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CHAPTER 5

Vacuum Tower Cut Points Held by an Ejector Curve That Breaks

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Edited by John D. Hedengren

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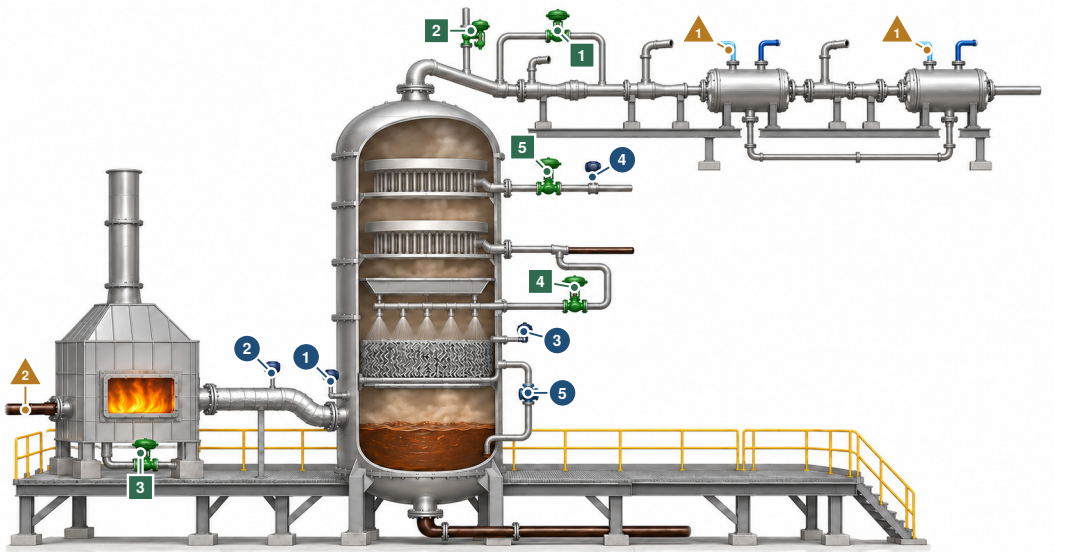
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CHAPTER 5

Vacuum Tower Cut Points Held by an Ejector Curve That Breaks



The controller moves 1 recycle valve around the first steam jet 2 air bleed valve 3 heater firing 4 wash oil valve 5 light gas oil draw valve

The controller reads 1 pressure where the feed flashes 2 heater outlet temperature 3 temperature above the wash bed 4 light gas oil temperature 5 overflash, the liquid that drains from the wash bed

What disturbs it ▲1 warm cooling water ▲2 a heavier feed ▲ air leaking in

Both valves at the first steam jet, at the top of the picture, can only raise the pressure in the tower, so the deepest vacuum is whatever the jets and their cooling water allow. Illustration, not to scale.

IN PLAIN TERMS **A Vacuum That Can Break**

The main idea. The heaviest part of crude oil would break down from the heat before it boiled, so a refinery boils it under a deep vacuum. A deeper vacuum lifts more oil for very little extra heat.

The challenge. Jets of steam make the vacuum, and they can carry away only so much leaked air and gas. Just past that limit the vacuum collapses within a minute, and it returns only when the load is cut well below the breaking point.

Why it matters. Warm cooling water lowers the limit, so a controller that pushes for more oil must watch how close the jets are to it.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	This page, the Did you know? boxes in Sections 5.1 and 5.5.2, the History boxes in Sections 5.2 and 5.3.2, the Try it boxes in Sections 5.5.3 and 5.5.4, and Key points in Section 5.8. No equations.
Study	45 min	The whole chapter in order, stopping at the three pause points, then Exercises 1 to 12.
Practice	20 min	This page, Section 5.5 with Figure 5.4, Section 5.6 and Section 5.7 with its Open challenge box.

The control question The flash-zone pressure is the cheapest handle on a vacuum tower's cut, but the ejectors that hold it break at a load the cooling water sets and recover only well below it. How far can the cut be pushed, and what must a lift controller watch?

Learning objectives

- Compute the shift of the cut per halving of the pressure from a vapor pressure line.
- Calculate an ejector set's critical and recovery loads from its curve and the cooling water.
- Explain why the wash oil holds the heavy gas oil's 95 % point and the overflash protects the wash bed.
- Measure a break and its hysteresis, and explain why an air bleed spends the critical load.
- Explain why a lift controller blind to the ejector load runs the heater to its limit.

Prerequisites Sections 1.4.3, 1.4.2, 1.4.6, 1.4.7 and 1.6.2, and Chapter 4 for the crude curve.

The app https://apmonitor.com/apps/vacuum-tower/

See also Volume 4, Chapter 2 for a limit cycle under a protective override, Volume 4, Chapter 4 for overrides that push throughput, Volume 5, Chapter 10 for an inferred quality corrected by a late laboratory and Volume 5, Chapter 3 for control through a slow analyzer.

5.1 Introduction

The residue of an atmospheric crude tower boils above 383 °C, and its heavier half would crack long before it boiled at atmospheric pressure. The vacuum tower simulated here takes 350 t/h of that residue through a heater to 405 °C and flashes it at 40.0 mbar a (30.0 mmHg), where 63.8 % of it vaporizes. Held at 30 mbar a instead of 50 with the same heater outlet and wash oil, the heavy vacuum gas oil (HVGO) grows from 130.3 to 155.1 t/h and its 95 % point climbs from 545.8 to 570.5 °C, past its 565 °C limit, for 0.7 MW more firing. No other handle on the unit moves the cut that far for so little heat. The pressure is made by three steam ejectors in series. Raising the air leaking into the tower from 120 to 600 kg/h lifts the flash zone only from 40.0 to 45.3 mbar a, but at about 695 kg/h the first stage breaks and the flash zone passes 70 mbar a within a minute, and the stage does not recover until the leak is cut to between 560 and 564 kg/h.

DID YOU KNOW? A Second Tower for the Heavy End of the Barrel

On 1 January 2026 the refineries of the United States could charge 8.4 million barrels per stream day to vacuum distillation, beside 19.2 million barrels of crude oil [1]. At the reduced pressure the columns are built with larger diameters than atmospheric ones, to keep comparable vapor velocities [2].

Two beliefs are what the simulator sets out to correct. The first is that a pressure loop on a vacuum tower is a free handle on the cut, whose cost grows smoothly with how hard it is pushed. In this plant the constraint underneath the loop has a cliff, a jump of 35 mbar on the ejector suction once the intercondenser after the first stage reaches the stage's maximum discharge pressure, and a hysteresis that makes the fix go further than the fault did. The second is that more heat always means more lift. Once the stage has broken the lift falls, and a lift controller that does not watch the ejector load answers by firing harder, which only adds cracked gas, so it drives the heater outlet to its limit. Plants with the same shape are common, among them compressors near surge (Volume 4, Chapter 2), condensers near their cooling limit and any unit whose capacity limit is a fold rather than a ceiling. Selector logic for active constraint switching is the general answer [3], and the industrial practice of pushing a unit against its constraints is usually written as model predictive control [4]. The vacuum tower adds that the constraint's position moves with the afternoon's cooling water.

However, the material a student meets keeps these pieces apart. Ejector analysis treats one stage and its mixing [5], unstable-mode testing treats the ejector set without the tower above it [6], troubleshooting texts describe the tower and its vacuum system from the field [7], and optimization studies of the column and its ejectors work at steady state [8]. This chapter works with a simulated

vacuum unit in which the cut, the ejector curve, the wash bed and the heater interact on one clock. It measures what a pressure step, an air leak, a starved wash bed, a hotter heater, warm cooling water, a heavier residue and a lift controller do to it. The equilibrium flash [9], the boiling point characterization [10, 11], the water vapor pressure [12] and the proportional-integral (PI) loops are all established practice. The results are measurements, taken on one generic unit at one seed. Among them, the app's teaching vapor pressure line shifts the cut 26 to 41 K per halving of the pressure where the design brief for the app expected about 10 K, and this is about a fifth more than the same flash gives with the Maxwell–Bonnell correlation [13]. The model has 17 states and a residue balance that closes to 2.1×10^{-14}. It is built on the same crude curve as the atmospheric tower of Chapter 4 and on a water vapor pressure copied unchanged from the flash steam vessel of Volume 1, Chapter 6, and the chapter gives every equation and default needed to rebuild it. Each of nine cases carries a rule that grants credit only for what the learner does and what the unit then reaches (Section 1.6.4).

Section 5.2 follows the domain from the first vacuum stills to the field practice of ejector troubleshooting. Section 5.3 sets out the unit: the residue and its vapor pressure line, the flash zone, the ejectors with their break, the wash bed and draws, the heater and the instruments, and the numerics and assumptions. Section 5.4 gives the four loops, the high select on the wash oil, the maximizer and the three models in play. Section 5.5 measures the cases: pressure and the cut (Section 5.5.1), the break and its hysteresis (Section 5.5.2), the wash oil, the heater and the cracked gas (Section 5.5.3), summer water and a heavier residue (Section 5.5.4) and the graded challenge (Section 5.5.5). Section 5.6 sets the loops beside the hardware of a working unit. Sections 5.7 and 5.8 state the limitations and conclude.

5.2 Vacuum, Ejectors and the Heavy Gas Oil

Vacuum distillation of petroleum began with lubricating oils, as the History box below relates. Fractions were characterized by their boiling ranges, and a 1933 method approximated the critical and thermal properties of petroleum fractions [10]. A temperature read under vacuum still had to be turned into a normal boiling point before it could be compared with a crude assay, and in 1957 Maxwell and Bonnell published a vapor pressure correlation for petroleum hydrocarbons that does that conversion [13] and that an open-source process simulator still implements. Computers then took over the flash itself, as the History box in Section 5.3.2 relates. A 2005 ASTM manual characterizes petroleum fractions as pseudo-components cut from the true boiling point curve, each with a correlated molar mass, latent heat and vapor pressure [11].

> ⧖ HISTORY **1883 to 1932: Vacuum Stills Begin With Lubricating Oil**
>
> Vacuum distillation of petroleum began with lubricating oils. A book of 1922 lists vacuum stills designed as far back as Henderson's of 1883, all working at relatively low vacuum, and a plant for high vacuum patented by Steinschneider in 1911 [14]. The still was strengthened against the outside pressure, the oil was always distilled with steam, and an air pump held the vacuum on a condenser set at the top of a barometric water column. The same book judged that vacuum had not received the attention it deserved, and it saw no advantage in applying it to the volatile fractions of crude oil [14]. A 1932 account credits the vacuum process with less cracking, a better separation of fractions and a lower heat input and condensing load [15]. Steam still enters the tower of this chapter, but steam ejectors hold its vacuum.

The vacuum came from steam. A one-dimensional analysis of ejectors with constant-pressure and constant-area mixing, checked against experiments, was published in 1950 [5], and multistage condensing ejectors with intercondensers are the subject of a 1994 monograph for the process industries [16]. Such ejectors have an unstable mode in which a critical stage loses its pumping capacity, and a 1994 test procedure measured it and predicted the cyclic region between the stable and unstable modes [6]. Field practice names the same events, the critical discharge pressure exceeded,

Table 5.1 Variables by Role at the Design Point (Case 2 at $t = 0$)

Symbol	Role	Design	Range
p_{fz}	CV, flash-zone pressure (mbar a)	40.0	SP 25–80
COT	CV, coil outlet (°C)	405.0	SP 385–440
$T_{95,inf}$	CV, HVGO 95 % point, inferred (°C)	558.0	SP 530–580
$T_{LV,inf}$	CV, LVGO cut point, inferred (°C)	428	SP 400–460
OF	CV (override), overflash (% of F)	4.43	floor 1–6
u_r, u_b	MV, recycle, air bleed valve (%)	46, 0	0–100
Q	MV, absorbed duty (MW)	22.6	0–40
r	MV, wash oil ratio (% of gas oil)	10.8	2–25
D_L	MV, LVGO draw (t/h)	70.0	20–140
G_{leak}	DV, air leak (kg/h)	120	0–1200
T_{cw}	DV, cooling water (°C)	28	15–40
S_{strip}	DV, stripping steam (t/h)	1.0	0–8
F	DV, residue charge (t/h)	350	250–420
τ_{tail}, m_{AR}	DV, tail stretch (°C), metals (ppm)	0, 40	0–100, 10–100
D_H	output, HVGO on pan level (t/h)	142.3	—
VR	output, vacuum residue (t/h)	137.4	—
T_{fz}, V/F	output, flash zone (°C), lift (%)	389.3, 63.8	—
G_{nc}, G_{crit}	output, vent gas, critical load (kg/h)	384, 964	—
m_H	output, HVGO Ni + V (ppm)	0.47	limit 1.0
T_{skin}	output, tube skin (°C)	489	limit 560

vacuum breaking, the water vapor pressure as a limit, warm cooling water, air leaks, cracked gas from the heater outlet temperature, and a positive feedback loop in vacuum tower pressure control [7].

In a fuels vacuum unit the wash section above the flash zone decides how deep a cut can go at a given gas oil quality [17]. Entrainment from industrial flash zones is typically 3 to 5 %, at least 98 to 99 % of it can be knocked back by a well-designed wash bed, and what passes carries the residue's metals into the HVGO [17]. Designers set the wash oil by an overflash target at the bottom of the bed, typically 0.1 to 0.2 gpm/ft^2 at 60 °F, and on heavy crudes six-year runs between wash-bed replacements are typical [18]. The reasons for a low HVGO yield from residual fuel oil have been examined [19], process models of the whole vacuum unit are part of integrated refinery modeling [20], and the column and its ejector system have been optimized together [8]. The control problem on the regulatory layer, a pressure loop that can only add load, a quality loop that moves the wash oil and a lift pushed against the ejectors, is the subject of this chapter.

5.3 The Unit as Modeled

The simulated unit is generic, with no plant behind it, and its sizes are teaching values. Its layout is shown in Figure 5.1. Atmospheric residue at 350 t/h and 360 °C passes a fired heater to the coil outlet temperature COT, and a transfer line drops it 120 mbar into the flash zone of a damp tower with 1.0 t/h of stripping steam and 0.5 t/h of coil steam. The vapor rises through a wash bed, an HVGO pumparound section with its pan, and a light vacuum gas oil (LVGO) pumparound section. The LVGO is drawn on flow, the HVGO drains its pan on level, and part of it returns as wash oil. What reaches the bottom of the wash bed is the overflash, which joins the vacuum residue to the coker of Chapter 11. Steam, air and cracked gas leave the top to three ejector stages with intercondensers, and a recycle from the first stage's discharge or an air bleed sets the pressure.

Table 5.1 lists the variables by role. The model integrates 17 states: the first-stage suction p_s, the beds' pressure drop Δp, the recycle and bleed valve positions u_r and u_b, the absorbed duty Q, the COT, the two lagged cut points T_{cut} and T_{LH}, the LVGO draw D_L, the wash oil W, the wash bed holdup H_w and coke K_w, the HVGO pan inventory M_{pan}, the coil coke δ, the top temperature T_{top}, and two ledgers of residue fed and products made. Time is in minutes, flows in t/h (gas loads in kg/h), pressures in mbar absolute and temperatures in °C.

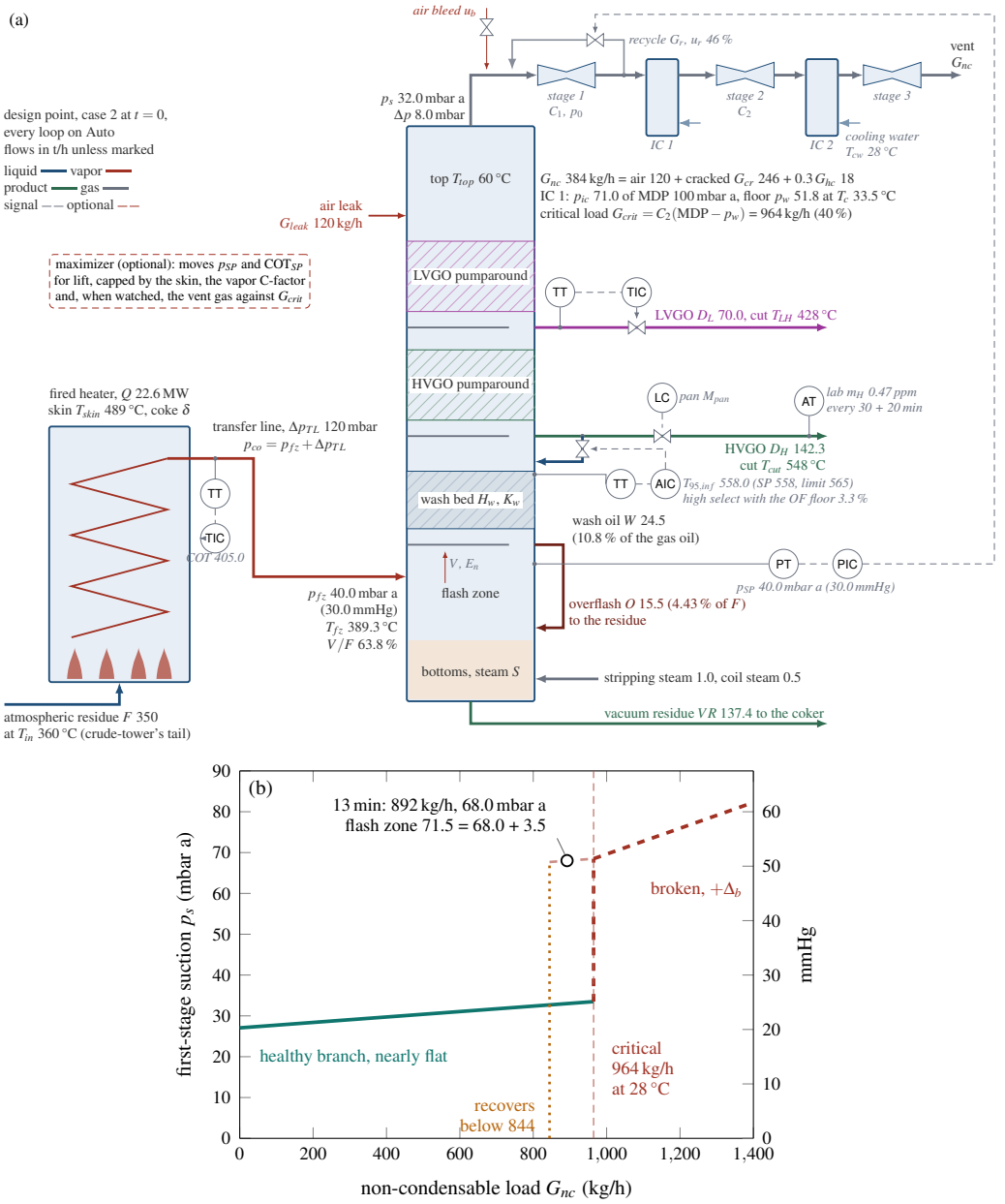


Figure 5.1 The vacuum unit as modeled. (a) Drawn after the Tower view of case 2 at $t = 0$, the design point with every loop on Auto, with the heater at 22.6 MW, the flash zone at 40.0 mbar a and 389.3 °C, the wash bed with its overflash collector, the HVGO pan on level with the wash oil returned above the bed, the LVGO draw, and the ejector set with the recycle around stage 1 and the air bleed. Flows in t/h unless marked. Process model only, not to scale. (b) The first-stage suction against the non-condensable load as the Ejectors view of case 2 draws it at 13 min, after the leak was raised to 700 kg/h and returned to 600 kg/h: the healthy branch to the critical load (thick solid), the 35 mbar jump and the broken branch (thick dashed), the hysteresis band (faint dashed) back to the recovery load (dotted), the critical load (thin dashed) and the operating point (open circle), still broken.

5.3.1 The Residue and Its Vapor Pressure

The feed is the tail of the crude curve of the atmospheric tower app, imported from that app unchanged so that the two towers slice the same crude. On it 40.0 % of the crude boils above 383 °C, 65.3 % of that residue boils below 565 °C and 16.7 % above 650 °C. The residue is cut into 13 slices of about 20 K up to 650 °C and one pitch lump that never vaporizes, and each slice has a vapor pressure on a line through its normal boiling point $T_{b,i}$, as shown in Equation (5.1).

$$\begin{aligned} z_i &= c(T_{i+1}) - c(T_i), \quad c(T) = \frac{v(T) - v_{383}}{1 - v_{383}} \\ \ln \frac{p_i^{sat}}{p_{atm}} &= A\left(1 - \frac{T_{b,i}}{T}\right), \qquad \lambda_i = \frac{ART_{b,i}}{M_i} \\ M_i &= 330\,\mathrm{g/mol}\,(T_{b,i}/673.15\,\mathrm{K})^{2.5} \end{aligned} \tag{5.1}$$

where $v(T)$ is the cumulative fraction of the crude boiling below T on the atmospheric tower's curve and v_{383} its value at 383 °C, z_i the mass fraction of slice i (taken equal to its volume fraction), T and $T_{b,i}$ absolute, $p_{atm} = 1013.25\,\mathrm{mbar}\,a$, R the gas constant, λ_i the latent heat and M_i a teaching molar mass law. A heavier residue stretches the curve above 383 °C by $\tau_{tail} x$ at a distilled fraction x of the residue. With $A = 16$ the design case cuts near 550 °C. The atmospheric equivalent temperature of a temperature T read at a hydrocarbon partial pressure p follows from the same line, $\mathrm{AET}(T, p) = T\,(1 + \ln(p_{atm}/p)/A)$ in kelvin, which is Equation (1.13) of Chapter 1, and its inverse $\mathrm{boil}(T_b, p)$ is the temperature at which a slice of normal boiling point T_b boils at p.

The line is a teaching value, not the Maxwell–Bonnell correlation [13]. Compared with that correlation in the form an open-source process simulator implements it, with a Watson factor of 12, which reproduces n-hexadecane's normal boiling point from its 10 mmHg point within 0.9 K, the line puts the normal boiling point of what boils at 391 °C under 40 mbar a at 525.2 °C against 528.1 °C, and over 380 to 400 °C and 20 to 80 mbar a the two agree within 7.1 K. Their slopes differ more. Halving the pressure at 391 °C lets a component 28.8 K heavier boil on the line, $T \ln 2/A$, and 24.0 K by Maxwell–Bonnell, so the line overstates the shift by about a fifth, the same as a line constant of 19.2.

5.3.2 The Flash Zone

The flash zone is one equilibrium stage with the steam as an inert vapor, solved by the Rachford–Rice equation [9] and reached from the coil outlet at constant enthalpy, as shown in Equation (5.2).

$$\begin{aligned} &\sum_i \frac{n_i(K_i - 1)}{1 + \beta(K_i - 1)} + \frac{n_s}{\beta} = 0, \qquad K_i = \frac{p_i^{sat}(T_{fz})}{p_{fz}} \\ &F c_p\,(\mathrm{COT} - T_{fz}) = H_V(T_{fz}, p_{fz}) \\ &\qquad\qquad - H_V(\mathrm{COT}, p_{fz} + \Delta p_{TL}) \end{aligned} \tag{5.2}$$

where $n_i = F z_i / M_i$ and n_s are the molar flows of the slices and the steam, β is the vapor share of all moles, $K = 0$ for the pitch, $H_V = \sum_i \lambda_i V_i$ is the latent heat carried by the vapor V_i at the named conditions, $c_p = 2.8\,\mathrm{kJ/(kg\,K)}$ and $\Delta p_{TL} = 120\,\mathrm{mbar}$. The temperature is found by the Illinois method on a fixed bracket and the vapor fraction by Newton steps held inside $(0, 1)$, so the flash is a pure function of its inputs. At design $T_{fz} = 389.32\,^{\circ}\mathrm{C}$, 15.68 K under the outlet, 223.4 t/h of oil vaporizes, and the vapor is 86.7 % hydrocarbon by moles ($y_0 = 0.867$). A lower pressure therefore lifts more oil at a slightly cooler flash zone.

> ⧖ HISTORY **1952: A Flash Calculation Arranged for a Machine**
>
> In 1952 a technical note in a petroleum journal observed an increasing interest in electronic digital computers for research and engineering calculations [9]. A problem, it said, must often be formulated for a machine quite differently from the way it would be arranged for manual solution, to use the machine's speed and to limit the need for number storage. The note arranged the vapor-liquid equilibrium of a flash vaporization as one implicit equation in one variable, a form well suited to sequence-controlled computing equipment [9]. That equation is the form the flash zone of this chapter solves, with the steam added as an inert vapor, in Equation (5.2).

5.3.3 Ejectors, the Break and the Pressure

The first stage empties the tower's vapor space at a capacity proportional to its suction pressure, and the intercondenser after it sets the pressure the stage discharges against, as shown in Equation (5.3).

$$\begin{aligned}
\frac{\mathrm{d}p_s}{\mathrm{d}t} &= \kappa\left[G_1 - 1000\,C_1\,(p_s - p_0 - \Delta_b)\right] \\
G_1 &= 1000\,S + G_{nc} + 0.7\,G_{hc} + G_r \\
G_{nc} &= G_{leak} + G_{cr} + B_{max}u_b + 0.3\,G_{hc} \\
p_{ic} &= p_w(T_c) + G_{nc}/C_2, \quad T_c = T_{cw} + \Delta T_{app} + \Delta T_{st}S \\
G_{crit} &= C_2\,(\mathrm{MDP} - p_w) \\
G_r &= 1000\,R_{max}u_r\sqrt{(p_{ic} - p_s)/50}
\end{aligned} \tag{5.3}$$

where $\kappa = RT/(V_g\bar{M})$ with 333 K, the vapor space $V_g = 2000\,\mathrm{m}^3$ and 19 g/mol, or 0.729 mbar per kg, G_1 is the first stage's load in kg/h (steam S in t/h, light oil G_{hc} of which 30 % is taken as non-condensable, and recycle G_r), $C_1 = 0.15\,\mathrm{t/(h\,mbar)}$, $p_0 = 3\,\mathrm{mbar}\,a$, $C_2 = 20\,\mathrm{kg/(h\,mbar)}$, the maximum discharge pressure $\mathrm{MDP} = 100\,\mathrm{mbar}\,a$, $\Delta T_{app} = 4\,\mathrm{K}$, $\Delta T_{st} = 1\,\mathrm{K}$ per t/h and p_w is the water vapor pressure of IAPWS-IF97 Region 4 [12]. That routine is copied byte for byte from the flash steam app, and its error against the release's verification values is below 1.8×10^{-9} at 300, 500 and 600 K. The stage breaks when p_{ic} reaches the MDP, which sets $\Delta_b = \Delta_{b,0} + k_b \max(0, p_{ic} - \mathrm{MDP})$ with $\Delta_{b,0} = 35\,\mathrm{mbar}$ and $k_b = 0.5$, and it recovers only when p_{ic} falls $h = 6\,\mathrm{mbar}$ under the MDP. Against the non-condensable load the suction $p_s = p_0 + \Delta_b + G_1/(1000C_1)$ is therefore nearly flat to the critical load and then jumps, the declared teaching curve of Figure 5.1b, with G_{crit} falling as the water warms, 964 kg/h at 28 °C, 709 at 32 and 637 at 33 °C. The stage's own slope gives a pressure time constant of $60/(\kappa\,1000\,C_1) = 0.55\,\mathrm{min}$.

The flash zone sits above the suction by the pressure drop of the overhead and the beds, which grows with the vapor's kinetic energy and with coke in the wash bed, as shown in Equation (5.4).

$$\begin{aligned}
p_{fz} &= p_s + \Delta p, \qquad \phi_K = 1 + 0.35\left[(1 - K_w)^{-2} - 1\right] \\
\tau_{\Delta p}\frac{\mathrm{d}\Delta p}{\mathrm{d}t} &= \Delta p_0\,\frac{n^2\bar{M}T/p_{fz}}{(n^2\bar{M}T/p_{fz})_0}\,\phi_K - \Delta p
\end{aligned} \tag{5.4}$$

where n is the vapor's molar flow, $\bar{M}$ its molar mass, T the flash zone temperature, the subscript 0 the design, $\Delta p_0 = 8\,\mathrm{mbar}$ and $\tau_{\Delta p} = 0.1\,\mathrm{min}$. Cracked gas comes from the coil and from the hot bottoms, $G_{cr} = G_{h0}2^{(\mathrm{COT}-405)/12} + G_{b0}2^{(T_{fz}-390)/12}$ with $G_{h0} = 150$ and $G_{b0} = 100\,\mathrm{kg/h}$, and the light oil the top pumparound does not condense is $G_{hc} = 60\exp((T_{top} - 60)/8)$ in kg/h, capped at 4000 kg/h, with the top relaxing in 2 min toward 60 °C, or 175 °C with the pumparound tripped. At design $G_{nc} = 384\,\mathrm{kg/h}$ (air 120, cracked gas 246, light oil 18), 39.8 % of the critical load, $p_{ic} = 71.0\,\mathrm{mbar}\,a$ over a water floor of 51.8 mbar a at 33.5 °C, and the recycle valve at 45.7 % returns 2.42 t/h.

5.3.4 Wash Bed, Draws and the 95 % Point

Residue droplets ride up with the vapor, and the wash bed holds a liquid inventory fed by the wash oil and the droplets it catches, emptied by evaporation and by drainage, as shown in Equation (5.5).

$$\begin{aligned} \frac{\mathrm{d}H_w}{\mathrm{d}t} &= W + (1-P)E_n - E_v - O, \quad E_v = \frac{\varepsilon V H_w}{H_w + H_h} \\ O &= \frac{H_w}{\tau_w}, \quad \omega = \min\Big(1, \frac{O}{O_{wet}}\Big), \quad E_n = e_0\Big(\frac{C}{C_0}\Big)^{n_E} V \\ P &= \min\Big(1,\ P_0\Big(\frac{C}{C_0}\Big)^{1.5}\sqrt{\frac{W_{ref}}{W}} + (1-\omega)^2\Big) \\ \frac{\mathrm{d}K_w}{\mathrm{d}t} &= k_K\,(1-\omega)^2 \end{aligned} \tag{5.5}$$

where $C = n\sqrt{T\bar{M}/p_{fz}}$ is a C-factor index, $e_0 = 0.02$, $n_E = 2$, $P_0 = 0.03$, $\varepsilon = 0.06$, $H_h = 0.01\,\mathrm{t}$, $\tau_w = 8\,\mathrm{min}$, the wetting minimum O_{wet} is 1.5 % of the feed, W_{ref} is 12 % of the design vapor and $k_K = 0.0025$ per minute. The wash oil actually delivered, written W below, is $W\min(1, M_{pan}/M_{lo})$ with $M_{lo} = 2\,\mathrm{t}$, so a starved pan starves the bed. At design 2.0 % of the vapor is entrained, the level a packing vendor reports for a well-designed vapor horn in tests and below the 3 to 5 % of industrial flash zones, and a wet bed catches 96.9 % of it, between the 95 % of that vendor's poorest case and the 98 to 99 % it calls attainable [17]. A dry bed passes 99.4 % and loses 17 % of its open area to coke in the 80 min case 4 keeps it dry, a compressed teaching rate against the six-year runs reported on heavy crudes [18].

The HVGO drains its pan on level, so its yield is what the lift leaves after the LVGO, the gas and the wash oil, and the cuts follow the products along the crude curve, as shown in Equation (5.6).

$$\begin{aligned} \dot{M}_{pan} &= V + E_v + PE_n - D_L - G_{hc} - W - D_H \\ D_H &= (M_{pan} - M_{lo})/\tau_{pan}, \quad VR = L_f - E_n + O \\ \tau_{cut}\dot{T}_{cut} &= T_{AR}\big((D_L + D_H)/F\big) - T_{cut} \\ T_{95} &= T_{cut} + \beta_H/\sqrt{W/D_H} \end{aligned} \tag{5.6}$$

where E_v is the evaporation of Equation (5.5), $T_{AR}(x)$ the residue's curve at distilled fraction x, $L_f = F - V - G_{cr}$ the flash-zone liquid after cracking, $\tau_{pan} = 3\,\mathrm{min}$, $\tau_{cut} = 6\,\mathrm{min}$ and $\beta_H = 4\,\mathrm{K}$. The LVGO cut T_{LH} follows $T_{AR}(D_L/F)$ in 4 min. The HVGO metals are what distills with a deep cut plus the droplets that pass the bed, $m_H = [0.4\,2^{(T_{95}-560)/15}D_H + PE_n m_{AR}F/L_f]/D_H$ in ppm. Of the design 0.47 ppm, 0.36 distills and the rest is entrainment. The residue ledgers close to 2.1×10^{-14} of the throughput over a disturbed 45 min run, and to at most 4.5×10^{-14} over four other seeds and the halved step.

5.3.5 Heater and Instruments

The firing reaches the coil through a 1 min firebox lag, and the coil's heat capacity integrates the duty against the sensible heat and the latent heat of what the coil outlet has already vaporized, as shown in Equation (5.7).

$$\begin{aligned} C_{coil}\frac{\mathrm{d}\,\mathrm{COT}}{\mathrm{d}t} &= 60\Big[Q - \frac{F h_{need}}{3600}\Big] \\ h_{need} &= c_p(\mathrm{COT} - T_{in}) + H_V^{co}/F \\ T_{skin} &= \mathrm{COT} + 45\,Q/Q_{ref} + \beta_c\,\delta \\ \frac{\mathrm{d}\delta}{\mathrm{d}t} &= k_c\,2^{(T_{film}-450)/10} \end{aligned} \tag{5.7}$$

where H_V^{co} is the latent heat of the vapor already made at the coil outlet (the skin follows the form of Equation (1.3)), $C_{coil} = 70\,\mathrm{MJ/K}$, Q in MW, F in t/h, $Q_{ref} = 26\,\mathrm{MW}$, $T_{film} = \mathrm{COT} + 45Q/Q_{ref}$,

Table 5.2 Parameters: A, Adjustable in the Parameter Panel. H, Hidden. S, Set in the Source. All Are Teaching Values

Symbol	Meaning	Value	Unit	
A	vapor pressure constant	16	—	A
c_p, T_{in}	residue heat capacity, inlet	2.8, 360	kJ/kg/K, °C	A
Δp_{TL}	transfer line drop	120	mbar	A
C_{coil}, τ_{fb}	coil capacity, firebox lag	70, 1.0	MJ/K, min	A
Q_{max}	absorbed duty limit	40	MW	A
β_c, δ_0	skin rise per coke, start coke	15, 3	K/mm, mm	A
k_c	coking rate at 450 °C film	0.004	mm/day	A
Q_{ref}, film	film rise reference	26, 45	MW, K	H
G_{h0}, G_{b0}	cracked gas, coil, bottoms	150, 100	kg/h	A
—	rise that doubles cracking	12	K	A
p_0, C_1	stage 1 shutoff, slope	3, 0.15	mbar a, t/h/mbar	A
MDP, C_2	max discharge, stage 2 slope	100, 20	mbar a, kg/h/mbar	A
ΔT_{app}, ΔT_{st}	approach, rise per t/h steam	4, 1	K	A
$\Delta_{b,0}$, h	jump at break, hysteresis	35, 6	mbar	A
k_b	jump per mbar over the MDP	0.5	—	H
V_g	tower vapor space	2000	m^3	A
R_{max}, B_{max}	recycle, bleed capacity	6, 1500	t/h, kg/h	A
Δp_0	beds' drop at design	8	mbar	A
e_0, n_E	entrainment, exponent	0.02, 2	—	A
P_0, ε	wet-bed pass, evaporation	0.03, 0.06	—	A
τ_w, O_{wet}	bed drain time, wetting minimum	8, 1.5	min, % of F	A
k_K	dry-bed coking rate	0.0025	per min	A
τ_{pan}, τ_{cut}, τ_{LH}	pan, cut lags	3, 6, 4	min	A
β_H, m_{d0}	tail spread, metals at 560 °C	4, 0.4	K, ppm	A
—	95 % point, metals, OF limits	565, 1.0, 3	°C, ppm, %	A
$T_{skin,max}$	tube skin limit	560	°C	A
—	slice width, pitch cut	20, 650	K, °C	S
—	light oil taken as non-condensable	0.3	—	S

$\beta_c = 15\,\mathrm{K/mm}$, $\delta_0 = 3\,\mathrm{mm}$ and $k_c = 0.004\,\mathrm{mm/day}$. The run left is the skin's margin to 560 °C over its rate of rise, 1768 days at design. Only a measurement packet reaches the controllers. Pressures lag 0.03 min, the COT 0.1 min, the wash-bed and LVGO thermocouples 0.5 min and the flows 0.1 to 0.2 min, with colored noise of 0.2 min correlation scaled to 0.08 mbar on p_{fz}, 0.06 mbar on p_s, 0.15 K on the COT, 0.25 K on the two thermocouples and 3 kg/h on the vent gas. The metals laboratory samples every 30 min and reports 20 min later, a sampled delay of the kind Equation (1.12) describes. Both cut points are inferred, as shown in Equation (5.8).

$$T_{95,inf} = \mathrm{AET}(T_{wb}, y_0 p_{wb}), \quad p_{wb} = p_{fz} - 0.35\,(p_{fz} - p_s) \tag{5.8}$$

where $T_{wb} = \mathrm{boil}(T_{95}, y\,p_{wb})$ is the vapor leaving the wash bed with y the true hydrocarbon share. The LVGO cut is inferred the same way from its draw temperature at p_s. A change in steam changes y, which the inferential does not see (Section 1.4.6).

5.3.6 Initialization, Numerics and Assumptions

Each case starts lined out on its setpoints. A steady-state solve puts the flash zone on its setpoint with the selected valve where it must be, the heater on its COT, the wash bed and pan at their balances and, for the quality loops on Auto, the LVGO draw and the wash ratio where the inferred cut points sit on their setpoints, never below the ratio that holds the overflash floor. The integrator is the engine's classical fourth-order Runge–Kutta method (Section 1.6.1) at 0.02 min (1.2 s), the controllers run every 0.04 min and the historian logs ten rows a minute. Halving the step moves the 235 quantities of the case measurements by at most one printed digit, such as case 2's break time (10.04 to 10.02 min) and the challenge's break (352.4 to 352.3 min), except the count of case 3's limit cycle, 21 to 22 in 20 min. Table 5.2 gives the parameters.

Table 5.3 Loops, Their Defaults and Limits

Loop	Measurement → handle	K_c, τ_I	Output
PIC	p_{fz} → recycle or bleed	2.5 %/mbar, 0.3 min	0–100 %
TIC	COT → absorbed duty	0.5 MW/K, 3 min	0–40 MW
AIC	$T_{95,inf}$ → wash ratio	0.4 %/K, 10 min	2–25 %
OF floor	overflash → wash ratio	1 %/%, 10 min	2–25 %
TIC	$T_{LV,inf}$ → LVGO draw	1.0 t/h per K, 5 min	20–140 t/h

The model is lumped. The flash zone is one equilibrium stage, and the stripping, wash and pumparound sections are lagged cut points with one tail spread, so it says nothing about tray or packing hydraulics, flooding or weeping. Mass fractions equal volume fractions, and the pitch above 650 °C never boils. The vapor pressure line runs about a fifth steeper than Maxwell–Bonnell. The ejector set is a declared curve, real curves and maximum discharge pressures come from the vendor and differ stage by stage [16], and the unstable region of a real ejector is a band of cyclic operation [6] rather than a latched flag. Cracked gas, entrainment, wash bed coking, metals and coil coking are teaching laws with declared constants, and the dry wash bed cokes in minutes so a case can show it. Only the mass balance closes exactly, while the steam passes through and the energy balance is used only for the coil and the transfer line.

5.4 Loops and Maximizer as Implemented

5.4.1 The Loops

Four loops close on the measurement packet, listed in Table 5.3. The Manual and Auto switch in the header overrides all, and each loop also has its own switch, so a loop on Man leaves its station with the operator. The pressure, heater and LVGO loops run the velocity-form PID law of Section 1.6.2 with the derivative off, as shown in Equation (5.9).

$$\begin{aligned} e_k &= \sigma\,(r_k - y_k), \qquad s_k = s_{k-1} + K_c\,(e_k - e_{k-1}) \\ \hat{u}_k &= s_k + I_{k-1}, \qquad u_k = \min(u_{max}, \max(u_{min}, \hat{u}_k)) \\ I_k &= I_{k-1} + \left[\frac{K_c}{\tau_I} e_k + \frac{u_k - \hat{u}_k}{\tau_I}\right]\Delta t \end{aligned} \tag{5.9}$$

where r_k is the setpoint, y_k the measurement, $\sigma = +1$ for all three (more recycle raises the pressure, more firing the COT, more LVGO the LVGO cut) and $\Delta t = 0.04$ min. In the symbols of Chapter 1, s_k is the running sum S_k of Equation (1.17), $\hat{u}_k$ is the output v_k before limiting of Equation (1.18) and the tracking time T_t of Equation (1.19) equals τ_I. The recycle only adds load to a stage that pulls as hard as it can, so the loop can raise the pressure above what the ejectors pull but never below it. A loop that is not driving its valve tracks it, so every transfer is bumpless.

The HVGO quality loop has no draw to move, so it moves the wash oil. Its ratio is the high select of two positional PI branches, the 95 % point and the overflash floor of 3.3 %, $r = \max(K_W e_{95} + I_W,\ K_O e_{OF} + I_O)$ with $e_{95} = T_{95,inf} - T_{95,SP}$ and $e_{OF} = \mathrm{OF}_{min} - \mathrm{OF}$. Each branch's integral is pulled toward the applied ratio over its own integral time instead of being set onto it, because when the app was built the shared PID's exact tracking rectified the 95 % point's noise through the select into a one-way climb of the wash ratio. The wash oil is r times the measured lifted gas oil, $D_L + D_H + O$.

5.4.2 The Maximizer

In Maximizer mode a constraint-pushing selector moves the pressure and COT setpoints every minute. It is not an optimization and solves nothing. Its lift signal is $e = (r^* - r)/r^* + (T_{95,SP} - T_{95,inf})/20$, filtered over 10 min, with $r^* = 11$ % the target wash ratio. Short of lift by more than 0.05, it lowers the pressure setpoint first, while the valve has room and the C-factor index is under 125 % of design, and then raises the COT. With lift to spare it lowers the COT first, down to 395 °C. Each move is at

Table 5.4 The Nine Cases

#	Settings and events	Teaching point
1	50 mbar a, wash oil by hand, learner lowers p_{SP} to 30	pressure moves the cut
2	PIC on Man, learner raises the air leak	the break, hysteresis
3	p_{SP} 40, 36, 44, 40 at 3, 8, 13 min, then air bleed	recycle against bleed
4	AIC on Man, learner cuts the wash oil to 4 %	a dry bed, metals, coke
5	design, learner raises the COT to 420 °C	the heater limit
6	leak 520 kg/h, PIC on Man, maximizer with load ignored	controller runaway
7	leak 250 kg/h, water 28 to 35 °C over 10–70 min	summer vacuum
8	tail +60 °C, 60 ppm metals at 10 min	an infeasible yield
9	challenge, 8 h: leak +300 at 2 h, water +5 °C from 5 h	the whole problem

most 0.5 K or 0.5 mbar per minute. Overrides cut the COT when the skin comes within 5 K of its limit and, when the ejector load is watched, when the measured vent gas comes within 15 % of the critical load the vendor curve gives at the measured water, and by 1 K a minute while the stage's discharge alarm reports it broken, and the pressure setpoint rises when the C-factor index passes its limit. With the load ignored, the maximizer does not know the ejectors exist. This is a selector and not model predictive control [4], and its structure is the active constraint switching of selector logic [3] that Section 1.4.7 places between the regulatory loops and optimization.

5.4.3 Three Models

The plant is Section 5.3. The identified model a learner can fit is the gain from pressure to cut in case 1 or from leak to pressure in case 2. The controllers' models are fixed numbers, the inferentials' design hydrocarbon share $y_0 = 0.867$ and the vendor curve $C_2(\mathrm{MDP} - p_w(T_c))$ evaluated with the parameters the case started with. The 565 °C 95 % point, the 1.0 ppm metals limit, the 3 % overflash minimum, the 100 mbar a MDP and the 560 °C skin are teaching values. The real ones come from the HVGO specification of the cracker downstream, whose catalyst the metals poison [17], the overflash the wash section is designed for [18], the ejector vendor's curves [16] and the tube alloy's design metal temperature.

5.5 Nine Cases, Measured

The cases are listed in Table 5.4, and Table 5.5 reads the application's own scorecard tiles at the instants the text uses. The measurements were made headless at the default seed with the engine stepping as the page does, the learner's moves applied at the times given. All nine cases produce identical logs whether opened first, opened after a different case or rerun with Reset, and the application's 43 checks pass. The exported file logs every instrument reading next to the simulated value it reads, the latter under a truth prefix (Section 1.6.4). Numbers that move with the noise were repeated at four more seeds (0, 1, 2, 3) and with the step halved.

5.5.1 Pressure Moves the Cut

Case 1 holds the COT at 405 °C with the wash oil fixed and lowers the flash zone from 50 to 30 mbar a at 5 min. An hour later the cut has moved 24.5 K and the 95 % point 24.7 K, from 545.8 to 570.5 °C, passing 565 °C 12.8 min after the change. The line alone gives 21.2 K for 50 to 30 mbar a. The HVGO rises from 130.3 to 155.1 t/h, the residue falls from 149.2 to 125.2 t/h, the firing rises from 22.2 to 22.9 MW because more of the charge is vapor at the coil outlet, and the metals rise from 0.27 to 0.87 ppm with the faster vapor. The flash zone runs 14.5 K under the outlet at 50 mbar a and 17.2 K at 30.

Pause. Try Exercise 5.1 before reading on.

Over a wider range the shift is shown in Figure 5.2a. At a fixed 405 °C outlet the cut of the lifted oil moves 30.3 K from 40 to 20 mbar a, 41.2 K from 80 to 40 and 26.0 K from 50 to 30, and the same flash with Maxwell–Bonnell moves it 26.1, 35.4 and 22.1 K. The design brief for the app expected

Table 5.5 The Application's Scorecard Tiles at the Instants the Text Reads

Case	Settings and instant	HVGO (t/h)	Ejector load (% of critical)	HVGO 95 % (°C)	Metals (ppm)	Overflash (% of F)	Run left (days)	Also
1	50 mbar a, 5 min	130.3	41	545.8	0.27	4.00	1877	
1	30 mbar a from 5, 65 min	155.1	39	570.5	0.87	5.52	1689	Q 22.9 MW
2	leak 600 from 6, 10 min	138.0	90	556.5	0.42	4.11	1796	p_{fz} 45.3
2	leak 700 at 10, 600 at 18, 24 min	111.3	92	532.0	0.13	3.10	2062	broken, p_{fz} 71.3
2	leak 500 from 24, 40 min	138.9	80	551.4	0.36	3.54	1795	recovered
3	bleed from 15, 35 min	141.8	81	557.9	0.48	4.55	1777	22 breaks
4	wash 4 % from 5, 65 min	157.9	40	580.7	4.16	0.04	1779	bed dry
4	wash 11 % from 95, 130 min	141.8	40	557.6	0.47	4.50	1798	coke stays
5	COT 420 from 5, 35 min	146.2	78	560.3	0.56	10.80	192	Q 28.7 MW
6	target 18 % from 5, 100 min	142.2	149	558.0	0.40	3.42	105	COT 425, p_{fz} 85.0
6	watched from 100, 200 min	143.1	85	558.0	0.47	5.49	1271	COT 407.4
7	as shipped, 70 min	129.7	111	556.3	0.38	4.12	1782	broken, p_{fz} 57.8
7	COT 398 from 40, 76 min	130.4	89	546.6	0.30	3.35	4792	never broke
8	as shipped, 120 min	114.5	41	546.5	0.28	3.30	2524	
8	maximizer from 30, 180 min	127.5	34	560.0	0.59	3.91	4150	p_{fz} 25.1, COT 400.8
9	shipped, 8 h	122.2	109	537.9	0.18	3.30	1939	1097 t, broke
9	suggested, 8 h	138.6	86	555.9	0.52	3.30	9921	1154 t, no break

about 10 K per halving, which would need a line constant of 46, far outside an entropy of vaporization, so the app reports the shift as the physics gives it and states the fifth by which its line overstates it. A 10 K hotter outlet moves the cut 18.8 K.

5.5.2 The Break and Its Hysteresis

Case 2 puts the pressure loop on Man, so the recycle valve stays where it is. From 120 to 600 kg/h of leak the flash zone rises only from 40.0 to 45.3 mbar a, because the first stage's suction follows its total load and the air is a small part of it. The intercondenser rises 5 mbar per 100 kg/h of non-condensable gas over its 51.8 mbar a floor, and held 20 min a leak of 690 kg/h leaves the stage critical while 694 breaks it (696 at steady state). Stepped to 700 kg/h at 10 min, the stage breaks 0.04 min later, the flash zone passes 60 mbar a within 20 s, reads 70.2 mbar a after a minute and 72.4 mbar a after a minute and a half, and the HVGO falls from 138.0 to 112.3 t/h by 18 min. Returned to 600 kg/h the stage stays broken, the situation of Figure 5.1b at 13 min, with 892 kg/h of non-condensable gas, a suction of 68.0 mbar a and a flash zone of 71.5 mbar a, 3.5 mbar above it because the beds' drop falls with the denser vapor. On a staircase of 2 kg/h every 3 min the stage breaks at 696 kg/h and recovers at 560 kg/h, as shown in Figure 5.2b, and raised every 2 min instead it breaks at 700 to 702 kg/h and recovers at 562 to 564 kg/h across four further seeds. The hysteresis alone is 6 mbar, or 120 kg/h at the second stage's slope, and the loop is wider because a broken stage's higher pressure raises the bottoms temperature and with it the cracked gas.

🕮 **Pause.** Try Exercise 5.2 before reading on.

Case 3 compares the two ways of raising the pressure. On the recycle, which loads the first stage only, the 36 mbar a step settles within 0.3 mbar in 1.06 min with the vent gas at 380 kg/h of 964. With both valves shut the ejectors pull the flash zone to 28.4 mbar a. An air bleed loads every stage, and holding 30 mbar a on it takes 370 kg/h of air and 77 % of the critical load, against 39 % on the recycle, while 31 mbar a would need 593 kg/h, 101 %. At 40 mbar a on the bleed the loop opens it, the stage breaks, the pressure overshoots, the bleed closes and the stage recovers, 21 times in 20 min with the bleed selected from the start and 22 in the 20 min after a switch at 15 min. The cycle is the cyclic region a real ejector shows between its stable and unstable modes [6] only in appearance, because here it comes from a latched curve under a loop whose setpoint the bleed cannot reach, and its count depends on the step, 21 at the default and 22 at half of it. No tuning removes it.

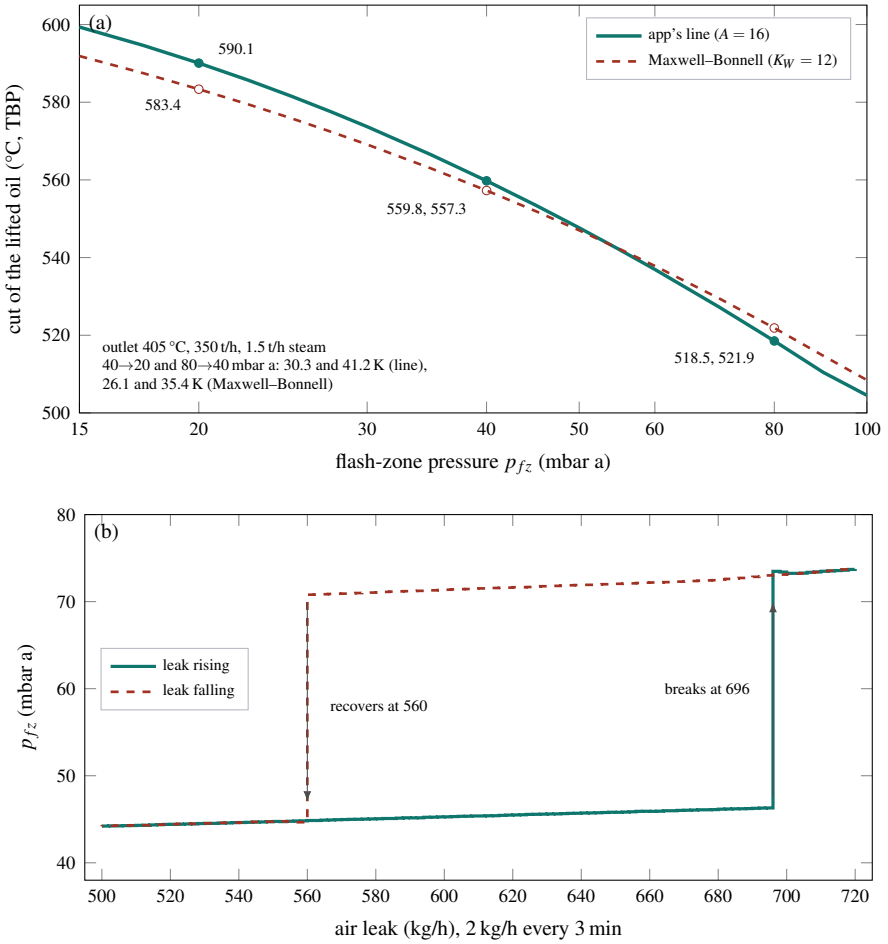


Figure 5.2 (a) The cut of the lifted oil on the crude curve against the flash-zone pressure at a 405 °C outlet, from the application's flash with its vapor pressure line (solid, filled markers) and from the same flash with Maxwell–Bonnell (dashed, open markers). (b) Case 2 with the pressure loop on Man and the air leak stepped 2 kg/h every 3 min from 500 to 720 and back, the flash-zone pressure at the end of each step, with the leak rising (solid) and falling (dashed).

✦ DID YOU KNOW? The Same Leak, Two Pressures

From the simulator (Table 5.5). With 600 kg/h of air leaking in, the flash zone holds 45.3 mbar a and the tower makes 138.0 t/h of heavy gas oil. After the leak has touched 700 kg/h and returned to the same 600 kg/h, the flash zone stands at 71.3 mbar a and the tower makes 111.3 t/h. Only a cut to 500 kg/h brings the stage back.

5.5.3 Wash Oil, Heater and Cracked Gas

Case 4 cuts the wash ratio from 11 to 4 % at 5 min. The 95 % point passes 565 °C 2.2 min later (2.1 to 2.2 at four other seeds), the inferred value 0.3 min after that, and the bed dries 9.5 min after the cut. The metals pass 1 ppm a minute later and settle at 4.2 ppm, nine times the design, while the 95 % point climbs to 581 °C and droplets make 2.8 % of the HVGO. The laboratory reports 4.18 ppm at 50 min, from the sample drawn at 30, 34.5 min after the truth crossed the limit. By 95 min coke covers 17 % of the bed's open area and the beds' drop has risen from 8.0 to 9.3 mbar. Restored to

11 %, the bed is wet in 3.7 min and the metals return to 0.46 ppm, but the coke stays at 18 % and the recycle holds the flash zone with 41.5 % of valve instead of 46.0. This bed dries and cokes as an extreme for teaching, against the multi-year runs a real one makes [18].

Case 5 raises the COT from 405 to 420 °C. With the 95 % point held, half an hour later the HVGO has risen only from 142.3 to 146.2 t/h, while the overflash has grown from 4.4 to 10.8 % of the feed. The extra lift goes to the wash. The coking rate rises 5.9 times, from 0.0026 to 0.0157 mm/day, the run left falls from 1786 to 192 days on 28.7 MW instead of 22.6, the skin rises from 489 to 515 °C, and the cracked gas rises 2.5 times, so the vent gas goes from 384 to 756 kg/h, 78 % of the critical load.

> **TRY IT IN THE APP** **5 · The heater limit**
>
> Load the scenario and press Run. Then raise the Heater outlet setpoint from 405 to 420 °C. Half an hour later the heavy gas oil has risen only from 142.3 to 146.2 t/h, while the overflash has grown from 4.4 to 10.8 % of the feed. The extra lift went to the wash.

Case 6 runs a tower leaking 520 kg/h of air, 81 % of the critical load, with the maximizer in charge and its ejector guard off, and the learner raises its wash ratio target to 18 % at 5 min. The COT climbs and the flash zone creeps up only to 42.1 mbar a by 30 min. At 33.3 min (33.2 to 33.7 over seeds), with the COT at 413.9 °C and 428 kg/h of cracked gas, the stage breaks, the lift falls, and the maximizer, still short of lift, raises the COT to its 425 °C ceiling by 57.0 min. At 100 min the flash zone is at 85.0 mbar a with 901 kg/h of cracked gas, 3.7 times the design. Watched from 100 min, the maximizer cuts the COT until the stage recovers 19.4 min later and then holds the vent gas 15 % under the critical load near 407 °C. The runaway goes only through the controller. Measured as the closed-loop response to 40 kg/h leak steps, the physical loop gain from vent gas through pressure and flash zone temperature back to cracked gas is 0.0057 to 0.0060 on the flat curve and 0.0131 to 0.0140 on the broken branch with the COT on its loop, and 0.022 and 0.063 with the firing fixed, far below the 1 a runaway needs, so the amplification $1/(1-L)$ of Equation (1.8) stays close to one. As shipped, with the target at 11 %, the COT setpoint never moves in 8 h, at the default seed or at any of four others, the COT stays within 0.11 K of 405 °C in the first hour, and the stage never breaks. Field practice describes a positive feedback loop in vacuum tower pressure control [7], and the case teaches that the loop that runs away here is the one a constraint pusher closes when it does not know the sign of its gain has changed.

Pause. Try Exercise 5.3 before reading on.

5.5.4 Summer Water and a Heavier Residue

Case 7 warms the cooling water from 28 to 35 °C over an hour from 10 min on a tower leaking 250 kg/h. Seven degrees add about 24 mbar to the water floor out of a 48 mbar margin. The critical load falls from 964 to 744 kg/h by 40 min and to 604 at 56.6 min, when CONDENSER FLOOR appears, and at 66.7 min, with the water at 34.6 °C, it meets the 515 kg/h the tower sends and the stage breaks. The flash zone goes to 57.6 mbar a and the HVGO falls from 142.3 to 123.9 t/h. A 398 °C COT at 40 min cuts the cracked gas to 162 kg/h and the stage never breaks, for 130.4 t/h. Cutting the stripping steam to zero also holds, with 142.2 t/h, but the inferred 95 % point then reads 558 °C against a true 554 °C, because the inferential assumes the design steam share. A soft sensor calibrated for one condition misleads in another in the same way in the spray dryer of Volume 5, Chapter 10.

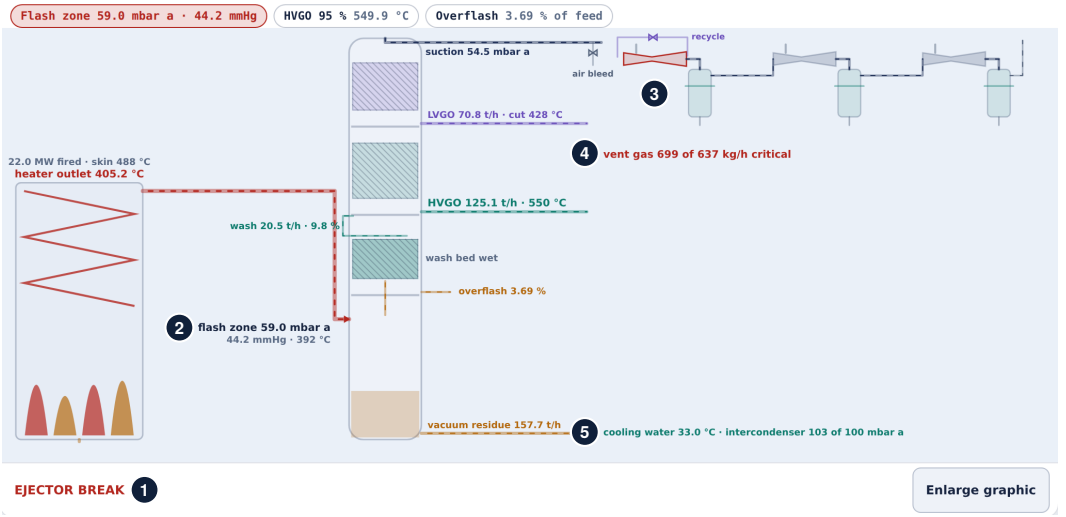


Figure 5.3 The challenge as shipped at $t = 6$ h on the Tower view, light theme, cropped to the plant view with numbered callouts. The stage broke at 352 min, so the status strip reads EJECTOR BREAK (1) and the flash zone reads 59.0 mbar a (44.2 mmHg) at 392 °C (2) against its 40 mbar a setpoint, with the suction at 54.5 mbar a. The first stage is drawn in red, with the recycle around it and the air bleed ahead of it (3). The vent gas of 699 kg/h stands over the critical load of 637 kg/h that the vendor curve gives at that water (4). The cooling water has warmed to 33.0 °C and the intercondenser reads 103 of 100 mbar a (5). The HVGO has fallen to 125.1 t/h with its inferred 95 % point at 549.9 °C and the residue risen to 157.7 t/h, with the COT held at 405.2 °C on 22.0 MW. In the full window, outside this crop, the recycle valve stands shut at 0 %, and the trends over a 4 h window show the pressure jump at the right edge and the vent gas crossing the falling critical line, with 262 kg/h of cracked gas and a true 95 % point of 549.2.

> **TRY IT IN THE APP** **7 · Summer cooling water**
>
> Load the scenario and press Run. Nothing has to be set. Watch the critical load line on the Ejectors view while the cooling water warms from 28 to 35 °C. CONDENSER FLOOR appears at 56.6 min. At 66.7 min the critical load meets the 515 kg/h the tower sends, the stage breaks, and the flash zone goes to 57.6 mbar a.

Case 8 switches to a residue whose curve is stretched 60 °C at its heavy end and carries 60 ppm of metals. Its share below 565 °C falls from 65 to 56 % and its pitch rises from 17 to 24 %. The HVGO falls from 142.3 to 114.5 t/h and the residue rises from 137.4 to 177.8 t/h, with the overflash on its 3.3 % floor and the 95 % point at 546.5 °C, under its 558 °C setpoint. The maximizer, on from 30 min, takes the pressure to its 25 mbar a floor and the COT near 401 °C for 127.5 t/h, 13 of the 28 lost. A sweep of steady states over the COT from 395 to 440 °C and every reachable pressure, each with the least wash meeting the 95 % point and the overflash, finds at most 134.2 t/h inside every limit, at 425 °C and 30.5 mbar a with the ejectors at 99 % of critical, against the design's 142.3 t/h. Above 425 °C nothing is feasible because the ejectors break. The case is honestly infeasible, and the design residue on the same sweep reaches 151.9 t/h.

5.5.5 The Challenge

The challenge runs 8 h. An air leak of 300 kg/h opens at 2 h, leaving the ejectors at 71 % of their critical load, and the cooling water warms 5 °C over an hour from 5 h. It passes with at least 1140 t of HVGO, no break, the 95 % point at most 565 °C, metals at most 1.0 ppm, overflash at least 3 % and

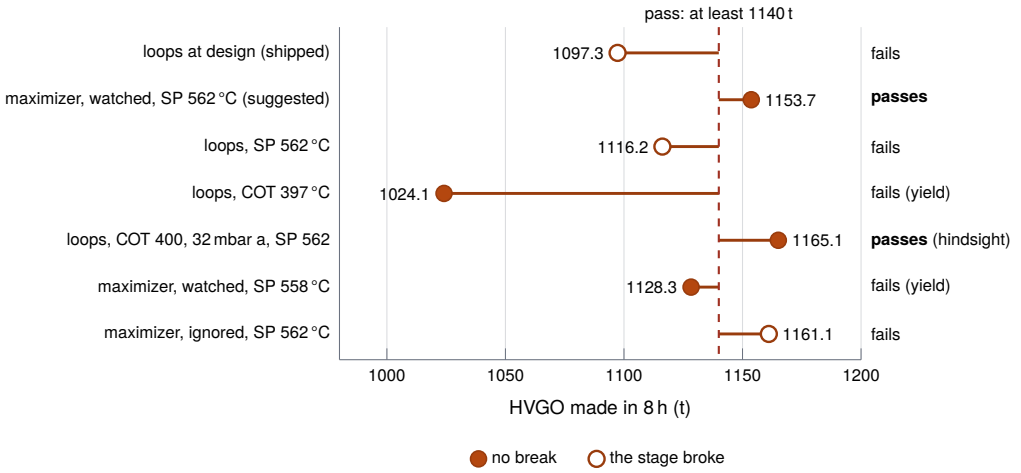


Figure 5.4 The runs of Table 5.6 as a chart: the HVGO made in 8 h, each stem drawn from the 1140 t the challenge asks for, with a filled marker where the stage never broke and an open marker where it broke. Notice that a run passes only to the right of the dashed line with a filled marker, and that the maximizer with the ejector load ignored makes more than the suggested run and still fails.

Table 5.6 The Challenge Over 8 h, Default Seed

Settings	HVGO (t)	Break	Verdict
loops at design (shipped)	1097.3	352.4 min	fails
maximizer, watched, SP 562 °C (suggested)	1153.7	none	passes
loops, SP 562 °C	1116.2	yes	fails
loops, COT 397 °C	1024.1	none	fails (yield)
loops, COT 400, 32 mbar a, SP 562	1165.1	none	passes (hindsight)
maximizer, watched, SP 558 °C	1128.3	none	fails (yield)
maximizer, ignored, SP 562 °C	1161.1	yes	fails

the skin under its limit, judged on the truth at every step after 10 min. As shipped, on fixed setpoints at the design point, the stage breaks at 352.4 min, when the water has reached 32.4 °C and the critical load has fallen to 683 kg/h against 684 kg/h of vent gas, the flash zone rises to 59 mbar a, and the run makes 1097.3 t, as shown in Figure 5.3. The settings tried are listed in Table 5.6, and Figure 5.4 draws them against the yield the challenge asks for. The suggested maximizer, watched, with the 95 % setpoint at 562 °C, cuts the COT as the critical load falls and lowers the pressure to win the lift back, and it passes with 1153.7 t and the 95 % point never above 563.1 °C. Over four further seeds and the halved step the shipped run makes 1096.9 to 1097.4 t and breaks between 352.0 and 352.4 min, and the suggested one makes 1152.7 to 1153.7 t with no break. Its benefit is adaptation without hindsight. A fixed 400 °C at 32 mbar a with the same setpoint passes with more, chosen knowing the afternoon.

5.6 Technology in Practice

Figure 5.5 draws the loops of Section 5.4 with the hardware a refinery installs in place of the model's ideal instruments.

What Measures It

The flash-zone pressure is read by an absolute pressure transmitter, and the 0.03 min lag of Section 5.3.5 stands for that instrument and its connection. The two cut points are thermocouple readings corrected for pressure by Equation (5.8). The vent gas is the hardest of the model's readings to obtain on a working unit. One refiner's account states that comparing an ejector with its curve is not easy,

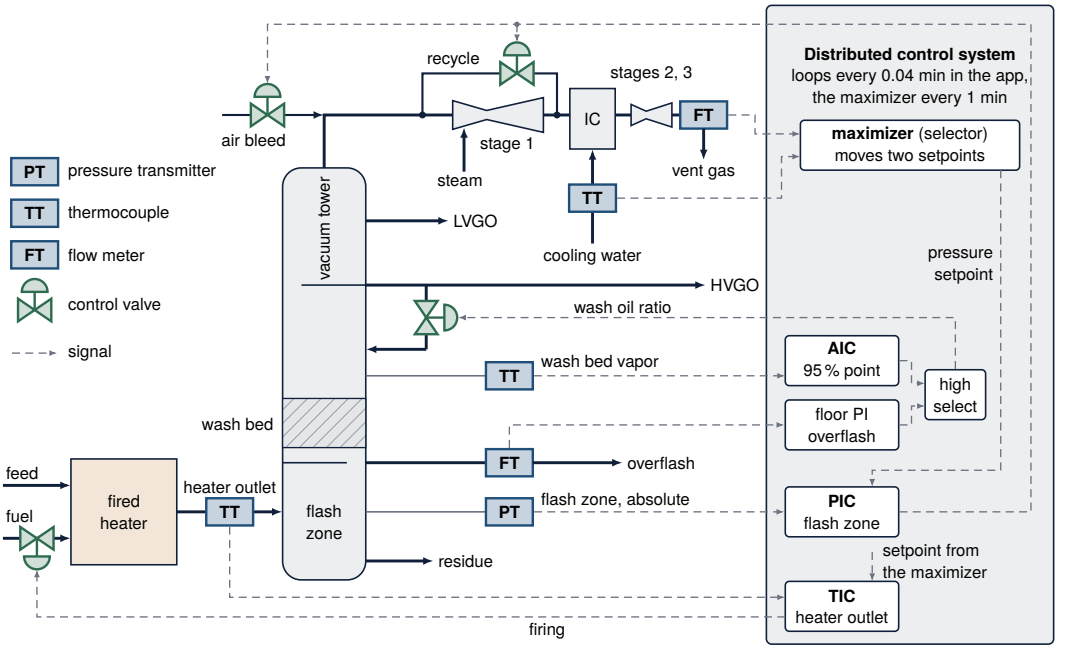


Figure 5.5 The pressure loop, the wash oil loop, the heater outlet loop and the maximizer with their hardware. Lettered boxes are sensing devices, valve symbols are final elements and dashed arrows are signals. IC is the first intercondenser. Notice that the pressure controller can only add load to the first stage, through the recycle or the air bleed, that two controllers reach the wash oil valve through one high select, and that the maximizer reads the vent gas and the cooling water but moves only setpoints. Not to scale, and not a piping or safety diagram.

because estimating the gas flow often poses difficulties, and that the vacuum level and the steam consumption are monitored instead [21].

> **TECHNOLOGY Sensor: Absolute Pressure Transmitter**
>
> The boiling temperature of a liquid is a function of the absolute pressure on it. Where boiling has to be controlled precisely the pressure is therefore measured absolute, and an open instrumentation textbook gives the vacuum distillation of crude oil as its example [22]. Such a transmitter is a differential pressure instrument with its low side sealed onto a vacuum chamber, so any pressure above a perfect vacuum reads as a positive difference. In a common design a taut metal diaphragm sits between two fixed plates, a fill fluid carries the pressure to it from an isolating diaphragm, and the two capacitances change as it flexes [22]. The weak point is the connection. A line that plugs makes the instrument respond too slowly or not at all, and a purge that flows too fast adds its own pressure drop to the reading [22].

What Moves It

The pressure controller moves a recycle valve around the first ejector stage, or an air bleed. Both only add load, so the ejectors set the lowest pressure, 28.4 mbar a in the model with both valves shut (Section 5.5.2). The design case holds 40.0 mbar a with the recycle 46 % open. The refiner's account above reports the opposite habit. It tries to keep its spill-back valve closed at all times and saves steam by taking parallel ejectors off line [21]. The firing reaches the coil through a firebox lag of 1 min in the model.

TECHNOLOGY Final Element: Steam Jet Ejector

An ejector has no moving part. A primary flow, here steam, accelerates and expands through a nozzle and entrains a secondary flow from a suction chamber. The flows mix, and a diffuser compresses the stream [23]. In its critical mode the entrained flow is choked and does not depend on the pressure downstream. As that back pressure rises a shock wave moves into the mixing chamber, and with a further rise the primary flow reverses into the suction chamber [23]. Refiners say that a stage breaks. One is expected to break when its motive steam is below the design pressure or its discharge is above the maximum on the maker's curve [21]. Vacuum units typically have three stages in series, each paired with a condenser that reduces the load on the next [21].

Where the Controller Runs

A refinery runs such loops in a distributed control system, in which a supervisory level sends set points to distributed controllers that act through the actuators from the feedback of the sensors [24]. A survey of industrial practice puts basic control at every second and constraint control at every minute, and builds the conventional constraint layer from PID algorithms, lead-lag blocks and high and low select logic [4]. The loops of this chapter execute every 0.04 min and the maximizer moves its setpoints every minute, the period the survey names. The high select on the wash ratio is a block of that layer. A controller that a selector has de-selected tends to wind up, so override schemes need integral limits that engage then [22]. The pull of each branch toward the applied ratio in Section 5.4.1 is such a limit.

What Is Modernizing It

Three developments bear on this unit. The first is the online analyzer in place of the sample. The air that leaks into a vacuum system shows in its off gas, and one refiner reported in 2012 that it required an online oxygen analyzer on the tail gas of units that send it to a fuel gas header, and had installed several in five years [25]. The second is predictive control, which typically carries the valve positions of the loops below it as extra controlled variables held inside their limits [4]. A 2023 review that defends selectors expects significant benefits from it where many constraints switch [26]. The third has not arrived. Dry vacuum pumps reached the chemical industry of the United States in the late 1980s, and a 2005 energy guide did not expect them to make inroads in refining except in special applications [27].

IN PRACTICE The Overflash Is Sampled, Not Trusted to a Loop

In the model a controller holds a floor under the measured overflash. A 2016 answer in a refiners' question record describes the practice [28]. The overflash is metered in a gravity loop with an orifice plate. The answer advises against cascading the wash oil from the measured rate. A sample is analyzed instead, its share of gas oil is calculated, and the gas oil leaving the bottom of the bed per unit of bed area is compared with a target. The wash oil stays on flow control and its setpoint is changed by hand. Sampling is hard, because the stream is hot and below atmospheric pressure, and the analysis must tell spent wash oil from liquid entrained from the flash zone [28].

5.7 Limitations

The unit is generic, its sizes, rates and limits are chosen for teaching, so its yields and break loads are not predictions for any tower. The vapor pressure line overstates the shift per halving by about a fifth against Maxwell–Bonnell, the flash is one equilibrium stage, the sections are lagged cut points with one tail spread, and the pitch never boils. The ejector curve is declared rather than fitted to a vendor's, its break is a latched flag with a fixed jump, and the cyclic region of a real ejector appears only as case 3's limit cycle, whose count changes with the integration step. The wash bed's dry-out and coking are compressed for teaching, and its entrainment and capture are typical values rather

than a design method. Cracked gas follows the COT and flash zone temperature through a doubling law with no residence time.

The controllers carry no process model beyond two fixed numbers, the inferentials' design steam share and the vendor curve, so they meet model error only in the cases built to show it, as in case 7's stripping steam. The maximizer is a rule-based selector with no prediction. Disturbances arrive as steps and ramps.

OPEN CHALLENGE A Design Method for Selector Logic

The high select on the wash oil and the maximizer of this chapter are built from selectors. A 2023 review finds that such structures have proven themselves over a century with little academic attention, so that proper design methods have not been developed and the engineer works mainly from the pattern of earlier designs [26]. Its list of neglected research tasks includes the structure of selector logic and the tuning of anti-windup for selectors, and it calls the analysis of switched systems mathematically very difficult [26]. The wash oil select of Section 5.4.1, which turned measurement noise into a one-way climb until its tracking was changed, is a small case. Progress would be a method that predicts such behavior before commissioning.

5.8 Conclusion

This chapter studied a vacuum tower on 350 t/h of residue from the crude curve of the atmospheric tower, with an equilibrium flash, a wash bed, two gas oil draws and a three-stage ejector set, and gave every equation and default needed to rebuild it. Lowering the flash zone from 50 to 30 mbar a at a fixed heater outlet moves the HVGO 95 % point 24.7 K, and the cut shifts 26 to 41 K per halving on the app's line against 22 to 35 K with Maxwell–Bonnell. The ejectors hold the pressure nearly flat to a critical load of 964 kg/h, break with a 35 mbar jump near 695 kg/h of leak and recover only near 560 kg/h. Starving the wash bed raises the HVGO metals nine times while the laboratory reports half an hour late, and a hotter heater buys mostly overflash. A lift controller blind to the ejector load runs the heater to its ceiling, although the physical loop gain is only 0.014, and watching the load prevents it. The challenge fails as shipped with 1097 t and passes with the watched maximizer at 1154 t. The model is lumped and its constants are teaching values. A fuller model would add a staged wash and stripping section, a vendor ejector curve with its cyclic region, a heavy-oil vapor pressure correlation in place of the line, and a predictive controller for comparison. The simulator shows that the deepest cut on a vacuum unit is bought with a margin the cooling water can take away in an afternoon.

KEY POINTS

- Lowering the pressure in the tower lifts more gas oil for very little extra heat. No other handle moves the cut that far.
- The ejectors hold the pressure nearly flat up to a critical load, break with a jump, and recover only well below the load that broke them.
- The critical load falls as the cooling water warms, so the limit moves during the day.
- A hotter heater buys mostly overflash, and it adds cracked gas to the ejector load.
- A lift controller blind to the ejector load runs the heater to its ceiling. Watching the load prevents it.

Where else this applies. A limit that ends in a limit cycle under a protective override returns in Volume 4, Chapter 2, overrides that push throughput in Volume 4, Chapter 4, and an inferred quality that is right for one condition only in Volume 5, Chapter 10.

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5.9 Exercises

5.1 Concept check · 2 min

Case 1 holds the heater outlet at 405 °C with the wash oil fixed by hand and lowers the flash zone from 50 to 30 mbar a. Which statement describes what the unit does in the next hour?

(a) The HVGO gains little, because the heater must fire several megawatts more to hold the outlet

(b) The 95 % point stays at its setpoint, because the HVGO loop raises the wash oil to hold it

(c) The cut moves about 10 K, the shift per halving the design brief for the app expected

(d) The HVGO gains about 25 t/h and its 95 % point passes its limit, for under 1 MW more firing

5.2 Concept check · 2 min

With the pressure loop on Man, raising the air leak from 120 to 600 kg/h lifts the flash zone only from 40.0 to 45.3 mbar a, yet at about 695 kg/h the first ejector stage breaks. Which explanation is right?

(a) Air is a small part of the first stage's load, but the second stage must pump it, so the intercondenser rises to the first stage's maximum discharge pressure

(b) The pressure loop opens the recycle valve to offset the leak until the valve reaches its stop and the pressure escapes

(c) The cracked gas falls as the leak rises and offsets the extra load, until the heater outlet loop can no longer hold the outlet

(d) The air raises the water vapor floor of the intercondenser until the floor itself reaches 100 mbar a

5.3 Concept check · 2 min

In case 6 the maximizer, with the ejector load ignored, drives the heater outlet to its 425 °C ceiling after the stage breaks. The measured physical loop gain from vent gas back to cracked gas is 0.0131 to 0.0140 on the broken branch. What runs away?

(a) The physical cracked-gas loop, whose gain rises above one once the stage has broken

(b) The loop closed through the maximizer, which keeps firing for lift after more heat has begun to give less lift

(c) The pressure loop, whose integral winds up while the recycle valve sits shut at its stop

(d) The HVGO loop, whose high select with the overflash floor rectifies noise into a climbing wash ratio

5.4 Theory and calculation · 6 min

The app's vapor pressure line is $\ln(p^{sat}/p_{atm}) = A(1 - T_b/T)$ with $A = 16$ and $p_{atm} = 1013.25\,\text{mbar}\,a$, so its atmospheric equivalent temperature is $\text{AET}(T, p) = T\,(1 + \ln(p_{atm}/p)/A)$ in kelvin.

(a) What normal boiling point does the line give to a component that boils at 391 °C under 40 mbar a? *Checkpoint:* 525.2 °C.

(b) At 391 °C, how much heavier a component boils when the pressure is halved, and when it falls from 50 to 30 mbar a? *Checkpoint:* 28.8 K and 21.2 K.

(c) What line constant would give 10 K per halving at 391 °C, and what constant matches the 24.0 K of Maxwell–Bonnell? *Checkpoint:* 46 and 19.2.

5.5 Theory and calculation · 8 min

Use Equation (5.3) and its constants: vapor space 2000 m^3 at 333 K with a molar mass of 19 g/mol, $C_1 = 0.15\,\mathrm{t/(h\,mbar)}$, $C_2 = 20\,\mathrm{kg/(h\,mbar)}$, MDP 100 mbar a, hysteresis 6 mbar. At design the water floor is $p_w = 51.8\,\mathrm{mbar}\,a$ and the non-condensable load is $G_{nc} = 384\,\mathrm{kg/h}$, of which 120 kg/h is air.

(a) Compute $\kappa = RT/(V_g\bar{M})$ in mbar per kg and the suction's time constant $60/(\kappa\,1000\,C_1)$ in minutes. *Checkpoint:* 0.729 mbar per kg and 0.55 min.

(b) Compute the intercondenser pressure and the critical load at design, and the load at which a broken stage recovers. *Checkpoint:* 71.0 mbar a, 964 kg/h and 844 kg/h.

(c) If only the air changed, at what leak would the stage break and at what leak would it recover? The app breaks near 694 to 696 kg/h and recovers near 560 kg/h. Explain both differences. *Checkpoint:* about 700 kg/h and 580 kg/h.

5.6 Theory and calculation · 6 min

The heater of Equation (5.7) has a film temperature $T_{film} = \mathrm{COT} + 45\,Q/26$ (°C, Q in MW), a coking rate $0.004 \times 2^{(T_{film}-450)/10}$ in mm/day, a skin $T_{skin} = T_{film} + 15\,\delta$ with $\delta = 3$ mm of coke, and a skin limit of 560 °C. The run left is the margin over the rate of rise.

(a) At design, 405 °C on 22.6 MW, compute the film temperature, the coking rate, the skin and the run left. *Checkpoint:* 444.1 °C, 0.002 66 mm/day, 489.1 °C, about 1776 days.

(b) Repeat for case 5 half an hour after the outlet is raised to 420 °C, when the heater fires 28.7 MW. *Checkpoint:* 469.7 °C, 0.0156 mm/day, 514.7 °C, about 193 days.

(c) By what factor did the coking rate rise, and why does the run left fall by more than that factor? *Checkpoint:* 5.9.

5.7 App challenge · 8 min

Load scenario 1, "Pressure moves the cut (wash oil by hand)", at the default seed and the default speed of 5. Press Run, and at about 5 min lower the Flash-zone pressure setpoint to 30 mbar a.

(a) Just before the change, read the HVGO and HVGO 95 % (truth) tiles. *Checkpoint:* 130.3 t/h and 545.8 °C.

(b) One hour after the change, read the HVGO, HVGO 95 % (truth) and Metals (truth) tiles. How far did the 95 % point move, and how does that compare with the line's 21.2 K for 50 to 30 mbar a? *Checkpoint:* about 155 t/h, 570.5 °C, 0.87 ppm; a move of 24.7 K.

(c) Export the CSV and find, in column `truth_t95_C`, how long after the change the 95 % point first exceeds 565 °C. *Checkpoint:* 12.8 min (±0.3 min).

5.8 App challenge · 9 min

Load scenario 2, "The ejector curve breaks" (the pressure loop is on Man), at the default seed and speed 5. Press Run and at about 2 min raise the Air leak into the tower to 600 kg/h.

(a) Four minutes later, read the flash-zone pressure on the PIC card and the Ejector load tile. *Checkpoint:* 45.3 mbar a (±0.2 mbar) and 90 % of critical.

(b) Raise the leak to 700 kg/h. How soon does EJECTOR BREAK appear, and what does the PIC card read a minute after it? *Checkpoint:* within a few seconds; about 70 mbar a (±1 mbar).

(c) About eight minutes later return the leak to 600 kg/h. Three minutes after that, is the stage still broken? Read the flash-zone pressure and the Ejector load tile. *Checkpoint:* still broken, 71.3 mbar a (±0.3 mbar), 92 %.

(d) Lower the leak by 10 kg/h every 3 min until the ejectors recover. At which leak does that happen, and why is it below the 580 kg/h that the hysteresis alone would give? *Checkpoint:* 550 to 560 kg/h.

5.9 App challenge · 8 min

Load scenario 9, "Challenge: a leak and a hot afternoon", at the default seed and speed 120. The run stops by itself at 8 h.

(a) Run it as shipped. Read the So far tile (hover over it for the full verdict). *Checkpoint:* 1097 t, broke, first miss an ejector break at 352 min.

(b) Reload the scenario, set the Architecture to Maximizer (Ejector load stays Watched) and the HVGO 95 % point setpoint to 562 °C before Run, and run 8 h. *Checkpoint:* 1154 t, no break, 95 % point at most 563.1 °C, passes.

(c) Reload, keep the Architecture on Loops, set only the Heater outlet setpoint to 397 °C before Run, and run 8 h. Why does this safe setting fail while the run of (b) passes? *Checkpoint:* 1024 t, no break, fails on the yield.

5.10 Application area · 4 min

In case 4 the wash oil is cut to 4 % at 5 min. The bed dries 9.5 min later and the true HVGO metals pass 1 ppm a minute after that, but the laboratory, which samples every 30 min and reports 20 min later, first shows the excursion at 50 min.

(a) How long after the true crossing does the laboratory report it, and what effective delay does Equation (1.12) give for this laboratory? What are the shortest and longest possible delays? *Checkpoint:* 34.5 min; 35 min; 20 and 50 min.

(b) The metals poison the catalyst of the cracker downstream. Which measured quantity warns the operator first, and which part of the control structure already acts on it? *Checkpoint:* the overflash; the floor override on the wash oil.

5.11 Application area · 4 min

On a hot afternoon the cooling water to the intercondensers warms. The condensing temperature is the water plus 4 K plus 1 K per t/h of steam (1.5 t/h here). Water's vapor pressure is 64.6 mbar a at 37.5 °C and 68.1 mbar a at 38.5 °C.

(a) Compute the critical load with the water at 32 and at 33 °C. In the challenge the vent gas is about 684 kg/h. At what water temperature does the stage break? *Checkpoint:* about 709 and 637 kg/h; between 32 and 33 °C.

(b) Name two loads an operator can take off the ejectors before the break, and what each one costs. *Checkpoint:* lower COT (cracked gas), less stripping steam.

5.12 Review the agent · 5 min

After running scenario 3, "Pressure loop: recycle against air bleed", an AI assistant writes: "On the air bleed the pressure loop cycles, 22 breaks in the 20 min after the switch. The loop is tuned too tight for the ejectors. Halve the Pressure gain to 1.2 % per mbar and double the Pressure integral time to 0.6 min, and the bleed will hold 40 mbar a smoothly." Find the flaw, and say how you would check it in the app.