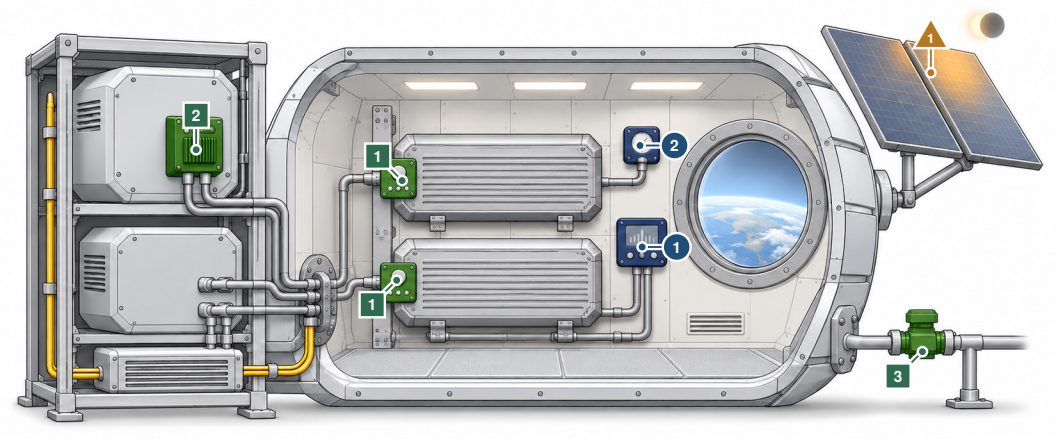
The app for this chapter
https://apmonitor.com/apps/space-station-eclss/

The volume online: contents, other chapters and citation records
https://apmonitor.com/apps/books/v06-multivariable-plantwide/#space-station-eclss

Copyright © 2026 Advanced Process Solutions, LLC. All rights reserved. Produced by Advanced Process Solutions, LLC.

CHAPTER 10

Sealed Orbiting Cabin Simulator Where Added Oxygen Shuts the Nitrogen Valve



The controller moves 1 bed swaps and heater of the two carbon dioxide beds
2 electrolysis power, which makes the oxygen 3 nitrogen makeup valve

The controller reads 1 gas analyzer: oxygen, carbon dioxide, vapor and nitrogen 2 total pressure

What disturbs it 1 sunlight and eclipse on the array that charges the battery

Notice that the oxygen maker, the beds and the makeup valve all act on one sealed volume of air and draw on one array and battery, so each loop meets the others in the cabin's total pressure or on the power bus. Illustration, not to scale.

IN PLAIN TERMS A Sealed Room That Can Only Add Air

The main idea. Six people in a closed room in orbit breathe in oxygen and breathe out carbon dioxide and water. Machines add oxygen and nitrogen, and two beds take turns pulling out the carbon dioxide.

The challenge. Both gases push on one shared pressure, so the two controllers that add them answer each other. The beds and the oxygen maker also share one battery, which runs low each time the station passes into Earth's shadow.

Why it matters. A week aboard stays safe only when the controllers, the bed timing and a running count of the nitrogen, which finds a slow leak, work as one plan.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	the first page, the history in Section 10.2, the fact in Section 10.3, the two try-its and the fact in Sections 10.4 and 10.6, and the key points at the end of Section 10.9
Study	45 min	the whole chapter with its three pause points and the twelve exercises at its end
Practice	15 min	the first page, the results (Section 10.6), Technology in Practice (Section 10.7), Limitations (Section 10.8) and the two open challenges

The control question A sealed cabin can only add gas, so its oxygen and pressure loops answer each other through one total, and its carbon dioxide beds share a battery with the oxygen generator through every eclipse. How must the loops, the bed schedule and a nitrogen balance work together so that a week aboard holds every limit and a leak is found before the tank runs low?

Learning objectives

- Estimate the hours to each atmospheric limit with the machines stopped from the crew's rates and the cabin's moles per kilopascal.
- Explain why a higher oxygen setpoint shuts the nitrogen valve, and classify the coupling by its gain matrix and relative gain.
- Compute the eclipse energy budget, and say which load a power-aware schedule must move out of the dark.
- Describe how an hourly nitrogen balance with a cumulative-sum test finds a leak that the pressure loop feeds and hides.
- Judge which layers a week aboard needs by running it with each one removed.

Prerequisites Sections 1.4.3, 1.4.5 and 1.4.7 (inventories, triangular plants, conditioning), 1.6.2 and 1.6.4. Chapter 8 treats an inert that leaves by one exit.

The app https://apmonitor.com/apps/space-station-eclss/

See also Volume 8, Chapter 12 for on-off loads on one shared supply scheduled by a hybrid predictive controller, and Volume 8, Chapter 14 for an integer actuator under a PI loop. Volume 9, Chapter 11 for an integer pump schedule by branch and bound and a night-flow leakage estimate, and Volume 9, Chapter 9 for cooling shifted in time by the price of energy.

10.1 Introduction

Six people in a sealed room of 400 m^3 at 22 °C give off 29.4 mol of water vapor and 5.4 mol of carbon dioxide an hour and take 6.0 mol of oxygen. With every machine of the simulated module switched off, the relative humidity passes 60 % at 1.46 h, the carbon dioxide partial pressure passes 0.53 kPa at 4.84 h and the oxygen partial pressure falls below 19.5 kPa only at 39.19 h. The total pressure meanwhile drifts from 101.30 to 102.13 kPa over two days, because the crew trades oxygen for carbon dioxide and water almost mole for mole. A cabin's priorities follow from that order, and so do its control problems. As for the spent-fuel pool of Volume 1, Chapter 9, the operative quantity with the machines stopped is a time to a limit rather than an error.

The environmental control and life support systems of crewed spacecraft have been documented for designers in a reference publication of the 1990s [1], a textbook of their subsystems [2], a baseline of design loads and assumptions [3] and a standard for the habitable atmosphere [4]. Carbon dioxide is removed in flight by alternating molecular sieve beds that are tested as whole assemblies [5] and modeled in detail as packed sorption columns [6], oxygen is recovered from that carbon dioxide by a Sabatier reactor fed with electrolysis hydrogen [7], and the crew's health sets how much carbon dioxide is tolerated [8]. The control problem belongs to a broader class. Any closed inventory whose actuators can only add material (an inerted vessel, a glove box, a submarine's atmosphere), any cyclic adsorber such as a pressure swing unit [9], and any plant whose discrete operations are scheduled against a periodic energy supply share its shape, and the integration of scheduling with process control has been reviewed as a field of its own [10]. The discrete half of such a problem is a mixed-integer program, for which branch and bound was written [11], and the diagnostic half is the reconciliation of flows and inventories against a mass balance [12] with a sequential test for a change in its mean [13].

One belief the simulator sets out to correct is that a pressure loop protects the inventory it controls. In this model a nitrogen valve that holds the total pressure inside its band is also the actuator that feeds a new leak without anyone noticing. In case 7 the valve opens from 6.0 to 37.0 % after the leak steps up at 24 h while the pressure stays between 101.00 and 101.40 kPa, well inside its 97 kPa to 103 kPa band. The same sum of partial pressures couples the two gas loops. Raising the oxygen

setpoint by 1 kPa shuts the nitrogen valve two and a half hours later, which a reader who has met each loop alone may not expect.

The material a student meets treats these pieces apart. Design references tabulate loads, limits and assembly performance [1, 3, 5], bed studies resolve one column's breakthrough [6], and scheduling studies fix the plant they schedule [10]. This chapter works with a browser simulator of a sealed orbiting cabin in which the gas inventories, the alternating beds, the oxygen and Sabatier chain, the battery and the leak share one run, and it measures on the running engine what fixed, adaptive and power-aware bed schedules, a crew-activity feedforward and a nitrogen balance achieve on the same week. The ideal-gas balances, the bed law, the cumulative-sum test, the proportional-integral loops and branch and bound over a linear relaxation are established methods. Behind the measurements are a forty-state model whose element balances close to the integrator's precision, a three-orbit power-aware program on the branch and bound that the apps share, which reports its proof or its gap to the reader, and a wall between the instruments and the hidden state that no controller, predictor or balance crosses. Ten cases, each graded by a completion rule (Section 1.6.4), range from a cabin with nothing running to eight crew on a faulted bed that no schedule can hold, and a graded week aboard follows them.

Section 10.2 follows the domain from expendable canisters to regenerable beds. Section 10.3 sets out the cabin, its beds, its humidity and power and its instruments, and Section 10.4 measures the three behaviors that shape its control: one total pressure for two gas loops, the saw-tooth of the beds and an eclipse budget that does not close. Section 10.5 describes the three loops, the fixed, adaptive and power-aware bed schedules and the nitrogen balance. Section 10.6 measures the cases and the week, with the program's proofs, the code verification and the agreement with published values, Section 10.7 describes the real analyzer, removal assembly and controllers, Section 10.8 states the limitations and Section 10.9 concludes. The Exercises at the end of the chapter run the cases and the week.

10.2 From Expendable Canisters to Regenerable Beds

The domain's early story, from pure oxygen to the first cabin with two gases, is told in the box below. A later long-duration station replaced superoxide oxygen cartridges with water electrolysis and its expendable canisters with a four-bed molecular sieve vented to space [1]. The same reference states the principle the simulator is built on, that the oxygen or nitrogen added is decided by monitoring the total pressure and the oxygen partial pressure, and that a tighter habitat loses leakage and venting as ways to remove an excess constituent [1].

> ⧖ HISTORY **1967 to 1974: From Pure Oxygen to a Two-Gas Cabin**
>
> The early crewed spacecraft of the United States breathed pure oxygen at 34.5 kPa. After a fire during a practice session on the launch pad in 1967, prelaunch testing used a mixture of 40 percent nitrogen and 60 percent oxygen, because nitrogen inhibits the flammability of oxygen. Carbon dioxide was absorbed by lithium hydroxide, which reacts irreversibly, so for missions longer than about two weeks the stored canisters became prohibitive. A ground test that began in 1972 kept a crew of three for 56 days in a sealed chamber, with two-gas control of oxygen and nitrogen among its subsystems. The three-person station it prepared flew three missions of 28, 59 and 84 days in 1973 and 1974, with a mixed oxygen and nitrogen atmosphere and a two-canister molecular sieve, regenerated by exposure to space vacuum, in place of lithium hydroxide [1].

The removal assembly of the current station era has four beds, two desiccant and two sorbent, which swap each half-cycle while the regenerating sorbent bed is heated under vacuum. Ground testing in 1999 reported flows averaged over a full cycle of 288 min, a half-cycle of 144 min, and contrasted the water-saving desiccant beds with the earlier two-bed design that vented its water to space [5]. Reduction of the removed carbon dioxide followed. A Sabatier assembly that combines carbon dioxide with electrolysis hydrogen into methane and water, under development for more than

Table 10.1 Classification of the Cabin's Variables and Their Starting Values

Variable	Role	Start	Limit or range
p_{CO_2}	CV, analyzer	0.37 kPa	$\leq$ 0.53 kPa (teaching)
p_{O_2}	CV, analyzer	SP 21.0 kPa	19.5–23.1 kPa
$x_{O_2} = p_{O_2}/P$	constraint	20.73 %	$\leq$ 23.5 %
$P = \sum p_i$	CV, transducer	SP 101.3 kPa	97–103 kPa
RH	CV, from analyzer	SP 50 %	40–60 %
E/E_{bat}	constraint, meter	90 %	floor 60 %
P_e	MV, electrolysis	1.2 kW manual	0–2 kW
u_{N_2}	MV, makeup valve	6 % manual	0–100 %
u_c	MV, condenser flow	70 % manual	0–100 %
swap, x_k	discrete MV, beds	bed A adsorbs	half-cycle 75–180 min[a]
n_c, a	DV, crew, activity	6, 1	2–10, 1 or 2.5
ΔC_{leak}, f	DV, leak step, bed fault	0, 1	0.05, 0.5
Q_A, Q_B	states, hidden	3.70, 0.30 mol	—
T_A, T_B	states, thermocouples	22 °C	to 227 °C
n_{N_2}, n_{O_2}	states, cabin	12 813, 3423 mol	—
L	leak, hidden	0.93 mol/h N_2	—

[a] Adaptive and power-aware schedules. The fixed half-cycle is 144 min as shipped.

twenty years, joined an oxygen generator launched in 2006, and its installation and activation were reported in 2011 [7]. Design studies take their loads from a baseline document that gives 0.84 kg of oxygen consumed and 1.01 kg of carbon dioxide and 2.27 kg of water vapor produced per crew member and day [3].

The tolerance for carbon dioxide has tightened as the record grew. An analysis of in-flight headache reports found that the odds of a headache doubled for each 1 mmHg of carbon dioxide and that a seven-day average below 2.5 mmHg would keep the risk under one percent, against an observed range of 1 to 9 mmHg [8]. The current standard limits the one-hour average partial pressure to 3 mmHg (0.40 kPa) [4]. Bed models in the literature are axially dispersed, nonisothermal, linear-driving-force descriptions of molecular sieve 5A columns, and their comparison with data called for two dimensions to capture wall effects [6].

10.3 The Cabin as Modeled

The simulated module is a generic teaching design that names no flight assembly, as shown in Figure 10.1. A well-mixed cabin of free volume $V = 400\,\mathrm{m}^3$ at a fixed $T = 22\,^\circ\mathrm{C}$ holds nitrogen, oxygen, carbon dioxide and water vapor. Six crew live in it, two visitors may come aboard and two crew may leave through a $12\,\mathrm{m}^3$ airlock for an excursion. A rack holds two carbon dioxide beds on outlet valves to a vacuum line, a Sabatier reactor on that line, an electrolysis unit, a condenser, a nitrogen tank on a makeup valve, an oxygen tank on a backup valve and a water tank. The orbit lasts $T_{orb} = 92\,\mathrm{min}$, of which $T_{ecl} = 35\,\mathrm{min}$ are in Earth's shadow, and every case starts at sunrise. Time is in hours, amounts in moles, pressures in kilopascals, power in kilowatts and energy in kilowatt-hours.

The variables are classified in Table 10.1. Forty states are integrated. Fourteen are physical, the cabin's four inventories n_i, the loadings Q_A, Q_B and temperatures T_A, T_B of the two beds, the battery energy E and the nitrogen, oxygen and water tanks. The other twenty-six are ledgers that integrate every source and sink, so that each species can be balanced at every step.

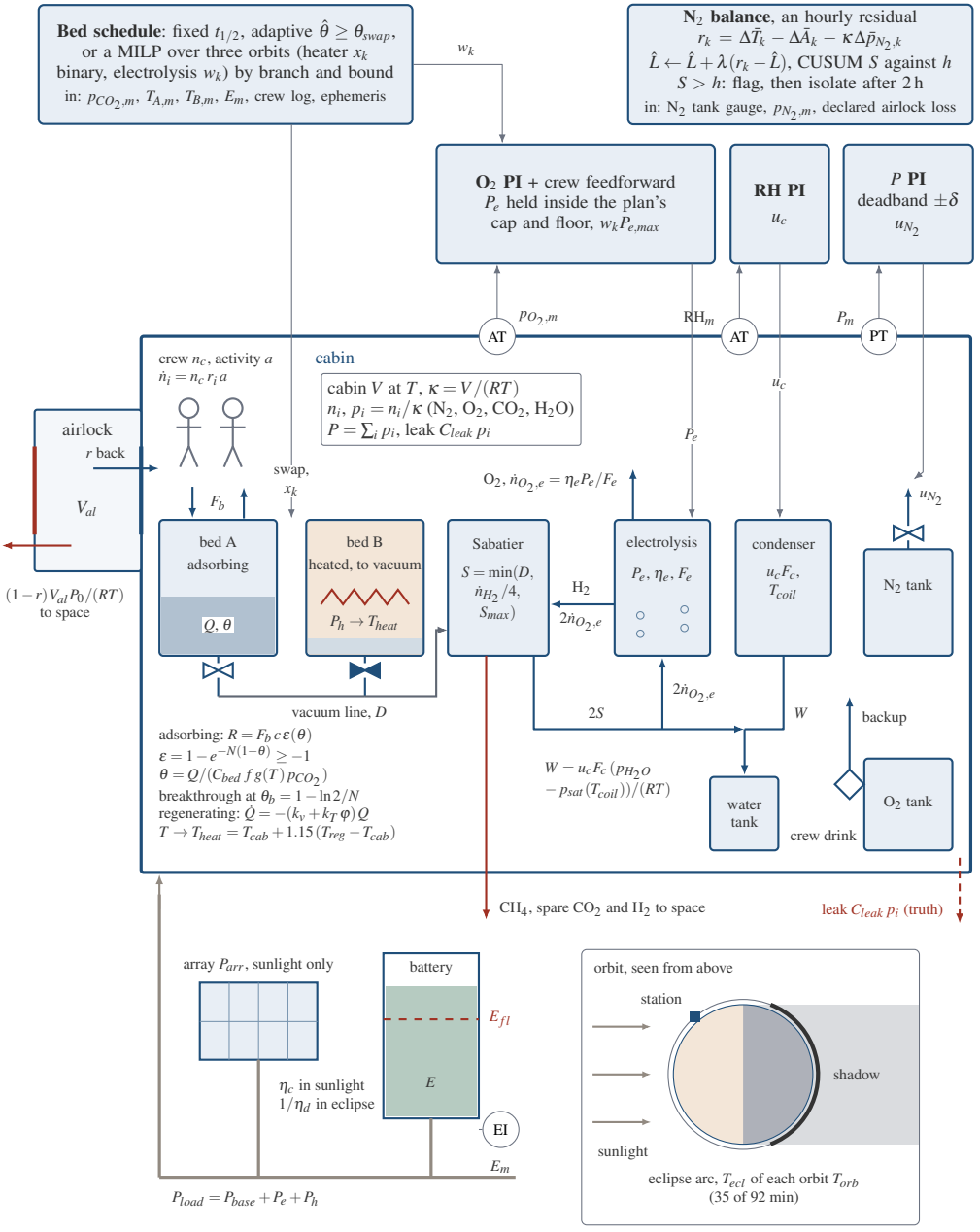


Figure 10.1 Sealed cabin, rack, power bus and orbit as modeled, drawn after the Module view. Bed A adsorbs cabin air at F_b with its outlet valve shut while bed B is heated toward T_{heat} with its valve open to the vacuum line that feeds the Sabatier reactor. The electrolysis unit sends oxygen to the cabin and hydrogen to the reactor, which vents methane and the spare carbon dioxide and hydrogen to space. The condenser, the reactor and the electrolysis share the water line, from which the crew also drink. The leak (dashed) is teaching truth that no instrument reads. The three loops read the analyzer (AT) and the pressure transducer (PT), and the schedule and the balance list their inputs. The inset draws the orbit at the radius whose shadow crossing lasts T_{ecl}. Process model only, not a flight layout. Not to scale.

10.3.1 A Sealed Inventory

Each gas changes only by what the crew, the machines, the leak and the airlock move, and its partial pressure is its inventory over the cabin's moles per kilopascal, as shown in Equation (10.1).

$$\begin{aligned}
\frac{\mathrm{d}n_{\mathrm{N_2}}}{\mathrm{d}t} &= u_{N_2} Q_{N_2} - (C+v)\, p_{\mathrm{N_2}} \\
\frac{\mathrm{d}n_{\mathrm{O_2}}}{\mathrm{d}t} &= \dot{n}_{O_2,e} + b\, Q_{O_2,b} - n_c r_{O_2} a - (C+v)\, p_{\mathrm{O_2}} \\
\frac{\mathrm{d}n_{\mathrm{CO_2}}}{\mathrm{d}t} &= n_c r_{CO_2} a - R - (C+v)\, p_{\mathrm{CO_2}} \\
\frac{\mathrm{d}n_{\mathrm{H_2O}}}{\mathrm{d}t} &= n_c r_{H_2O} a - W - W_{wall} - (C+v)\, p_{\mathrm{H_2O}} \\
p_i &= n_i/\kappa, \qquad \kappa = V/(RT), \qquad P = \textstyle\sum_i p_i
\end{aligned} \tag{10.1}$$

where n_c counts the crew and visitors in the cabin, a is 1 at rest and $a_{ex} = 2.5$ while everyone exercises, u_{N_2} is the makeup valve's opening on a full flow of $Q_{N_2} = 15\,\mathrm{mol/h}$, b is the backup oxygen valve (open or shut, $Q_{O_2,b} = 10\,\mathrm{mol/h}$), $C = C_{leak} + \Delta C_{leak}$ is the leak coefficient until a step is isolated, and v is the airlock's vent coefficient. At $R = 8.314\,462\,618 \times 10^{-3}\,\mathrm{kPa\,m^3/(mol\,K)}$, $\kappa = 163.00\,\mathrm{mol/kPa}$, so one mole of any gas raises the total by 0.006 135 kPa. A leak to vacuum takes the cabin's mixture, so the hole passes each species in proportion to its partial pressure. The airlock is depressurized over $t_{dep} = 0.5\,\mathrm{h}$, and the vent coefficient is

$$v = \frac{(1-r)\, V_{al}\, P_0}{R\, T\, t_{dep}\, P} \tag{10.2}$$

during that stage and zero otherwise, where $r = 0.90$ is the reclaimed fraction and P_0 the cabin pressure when the stage starts. The vent therefore loses $(1-r)V_{al}P_0/(RT)$, 49.5 mol at 101.3 kPa, and the crew outside for $t_{eva} = 6.5\,\mathrm{h}$ leave the cabin's count.

10.3.2 Crew, Electrolysis and Sabatier Reduction

The resting rates per person are $r_{O_2} = 1.0$, $r_{CO_2} = 0.9$ and $r_{H_2O} = 4.9\,\mathrm{mol/h}$. A day with one exercise hour then consumes 0.816 kg of oxygen and produces 1.010 kg of carbon dioxide and 2.251 kg of vapor per person. Electrolysis makes oxygen from the tank's water at the Gibbs energy of the reaction, and its hydrogen feeds the Sabatier reactor, which reduces the carbon dioxide arriving on the vacuum line, as shown in Equation (10.3).

$$\begin{aligned}
\dot{n}_{O_2,e} &= \eta_e P_e / F_e, \qquad \dot{n}_{H_2} = 2\dot{n}_{O_2,e} \\
S &= \max\left(0,\ \min(D,\ \dot{n}_{H_2}/4,\ S_{max})\right) \\
\frac{\mathrm{d}W_t}{\mathrm{d}t} &= W + 2S - 2\dot{n}_{O_2,e} - n_c r_{H_2O} a
\end{aligned} \tag{10.3}$$

where $F_e = 0.131\,74\,\mathrm{kWh/mol}$ is twice the Gibbs energy of formation of liquid water per mole of oxygen, $\eta_e = 0.70$, so the full $P_{e,max} = 2\,\mathrm{kW}$ makes 10.63 mol/h, D is the desorbing bed's flow and $S_{max} = 1.5\,\mathrm{mol/h}$. The reaction $\mathrm{CO_2 + 4\,H_2 \rightarrow CH_4 + 2\,H_2O}$ is the one tabulated for this service [1, 7]. Methane, the carbon dioxide the reactor cannot take and the spare hydrogen are vented. The crew drink exactly the water they exhale, a declared closure that makes the water tank a ledger rather than a water recovery system.

> ✦ DID YOU KNOW? **How Much Water Comes Back**
>
> On the current station, distillation recovers about 87 percent of the water in urine, a limit set to prevent unwanted precipitation. Missions beyond low Earth orbit are to show more than 98 percent [14]. The model of this chapter skips that loop: its crew drink exactly the water they exhale.

10.3.3 Two Beds That Fill and Empty

The adsorbing bed takes carbon dioxide from the air drawn through it with the efficiency of N transfer units at its loading fraction θ, and the regenerating bed gives its carbon dioxide up to vacuum at a rate that heat raises, as shown in Equation (10.4).

$$\begin{aligned} R &= F_b\, c\, p_{\mathrm{CO_2}}\, \varepsilon(\theta), \quad \varepsilon = \max\left(-1,\ 1-\mathrm{e}^{-N(1-\theta)}\right) \\ \theta &= \frac{Q_j}{C_{bed} f_j\, g(T_j)\, p_{\mathrm{CO_2}}}, \quad g(T) = \mathrm{e}^{-\max(0,\,T-T_{cab})/\Delta T_c} \\ \frac{\mathrm{d}Q_j}{\mathrm{d}t} &= R, \quad \frac{\mathrm{d}Q_k}{\mathrm{d}t} = -D = -\left(k_v + k_T\, \varphi(T_k)\right) Q_k \\ \varphi &= \min\left(1,\ \max(0,\ \Theta)\right), \qquad \Theta = \frac{T - T_{cab}}{T_{reg} - T_{cab}} \end{aligned} \tag{10.4}$$

where bed j adsorbs and bed k regenerates, $c = 1/(RT) = 0.407\,50\,\mathrm{mol/(m^3\,kPa)}$, $F_b = 55\,\mathrm{m^3/h}$, $N = 2.5$, $C_{bed} = 40\,\mathrm{mol/kPa}$, f_j is 1 or one half on a faulted bed, $\Delta T_c = 40\,\mathrm{K}$, $k_v = 0.15\,\mathrm{h^{-1}}$, $k_T = 3.5\,\mathrm{h^{-1}}$ and $T_{reg} = 200\,^\circ\mathrm{C}$. The outlet reaches half its inlet, which is breakthrough, at $\theta_b = 1 - \ln 2/N = 0.7227$. The floor on ε lets a bed swapped in while still hot give carbon dioxide back to the cabin. The bed temperatures follow first-order laws, $\tau_h \dot{T} = T_{heat} - T$ with the heater on, $\tau_v \dot{T} = T_{cab} - T$ for a bed under vacuum without heat and $\tau_a \dot{T} = T_{cab} - T$ for the bed in the air flow, with $\tau_h = 0.3\,\mathrm{h}$, $\tau_v = 0.8\,\mathrm{h}$, $\tau_a = 0.25\,\mathrm{h}$ and $T_{heat} = T_{cab} + 1.15\,(T_{reg} - T_{cab}) = 226.7\,^\circ\mathrm{C}$. With the beds stopped, neither takes air and both cool at τ_v. A regenerating bed's θ rises far above one because its hot capacity is small, so the scene draws it on its cool capacity $Q/(C_{bed} f\, p_{\mathrm{CO_2}})$ and the export logs both.

10.3.4 Humidity and Power

The condenser passes a fraction u_c of $F_c = 400\,\mathrm{m^3/h}$ of cabin air over a coil at $T_{coil} = 7\,^\circ\mathrm{C}$ and keeps the vapor above the coil's saturation, while vapor above saturation in the cabin itself condenses on the walls, as shown in Equation (10.5).

$$\begin{aligned} W &= u_c F_c\, c\, \max\left(0,\ p_{\mathrm{H_2O}} - p_{sat}(T_{coil})\right) \\ W_{wall} &= K_{wall}\, \kappa\, \max\left(0,\ p_{\mathrm{H_2O}} - p_{sat}(T)\right) \\ p_{sat}(T) &= 0.61094\, \exp\left(17.625\, T/(T + 243.04)\right) \end{aligned} \tag{10.5}$$

where $K_{wall} = 5\,\mathrm{h^{-1}}$ and p_{sat} is the Magnus form in kPa with T in °C, 2.638 kPa at the cabin temperature and 1.0007 kPa at the coil. The wall term is a teaching closure that limits the humidity growth but does not enforce a saturation cap: case 1 settles near 101.37 %. The bus carries a base load, the electrolysis and the regenerating bed's heater, as shown in Equation (10.6).

$$\begin{aligned} P_{load} &= P_{base} + P_e + x P_h, \qquad P_{sun} = P_{arr}\, s(t) \\ \frac{\mathrm{d}E}{\mathrm{d}t} &= \begin{cases} \eta_c (P_{sun} - P_{load}) & P_{sun} \geq P_{load},\ E < E_{bat} \\ (P_{sun} - P_{load})/\eta_d & P_{sun} < P_{load} \end{cases} \end{aligned} \tag{10.6}$$

where $s(t)$ is 1 in sunlight and 0 for the last 35 min of each orbit, $P_{arr} = 11\,\mathrm{kW}$, $P_{base} = 4\,\mathrm{kW}$, $P_h = 1\,\mathrm{kW}$, $E_{bat} = 8\,\mathrm{kWh}$ and $\eta_c = \eta_d = 0.95$. The battery is clipped to $[0, E_{bat}]$ after each step, and a protection sheds the electrolysis and the heater below 35 % and restores them above 50 %. The base load alone takes $4 \times 35/60/0.95 = 2.456\,\mathrm{kWh}$ in an eclipse, of the 3.2 kWh that a full battery holds above its 60 % floor.

Table 10.2 Model Parameters. S Is Read From a Source, T a Teaching Value, D Derived

Symbol	Meaning	Value	Unit	
V, T	cabin volume, temperature	400, 22	m^3, °C	T
κ	moles per kilopascal	163.00	mol/kPa	D
r_{O_2}, r_{CO_2}, r_{H_2O}	rates per person	1.0, 0.9, 4.9	mol/h	T[a]
a_{ex}	activity, exercising	2.5	—	T
C_{bed}	bed capacity, cool	40	mol/kPa	T
F_b, N	bed air flow, transfer units	55, 2.5	m^3/h, —	T
ΔT_c	capacity e-fold	40	K	T
k_v, k_T	desorption rates	0.15, 3.5	h^{-1}	T
T_{reg}, P_h	regeneration, heater	200, 1.0	°C, kW	T
τ_h, τ_v, τ_a	bed thermal lags	0.3, 0.8, 0.25	h	T
f	faulted bed's capacity	0.5	—	T
F_e	energy per mole O_2	0.13174	kWh/mol	S
η_e, $P_{e,max}$	electrolysis	0.70, 2.0	—, kW	T
S_{max}	Sabatier capacity	1.5	mol/h	T
Q_{N_2}, $Q_{O_2,b}$	makeup, backup flows	15, 10	mol/h	T
tanks	N_2, O_2, water	900, 600, 3000	mol	T
reserves	N_2, O_2	575, 300	mol	T
F_c, T_{coil}	condenser flow, coil	400, 7	m^3/h, °C	T
C_{leak}, ΔC_{leak}	leak, leak step	0.0118, 0.05	mol/(h kPa)	T[b]
V_{al}, r	airlock, reclaimed	12, 0.90	m^3, —	T, S[c]
t_{dep}, t_{eva}, t_{rep}	airlock stages	0.5, 6.5, 0.25	h	T
P_{arr}, P_{base}	array, base load	11, 4.0	kW	T
E_{bat}	battery	8	kWh	T
floor, shed	battery limits	0.60, 0.35	—	T
η_c, η_d	battery efficiencies	0.95, 0.95	—	T
T_{orb}, T_{ecl}	orbit, eclipse	92, 35	min	T

[a] A day with one exercise hour is within 3 % of the baseline's 0.84, 1.01 and 2.27 kg [3]. [b] About 0.83 kg of air a day, roughly ten times the baseline's upper module leakage of 0.09 kg/day [3]. [c] The baseline gives about 10 % of an airlock's gas lost per cycle [3].

10.3.5 Measurements

A gas analyzer reports the four partial pressures once a minute with white noise of standard deviation 0.03, 0.03, 0.0015 and 0.01 kPa for nitrogen, oxygen, carbon dioxide and vapor, and holds each report. The humidity is computed from its vapor reading. A pressure transducer (0.005 kPa), the three tank gauges (0.5 mol), a battery energy meter (0.02 kWh) and the two bed thermocouples (0.5 °C) are scanned with it, each with colored noise. The crew's log, the electrolysis trip contact, the bed fault annunciation and the airlock stage are status inputs. The bed loadings and the leak are never measured. Each instrument draws from its own stream seeded by the case, so a run replays bit for bit (Section 1.6.1). The exported file logs each measurement next to the truth it reads, with the actuators, the schedule and the program's status, nodes and gap, the nitrogen ledger and the balance's residual, estimate and flag.

10.3.6 Parameters, Start and Numerics

Table 10.2 lists the parameters. All appear in the Parameters panel and can be changed by the reader. Each case starts with the oxygen at its setpoint, the carbon dioxide at 0.37 kPa, the vapor at the humidity setpoint and nitrogen making up the total, bed A a quarter of the way to its equilibrium loading and bed B freshly regenerated, both at cabin temperature, the battery at 90 % and the tanks full. The engine of Section 1.6.1 integrates in hours with the classical fourth-order Runge-Kutta method at a step of $\Delta t = 10$ s, holds every event for the step it falls in, and applies discrete changes (an event, a bed swap, an airlock stage, the clipping of a tank or the battery) once at a step boundary. Halving the step moves the challenge week's nitrogen losses by 0.0014 % as shipped and 0.016 % with the suggested settings.

10.3.7 Assumptions

The cabin is one well-mixed volume at a fixed temperature, so the pocket of exhaled carbon dioxide around a sleeping crew member, which the standard's rationale names, and the thermal control loop are absent. Each bed is one loading and one temperature with a linear isotherm whose capacity falls as the bed warms, which reproduces breakthrough and the cost of swapping in a hot bed but not the axial and radial profiles of a real column. The real assembly's desiccant beds are left out, and the condenser carries all of the humidity. The crew's rates are constant per person, and exercise multiplies them for the whole crew at once. The airlock's lost gas leaves at a constant rate over the depressurization. The power model has one array, one battery with constant efficiencies and one fixed orbit. Every limit, reserve and efficiency other than those marked S in Table 10.2 is a teaching value, and a run that holds them is not evidence about any real vehicle.

10.4 The Sum, the Saw-Tooth and the Shadow

10.4.1 One Total Pressure for Two Loops

Adding oxygen alone raises both the total and the oxygen fraction. One mole raises P by $1/\kappa = 0.006\,135$ kPa and the fraction by $(P - p_{O_2})/(\kappa P^2)$, 0.004 801 points at the start. In case 2 the oxygen setpoint is raised from 21.0 to 22.0 kPa at 1 h. The electrolysis runs at its full 2 kW, the backup tank opens because the oxygen is more than 0.8 kPa under its new setpoint, and the extra oxygen pushes the total past the pressure loop's 0.2 kPa deadband. The nitrogen valve, open 6.0 % to feed the everyday leak, shuts at 3.52 h, 2.52 h after the step. Nothing can remove the excess except the crew and the leak, so at 24 h the total is 102.16 kPa, the oxygen 21.97 kPa and its fraction 21.51 % against 20.73 % before the step, and the backup tank has given 58 mol. The two loops are coupled through the sum, and only one of them can see it. The oxygen added moves the total, while the nitrogen added leaves the oxygen partial pressure alone, so the gain matrix from the two gases to the oxygen partial pressure and the total is triangular. Its relative gain is one however strong the coupling (Section 1.4.5), and the coupling runs one way. Nothing in the cabin removes the excess, which is the closed inventory of Section 1.4.3 with actuators that can only add.

Pause. Try Exercise 10.1 before reading on.

> **TRY IT IN THE APP 2 · The Oxygen Loop and the Pressure It Shares**
>
> Run the scenario at 0.25 h/s. After the first half hour raise the O_2 setpoint from 21.0 to 22.0 kPa, then follow the Nitrogen valve strip on the Atmosphere view. Open about 6 % to feed the everyday leak, it shuts about two and a half hours after the step, and the total pressure and the oxygen fraction stay high, because only the crew and the leak remove gas.

10.4.2 A Saw-Tooth Set by the Half-Cycle

A fresh bed takes most of the carbon dioxide in the air through it, and its removal falls as it loads, so the cabin's carbon dioxide rises through each half-cycle and drops at each swap. With six crew at rest and the fixed 144 min half-cycle of case 3, the beds produce one tooth every 144.0 min, and between 12 and 24 h the partial pressure stays between 0.3713 and 0.3831 kPa with a mean of 0.3754 kPa. A longer half-cycle of 180 min raises the band to 0.4043 kPa to 0.4328 kPa (mean 0.4156), and a shorter one of 96 min lowers the mean to 0.3324 kPa at the price of 15.00 kWh of heater energy a day against 10.00. The tooth itself is small because the cabin holds 163 mol per kilopascal against roughly 13 mol produced in a half-cycle. A separate periodic calculation, two beds integrated by Euler's method at a frozen mean partial pressure, gives teeth of 0.0104, 0.0196 and 0.0315 kPa at 144, 180 and 216 min against the engine's 0.0102, 0.0190 and 0.0301 kPa on day 3 of case 3. At 180 min the teeth grow with the crew as well, to 0.0129, 0.0190 and 0.0255 kPa for four, six and eight people against 0.0131, 0.0196 and 0.0262 kPa by the same calculation.

10.4.3 Breakthrough and a Bed Swapped Too Soon

On a 240 min half-cycle a cool adsorbing bed passes half its inlet 102 min into its half-cycle, at a true loading of 0.7226 to 0.7234 across the step, against the analytic $\theta_b = 0.7227$. Case 4 puts the crew's exercise hour at 11:00, at the end of a half-cycle that swaps at 12:00. The carbon dioxide then rides to 0.4289 kPa, against 0.3865 kPa for the same day without exercise. Swapping at 10:54 meets the hour with a regenerated bed and lowers the peak to 0.4177 kPa, while a swap at 09:45, nine minutes after the last one, brings on a bed still hot and loaded and raises it to 0.4770 kPa. The floor on ε is what lets that hot bed give carbon dioxide back.

10.4.4 An Eclipse Budget That Does Not Close

A full battery holds 3.2 kWh above its floor, and the base load takes 2.456 kWh of it in each eclipse. A heater run through a whole eclipse adds 0.614 kWh, which still fits and leaves 61.6 % of a full battery. The oxygen loop's steady 1.176 kW for six crew, run through the eclipse, would take the battery to 60.3 % on its own and to 52.6 % with the heater. Full electrolysis in sunlight makes 10.10 mol of oxygen per orbit against the 9.58 mol that six crew and the leak consume, so the oxygen can wait for the sun, and once it does the heater can run in the dark. Sunlight with the heater and full electrolysis returns 3.61 kWh per orbit, more than an eclipse may take. In case 5 the adaptive schedule heats wherever its swaps fall and the oxygen loop runs the electrolysis at all hours, and the battery is below its floor at 1.478 h in the first eclipse, spends 169.7 min of the day below it and reaches 51.55 %.

10.5 The Control Layers as Implemented

The controller executes every minute ($\Delta t_c = 1$ min), on the analyzer's report period, in the order of work of Figure 1.10. The plant-side bookkeeping of each step covers events, swaps, airlock stages, clipping and protection. Every decision reads the measurement record of the previous subsection, the controls, the crew's declared timeline and the declared model's parameters, and an automated check in the application's suite scans the controller, the scheduler, the balance and the crew procedures for any read of the simulator's truth.

10.5.1 Three Proportional-Integral Loops

Each of the three loops runs the velocity-form PID of Section 1.6.2, Equations (1.11) to (1.14), with no derivative term, the limit on the emitted output only and the integral back-calculated against it with a tracking time T_t equal to τ_I. An integral time of zero turns the integral off. The oxygen loop sets P_e from the analyzer's oxygen with $K_c = 8\,\mathrm{kW/kPa}$ and $\tau_I = 4\,\mathrm{h}$ on 0 to 2 kW. The optional crew-activity feedforward is its output bias u_b,

$$u_{ff} = \frac{n_c\, r_{O_2}\, a(t) + C_{leak}\, p_{O_2,SP}}{\eta_e / F_e}, \tag{10.7}$$

taken from the crew's log and the exercise timetable. Toggling it shifts the integral by the feedforward's value, which keeps the output continuous. The pressure loop sets u_{N_2} with $K_c = 200\,\%/\mathrm{kPa}$ and $\tau_I = 6\,\mathrm{h}$ on an error that is zero inside $\pm\delta = \pm 0.2\,\mathrm{kPa}$ of the setpoint and is reduced by δ outside it, so the valve holds still inside the band. The humidity loop sets u_c with $K_c = 10\,\%$ per point of relative humidity and $\tau_I = 1\,\mathrm{h}$, direct acting, with the action $a = -1$ of Section 1.6.2. Every loop tracks its manual station in Manual, so a transfer is bumpless. The backup oxygen valve opens when the analyzer's oxygen falls 0.8 kPa under its setpoint and shuts at 0.4 kPa under it, in both modes.

10.5.2 Fixed and Adaptive Bed Schedules

The fixed schedule swaps the beds every $t_{1/2} = 144\,\mathrm{min}$ and heats the regenerating bed for the first $t_h = 60\,\mathrm{min}$ of each half-cycle, wherever the orbit is. Because the loadings are not measured, the adaptive schedule carries both predicted loadings forward each minute by the declared bed law of Equation (10.4), from the declared starting loadings, on the measured carbon dioxide and bed

temperatures, and swaps when the predicted $\hat{\theta}$ of the adsorbing bed reaches $\theta_{swap} = 0.60$, no sooner than 75 min and no later than 180 min after the last swap. A faulted bed is annunciated, so the predictor uses its halved capacity. A visiting-crew mode shortens the fixed half-cycle to 96 min while visitors are aboard.

10.5.3 A Power-Aware Program Over Three Orbits

The power-aware schedule keeps the adaptive swaps and places the heater runs and the electrolysis by a mixed-integer linear program over the next $H = 3T_{orb} = 4.6$ h. A forecast with the declared bed law and the crew aboard now predicts the swaps over the horizon, and the horizon is cut at every sunrise, sunset and predicted swap and then into slots k of at most 20 min, so each slot lies in one light and one window j between swaps. Per slot of length Δ_k the heater $x_k \in \{0,1\}$ is binary and the electrolysis fraction $w_k \in [0,1]$, the spilled array energy g_k, the floor shortfall σ_k, the tank oxygen o_k and the start indicator ζ_k are continuous, and each window carries a heating shortfall h_j. The program is Equation (10.8).

$$
\begin{aligned}
\min\ & \textstyle\sum_k \left(100\,\sigma_k + 2\,o_k + 0.05\,\zeta_k\right) + 50\sum_j h_j - E_K \\
& \quad + \textstyle\sum_k 0.01\,\Delta_k\,(t_k - t_{j(k)})\,x_k \\
\text{s.t. } & E_k = E_0 + \textstyle\sum_{i\le k}(\alpha_i - \beta_i x_i - \gamma_i w_i - g_i) \\
& E_k + \sigma_k \ge E_{fl} + 0.2, \qquad E_k \le E_{bat} \\
& n_k = n_0 + \textstyle\sum_{i\le k}(q_{max}\Delta_i w_i + o_i - \Delta_i \bar{D}_i) \\
& |n_k - n_{SP}| \le 0.25\,\kappa \\
& \textstyle\sum_{k\in j} \Delta_k x_k + h_j \ge t_{h,j}, \qquad \zeta_k \ge x_k - x_{k-1} \\
& \textstyle\sum_{k\in j} \zeta_k \le 2, \qquad x_k = 0 \text{ near a swap}
\end{aligned}
\tag{10.8}
$$

where $\alpha_k = \eta_c \Delta_k (P_{arr} - P_{base})$, $\beta_k = \eta_c \Delta_k P_h$ and $\gamma_k = \eta_c \Delta_k P_{e,max}$ in sunlight, $\alpha_k = -\Delta_k P_{base}/\eta_d$, $\beta_k = \Delta_k P_h/\eta_d$ and $\gamma_k = \Delta_k P_{e,max}/\eta_d$ in eclipse, $g_k = 0$ in eclipse, $E_{fl} = 4.8$ kWh is the floor, $q_{max} = 10.63$ mol/h, $\bar{D}_k$ is the crew timeline's oxygen use plus the declared leak at the slot's middle, $t_{h,j}$ is what window j still needs of its hour of heat, the heater is off for $t_{cool} = 12$ min before each swap, $t_{j(k)}$ is the start of slot k's window, and the oxygen at the horizon's end may sit no more than 0.05 kPa under the setpoint. The penalized slacks keep every program feasible, so a result reports how far the floor, the heating or the oxygen band is missed rather than failing. The battery model is linear because the sign of each slot's battery flow is known from the light. The same mix of on-off and continuous decisions on one shared supply recurs in the refrigeration pack of Volume 8, Chapter 12, whose hybrid predictive controller schedules the compressor starts.

Over the suggested week the program is solved 236 times, once at the start, 121 times at a swap, 108 times at sunrise and 6 times on a change of status, and every solve branches, with a median of 31 nodes. It is solved by depth-first branch and bound on the linear relaxation with the bounded simplex that the apps share, in the module that the hourly pump schedule of Volume 9, Chapter 11 first used, branching on the earliest fractional heater slot and exploring first the child nearer its fractional value. Any node whose relaxation is infeasible, or no better than the incumbent, is discarded. At a limit of 200 nodes the search returns its incumbent with the best open bound, and the scene says whether the plan was proved optimal or by how much it lies above that bound. It is re-solved at the start, at every swap, at every sunrise, when the crew aboard, a trip or a fault changes, and before the horizon runs out. In the eclipse the electrolysis runs at the plan's rate $w_k P_{e,max}$, which is both a cap and a floor, and in sunlight the plan's rate is a floor that the oxygen loop may exceed. The loop's integral is back-calculated against what the plan let through, and the backup valve delivers the plan's tank oxygen at the start of its slot.

10.5.4 The Nitrogen Balance and the Crew's Procedures

Nitrogen does not react, so it enters only from the tank and leaves only by the leak and the airlock, much as the inert of Chapter 8 leaves only by the purge (Section 1.4.3). Each hour the balance

Table 10.3 The Ten Cases and the Week

#	Case and events	Teaching point
1	Manual, every machine off, 48 h	the hours to each limit
2	Oxygen setpoint 21 to 22 kPa after the first half hour	loops coupled by the sum
3	Fixed half-cycle 144, then 180 or 96 min	the saw-tooth
4	Exercise hour at 11:00, a manual swap	timing the swap
5	Adaptive, then power-aware, 24 h	the eclipse budget
6	Excursion at 2 h, 12 h	the airlock's cost
7	Balance on, leak step at 24 h, 48 h	the balance finds the leak
8	Bed A faulted, two visitors at 2 h, adaptive	rationing capacity
9	Challenge, 168 h: excursions at 30 and 54 h, visitors 72 to 120 h, leak step at 126 h	the week aboard
10	Eight crew, bed A faulted, exercise, CO_2 from 0.45 kPa	infeasible at any schedule

averages the tank gauge T, the declared airlock loss A and the analyzer's inventory $\kappa p_{\mathrm{N}_2,m}$ over the hour and forms the residual and the tests of Equation (10.9).

$$
\begin{aligned}
r_k &= \frac{(\bar{T}_{k-1} - \bar{T}_k) - (\bar{A}_k - \bar{A}_{k-1}) - \kappa(\bar{p}_{N_2,k} - \bar{p}_{N_2,k-1})}{1\,\mathrm{h}} \\
\hat{L}_k &= \hat{L}_{k-1} + \lambda\,(r_k - \hat{L}_{k-1}) \\
S_k &= \max\left(0,\; S_{k-1} + (r_k - L_{ref,k-1})/\sigma_r - \tfrac{1}{2}\right)
\end{aligned}
\tag{10.9}
$$

where $\lambda = 0.15$, the declared $\sigma_r = 1.0\,\mathrm{mol/h}$ comes from the instruments' noise, and the reference L_{ref} follows the residual with the slow weight 0.05. When S passes $h = 5$ the test flags a step, estimates its size as the mean residual since S left zero less the reference, resets S and moves the reference by that step. The declared airlock loss is $(1-r)V_{al}Px_{N_2}/(RT)$ at the pressure and nitrogen fraction measured when the depressurization starts, spread over it. With "Isolate on a flag" on, the crew closes off the leaking volume two hours after a flag, a single search that removes a leak step if one is there. An excursion is a four-stage procedure, depressurize, outside, repressurize and idle, run on the clock.

10.5.5 Plant, Controller Model and Identified Model

The plant is everything in Section 10.3. The controller's model is the declared bed law and power arithmetic with the plant's own parameters, run on measurements, so the cases meet model error only through the hidden loadings, the noise and visitors the forecast cannot know about. A reader identifies the hours to each limit in case 1 and the tooth against the half-cycle in case 3.

10.6 Ten Cases and a Week, Measured

The cases are listed in Table 10.3. All share the starting state of Section 10.3, the loop tunings above and the fixed schedule unless a row says otherwise. Every number here was measured on the engine running headless and stepped as the browser steps it, on the case's own seed unless several are named, with any setting a sentence names made before Run. Limits are judged on the truth at every step.

10.6.1 The Airlock and the Leak

In case 6 the airlock vents 49.534 mol, of which 38.437 mol is nitrogen and 10.269 mol oxygen, equal to $(1-r)V_{al}P_0/(RT)$ at $P_0 = 101.298\,\mathrm{kPa}$. The pressure falls to 101.005 kPa at 2.733 h, just past the deadband, so the valve answers a small error slowly, and by 12 h the total is back only to 101.129 kPa while the tank has given 21.97 mol. Case 7 opens a leak step of $\Delta C_{leak} = 0.05$ at 24 h, which adds about 3.9 mol/h of nitrogen to the 0.93 mol/h the everyday leak takes. The pressure never leaves 101.001 kPa to 101.403 kPa over the two days, because the valve opens from 6.00 to 37.01 % at 48 h (39.89 % at its widest). The cumulative sum flags the step at 27.00 h, three hours after it opened, and at 48 h the estimate reads 4.689 mol/h against a true nitrogen leak of 4.841 mol/h. Over

Table 10.4 Measured Results of the Teaching Cases

Case	Configuration	CO_2 peak (kPa)	Battery low (%)	Below floor (min)
4, 24 h	no extra swap	0.4289	—	—
	swap at 10:54	0.4177	—	—
	swap at 09:45	0.4770	—	—
5, 24 h	adaptive	—	51.55	169.7
	power-aware	—	61.58	0.0
8, 24 h	fixed 144 min	0.5926	48.68	150.5
	adaptive	0.4738	49.18	225.3
	power-aware	0.4740	61.64	0.0
10, 48 h	best fixed (72 min)	0.565	—	—
	adaptive	0.5565	—	—
	power-aware	0.5585	—	—

the case's seed and ten others the flag comes 2.0 to 3.0 h after the step with no flag before it, the estimate is within 0.27 mol/h of the truth at 48 h, and the hourly residual scatters about the true leak with a standard deviation of 0.71 to 1.05 mol/h on the first day, against the declared 1.0 mol/h.

Pause. Try Exercise 10.2 before reading on.

> **TRY IT IN THE APP** **7 · A Leak Step and the Nitrogen Balance**
>
> Load the scenario, press Run at 1 h/s on the Module view and watch the total pressure and the Nitrogen valve strips after the leak opens at 24 h. The pressure never leaves 101.00 to 101.40 kPa, while the valve opens from 6.0 to 37.0 % to feed the leak. Only the nitrogen balance panel shows the step, with its flag at 27.00 h.

10.6.2 Schedules Against the Eclipse

The adaptive and power-aware schedules of case 5 make the same 17 swaps in the day. What the program moves is the electrolysis. Over the day it puts 0.86 kWh of its 28.98 kWh of electrolysis in the eclipses, against 11.23 kWh of 30.23 kWh on the adaptive schedule, while its heater still runs for 380 min of the 528 min of eclipse (402 min on the adaptive schedule), as the budget above allows. The battery's lowest point rises from 51.55 to 61.58 % with no time below the floor, as shown in Figure 10.2. Over the suggested week the same pattern holds, with 14.62 kWh of electrolysis in the eclipses against 88.65 kWh as shipped. Case 8 adds a faulted bed and two visitors, and the three schedules each fail differently, as listed in Table 10.4. The fixed half-cycle is too long for eight people on one and a half beds, and its carbon dioxide peaks at 0.5926 kPa, over the limit for 519.5 min. The adaptive schedule shortens its half-cycles and holds the carbon dioxide at 0.4738 kPa, but its 18 regenerations heat in the eclipses and the battery spends 225.3 min below its floor. The power-aware program keeps the same 18 swaps and 0.4740 kPa and holds the battery at 61.64 % or more. Figure 10.3 draws the peaks and the battery lows of Table 10.4 side by side.

10.6.3 An Honest Infeasibility

Case 10 puts eight crew on one healthy and one faulted bed with the daily exercise hour, from a steady 0.45 kPa. Every fixed half-cycle from 36 to 240 min in 12 min steps breaks the 0.53 kPa limit, the best at 72 min with a peak of 0.565 kPa, because short half-cycles bring the beds back hot and long ones let them saturate. The adaptive schedule does best and still passes the limit in the first exercise hour at 10.84 h and peaks at 0.5565 kPa, and the power-aware program peaks at 0.5585 kPa. Eight people exercising produce 18.0 mol/h of carbon dioxide, while a fresh cool bed at 0.5 kPa takes at most 10.29 mol/h, so the answer lies in the demand (staggered exercise, a repaired bed, a postponed visit) and not in the controller.

Pause. Try Exercise 10.3 before reading on.

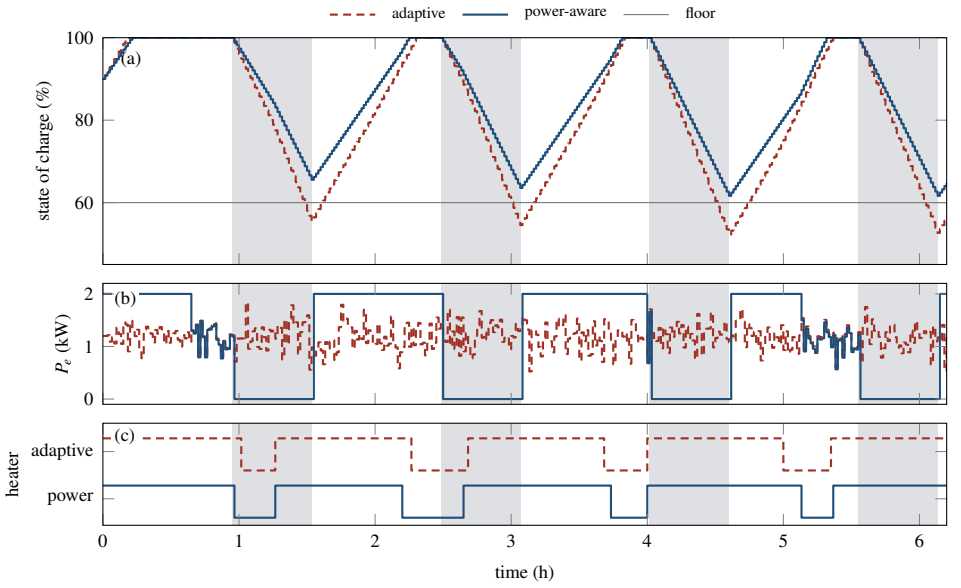


Figure 10.2 The first four orbits of case 5 on the adaptive (dashed) and the power-aware (solid) bed schedules, from the engine, eclipses shaded. (a) True state of charge against the 60 % floor (thin gray line). (b) Electrolysis power. (c) Heater on or off, the adaptive run on the upper row. The adaptive run breaches the floor at 1.478 h, while the program keeps the electrolysis out of the dark and lets the heater run there.

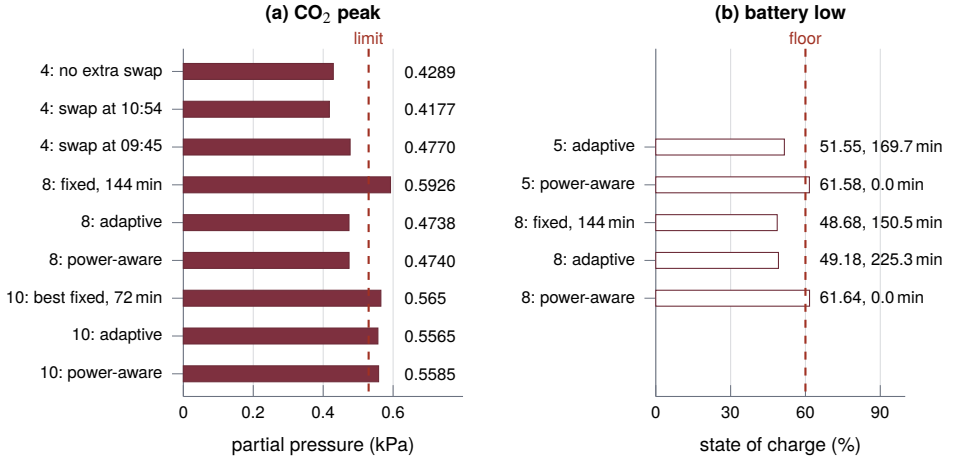


Figure 10.3 The teaching cases of Table 10.4: (a) the carbon dioxide peak against the 0.53 kPa teaching limit (dashed), (b) the battery's lowest state of charge against its 60 % floor (dashed), with the minutes spent below the floor. Notice that in case 8 the power-aware program keeps the adaptive schedule's carbon dioxide and alone holds the battery, and that in case 10 no schedule stays under the limit.

10.6.4 The Week Aboard

The challenge runs 168 h with six crew and their exercise hour at 10:00, excursions at 30 and 54 h, two visitors from 72 to 120 h and a leak step at 126 h. Its target is every atmospheric limit held on the truth, the battery never below its floor, both tanks above their reserves at the end (575 mol

Table 10.5 The Week Over the Case's Seed and Ten Others, Judged on the Truth

Configuration	Pass	CO_2 (kPa)	Battery (%)	N_2 left (mol)	Flag (h)
shipped	0/11	0.564	46.51–46.87	520–522	—
suggested	11/11	0.493–0.496	61.23–61.29	646–666	2.0–3.0
no feedforward	11/11	0.493–0.496	61.23–61.29	646–668	2.0–3.0
no balance	0/11	0.493–0.496	61.23	484–503	—
isolation off	0/11	0.493–0.496	61.23	484–503	2.0–3.0
adaptive	0/11	0.489–0.491	46.29–47.68	666–674	2.0–3.0
fixed, visit mode	0/11	0.497	47.40–48.05	683–690	2.0–3.0

of nitrogen and 300 mol of oxygen) and the leak step flagged within 12 h. Table 10.5 gives seven configurations over the case's seed and ten others, judged from the logged truth. As shipped (fixed schedule, no feedforward, no balance) the week fails four ways, with the carbon dioxide over its limit for 494 min while the visitors are aboard (worst 0.564 kPa), the battery below its floor for 901 min, the leak never flagged and 520 mol of nitrogen left. The suggested settings (power-aware, feedforward, balance) pass every seed with at least 0.034 kPa, 1.23 points of charge, 71 mol of nitrogen and 9 h of margin. The schedule and the balance are each necessary, while the feedforward is not. Without the balance the same schedule never flags the leak and ends with 484 to 503 mol. Under the program the electrolysis runs at the plan's rate, so the week's largest oxygen dip in an exercise hour is 0.1204 kPa without the feedforward and 0.1194 kPa with it. Where the loop owns the electrolysis, as in case 4, the feedforward roughly halves the dip, from 0.047 to 0.027 kPa.

The reserve of 575 mol sits at the midpoint of the measured gap between weeks whose leak is isolated (646 to 666 mol) and weeks whose leak is left open (484 to 503 mol), so the verdict turns on the response by at least 71 mol at every seed. The carbon dioxide limit of 0.53 kPa is a teaching value. Under the standard's one-hour average of 0.40 kPa [4] the suggested week would fail, since its highest one-hour average is 0.490 kPa, and even the six-person design point of case 3 averages 0.375 kPa. The crews of this simulator would not meet the real limit through a week. The week at 129.5 h, half an hour after the balance flagged the leak, is shown in Figure 10.4.

> ✦ DID YOU KNOW? **A Leak Found but Not Stopped**
>
> From the simulator (Table 10.5). With Isolate on a flag off, the balance still flags the week's leak 2.0 to 3.0 h after it opens, yet the week fails on all eleven seeds. It ends with 484 to 503 mol of nitrogen, exactly as with no balance at all, against 646 to 666 mol when the crew isolate the leak.

10.6.5 The Program's Proofs and Gaps

Over the suggested week the program is solved 236 times, and 230 solves are proved optimal within the 200-node limit. The other six return an incumbent up to 20.07 above the best open bound in the objective's units, which the Orbit view prints as "not proved optimal". Searched to the end, each of the six incumbents is the optimum, reached after 205 to 311 nodes, so the large gaps measure a weak relaxation rather than a poor plan. At 500 and 5,000 nodes every solve is proved, and the eleven seeds give the same verdicts and ranges as at 200. At the earlier limit of 60 nodes, 67 of 237 solves stopped short.

10.6.6 Code Verification

Verification is kept apart from agreement with published data. Counting atoms through the electrolysis and the Sabatier stoichiometry, the nitrogen, carbon, hydrogen and oxygen held in the cabin, the beds, the tanks and the ledgers close to within 2.2×10^{-9} mol at every step of the shipped and suggested weeks and of cases 1, 6, 8 and 10. The total pressure equals $\sum_i n_i / \kappa$ to 4.3×10^{-14} kPa. Each species balances to its sources and sinks within 8.8×10^{-10} mol over the first 72 h of the suggested week.

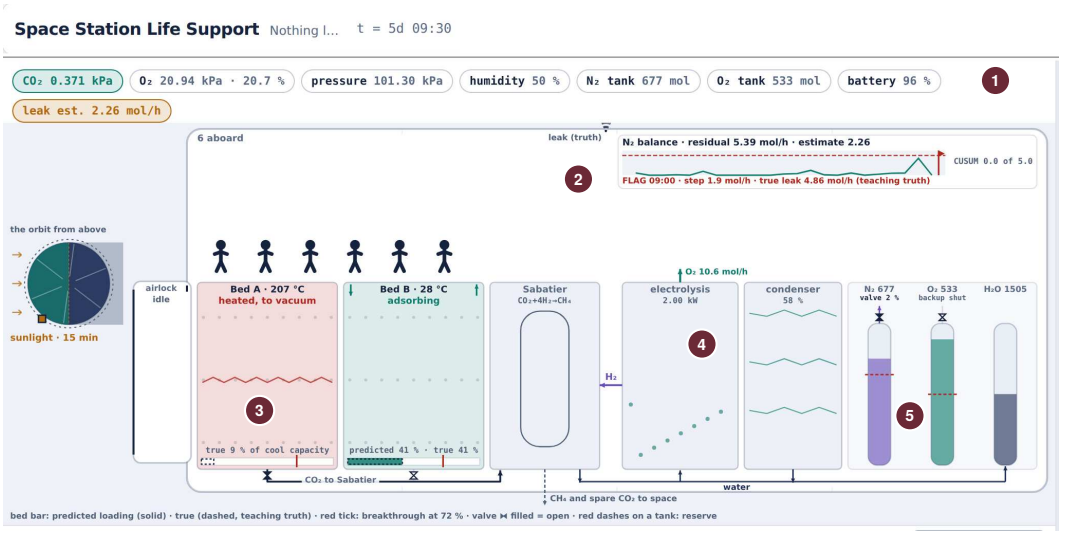


Figure 10.4 The week aboard with the suggested settings at $t = 129.5$ h (day 6, 09:30) on the Module view, in sunlight with 15 min to sunset, a composite of the app's header and its Module view. The leak step opened at 126 h, and the balance panel (2) shows the flag raised at 09:00 with an estimated step of 1.9 mol/h, a last hourly residual of 5.39 mol/h, an estimate of 2.26 mol/h against a true nitrogen leak of 4.86 mol/h (teaching truth) and the cumulative sum reset to 0.0 of 5.0. The crew isolate the leak at 131.0 h. Six are aboard, bed A (3) is heated to 207 °C under vacuum at 9 % of its cool capacity, and bed B adsorbs at 28 °C with a predicted and a true loading of 41 %. The badges (1) read 0.371 kPa of carbon dioxide, 20.94 kPa of oxygen (20.7 %), 101.30 kPa, 50 % humidity, 677 mol of nitrogen, 533 mol of oxygen in the tanks and a battery at 96 %. The electrolysis (4) and the nitrogen tank with its makeup valve (5) are the final elements of the oxygen and pressure loops. On the app's carbon dioxide trend, cut from this picture, the visitors' stay shows over the 48-hour window, and their exercise hour on day 5 sets the week's highest value, 0.494 kPa at 107.0 h.

The airlock loss matches its declaration, breakthrough matches its analytic loading and the saw-tooth matches the independent periodic calculation within 5 %, as set out in Section 10.4. The application's own suite checks the branch and bound against exhaustive enumeration on small instances. Halving the step moves the week's nitrogen losses (leak and airlock) by 0.0014 % as shipped and 0.016 % suggested, and the shipped, adaptive, visiting-mode and no-feedforward weeks rerun at half the step keep their verdicts. The tank's draw moves 0.72 % with the suggested settings, which fails a literal reading of a 0.5 % tolerance on nitrogen use. The difference, 1.7 mol, is the cabin's nitrogen left at a different point inside the pressure deadband of ± 0.2 kPa (± 33 mol), since the draw less the losses less the change in the cabin is zero at both steps.

10.6.7 Agreement With Published Values

Agreement is limited to declared values. The crew's day with one exercise hour is within 3 % of the baseline's 0.84, 1.01 and 2.27 kg [3], the half-cycle of the fixed schedule is the 144 min of the tested assembly [5], and F_e agrees within 0.004 % with the 0.131 745 kWh/mol computed from the reference enthalpy of formation and entropies of liquid water, hydrogen and oxygen [15]. The leak is ten times the baseline's upper module leakage on purpose, so that the balance has something to find within a day, and the bed, battery and electrolysis figures are teaching values. No measured trajectory of a flight system was compared.

10.6.8 Runtime

A week takes 60 480 steps. In a browser engine on one host shared with other work, three suggested weeks at each of two window sizes put the median program solve at 25.6 to 26.4 ms. The slowest solve of a week was 149 to 196 ms in four weeks and 274 and 462 ms in the other two. Both outliers are the solve at 19.28 h, which took 129 to 149 ms in three of the other weeks, so they come from the host rather than the problem. A week took 42.0 to 42.1 s shipped and 43.2 to 43.9 s suggested at the top speed of 4 h/s, bounds on one machine rather than benchmarks. A slow solve stalls one frame and changes no result.

10.7 Technology in Practice

What Measures It

Every loop of this chapter reads one gas analyzer and one pressure transducer. On the current station the analyzer is a mass spectrometer, the primary resource for keeping oxygen and carbon dioxide at safe levels, and its partial pressures are normalized to the total of the compartment sampled [16]. The sum that couples the two gas loops of Section 10.4 is thus built into the instrument as well. The model's analyzer reports four partial pressures once a minute with white noise of 0.03, 0.03, 0.0015 and 0.01 kPa and holds each report, and it neither drifts nor fails. A real one is recalibrated against a verification gas and is replaced when its ion pump wears out [16], so separate analyzers for single gases are kept beside it for redundancy [1].

> **TECHNOLOGY Sensor: The Magnetic-Sector Mass Spectrometer**
>
> On the current station a mass-spectrometer-based analyzer monitors nitrogen, oxygen, carbon dioxide, methane, hydrogen and water vapor. Sampled gas passes an inlet into an ion source, a single-focusing magnetic sector spreads the ions, and six electrometers in a spatial array collect them while an ion pump holds the vacuum. The nitrogen reading is used to watch the cabin for air leakage. The partial pressures are normalized to sum to the total, so an error in one gas appears as compensating errors in the others. A verification gas recalibrates the analyzer in orbit. As the ion pump ages its current rises, and at a set current the analyzer protects its filaments and shuts down [16]. A mass spectrometer cannot tell apart two compounds of the same molecular weight, such as nitrogen and carbon monoxide [1].

What Moves It

The oxygen loop moves the electrolysis power, the pressure loop the nitrogen makeup valve, the humidity loop the condenser's air flow, and the bed schedule the swaps and the heater, as Figure 10.5 draws them. In the model a swap takes effect at a step boundary and the beds warm and cool by first-order lags. On the real assembly the selector valves, the bed heaters, the air-save pump and the blower have their own controllers [5], and its air flow, half-cycle and heater set point trade removal against power [17], the trade that Section 10.4 measures as heater energy against the tooth.

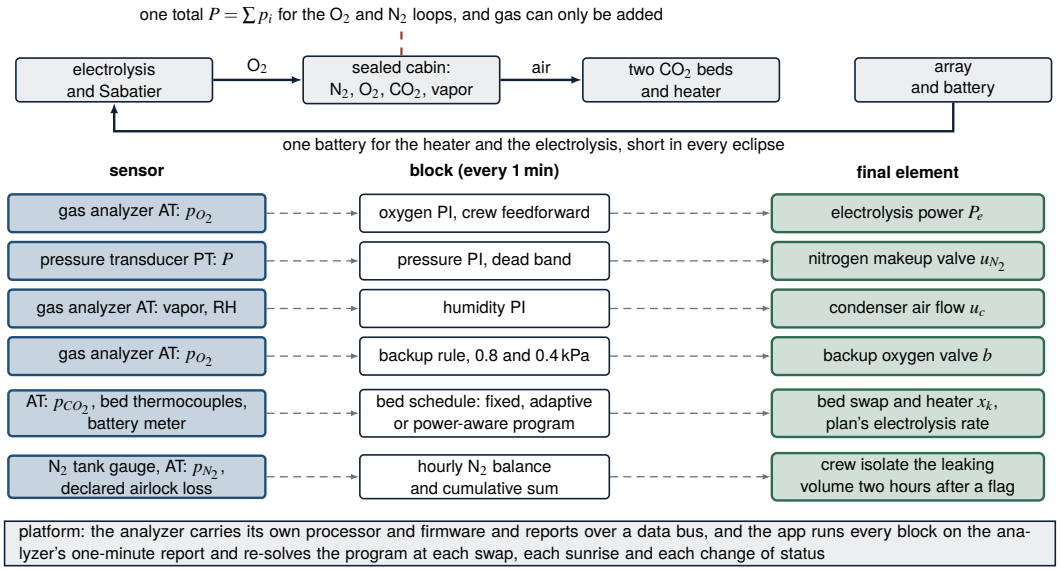


Figure 10.5 The loops of Section 10.5 on real hardware, sensor to block to final element, below the shared quantities that couple them. Notice that one analyzer serves five of the six rows, and that the only path that sees the leak runs through the nitrogen balance, not through the pressure loop that feeds it.

> **TECHNOLOGY** **Final Element: The Four-Bed Removal Assembly**
>
> The removal assembly of the current station holds two desiccant and two sorbent beds. One of each adsorbs while the other two desorb, and selector valves switch them at each half-cycle. Its air comes from the outlet of a condensing heat exchanger, cool and dry, which favors removal. Integral heaters warm the desorbing sorbent bed under space vacuum, and for the first 15 min of each half-cycle a pump returns its residual air to the cabin. The vent valves to vacuum close on a power failure [5]. Cutting the nominal cycle time of 144 min to 90 min is near the limit that still lets the beds heat to their 204 °C set point. The current revision came from an investigation of an anomaly in orbit and brought redesigned heaters, screens serviceable in orbit and new sorbents [17].

Where the Controller Runs

The station's analyzer carries its own processor, memory and firmware, reports to the station's command and data handling system over a 1553B data bus, and a built-in test in its firmware shuts it down when its internal transducers read wrong [16]. A design reference asks for a system controller that adjusts the operation automatically when more people come aboard, and for monitoring that alerts the crew to a failure [1]. The app executes its three PI loops, the bed schedule and the nitrogen balance every minute, on the analyzer's report period, over a 10 s integration step, and re-solves the power-aware program at each swap, each sunrise and each change of status. The plantwide structure sits above the loops: a schedule that shares the battery between the heater and the electrolysis, and a balance that watches what the pressure loop feeds.

What Is Modernizing It

Three developments bear on this chapter. New carbon dioxide scrubbers are tested in orbit: a thermal amine scrubber launched in 2019 has removed four crew members' carbon dioxide at slightly above the target cabin level, and it is to join a four-bed scrubber in a selection for long-duration testing [14]. A virtual test bed that solves the coupled heat transfer, mass transfer and low-pressure flow of an adsorption assembly tries many combinations of flow, cycle time, heater ramp rate and set point

before ground hardware confirms the best [17], the role the declared bed law plays for the adaptive and power-aware schedules here. Model-based reasoning compares sensor data with the predictions of a computer model of the system to locate a problem and alert the crew [1], which the nitrogen balance does for one species.

> **IN PRACTICE** **Atmosphere Requirements Taken as a Whole**
>
> The human-system standard for spaceflight, NASA-STD-3001 Volume 2, sets pressure, humidity, temperature, ventilation, oxygen and carbon dioxide one by one, then states that they must be considered as a whole because they depend on each other. It asks for local and remote control of pressure, humidity, temperature, ventilation and oxygen [V2 6017], for environmental control that meets the added oxygen use and carbon dioxide of exercise [V2 7041], for automatic, continuous recording of pressure, humidity, temperature and both partial pressures in every compartment that a hatch can isolate [V2 6020], and for alerts to the crew, locally and remotely, when any of them leaves its safe limits [V2 6022] [4].

10.8 Limitations

The cabin is well mixed and isothermal, so ventilation dead zones, trace contaminants and thermal control are outside the model. The beds are lumped and the desiccant half of a real assembly is absent, so the tooth and the cost of a hot swap are plausible for a teaching bed rather than predicted for a flight assembly. The leak is ten times a module's published upper value, the crews here would not meet the standard's carbon dioxide limit, and the battery, array, electrolysis and Sabatier figures are teaching values.

> **OPEN CHALLENGE** **Lower Carbon Dioxide Without More Power**
>
> Crew members on the current station have had headaches at its carbon dioxide levels, and a future removal system must hold 2 Torr with four crew. A ground test met that level with more air flow and shorter half-cycles, but the heater power alone rose by 200 W on average, and power is at a premium, the more so on missions that cannot draw on the sun [17]. A key performance parameter now asks for 2600 ppm of carbon dioxide with four crew [14]. Progress would be the flow, cycle time and heater set point with the best removal at the least power, found on a virtual test bed and confirmed on ground hardware [17].

The program's battery model is linear, its heater runs whole slots and its swap forecast does not know about visitors before they arrive. Its node limit leaves six of 236 solves unproved in the suggested week. The controller's model is the plant's own law with the plant's parameters, so the cases meet model error only through hidden states and noise. The balance's residual scatters by about 1 mol/h, so a leak step much smaller than that is found late or not at all. A simulated pass is a statement about this teaching model and not a certification of any design.

> **OPEN CHALLENGE** **Recovering More of the Oxygen**
>
> For long transit missions the target is to recover more than 75 percent of the oxygen in exhaled carbon dioxide, and more than 90 percent on a planetary surface. The paths under development improve the Sabatier reactor, recover the hydrogen that leaves in its methane by pyrolysis and return it to make more water for oxygen, or replace the reactor with more efficient Bosch technologies. On a transit to Mars every spare must launch with the vehicle, so reliability becomes paramount [14]. In this chapter's model the methane, the spare hydrogen and the carbon dioxide the reactor cannot take are all vented.

10.9 Conclusion

A sealed cabin is an inventory that machines can only add to. The simulator of this chapter integrates its four gases, two cyclic beds, oxygen and Sabatier chain, airlock, leak and battery with element balances that close to 2.2×10^{-9} mol. With nothing running, the humidity and the carbon dioxide reach their limits in hours and the oxygen in more than a day. Raising the oxygen setpoint by 1 kPa

shuts the nitrogen valve 2.52 h later because both gases share one total. The beds' tooth grows with the half-cycle, and the eclipse takes the battery below its floor at 1.478 h unless a three-orbit program keeps the electrolysis out of the dark, which holds it at 61.58 %. A pressure loop feeds a new leak inside its band while a nitrogen balance flags it in three hours. Over a week aboard, the power-aware schedule and the balance are each necessary and together pass eleven seeds out of eleven, while the feedforward changes little. The bed model is lumped and the limits are teaching values. A fuller model would add a desiccant pair, a distributed bed, a thermal loop and a stronger relaxation for the program. In a sealed system the schedule, the loops and the ledger are one control problem.

KEY POINTS

- A sealed cabin is an inventory that machines can only add to: nothing but the crew and the leak removes an excess of gas.
- Raising the oxygen setpoint by 1 kPa shuts the nitrogen valve 2.52 h later, because both gases share one total pressure.
- A pressure loop feeds a new leak inside its band, while an hourly nitrogen balance flags it in three hours.
- The eclipse takes the battery below its floor unless a three-orbit program keeps the electrolysis out of the dark, which holds it at 61.58 %.
- Over a week aboard, the power-aware schedule and the balance are each necessary, while the feedforward changes little.

Where else this applies. The gas transmission line of Volume 10, Chapter 12 finds its leaks with a balance of the same kind, metered inflow less metered outflow less the change in a line pack computed from three pressure transmitters.

References

[1] P. O. Wieland, "Designing for human presence in space: An introduction to environmental control and life support systems," National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Marshall Space Flight Center, AL, NASA Reference Publication RP-1324, 1994. [Online]. Available: https://ntrs.nasa.gov/citations/19940022934

[2] P. Eckart, *Spaceflight Life Support and Biospherics*. Springer Netherlands, 1996.

[3] M. K. Ewert, T. T. Chen, and C. D. Powell, Eds., *Life Support Baseline Values and Assumptions Document*, ser. NASA Technical Publication. Houston, TX: National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Feb. 2022, no. NASA/TP-2015-218570/REV2. [Online]. Available: https://ntrs.nasa.gov/citations/20210024855

[4] National Aeronautics and Space Administration, "NASA spaceflight human-system standard, volume 2: Human factors, habitability, and environmental health," National Aeronautics and Space Administration, Office of the Chief Health and Medical Officer, Technical Standard NASA-STD-3001, Volume 2, Revision E, 2025. [Online]. Available: https://ntrs.nasa.gov/citations/20250004555

[5] J. C. Knox, "International space station carbon dioxide removal assembly testing," in *SAE Technical Paper Series*, no. 2000-01-2345. SAE International, 2000.

[6] H. Mohamadinejad, J. C. Knox, and J. E. Smith, "Experimental and numerical investigation of adsorption/desorption in packed sorption beds under ideal and nonideal flows," *Separation Science and Technology*, vol. 35, no. 1, pp. 1–22, 2000.

[7] D. Samplatsky, K. Grohs, M. Edeen, J. Crusan, and R. Burkey, "Development and integration of the flight Sabatier assembly on the ISS," in *41st International Conference on Environmental Systems*. American Institute of Aeronautics and Astronautics, 2011, paper AIAA 2011-5151.

[8] J. Law, M. Van Baalen, M. Foy, S. S. Mason, C. Mendez, M. L. Wear, V. E. Meyers, and D. Alexander, "Relationship between carbon dioxide levels and reported headaches on the International Space Station," *Journal of Occupational & Environmental Medicine*, vol. 56, no. 5, pp. 477–483, 2014.

[9] S. Sircar, "Pressure swing adsorption," *Industrial & Engineering Chemistry Research*, vol. 41, no. 6, pp. 1389–1392, 2002.

[10] M. Baldea and I. Harjunkoski, "Integrated production scheduling and process control: A systematic review," *Computers & Chemical Engineering*, vol. 71, pp. 377–390, 2014.

[11] A. H. Land and A. G. Doig, “An automatic method of solving discrete programming problems,” *Econometrica*, vol. 28, no. 3, p. 497, 1960.

[12] R. S. Mah, G. M. Stanley, and D. M. Downing, “Reconcillation and rectification of process flow and inventory data,” *Industrial & Engineering Chemistry Process Design and Development*, vol. 15, no. 1, pp. 175–183, 1976.

[13] E. S. Page, “Continuous inspection schemes,” *Biometrika*, vol. 41, no. 1-2, pp. 100–115, 1954.

[14] J. L. Broyan, Jr., L. Shaw, M. McKinley, C. Meyer, M. K. Ewert, W. F. Schneider, M. Meyer, G. A. Ruff, A. C. Owens, and R. L. Gatens, “NASA environmental control and life support technology development for exploration: 2020 to 2021 overview,” in *50th International Conference on Environmental Systems*, no. ICES-2021-384, 2021. [Online]. Available: https://ntrs.nasa.gov/citations/20210010866

[15] P. Linstrom, “NIST chemistry WebBook, NIST standard reference database 69,” National Institute of Standards and Technology, 1997.

[16] B. D. Gardner, P. M. Erwin, T. Cougar, and B. Ulrich, “International space station major constituent analyzer on-orbit performance,” in *47th International Conference on Environmental Systems*, no. ICES-2017-17, Charleston, SC, 2017. [Online]. Available: https://ntrs.nasa.gov/citations/20170005402

[17] J. C. Knox and C. M. Stanley, “Optimization of the carbon dioxide removal assembly (CDRA-4EU) in support of the international space system and advanced exploration systems,” in *45th International Conference on Environmental Systems*, no. ICES-2015-165, Bellevue, WA, 2015. [Online]. Available: https://ntrs.nasa.gov/citations/20150016500

10.10 Exercises

10.1 Concept check · 2 min

In case 2 the oxygen setpoint is raised from 21.0 to 22.0 kPa at 1 h, and the nitrogen valve, open 6 % until then, shuts 2.52 h later. Why does it shut?

(a) The pressure loop is cascaded under the oxygen loop and takes its setpoint from the oxygen error

(b) The added oxygen lifts the total pressure past the deadband, and the pressure loop answers the total

(c) The backup oxygen tank opens and shares a supply line with the makeup valve, which it closes

(d) The analyzer reads nitrogen low when oxygen rises, so the valve answers a false reading

10.2 Concept check · 1 min

Case 7 opens a leak step at 24 h that adds about 3.9 mol/h of nitrogen loss, yet the total pressure stays between 101.001 and 101.403 kPa for the two days. What does this show?

(a) The leak is too small to move the total by more than the transducer’s noise

(b) The deadband absorbs the loss, so the valve never has to move

(c) The makeup valve replaces what the leak takes, so the pressure loop feeds the leak and hides it

(d) The leak takes oxygen first, which the electrolysis replaces before the total can move

10.3 Concept check · 2 min

In case 10 eight crew live on one healthy and one faulted bed with a daily exercise hour. Every fixed half-cycle from 36 to 240 min breaks the 0.53 kPa carbon dioxide limit, and so do the adaptive and the power-aware schedules. What is the right conclusion?

(a) A half-cycle between two of the swept values, finer than the 12 min step, would hold the limit

(b) The power-aware program needs a larger node limit to find a schedule that holds the limit

(c) The crew-activity feedforward should be on, so the exercise hour is met before the peak

(d) The exercising crew make more carbon dioxide than a fresh bed can take, so the demand must change

10.4 Theory and calculation · 6 min

The cabin of Equation (10.1) holds 400 $\mathrm{m^3}$ at 22 °C. At the start the oxygen is 21.0 kPa and the total 101.3 kPa. Take the gas constant as $R = 8.314\,462\,618 \times 10^{-3}\ \mathrm{kPa\,m^3/(mol\,K)}$.

(a) Find $\kappa = V/(RT)$ and the rise in total pressure for one mole of any gas added. *Checkpoint:* 163.00 mol/kPa and 0.006 135 kPa.

(b) The oxygen fraction is $x = p_{O_2}/P$. Show that one mole of oxygen added raises it by $(P - p_{O_2})/(\kappa P^2)$, and evaluate this in percentage points. *Checkpoint:* 0.004 801 points per mole.

(c) Write the steady gain matrix from the moles of oxygen and nitrogen added, $(\Delta n_{O_2}, \Delta n_{N_2})$, to $(\Delta p_{O_2}, \Delta P)$. Find the relative gain λ_{11} of the pairing oxygen to p_{O_2} and nitrogen to P, and the condition number of the matrix. *Checkpoint:* $\kappa^{-1}\left[\begin{smallmatrix}1 & 0\\ 1 & 1\end{smallmatrix}\right]$, $\lambda_{11} = 1$, $\gamma = 2.62$.

10.5 Theory and calculation · 6 min

Use the power model of Equation (10.6): the eclipse lasts 35 min of a 92 min orbit, the base load is 4 kW, the heater 1 kW, the array 11 kW, the battery 8 kWh with a 60 % floor, and $\eta_c = \eta_d = 0.95$.

(a) Starting full, find the energy the base load draws in one eclipse and the state of charge after an eclipse with the heater on throughout. *Checkpoint:* 2.456 kWh of the 3.2 kWh above the floor; 61.6 %.

(b) The oxygen loop's steady load replaces six resting crew (1.0 mol/h each) and the oxygen in the leak, $C_{leak}\, p_{O_2,SP}$ with $C_{leak} = 0.0118$ mol/(h kPa). With $F_e = 0.131\,74$ kWh/mol and $\eta_e = 0.70$, find that load and the state of charge after a full eclipse of it, without and with the heater. *Checkpoint:* 1.176 kW; 60.3 % and 52.6 %.

(c) Find the oxygen that full electrolysis (2 kW) makes in the sunlit part of one orbit, and compare it with what the crew and the leak use in a whole orbit. *Checkpoint:* 10.10 mol against 9.58 mol.

10.6 Theory and calculation · 6 min

Use the bed law of Equation (10.4) with $N = 2.5$, $F_b = 55\,\mathrm{m^3/h}$ and $c = 0.407\,50\,\mathrm{mol/(m^3\,kPa)}$, and the balance of Equation (10.9) with $\sigma_r = 1.0$ mol/h and $h = 5$.

(a) Find the breakthrough loading θ_b and the removal efficiency ε of a fresh bed ($\theta = 0$). *Checkpoint:* $\theta_b = 0.7227$, $\varepsilon = 0.918$.

(b) Find the largest removal of a fresh cool bed at $p_{CO_2} = 0.5$ kPa and compare it with eight crew exercising at $a = 2.5$, each giving 0.9 mol/h of carbon dioxide at rest. *Checkpoint:* 10.29 mol/h against 18.0 mol/h.

(c) A leak step raises every hourly residual by 3.9 mol/h above the reference, with no noise. How many full hours of the step does the cumulative sum need to pass h? *Checkpoint:* Two hours ($S = 3.4$, then 6.8).

10.7 App challenge · 8 min

Load scenario 1, Nothing runs: the hours to each limit, and change no setting. Use the default seed and 1 h/s. The run pauses when a limit has been out for an hour. Press Run each time until 48 h.

(a) Before running, estimate from the crew's rates and $\kappa = 163.00$ mol/kPa the hours until the humidity passes 60 % (from 50 % of 2.638 kPa), the carbon dioxide passes 0.53 kPa (from 0.37) and the oxygen falls below 19.5 kPa (from 21.0). Ignore the leak. *Checkpoint:* 1.46, 4.83 and 40.75 h.

(b) Export the file and find the first row past each limit in the columns `truth_rh_pct`, `truth_co2_kPa` and `truth_o2_kPa`. Explain the oxygen's difference from (a). *Checkpoint:* 1.47, 4.85 and 39.20 h, within 0.02 h.

(c) Read `truth_p_kPa`, `truth_co2_kPa`, `truth_o2_kPa` and `truth_n2_kPa` at 48 h, and account for the change in the total since the start. *Checkpoint:* 102.13 kPa: carbon dioxide +1.59, oxygen −1.84, nitrogen −0.27, water vapor about +1.36.

10.8 App challenge · 8 min

Load scenario 2, The oxygen loop and the pressure it shares, at the default seed and the default 0.25 h/s. Pause between 0.95 and 1.05 h, set the O_2 setpoint to 22.0 kPa, and run to 24 h.

(a) In the exported file, read `n2_valve_pct` just before the step, and find how long after the step the valve first reads zero. *Checkpoint:* 6 %; 2.53 h, within 0.05 h.

(b) At 24 h read `truth_p_kPa` and `truth_frac_pct`, and the oxygen tank used on the Consumables tile. *Checkpoint:* 102.16 kPa and 21.51 %, within 0.02; 58 mol.

(c) With the valve shut, the total falls only as the everyday leak removes nitrogen, about 0.93 mol/h. Estimate from the total in (b) when the pressure will reach the lower edge of the deadband, 101.1 kPa, so that the valve can open again. *Checkpoint:* About 186 h after 24 h, near 210 h.

10.9 App challenge · 9 min

Load the challenge, A week aboard (case 9 of Table 10.3), at the default seed. Run each week to 168 h at 4 h/s, about 42 s, and read the Challenge target tile at the end.

(a) Run the week as shipped. List the requirements it fails. *Checkpoint:* Carbon dioxide over the limit 494 min (worst 0.564 kPa), the battery below its floor 901 min, 520 mol of nitrogen, under the reserve, and the leak not flagged in time.

(b) Set the Bed schedule to Power-aware, the Crew-activity feedforward On and the Nitrogen balance test On, press Reset (which keeps the settings) and run the week again. *Checkpoint:* Met: carbon dioxide worst 0.494 kPa, battery lowest 61 %, 664 mol of nitrogen, the leak flagged after 3.0 h.

(c) From the settings of (b), turn the Nitrogen balance test Off, Reset and run. Then turn it On, turn the feedforward Off, Reset and run. Which of the two layers is necessary? *Checkpoint:* Balance off: 495 mol, under the reserve, not met. Feedforward off: met with 658 mol.

10.10 Application area · 3 min

The challenge limits the carbon dioxide to 0.53 kPa at every instant, a teaching value. The standard limits the one-hour average to 3 mmHg, and an analysis of flight reports found that the odds of a headache double for each 1 mmHg. Take $1\,\text{mmHg} = 0.133\,32\,\text{kPa}$.

(a) Convert the standard's limit to kilopascals, and the teaching limit and the suggested week's highest one-hour average, 0.490 kPa, to mmHg. *Checkpoint:* 0.400 kPa; 3.98 and 3.68 mmHg.

(b) By the headache relation, how much higher are the odds at the suggested week's highest hour than at the standard's limit? Case 3's six crew at rest average 0.375 kPa. What does that say about where a remedy must come from? *Checkpoint:* About 1.6 times; 2.81 mmHg, above a seven-day 2.5 mmHg.

10.11 Application area · 4 min

The everyday leak is $C_{leak}P$ with $C_{leak} = 0.0118\,\text{mol}/(\text{h}\,\text{kPa})$ at 101.3 kPa, and it takes the cabin's mixture. The nitrogen tank holds 900 mol at the start with a reserve of 575 mol.

(a) Find the air lost per day in moles and in kilograms, with a molar mass of the cabin air of 28.77 g/mol, and compare it with a module leakage of 0.09 kg/day. *Checkpoint:* 28.7 mol, 0.83 kg, about nine times.

(b) With the nitrogen part of the leak at 0.93 mol/h, how many days of everyday leak does the tank hold above its reserve, and how many hours with the case 7 leak step open (4.84 mol/h in all)? Each excursion vents 38.4 mol of nitrogen. *Checkpoint:* About 14.6 days; about 67 h.

10.12 Review the agent · 5 min

An AI assistant summarizes case 5 for a design review: “The adaptive schedule breaks the battery floor because its bed heater runs land in the eclipse. The power-aware program fixes this by moving the heater runs into sunlight, while the oxygen loop keeps the electrolysis as it was. On a vehicle with a smaller battery, the first measure is therefore an interlock that allows the bed heaters only in sunlight.” Find the flaw, and say how you would check the claim.