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CHAPTER 2

Crude Desalter Simulator With a Mixing Optimum and a Misread Rag Layer

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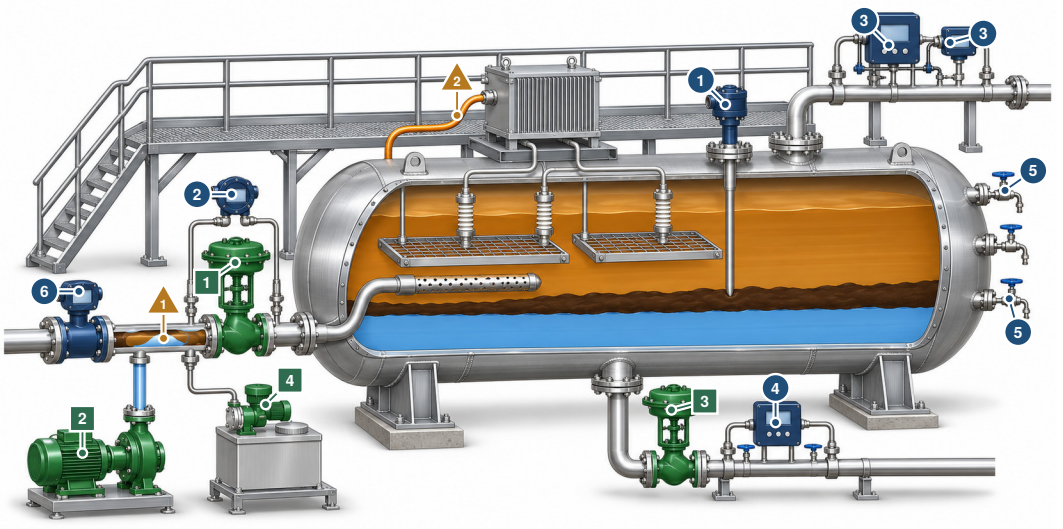
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CHAPTER 2

Crude Desalter Simulator With a Mixing Optimum and a Misread Rag Layer



The controller moves 1 mixing valve 2 wash-water pump 3 brine valve 4 demulsifier pump

The controller reads 1 interface probe 2 pressure drop across the mixing valve 3 salt analyzer and water meter 4 oil in the brine 5 try-cocks for profile samples 6 crude flow

What disturbs it 1 a slug of free water 2 the transformer supply ▲ a heavier crude

The rod of the interface probe ends in the dark rag between the oil and the water, and the perforated inlet distributor lies in the oil between the rag and the grids. Illustration, not to scale.

IN PLAIN TERMS Washing the salt out of crude oil

The main idea. Crude oil arrives with a little salty water in it. A desalter mixes in fresh water to wash the oil, then lets the water sink and take the salt with it.

The challenge. Mixing harder washes better but makes drops too small to sink, so the best setting lies in between and moves with each oil. The gauge for the water level can be fooled by the rag, a layer of oil and water that will not come apart, and the controller then holds the wrong level.

Why it matters. Salt left in the oil turns to acid and scale in the units downstream.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	This page, the two History boxes in Section 2.2, the Did you know? boxes in Sections 2.1 and 2.6, the Try it boxes in Sections 2.3 and 2.4, and Key points in Section 2.9. No equations.
Study	60 min	The whole chapter in order, stopping at the three pause points, then Exercises 1 to 12.
Practice	20 min	This page, Section 2.6 with Figure 2.4, Section 2.7, Section 2.8 and its Open challenge box.

The control question Harder mixing contacts more brine but makes drops too small to settle, and the interface probe reads part of the rag as water. Where should the mixing pressure drop sit when the crude changes, and what does a loop on that reading do to the true water and the grid?

Learning objectives

- Explain the interior salt minimum, and why the demulsifier decides whether any pressure drop meets the water specification.
- Compute the integrating gain of the water layer and the offset of a proportional-only interface loop.
- Predict how the true water and the rag top move under a reading that counts part of the rag as water.
- Compute the grid voltage, current and trip gap.
- Compare tunings, the optimizer, the rag trim and a fixed dose on measured runs.

Prerequisites Sections 1.6.2 (PI loops), 1.4.6 (analyzers and the misread interface), 1.4.7 (optimizers) and 1.6.4 (cases).

The app https://apmonitor.com/apps/crude-desalter/

See also Volume 3, Chapter 6 and Volume 3, Chapter 7 for doses and ratios trimmed on a slow quality. Volume 5, Chapter 3 for a slow analyzer and Volume 5, Chapter 12 for a misleading sensor. Volume 9, Chapter 8 and Volume 9, Chapter 10 for setpoints chosen above the loops.

2.1 Introduction

Crude oil reaches a refinery with a few tenths of a percent of water in it, and that water is brine. In the generic unit simulated here, 500 m^3/h of crude at 130 °C arrives with 10 pounds of salt per thousand barrels (PTB) dissolved in 0.2 % of water. It takes in 5 % of wash water ahead of a mixing valve and leaves an electrostatic vessel with 0.67 PTB of salt and 0.104 % of water, so 93.3 % of its salt goes out with 25.5 m^3/h of brine. Raising the mixing valve's pressure drop from 1.0 to 1.29 bar lowers the salt to 0.54 PTB. Raising it further, to 2.0 bar, brings the salt back up to 0.89 PTB while the basic sediment and water (BS&W) left in the crude climbs to 0.45 %, more than twice its 0.2 % specification.

The salt matters to every unit downstream. Calcium and magnesium chlorides hydrolyze to hydrochloric acid when they meet steam at crude-unit temperatures, salts deposit as scale where water turns to steam, and metals carried with reservoir solids poison hydrotreating and catalytic cracking catalysts [1, 2]. The desalter is therefore the first process unit a refinery runs and the one whose upsets reach all the others.

> **DID YOU KNOW? Every Barrel Passes This Unit First**
>
> Desalting is the first step of the refining process [3]. On January 1, 2026 the 130 operable refineries of the United States could distill 18.16 million barrels of crude oil per calendar day [4]. The unit simulated in this chapter charges about 75 000 barrels per day.

The simulator is built around two beliefs that the unit contradicts. The first is that more mixing always washes out more salt. A mixing valve contacts more of the brine with wash water as its pressure drop rises, 83 % at 0.6 bar and 95 % at 1 bar in this model, but it also shears the water into drops that the field and gravity cannot recover, so the salt has an interior minimum and the optimum moves with every crude. The second belief is that an interface loop sitting on its setpoint holds the water where the setpoint says. The simulated capacitance probe counts half of the rag as water. With a 500 mm rag on a heavier crude the probe reads 1000 mm with the water at 750 mm, and over eight hours with the reading on its setpoint the water falls to 632 mm while the brine passes 200 mg/L of oil at 192 min.

Both features belong to classes a control engineer meets well outside a refinery. A manipulated variable with two opposing effects on one quality has an optimum that moves with the feed, the

situation in which a steady-state optimizer above the regulatory loops earns its place [5], as excess air does on a burner or reflux on a column. It is one of the few optima inside the operating range that Section 1.4.7 names, beside the recovery maximum of Chapter 13. A measurement whose bias grows with an unmeasured state of the process is followed faithfully by any loop that trusts it, and a level that integrates the difference of two flows is the textbook integrating process, with tuning rules of its own [6, 7]. The desalter adds a hazard above the level, since the energized grid trips when a conductive layer comes close to it.

The desalting literature treats these pieces apart. Electrostatic coalescence is reviewed as physics [8, 9], industrial desalters are simulated at steady state for their salt and water removal [10], and laboratory studies vary settling, chemical, wash water, heat and mixing one factor at a time [11], while a student who meets an interface loop meets it as a transfer function with a clean measurement. This chapter works with a dynamic simulator of a single-stage electrostatic desalter that computes the salt map, the rag, the interface instrument and the grid current together. It tests how loop tuning, ratio stations, a rag trim and a steady-state optimizer handle a crude switch, a misread interface and a water slug, and it states the simulator completely enough to be rebuilt. The correlations are teaching values, and proportional-integral (PI) control, ratio control and bias-updated optimization are established practice. The results are measurements on one generic unit at the default seed, with the challenge checked at five more. Among them are that the BS&W has a minimum of its own below the salt optimum and that the graded challenge is met by a fixed demulsifier ratio with no trim and no optimizer. The model has twenty states, its water and salt ledgers close to 6×10^{-13} of the throughput, and a measurement boundary keeps the true water, rag and salt hidden from every controller.

Section 2.2 follows desalting from the electrical treater to the modern unit. Section 2.3 sets out the model, from the vessel's geometry to the probe that misreads the rag, and Section 2.4 draws from it the three behaviors the cases turn on: an integrating water layer, an interior salt optimum and a reading that drifts with the rag. Section 2.5 describes the loops, the ratio stations, the rag trim, the correction by profile, the steady-state optimizer and model-free extremum seeking. Section 2.6 measures the ten cases of the app, and Sections 2.8 and 2.9 state the limitations and the conclusions.

2.2 Water, Salt and the Electrical Treater

Two patents mark the start of the methods a desalter combines, one electrical and one chemical. The first History segment gives the electrical patent of Cottrell and Speed [12]. Its warning against complete chains of drops between the electrodes is the grid current and the grid trip of the simulator.

> ⧖ HISTORY **1911: A High Voltage Breaks the Emulsion**
>
> Crude petroleum comes from the wells carrying water drops whose sizes run from easily visible to the limit of a microscope, and the patent of Cottrell and Speed, issued in 1911 and assigned to the Petroleum Rectifying Company of San Francisco, opens by listing what producers then did about them [12]. Some water settled on standing, faster when the oil was heated, and centrifuges had a limited place. Oils whose drops were finer than a thousandth of an inch could be dried only by distillation, where water made the still boil over and fouled its bottoms. The remedy was a high potential, preferably alternating, between electrodes immersed in the emulsion. Under a microscope the drops lined up in chains from one electrode toward the other and coalesced, and the claims require that the coalescing globules not form complete chains that short-circuit the electrodes.

The chemical route was patented three years later, as the second History segment tells [13]. The middle stratum of the three that the treatment left is what a desalter operator now calls the rag. By 1938 a survey of desalting in the Transactions of the AIME reported that settling with and without chemicals had given poor results, that acidized wells had loaded crudes with sodium, magnesium and calcium chlorides at anywhere from a few pounds to more than 1000 pounds per thousand barrels, and that severe corrosion had appeared in the topping and cracking units of many refineries [14].

> ⧖ HISTORY **1914: A Chemical Leaves Three Layers**
>
> Barnickel, of St. Louis, found that a small percentage of a soluble metallic sulfate, preferably copperas, broke the "roily" oils of Louisiana, Texas, Oklahoma and California into three strata, clear petroleum above, clear water below and a stratum of slimy substance between the two [13]. In some cases a hundredth of one percent of the oil treated was enough. The mixture was preferably heated to 100 to 140 °F, the water separated at once and the slimy stratum within eight to twelve hours. By the patent's own account the method had already recovered many thousands of barrels from wells whose production would otherwise have been waste.

The reasons a refinery desalts are now stated in terms of the units after the desalter. Chloride salts form hydrochloric acid in the presence of steam, and the hydrolysis of magnesium, calcium and sodium chlorides has been measured in flowing steam from 100 to 350 °C [1]. Salt also deposits as scale, and metals from reservoir solids adsorb on hydrotreating and cracking catalysts [2]. A current account of the process puts the refinery's target near 1.5 PTB, quotes about 90 % removal for one stage and 99 % for two, gives the mixing valve a pressure drop of 10 to 50 psi and the electrodes 12 to 35 kV, and states the trade the mixing valve makes, smaller drops that improve contact but can stabilize an emulsion the vessel then fails to break [2]. The simulated unit runs inside those ranges, with 1 bar (14.5 psi) of mixing, about 25 kV on the grids and 93.3 % of the salt removed in one stage.

The electrical stage has a literature of its own. A review of electrostatic phase separation finds alternating and pulsed fields preferred over a constant direct field, names chain formation and partial coalescence as the unwanted effects, and concludes that electrocoalescer design has not yet left empiricism [8], and the electrocoalescers used on crude oil have been assessed for their strengths and limits [9]. The emulsions are stabilized by asphaltenes, to a degree that depends on how well the rest of the crude solvates them [15]. Laboratory work on a Kuwaiti crude varied settling time, chemical treatment, fresh water, heating and mixing, and found that too much demulsifier hurt both desalting and dehydration [11], and an industrial desalter has been simulated with its mixing valve and electrostatic drum modeled together [10].

2.3 The Desalter as Modeled

The simulated unit is a generic single-stage desalter on a crude unit charging 500 m^3/h, about 75 000 barrels per day, as shown in Figure 2.1. Crude already heated to 130 °C takes in demulsifier and wash water ahead of the mixing valve, enters a horizontal vessel 3.6 m across and 24 m long through a distributor below two grids, and leaves from the top for the preheat train of Chapter 3. Water settles to the bottom and leaves as brine through a valve under interface control. A capacitance probe and its level transmitter (LT) read the interface, try-cock profile samples report the rag and the water height, an online analyzer and a meter report the salt and the BS&W of the desalted crude, and a third analyzer reports the oil in the brine. Crude flows and salt concentrations are per standard volume at 15 °C, while the oil occupies its volume at 130 °C inside the vessel. The clock is the minute, and flows in m^3/h are divided by 60 where they are integrated.

Each variable in Table 2.1 has a role in the loops, controlled (CV), manipulated (MV), disturbance (DV), state or computed output. Twenty states are integrated. Twelve are physical, the water layer's volume V_w and salt S_w, the rag's volume V_r and salt S_r, the water x_w and salt x_s leaving with the crude, the demulsifier at the drop surfaces D_{eff}, the brine and mixing valve positions u_b and u_m, the wash and dosing flows q_w and q_d, and the share x_h of the heavier crude in the charge. Eight are ledgers that integrate the transit holdups and every boundary flow of water and salt, so that both balances can be checked to round-off.

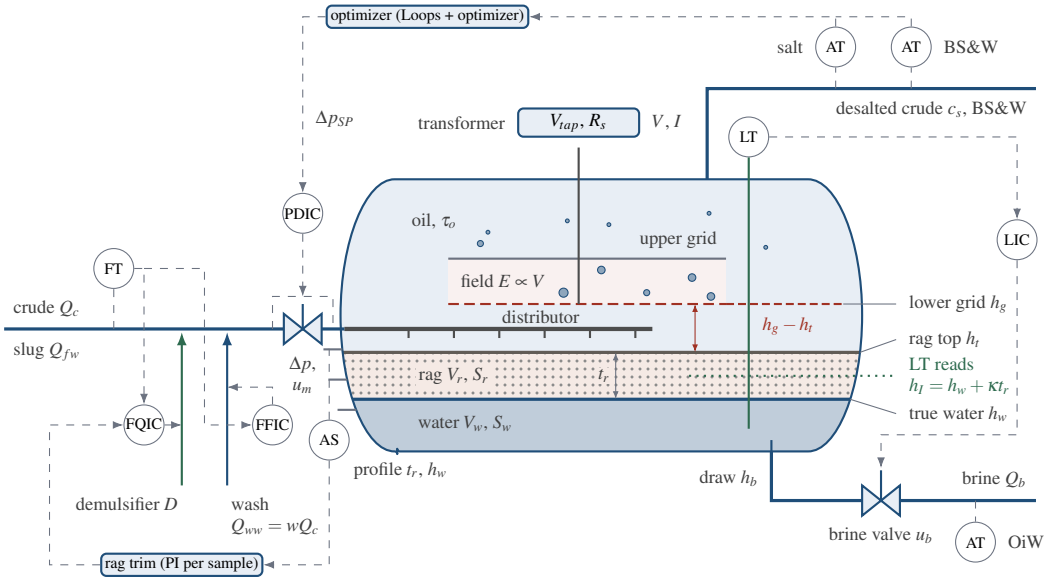


Figure 2.1 Single-stage electrostatic desalter as modeled, after the application's Vessel view. Crude Q_c (and any slug of free water Q_{fw}) takes in demulsifier D and wash water $Q_{ww} = wQ_c$ from ratio stations on the metered crude flow, crosses the mixing valve at pressure drop Δp and opening u_m, and enters the distributor. The water layer (V_w, S_w) rises to h_w, the rag (V_r, S_r, thickness t_r) to h_t, and the oil zone with residence τ_o fills the rest. The lower grid at h_g is fed through the reactor R_s from the tap V_{tap} at voltage V and current I. The lower grid is the dashed line under the field. The probe reads $h_I = h_w + \kappa t_r$ (dotted line), the true water is the solid line under the dotted rag, and the LIC moves the brine valve u_b to hold it. Brine Q_b leaves from the draw at h_b. The try-cock sample (AS) feeds the rag trim, and the salt analyzer and BS&W meter feed the optimizer, which writes the PDIC setpoint. Signals are dashed arrows. Heights at 1 cm per meter in the state of case 7 near 195 min, length not to scale. Process model only, not a piping or safety diagram.

2.3.1 One Volume Function for Three Layers

Every height in the vessel comes from one volume function of the horizontal cylinder and its inverse, as shown in Equation (2.1).

$$\begin{aligned} V_s(h) &= L\left[R^2 \cos^{-1}\frac{R-h}{R} - (R-h)\sqrt{2Rh-h^2}\right] \\ h_w &= V_s^{-1}(V_w), \qquad h_t = V_s^{-1}(V_w + V_r) \\ t_r &= h_t - h_w \end{aligned} \tag{2.1}$$

where $V_s(h)$ is the volume below height h, $R = D/2$ and L is the tangent length. The heads are drawn but carry no volume, so the vessel holds $V_{ves} = \pi R^2 L = 244.3\,\mathrm{m}^3$. The inverse is found by 18 bisection steps and 3 Newton steps, a fixed count, so a height is a function of its volume alone and repeated runs reproduce it exactly. The construction keeps $0 \le h_w \le h_t \le D$ without any test. At design the water stands at 1210 mm under an 80.4 mm rag whose top is at 1290 mm, 660 mm below the lower grid. At 1.25 m the interface is 3.43 m wide and 82.3 m^2 in area, so one cubic meter of water moves it 12.2 mm.

2.3.2 The Crude and Its Assay

Two assays are declared. The design crude has a density at 15 °C of 865 $\mathrm{kg/m}^3$, a viscosity at 130 °C of 1.4 mPa s, 10 PTB of salt in 0.2 % of brine, 5 PTB of filterable solids and 1.0 wt% of asphaltenes.

Table 2.1 Desalter Variables, Their Roles and Design Values (Case 3 at $t = 0$)

Variable	Role	Design	Range
h_I	CV, interface reading	1250 mm	SP 800–1700 mm
Δp	CV, mixing pressure drop	1.00 bar	SP 0.3–2.5 bar
u_b	MV, brine valve	42.5 %	0–100 %
u_m	MV, mixing valve	50.1 %	3–100 %
w	MV, wash ratio	5 % of crude	0–10 %
D	MV, demulsifier	5 ppm	0–60 ppm
Δp_{SP}	MV of the optimizer	1.00 bar	0.3–2.0 bar
assay	DV, crude charged	design	design, heavier
Q_c	DV, crude charge	500 m^3/h	60–110 %
Q_{fw}	DV, free water (slug)	0	0–10 % of crude
a_g	DV, transformer supply	100 %	40–100 %
b_I	DV, probe offset	0	±200 mm
a_w, a_D	DV, wash and dosing pumps	on	on, off
V_w, S_w	states, water layer	72.1 m^3, 37.6 kg	—
V_r, S_r	states, rag	6.61 m^3, 1.73 kg	—
x_w, x_s	states, carried water, salt	0.521 m^3/h, 0.956 kg/h	—
D_{eff}	state, demulsifier at drops	5.0 ppm	—
h_w, t_r, h_t	outputs, layers	1210, 80, 1290 mm	—
c_s	output, salt	0.670 PTB (1.91 mg/L)	—
BS&W	output, water in crude	0.104 %	—
V, I	outputs, grid	24.9 kV, 1.06 A	trip 3 A
Q_b, OiW	outputs, brine	25.5 m^3/h, 63 mg/L	limit 200 mg/L

The heavier crude has 898 kg/m^3, 1.9 mPa s, 10 PTB in 0.5 % of brine, 16 PTB of solids and 3.2 wt% of asphaltenes. Their properties enter the model as shown in Equation (2.2).

$$\begin{aligned} \mathrm{API} &= \frac{141.5}{\rho_{15}/999} - 131.5, \qquad \rho = \rho_{15}\,(1 - 115\,\beta) \\ s_e &= \frac{1}{2}\,\frac{\text{solids}}{5\,\text{PTB}} + \frac{1}{2}\,\frac{\text{asphaltenes}}{1\,\text{wt\%}} \\ \tau_{bl}\,\frac{\mathrm{d}x_h}{\mathrm{d}t} &= \chi_h - x_h \end{aligned} \tag{2.2}$$

where ρ is the oil density at 130 °C with the expansion coefficient β, s_e is an emulsion stability index of 1.0 for the design crude and 3.2 for the heavier one, and a crude switch, which sets χ_h from 0 to 1, blends in over $\tau_{bl} = 10$ min of line mixing. Blend properties are linear in x_h except the viscosity, which is log-linear. The two crudes are API 31.9 and 25.9. API 26 is a medium crude by the usual API gravity classes, in which heavy begins below 22.3, and it is heavy only beside the design crude. What makes it hard to desalt is its stability index, three times the design value. The viscosities lie 4.8 % above and 8.3 % below the Beggs–Robinson dead-oil correlation at API 32 and 26 [16], and the oil densities at 130 °C are 790.4 and 820.5 kg/m^3 against 935 kg/m^3 for the water.

2.3.3 Contact, Drop Size and Coalescence

The mixing valve has two effects, as shown in Equation (2.3). It brings a share η_c of the crude's own brine into contact with the wash water, and it shears the water into drops whose volume median d_v

falls with the pressure drop. The field between the grids then grows those drops to d_m.

$$\begin{aligned} \eta_c &= 1 - \exp\Big[-b\,\Delta p \Big(\frac{w}{w_0}\Big)^{c} \Big] \\ d_v &= d_0 \Big(\frac{\Delta p}{1\,\mathrm{bar}}\Big)^{-a} \\ d_m &= d_v \max\Big\{1,\; G_0 \Big[\Big(\frac{V}{V_0}\Big)^{2} \Big(\frac{\varphi}{\varphi_0}\Big)^{m} \psi \Big]^{1/3} \Big\} \\ \psi &= \frac{1+\alpha\,\theta_D}{1+\alpha\,\theta_{D,0}}\, s_e^{-q}, \qquad \theta_D = \frac{D_{eff}}{D_{eff}+K_D} \end{aligned} \tag{2.3}$$

where w is the wash and free water as a percentage of the crude, V is the grid voltage standing in for the field, φ is the water fraction of the treating zone with design value $\varphi_0 = 0.0494$, and $\theta_{D,0}$ is θ_D at the reference dose $D_0 = 5\,\mathrm{ppm}$. The exponent $a = 0.6$ is the breakup scaling of Hinze [17], the largest stable drop falling as the 0.4 power of the dissipation, with the dissipation in the valve taken to rise as $\Delta p^{1.5}$. The cube root follows from the dipole attraction between drops in a field, which grows as E^2 and as the sixth power of the drop size over the fourth power of their spacing [2]. At a fixed water fraction the spacing scales with the drop size, so the collision rate scales with E^2 and not with drop size, and the mean drop volume grows in proportion to the collisions. With the field 20 % weaker the carried-over share defined below rises from 0.018 to 0.033, where an exponential law in E^2 calibrated to the same design value would give about 0.60. At design $\eta_c = 0.950$, $d_v = 15.0\,\mu\mathrm{m}$ and $d_m = 695\,\mu\mathrm{m}$, a growth of 46.3 times at 24.9 kV.

2.3.4 Settling Against the Rising Oil

A drop settles if its hindered Stokes velocity beats the oil's upflow through the horizontal section at the rag top, which defines a cut size d_c, as shown in Equation (2.4).

$$\begin{aligned} u &= \frac{Q_c/(1-115\beta)}{3600\,L\,c(h_t)}, \qquad F = \Phi\Big(\frac{\ln(d_c/d_m)}{\ln\sigma_g}\Big) \\ d_c &= \sqrt{\frac{18\,\mu\,u}{(\rho_w-\rho)\,g\,(1-\varphi)^{4.65}}} \\ \varphi &= \frac{Q_n + Q_{ww} + Q_{fw}}{Q_c + Q_n + Q_{ww} + Q_{fw}} \end{aligned} \tag{2.4}$$

where $c(h)$ is the chord at height h, $\rho_w = 935\,\mathrm{kg/m^3}$, the exponent 4.65 is the Richardson–Zaki hindrance for creeping flow [18], Φ is the standard normal distribution and F is the share of the contacted water in drops smaller than d_c under a log-normal distribution of spread σ_g. At design the oil rises at 1.83 mm/s over $82.9\,\mathrm{m^2}$, the hindrance factor is 0.790, $d_c = 203\,\mu\mathrm{m}$ at a drop Reynolds number of 0.21, at the edge of the creeping-flow range in which both Stokes' law and the exponent apply, and $F = 0.0182$.

2.3.5 Where the Water and the Salt Go

Brine that the wash water never reached keeps its salt and its fine drops and leaves with the crude, while the contacted water settles except for the share F, as shown in Equation (2.5).

$$\begin{aligned} Q_{cont} &= \eta_c Q_n + Q_{ww} + Q_{fw} \\ S_{cont} &= \eta_c Q_n c_n + Q_{ww} c_{ww} + Q_{fw} c_{fw} \\ x_w^{*} &= F\,Q_{cont} + (1-\eta_c) Q_n \\ x_s^{*} &= F\,S_{cont} + (1-\eta_c) Q_n c_n \\ Q_{set} &= (1-F)\,Q_{cont}, \qquad S_{set} = (1-F)\,S_{cont} \end{aligned} \tag{2.5}$$

where Q_n is the crude's own brine at salinity c_n, 1.00 m³/h at 14 265 mg/L at design, and c_{ww} and c_{fw} are the salinities of the wash water and of tank-bottom free water. The salt removed is therefore $\eta_c(1-F) = 93.30\,\%$ at design. The salt and BS&W of the desalted crude follow from what it carries, $c_s = 1000\,x_s/Q_c$ in mg/L and BSW $= 100\,x_w/(Q_c + x_w)$ in percent by volume, a BS&W that counts water alone because the model carries no sediment. Because pounds per thousand barrels and milligrams per liter are both mass per standard volume, 1 PTB $= 453.59/158.99 = 2.853$ mg/L whatever the crude, and the density at 15 °C enters only a conversion to mg/kg.

The water and salt in the layers and in transit obey the balances of Equation (2.6).

$$\begin{aligned}
\frac{\mathrm{d}V_w}{\mathrm{d}t} &= Q_{set} - x_r R_f + x_r R_d - f_w Q_b \\
\frac{\mathrm{d}S_w}{\mathrm{d}t} &= S_{set} - x_r R_f c_{set} + x_r R_d c_r - f_w Q_b c_w \\
\frac{\mathrm{d}V_r}{\mathrm{d}t} &= R_f - R_d, \qquad \frac{\mathrm{d}S_r}{\mathrm{d}t} = x_r R_f c_{set} - x_r R_d c_r \\
\tau_o \frac{\mathrm{d}x_w}{\mathrm{d}t} &= x_w^* - x_w, \qquad \tau_o \frac{\mathrm{d}x_s}{\mathrm{d}t} = x_s^* - x_s
\end{aligned} \tag{2.6}$$

where $x_r = 0.5$ is the water share of the rag, $c_{set} = S_{set}/Q_{set}$, $c_r = S_r/(x_r V_r)$ and $c_w = S_w/V_w$ are the salinities of the settling water, the rag water and the layer, f_w is the water share of the brine draw from Equation (2.9), and $\tau_o = (V_{ves} - V_w - V_r)(1 - 115\beta)/Q_c$ is the residence time of the well-mixed oil zone, 18.2 min at design. Carried water and salt therefore reach the outlet with a first-order lag. At design 0.521 m³/h of water leaves in the crude, a BS&W of 0.104 %, with 1.913 mg/L or 0.670 PTB of salt.

2.3.6 The Rag Layer

The rag forms from the arriving emulsion in proportion to its stability and to the mixing, and it is broken by demulsifier and by its own slow resolution, both slower on a stable emulsion, as shown in Equation (2.7).

$$\begin{aligned}
R_f &= \min\left[k_r s_e \left(\frac{\Delta p}{1\,\mathrm{bar}}\right)^n \frac{Q_c}{Q_{c,0}},\ \frac{Q_{set}}{x_r}\right] \\
R_d &= \frac{k_d\,\theta_D + 1/\tau_r}{s_e} V_r
\end{aligned} \tag{2.7}$$

where the cap keeps the rag from taking more water than settles. Over cases 1 to 9 as shipped it binds only after the wash pump of case 5 trips, when nothing is contacted and nothing settles. The steady rag volume $R_f s_e/(k_d\theta_D + 1/\tau_r)$ therefore grows as s_e^2. At design $R_f = 2.48\,\mathrm{m}^3/\mathrm{h}$ and the rate constant is 0.375/h, which hold 6.61 m³, an 80.4 mm rag. On the heavier crude at the same 5 ppm the steady volume is 10.24 times larger, 3.2^2, and the rag 832 mm thick, 10.4 times the design thickness because the chord changes with height.

2.3.7 Grid Voltage, Current and Trip

The transformer drives the lower grid through a current-limiting reactor, and the load conductance rises with the crude's solids, with how wet the oil leaves and steeply as the rag top nears the grid, as shown in Equation (2.8).

$$\begin{aligned}
G &= g_o\,[1 + 0.2(s_e - 1)]\,[1 + 0.1\max(0, \omega - 1)] \\
&\quad + g_p\,\mathrm{e}^{-(h_g - h_t)/\lambda} \\
V &= \frac{a_g V_{tap}}{1 + R_s G}, \qquad I = GV
\end{aligned} \tag{2.8}$$

where ω is the carried water per unit of crude against its design value, V_{tap} is the open-circuit tap, an Advanced control at 27 kV, a_g is the supply's availability and $V = 0$ once the grid has tripped.

At design $G = 0.0427\,\mathrm{A/kV}$, of which 0.0027 A/kV is the path to the rag top, so $V = 24.87\,\mathrm{kV}$ and $I = 1.063\,\mathrm{A}$. On the dry design crude the current reaches the 3.0 A trip at a gap of 297 mm, 2.0 A at 375 mm and 1.5 A at 449 mm, so the last 150 mm carry most of the rise, and water at the grid would draw 10.84 A against the reactor's limit of $V_{tap}/R_s = 13.5\,\mathrm{A}$. The reactor also pulls the voltage down as the current rises, which weakens the field when the emulsion is wettest. A current at or above 3.0 A held for 12 s trips the grid, the trip latches, and the run stops.

> **TRY IT IN THE APP** **6 · Let the interface rise: the grid trip (Manual)**
>
> Load the case and press Run. Nothing has to be set. The brine valve is pinched at 30 min and the water begins to rise. Watch the grid current. It is 1.06 A at 30 min and only 1.21 A at 60 min, then passes its alarm at 100 min and trips the grid at 119.6 min, with the rag top 297 mm below the grid.

2.3.8 Brine and the Oil It Carries

The brine valve passes water while the layer stands above the draw nozzle, and the oil it carries rises as the water's residence falls, as rag nears the draw, and once oil is drawn straight through, as shown in Equation (2.9).

$$\begin{aligned} f_w &= \mathrm{clip}\Big(\frac{h_w}{h_b}, 0, 1\Big), \qquad Q_b = Q_{b,max}\,u_b \\ \tau_w &= \frac{V_w}{f_w Q_b}, \qquad \mathrm{OiW} = \mathrm{OiW}_0\sqrt{\frac{3\,\mathrm{h}}{\tau_w}} \\ &\quad + \min\left[\mathrm{OiW}_r e^{-(h_w-h_b)/\lambda_b},\ 2\times 10^5\right] \\ &\quad + (1-f_w)\,8\times 10^5\ \mathrm{mg/L} \end{aligned} \tag{2.9}$$

where $h_b = 150\,\mathrm{mm}$ is the draw nozzle and the brine valve is linear in flow. At design the water turns over in $\tau_w = 2.83\,\mathrm{h}$ and the brine carries 63.2 mg/L of oil against a 200 mg/L limit to the wastewater plant.

2.3.9 Actuators and Instruments

The valves and pumps follow their commands with first-order lags, and the mixing valve's pressure drop is quadratic in flow, as shown in Equation (2.10).

$$\begin{aligned} \tau_{bv}\frac{\mathrm{d}u_b}{\mathrm{d}t} &= u_b^{cmd} - u_b, \qquad \tau_{mv}\frac{\mathrm{d}u_m}{\mathrm{d}t} = u_m^{cmd} - u_m \\ \Delta p &= \Delta p_{open}\Big(\frac{Q_{tot}}{Q_0}\Big)^2 \frac{1}{\max(0.03, u_m)^2} \\ \tau_{ww}\frac{\mathrm{d}q_w}{\mathrm{d}t} &= a_w q_{w,SP} - q_w, \qquad \tau_p\frac{\mathrm{d}q_d}{\mathrm{d}t} = a_D q_{d,SP} - q_d \\ \tau_D\frac{\mathrm{d}D_{eff}}{\mathrm{d}t} &= q_d - D_{eff} \end{aligned} \tag{2.10}$$

where Q_{tot} is the crude with its brine, wash and free water, $Q_0 = Q_{c,0}(1 + w_0/100)$ is its design value, and a_w and a_D are 1 with the wash and dosing pumps running and 0 with either tripped. The demulsifier reaches the drop surfaces and the rag through $\tau_D = 45\,\mathrm{min}$, which makes it the slow handle. At design the mixing valve stands 50.1 % open for 1.00 bar. The charge is held whatever the mixing valve does, so the manual station stops at 15 %, where the drop at design flow is already 11.2 bar.

The interface instrument is the center of the chapter. The probe reads the water and part of the rag, with an offset, a lag and noise, as shown in Equation (2.11).

$$\begin{aligned} y &= h_w + \kappa t_r + b_I \\ \tau_{LT}\frac{\mathrm{d}y_f}{\mathrm{d}t} &= y - y_f, \qquad h_I = y_f + \sigma_I n_k \end{aligned} \tag{2.11}$$

where $\kappa = 0.5$ is the share of the rag the probe counts as water, $\tau_{LT} = 0.5\,\text{min}$, $\sigma_I = 4\,\text{mm}$ and n_k is a unit normal deviate drawn at each control execution. Water's permittivity is many times that of oil, so a capacitance probe responds to a water-continuous emulsion almost as to water and to an oil-continuous one only in part, and a reading partway into the rag stands closer to such a probe than a reading at its top. The value 0.5 is a teaching value chosen for margin in the challenge, where the shipped settings' current would peak at 3.80, 3.39 and 3.10 A with κ at 0.5, 0.6 and 0.7 if the trip were disabled. The BS&W meter has a 2 min lag and 0.003 % of noise, the mixing pressure drop 0.004 bar of noise, the oil-in-brine analyzer a 5 min lag. The salt analyzer draws a sample every 15 min and reports it 10 min later with 0.02 PTB of noise. A try-cock profile is drawn every 24 h, 8 h or 2 h, the first at $t = 0$, and reports the rag thickness and the water height 15 min later with 15 and 10 mm of noise. Flows, valve positions and the grid's voltage and current are read without lag or noise. The random draws of an execution do not depend on any setting, which keeps two runs that differ in one setting aligned noise for noise.

2.3.10 Parameters, Initialization and Numerics

Table 2.2 gives every parameter, marked adjustable (A) when it appears in the application's Parameters panel, hidden (H) when it does not, and fixed (F) for the constants written into the equations. None of the values was measured on a plant. They were chosen as typical of a single-stage desalter and so that the design point closes. A case begins lined out at its own settings. The rag takes its steady volume or the case's starting thickness, the water is placed by bisection so that the instrument reads the interface setpoint, the carried water and the grid voltage are iterated together thirty times, and the brine valve passes exactly the water that settles. The integrator is the classical fourth-order Runge–Kutta method with a step of 2 s. Halving it moves no quantity of the heavier-crude case at 6 h by more than 6.4×10^{-9} of its value. At the end of each of cases 1 to 9 the water ledger closes to 5.8×10^{-13} and the salt ledger to 2.2×10^{-13} of what entered. A simulated hour costs about 80 ms of computing in a JavaScript engine.

2.3.11 Assumptions

The vessel is one oil zone, one rag and one water layer, each well mixed, and the oil carries water to the outlet with a first-order lag. A real desalter has a distributor, a treating zone and a collector, so its outlet answers with more delay and less smoothing. The separation is a teaching correlation and not a population balance. It gives the right directions and plausible sizes, and it is not a design method. Brine the wash water never reached keeps its salt and leaves, so nothing is removed with the wash water lost, while a real desalter would still dehydrate some native brine. The rag kinetics, the grid conductance, the oil-in-brine law and the probe's rag share κ are synthetic correlations chosen for an 80 mm design rag, a current near 1 A at 25 kV and a trip near a 300 mm gap, and none is a prediction for a vessel, crude or chemical. The demulsifier helps monotonically up to the 60 ppm limit, whereas an overdose can hurt a real emulsion [11]. Temperature is fixed at 130 °C and the vessel is liquid full, so heat, pressure and the preheat train are absent, and the heads carry no volume. The grid trip, the alarm, the oil-in-brine limit and the salt and BS&W specifications are teaching values. The real ones come from the transformer rating and the vendor, the refinery's wastewater permit and its crude-unit specifications [2].

2.4 An Integrator, an Optimum and a Drifting Reading

2.4.1 The Water Layer Integrates

The water layer holds the difference between the water that settles and the brine drawn off, and nothing in the vessel pushes back until the water reaches the draw nozzle, so the layer is an integrating process. One percent of brine valve passes 0.6 m^3/h, which moves the interface 7.29 mm/h, the integrating gain. In case 1 the brine valve opens from 42.5 to 54.5 % at 20 min and the true water falls 89.5 mm/h, reaching 663 mm at 360 min with 235 mg/L of oil in the brine. Setting the valve to

Table 2.2 Model Parameters, Marked A When Adjustable in the Parameters Panel, H When Hidden and F When Fixed in the Equations

Symbol	Meaning	Value	Unit	
D, L	vessel diameter, tangent length	3.6, 24	m	A
h_g, h_b	lower grid, brine draw height	1950, 150	mm	A
$Q_{c,0}$	design crude charge (15 °C)	500	m³/h	A
β	crude expansion coefficient	7.5×10^{-4}	1/K	A
ρ_w	water density at 130 °C	935	kg/m³	A
w_0	design wash rate	5	%	H
Δp_{open}	mixing valve drop, wide open	0.25	bar	A
τ_{mv}, τ_{bv}	mixing, brine valve lags	0.1, 0.1	min	A
b, c	contact coefficient, wash exponent	3.0, 0.7	bar, —	A
d_0, a	drop median at 1 bar, exponent	15, 0.6	µm, —	A
G_0	coalescence growth at design	46.5	—	A
m, q	exponents on φ and s_e	1.0, 0.45	—	A
α, K_D	demulsifier effect, half dose	6, 25	—, ppm	A
D_0, V_0	reference dose, voltage	5, 25	ppm, kV	H
σ_g	drop-size spread	1.8	—	A
4.65	hindered-settling exponent	4.65	—	F
τ_D	demulsifier action lag	45	min	A
k_r, n	rag formation, exponent on Δp	2.48, 1.0	m³/h, —	A
k_d, τ_r	rag breaking, resolution time	1.5, 8	1/h, h	A
x_r	water share of the rag	0.5	—	H
κ	share of the rag read as water	0.5	—	A
$t_{r,0}$	starting rag (0 = steady)	0	mm	A

Symbol	Meaning	Value	Unit	
V_{tap}	transformer tap (open circuit)	27	kV	H
R_s	current-limiting reactor	2.0	kV/A	A
g_o, g_p	emulsion, contact conductance	0.040, 2.0	A/kV	A
λ	decay length of the path	100	mm	A
0.2, 0.1	conductance gains on s_e, ω	0.2, 0.1	—	F
I_{trip}, I_{HA}	grid trip (12 s), alarm	3.0, 2.0	A	A
$Q_{b,max}$	brine valve capacity	60	m³/h	A
τ_{ww}, τ_p	wash loop, dosing pump	0.5, 1	min	H
c_{ww}, c_{fw}	wash, free-water salinity	0, 1000	mg/L	A
OiW_0, OiW_r	oil in brine, base and rag	60, 10 000	mg/L	A
λ_b	decay length of rag entrainment	120	mm	A
τ_{bl}	line mixing of a crude switch	10	min	A
salt, BS&W	specifications	1.0, 0.2	PTB, %	A
OiW limit, rag alarm	brine and rag limits	200, 300	mg/L, mm	A
τ_{LT}, σ_l	probe lag, noise	0.5, 4	min, mm	F
—	LIC input filter	1	min	F
—	salt analyzer cycle, delay	15, 10	min	F
—	profile delay / noise (t_r, h_w)	15 / 15, 10	min / mm	F
Assays (design, heavier)				
ρ_{15} / μ	density at 15 °C / viscosity at 130 °C	865, 898 / 1.4, 1.9	kg/m³ / mPa s	F
salt / brine	raw salt / own water	10, 10 / 0.2, 0.5	PTB / %	F
solids / asph.	filterable solids / asphaltenes	5, 16 / 1.0, 3.2	PTB / wt%	F

pass the water arriving, 42.4 %, stops the fall wherever the interface happens to be, and the rag and the reading ride down with the water.

2.4.2 An Interior Optimum in the Mixing Valve

The steady salt and BS&W against the mixing pressure drop, computed with the model's own functions at three states the cases visit, are shown in Figure 2.2. On the design crude the salt is 1.69, 0.67, 0.54 and 0.89 PTB at 0.6, 1.0, 1.29 and 2.0 bar, with its least value of 0.540 PTB at 1.292 bar. Below the optimum too little brine meets wash water, and above it the drops leave the field too small to settle. The BS&W reaches the 0.2 % specification at 1.356 bar, just past the salt optimum, so on the design crude the optimum is feasible with a margin of 0.064 bar. The BS&W is not monotonic

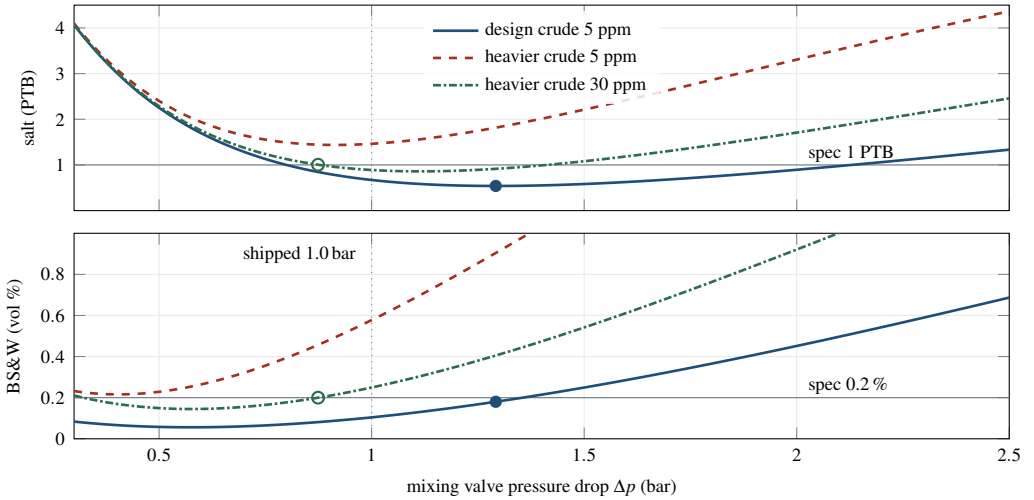


Figure 2.2 Steady salt and BS&W of the desalted crude against the mixing pressure drop, from the application's own map. Design crude at 5 ppm (case 3 at $t = 0$), heavier crude at 5 ppm (case 4 at 240 min, rag 292 mm, dashed) and at 30 ppm (case 4 with 30 ppm from 120 min, at 720 min, rag 320 mm, dash-dotted). The design crude is the solid line. Thin gray lines mark the specifications, and the dotted vertical line the shipped pressure drop. The filled dot is the design crude's least salt, 0.540 PTB at 1.29 bar. The ring is the least salt meeting 0.2 % on the heavier crude at 30 ppm, 1.005 PTB at 0.87 bar. At 5 ppm no pressure drop meets the BS&W specification on the heavier crude.

either. It falls from 0.084 % at 0.3 bar to a minimum of 0.056 % at 0.57 bar and then rises, because below that point the uncontacted brine, which keeps its fine drops, outweighs the settling that gentler mixing allows.

🕮 **Pause.** Try Exercise 2.1 before reading on.

A crude switch moves the whole map. On the heavier crude at 5 ppm, at 240 min in case 4, three hours after the switch, the least BS&W anywhere is 0.216 % at 0.40 bar, where the salt is 3.06 PTB, so no setting of the fast handle meets the specification. Raising the demulsifier to 30 ppm restores feasibility. The least salt with the BS&W at 0.2 % or less is then 1.005 PTB at 0.87 bar, while the unconstrained least salt, 0.860 PTB at 1.11 bar, carries 0.304 % of water. The fast handle chooses where on a curve to sit, and the slow handle decides which curve exists. With the wash water lost the salt is 10.0 PTB, the raw crude's, at every pressure drop.

🕮 **Pause.** Try Exercise 2.3 before reading on.

2.4.3 A Reading That Drifts With the Rag

From Equation (2.11), a loop that holds h_I at its setpoint holds $h_w = h_{I,SP} - \kappa t_r - b_I$, so every millimeter the rag grows lowers the true water by κ millimeters with no change in the reading, no error in the loop and no move of the valve that an operator would notice. The water then has less time to release its oil and the rag comes closer to the draw. The same reading also lifts the rag top as the rag grows, $h_t = h_{I,SP} + (1 - \kappa)t_r - b_I$, toward the grid. A profile sample measures the bias κt_r directly, but only as often as it is drawn, and it ages between samples while the rag keeps changing. Section 1.4.6 places this misread interface among the refinery's measurement problems.

🕮 **Pause.** Try Exercise 2.2 before reading on.

> **TRY IT IN THE APP 7 · The rag fools the interface instrument**
>
> Open the app, pick this case from the list and press Run. Nothing has to be set. Watch the labels at the right of the vessel. The reading stays near its 1000 mm setpoint for eight hours while the true water sinks from 750 to 632 mm. At 192 min the brine passes its limit for oil.

2.5 The Control System as Implemented

The controllers execute every $\Delta t_c = 6\,\text{s}$, three physics steps, and the historian logs a row every 30 s. The order of the work within a step is that of the shared engine (Section 1.6.1). Apart from extremum seeking, which reads less, the controllers see the plant only through a packet of the instrument readings of Section 2.3 and the declared assay of the tank on charge, and one of the application's tests checks that no other key ever appears in that packet.

2.5.1 Interface and Pressure-Drop Loops

Both valve loops use the velocity-form PID of Equations (1.16) to (1.19), executed at Δt_c with no derivative action, a tracking time equal to τ_I and the limit on the output alone. Both are direct acting in the instrument sense ($a = -1$, so the error is PV $-$ SP), a high interface opening the brine valve and a high pressure drop opening the mixing valve. An integral time of 600 min or more removes integral action. The interface controller (LIC) reads h_I through a first-order filter of 1 min, which keeps the probe's noise out of the brine valve, and its defaults are $K_c = 0.3\,\%$ of valve per millimeter and $\tau_I = 60\,\text{min}$ on a 0 to 100 % output. With the integrating gain $K = 7.29\,\text{mm/h}$ per percent, proportional action alone gives a closed-loop time constant $1/(KK_c) = 27.4\,\text{min}$, and a PI loop on an integrating process is critically damped at $\tau_I = 4/(KK_c)$, 110 min here, so the default 60 min trades some overshoot for speed. The pressure-drop controller (PDIC) has $K_c = 20\,\%$ per bar and $\tau_I = 0.5\,\text{min}$ on a 3 to 100 % output.

The header's Manual and Auto switch both valves. In Manual each valve sits at its operator station and both PIs track it as Section 1.6.2 describes, so the transfer back to Auto is bumpless. The ratio stations keep running in Manual, because a wash pump and a dosing pump are always in ratio, while the trim and the optimizer hold.

2.5.2 Ratio Stations and the Rag Trim

The wash water setpoint is $q_{w,SP} = (w/100)\,Q_{c,m}$ on the metered crude flow. The demulsifier setpoint is the operator's ratio D, or the output of a rag trim when the trim is on, much as a slow trim on a ratio dose works in Volume 3, Chapter 6. The trim is the same PI with $K_c = 0.6\,\text{ppm}$ per millimeter, $\tau_I = 120\,\text{min}$ and a target of 80 mm, executed once per reported profile sample over the time since its last execution, as shown in Equation (2.12).

$$q_{d,SP} = \text{clip}\big(D + \text{PI}(t_{r,sample} - t_{r,SP}),\; D,\; 60\,\text{ppm}\big) \tag{2.12}$$

where the floor is the operator's ratio, so the trim only adds. Between samples the dose holds. An earlier version of the trim, replaced when the application was reviewed, tracked the dose on its floor while it was off or at the moment it was switched on. It so stored the gap between a thin rag and its target as integral action the floor hid, 21.7 ppm with the rag at 44 mm against 80 mm, which the first reported sample then released as a dose increase although the rag was still below target. A trim on its floor now holds no positive integral action, the state its own back-calculation reaches there, and with the rag above target the transfer is bumpless.

2.5.3 Correcting the Reading by Profile

With Interface reading set to Corrected by profile, each reported sample updates a bias $b = h_I(t_s) - h_{w,sample}$, where $h_I(t_s)$ is the reading logged when the sample was drawn, and the LIC holds $h_I - b$ instead of h_I. The bias is the update of Equation (1.14) with a gain of 1, so it takes each new sample's

value, and a bound of 1.5 m. The correction removes the rag bias, and in doing so it moves the water, and the rag on it, by the bias at once.

2.5.4 The Steady-State Optimizer

With Loops + optimizer selected, a steady-state optimizer writes the PDIC setpoint, as shown in Equation (2.13).

$$\begin{aligned} \Delta p_{SP} &= \arg \min_{0.3 \le \Delta p \le 2.0} \hat{c}_s(\Delta p)\, \mathrm{e}^{b_s} \\ \text{s.t.} \quad & \widehat{\mathrm{BSW}}(\Delta p)\, \mathrm{e}^{b_w} \le \mathrm{BSW}_{max} \\ & \hat{I}(\Delta p) \le 2.5\,\mathrm{A} \end{aligned} \tag{2.13}$$

where the hats are the steady state of Equations (2.3) to (2.8) computed with the parameters the case was commissioned with, from the metered crude and wash flows, the dosing pump's delivery through the nominal 45 min lag, the declared assay, the tap, and a rag top estimated as $h_I + (1-\kappa)t_{r,sample}$. Free water from a slug is not measured and enters the model as zero. The search runs on a 0.01 bar grid every 30 min and at once when the declared assay changes, the setpoint moves at most 0.25 bar per execution, and BSW_{max} defaults to 0.18 %, a margin under the specification. The biases b_s and b_w compare the logarithms of the salt analyzer and the BS&W meter with the model at the present pressure drop, through a filter gain of 0.3, and only when the plant is steady, which requires the setpoint to have stayed put for 30 min and both the meter and the model's own prediction to lie within 3 % of their values 20 min earlier. A new assay clears them. With no feasible point the optimizer reports infeasible and takes the least value of the salt plus 10 PTB per percent of BS&W or ampere of current over its limit. The optimizer is a one-dimensional search that ran on a model and on measurements, so it is real-time optimization in the narrow sense, and nothing in the application is a model predictive controller.

2.5.5 Model-Free Extremum Seeking

Extremum-seeking control (ESC) perturbs a command to infer an improving direction from measured performance [19, 20]. Here it writes only the PDIC setpoint and uses no input–quality map, declared assay, hidden emulsion state or plant predictor. At sample time s_n, the quality cost is

$$J_n = c_{s,m}(s_n) + 10\max\{B_m(s_n) - B_{max}, 0\}, \tag{2.14}$$

where $c_{s,m}$ is reported salt in PTB, B_m is measured BS&W in percentage points and $B_{max} = 0.18$ is the selected quality limit. The coefficient is 10 PTB per percentage point, so J_n has units PTB. The analyzer draws every 15 min and reports 10 min later. Each distinct fresh timestamp is consumed once and paired with the historical meter reading at s_n, rather than its value when the report arrives.

With period $P = 360$ min, amplitude $a_p = 0.10$ bar and $\tau_f = P/4 = 90$ min, the executed recurrences are

$$\begin{aligned} \alpha_n &= 1 - \exp(-\Delta s_n/\tau_f), \quad h_n = J_n - b_{n-1} \\ b_n &= b_{n-1} + \alpha_n h_n \\ \hat{g}_n &= (1-\alpha_n)\hat{g}_{n-1} + \alpha_n \frac{2h_n}{a_p}\sin\theta_n \\ z_n &= \Pi[z_{n-1} - \Delta s_n\, \mathrm{clip}(k_g \hat{g}_n, -v_c, v_c)] \\ \Delta p_{SP}(t) &= \Pi\left[z_n + a_p \sin\frac{2\pi(t-t_0)}{P}\right], \end{aligned} \tag{2.15}$$

where $\Delta s_n = s_n - s_{n-1}$, $\theta_n = 2\pi(s_n - t_0)/P$, b_n is the baseline, h_n its washout output, $\hat{g}_n$ the filtered gradient estimate in PTB/bar, z_n the center and t_0 the activation or recovery time. Projection Π clips to 0.3–2.5 bar, $k_g = 0.001$ bar^2/(PTB min), and $v_c = 0.001$ bar/min. The first accepted report initializes b to J with $h = 0$, $\hat{g} = 0$ and a 15 min interval. Center adaptation is disabled until $s_n - t_0 \ge \tau_f$. Thus

Table 2.3 The Ten Cases

#	Case, preset and events	Teaching point
1	Manual, brine valve +12 points at 20 min	the integrating layer
2	P-only LIC, SP +100 mm at 60, wash 5 to 7 % at 240 min	P and PI on an integrator
3	Salt map view, optimizer available	the interior optimum
4	Heavier crude from 60 min	rag, grid current, demulsifier
5	Wash pump trips at 360 min	wash ratio, brine load
6	Manual, brine valve pinched to 8 % at 30 min	the grid trip
7	Heavier crude, 500 mm rag, SP 1000 mm, 2 h samples	the rag bias
8	350 mm rag, LIC 0.1/120 min, slug at 60 min	averaging against tight
E	Extremum seeking, 0.9 bar, 30 ppm, crude switch at 360 min	learning from delayed quality
9	Challenge: heavier crude at 3 h, slug at 8 h	the whole problem

the first ordinary adaptation is at clock 100 min, on the sample drawn at 90 min. The center changes only on fresh reports, by at most 0.015 bar for an ordinary 15 min interval. It holds between reports while the probe changes every 6 s. Tuning ranges are 240–720 min for P, 0.02–0.20 bar for a_p and 0–0.005 bar^2/(PTB min) for k_g. The displayed probe is the clipped request minus z_n. A positive gradient lowers the center. For a static smooth cost, $J(z + a_p \sin\theta) = J(z) + a_p J'(z) \sin\theta + O(a_p^2)$ explains the sign and the factor $2/a_p$, without making $\hat{g}_n$ an exact plant derivative.

The raw measured interface reaching $h_g - 0.30$ m is a hold of the ESC alone, not an interface alarm or a rag-top estimate. Measured current at I_{HA}, reported rag at 300 mm, a grid trip, Manual, nonfinite data or salt timestamp age above 45 min also stop probing and adaptation, preserving the current bounded request. Recovery starts acquisition again and discards pre-recovery draws. Numerical failure causes this same hold, without a transfer to the optimizer. The LIC, PDIC, ratio stations, rag trim and physical trip keep their functions. ESC entry has zero setpoint and valve jump in the transfer tests. On ESC exit to the map optimizer, the new target jumps 0.247 08 bar, while PDIC tracking keeps the valve command continuous. These tests do not establish quality feasibility.

2.5.6 Protection and the Three Models

The grid trip of Section 2.3 reads the simulator's truth and is a teaching guardrail, not certified protection. The application keeps three models apart. The plant is the whole of Section 2.3. The identified model is whatever slope a learner fits to the falling interface of case 1, 7.29 mm/h per percent of valve in the plant. The controller's model is the optimizer's copy of the steady-state map with the commissioned parameters, which knows neither the slug's free water, nor the probe's offset, nor a parameter changed after the case started, and which the biases correct only on steady data.

2.6 Ten Cases, Measured

The ten cases appear in Table 2.3. All start from the defaults of Section 2.5 with 1.0 bar of mixing, 5 % of wash water, 5 ppm of demulsifier, the trim off, daily samples and the design crude, and depart from them only as their rows say. The numbers that follow were produced by stepping the engine of Section 1.6.1 headless at the default seed, in the order the browser steps it, and a setting named for a case is entered before the run unless a time is given. A case gives the same trajectory whether it is the first one opened, picked from the list after a different case, or restarted with Reset. The measured outcomes are collected in Table 2.4. The extremum-seeking case carries no number in the app, which lists it just before the challenge, and this chapter calls it case E. A requirement of a case is met only by a combination of something the learner did and a state the vessel reached (Section 1.6.4), and the chapter's exercises are built on the cases.

2.6.1 Proportional and Integral Action on the Layer

Case 2 ships a proportional-only LIC. The 100 mm setpoint step at 60 min settles with no offset, −0.2 mm over 200 to 240 min, because at the old brine flow the layer is already balanced. After the wash water rises from 5 to 7 % at 240 min, 10 m^3/h more water has to leave for good, the brine

Table 2.4 Measured Outcomes by Case, Default Seed

#	Setting	Outcome
1	as shipped	water −89.5 mm/h, 663 mm and 235 mg/L at 360 min
2	P-only	SP step −0.2 mm, wash step +55.3 mm offset
	τ_I 60, 30 min	offset −1.0 mm, overshoot 28, 39 mm
3	0.6, 1.0, 2.0 bar	1.69, 0.67, 0.89 PTB, BS&W up to 0.452 %
	optimizer	1.25 then 1.29 bar, 0.539 PTB, 0.179 %
4	as shipped	BS&W 0.526 % at 120, alarm 140.5 min, rag 619 mm, 2.72 A
	30 ppm at 120 min	rag 320 mm, 0.250 %, 0.89 PTB at 720 min
	trim, 2 h samples	60 ppm at 261 min, rag 261 mm, 0.197 %
5	wash 3, 5, 7, 8 %	1.48, 0.67, 0.36, 0.28 PTB, brine 15.5 to 40.5 m^3/h
	pump trip	5 PTB at 373 min, 10.0 PTB by 600 min
6	as shipped	alarm 100 min, trip 119.6 min at 3.01 A, gap 297 mm
7	as shipped	water 750 to 632 mm, oily at 192 min, bias 372 mm
	corrected, SP 1000	water 688 to 986 mm, trip 259.9 min
	corrected, SP 850	water 853 mm, 106 mg/L, peak 2.65 A
8	averaging (shipped)	brine 42.4 m^3/h, rag top 1613 mm, 2.45 A, 75 mg/L
	tight, 1.0/30 min	brine 60 m^3/h, rag top 1487 mm, 1.48 A, 99 mg/L

valve must stay 17.4 points further open (42.1 to 59.5 %), and the loop holds it there with an error of 55.3 mm at 0.3 % per millimeter, against 55.6 mm predicted from 10 m^3/h at 0.6 m^3/h per percent of valve and the gain. A 60 min integral time removes the offset to −1.0 mm over the last hour with 28 mm of overshoot on the setpoint step, and 30 min overshoots by 39 mm.

2.6.2 The Optimizer on the Salt Map

In case 3 the optimizer moves the setpoint from 1.00 to 1.25 and then to 1.29 bar and holds the salt at 0.539 PTB with the BS&W at 0.179 %, its own limit, after four hours. Its biases stay small, 0.002 on the logarithm of the BS&W and 0.030 on that of the salt, because its map is the plant's own correlation and only the instruments and its estimate of the rag top separate the two. Steps by hand to 0.6 and 2.0 bar settle at 1.69 PTB and at 0.89 PTB with 0.450 % of water.

2.6.3 A Heavier Crude, Wash Water and the Grid

The heavier crude of case 4 hardens the emulsion at once, and within an hour of the switch the BS&W rises from 0.104 to 0.526 % and the salt from 0.67 to 1.37 PTB. The rag grows more slowly, from 80 to 619 mm by 720 min. Because the probe reads half of it as water, the loop lets the true water fall to 940 mm and lifts the rag top to 1559 mm, 391 mm below the grid, and the current passes its 2.0 A alarm at 140.5 min and reaches 2.72 A. Demulsifier at 30 ppm from 120 min holds the rag at 320 mm, and the trim on 2 h samples, switched on at 120 min, takes the dose to its 60 ppm limit by 261 min and holds the rag at 261 mm with the BS&W at 0.197 %.

In case 5 the salt at 3, 5, 7 and 8 % of wash is 1.48, 0.67, 0.36 and 0.28 PTB while the BS&W stays between 0.104 and 0.115 %, and the brine rises from 15.5 to 40.5 m^3/h with its oil from 50 to 79 mg/L. After the wash pump trips at 360 min the salt passes 5 PTB at 373 min and reaches the raw 10.0 PTB by 600 min, a target no tuning can recover. In case 6, with the brine valve pinched to 8 % at 30 min, the current is 1.06 A at 30 min and only 1.21 A at 60 min while the rag top is far from the grid, then passes the alarm at 100 min and trips the grid at 119.6 min with 3.01 A and the rag top 297 mm below it. Opening the brine valve to 42.5 % at the alarm prevents the trip with a peak of 2.01 A, and so does a wide-open valve as late as 115 min, with 2.70 A.

2.6.4 The Rag Fools the Instrument

Case 7 starts on the heavier crude with a 500 mm rag and the interface setpoint at 1000 mm, so the probe reads 1000 mm with the water at 750 mm. The loop holds its reading for eight hours while the rag grows to 735 mm and the water falls to 632 mm. The brine passes 200 mg/L of oil at 192 min, by which time the water turns over in 1.34 h instead of 1.50 h at the start, and by 480 min the reading

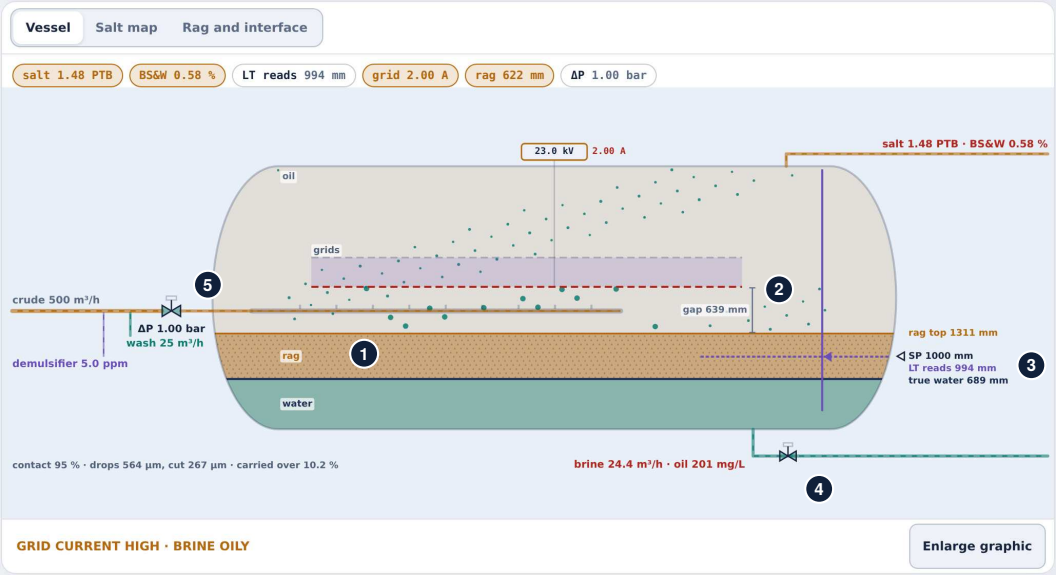


Figure 2.3 The rag misleading the interface instrument in case 7 at $t = 195$ min, Vessel view, as shipped, cropped to the plant view with numbered callouts. On the heavier crude the rag (1) has grown to 622 mm and its top stands at 1311 mm, 639 mm below the energized grid (2). The probe reads 994 mm (dotted) against its 1000 mm setpoint while the true water is at 689 mm (3). The brine valve (4) at 40.6 % passes 24.4 m³/h carrying 201 mg/L of oil, the grid draws 2.00 A at 23.0 kV, and the status strip reads GRID CURRENT HIGH and BRINE OILY. The mixing valve (5) holds 1.00 bar. Under the vessel, contact is 95 %, the drops leave the field at 564 µm against a 267 µm cut and 10.2 % of the contacted water is carried over, so the analyzer reports 1.48 PTB and the meter 0.579 % of water, with 85.3 % of the salt removed. In the full window, outside this crop, the trends over a two-hour window show the reading on setpoint with the true water and rag top drawn beside it, and the progress panel shows the first of the case's four completion steps met.

sits 372 mm above the water. The state at 195 min is shown in Figure 2.3. Correcting the reading at 200 min with the setpoint left at 1000 mm makes the loop close a bias of 282 mm, lifting the water from 688 to 986 mm and the rag with it until the grid trips at 259.9 min. Corrected with the setpoint at 850 mm, the water holds at 853 mm, the brine clears to 106 mg/L and the current peaks at 2.65 A. A thick rag leaves only a narrow band for the water between the draw and the grid. Corrected at 200 min with a setpoint of 900 mm, the water meets the case's one-hour hold at 301.8 min and the grid still trips at 464.3 min.

> ✦ **DID YOU KNOW? Correcting the Instrument Tripped the Grid**
>
> From the simulator (Table 2.4, case 7). With the reading corrected by profile and the setpoint left at 1000 mm, the true water rose from 688 to 986 mm and the grid tripped at 259.9 min. The same correction with the setpoint at 850 mm held the water at 853 mm with a peak of 2.65 A.

2.6.5 Averaging Against Tight Control Through a Slug

The slug of case 8 brings 50 m³/h of free water for 30 min, 25 m³ in all, onto a rag whose top stands 566 mm below the grid when it arrives. The brine valve passes at most 60 m³/h and normally runs at 26, so the layer must store part of the slug under any tuning. With the shipped averaging tuning, 0.1 % per millimeter and 120 min, the brine rises only to 42.4 m³/h, the rag top from 1384 to 1613 mm and

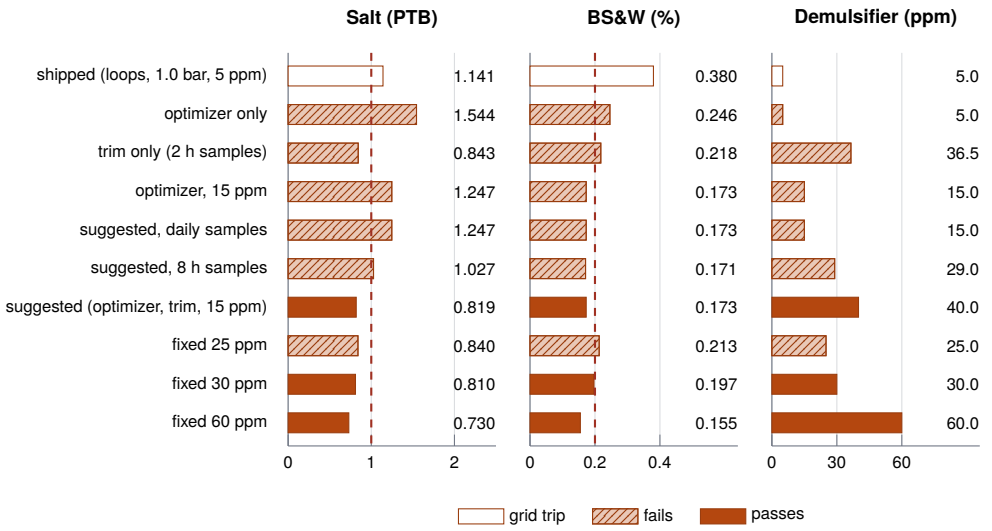


Figure 2.4 The ten challenge runs of Table 2.5 as bars for the average salt, the average BS&W and the average demulsifier over 12 h. The fill carries the verdict, solid for a pass, hatched for a miss and white for the run that tripped the grid, and the dashed lines are the targets of 1 PTB and 0.2 %. Notice that a run passes only with both of its first two bars left of the dashed lines, that the optimizer alone leaves both bars past their lines and the trim alone leaves one, and that the fixed 30 ppm passes with a shorter demulsifier bar than the suggested settings. The worst-sample column of the table is not drawn.

Table 2.5 The Challenge Over 12 h. Salt in PTB, Worst Analyzer Sample, BS&W Average and Demulsifier Average

Settings	Salt	Worst	BS&W (%)	ppm	Verdict
shipped (loops, 1.0 bar, 5 ppm)	1.141	1.471	0.380	5.0	trip 493.3 min
optimizer only	1.544	2.054	0.246	5.0	fails
trim only (2 h samples)	0.843	1.360	0.218	36.5	fails
optimizer, 15 ppm	1.247	1.783	0.173	15.0	fails
suggested, daily samples	1.247	1.783	0.173	15.0	fails
suggested, 8 h samples	1.027	1.744	0.171	29.0	fails
suggested (optimizer, trim, 15 ppm)	0.819	1.374	0.173	40.0	passes
fixed 25 ppm	0.840	1.428	0.213	25.0	fails
fixed 30 ppm	0.810	1.303	0.197	30.0	passes
fixed 60 ppm	0.730	0.985	0.155	60.0	passes

the current to 2.45 A, past its alarm. With tight tuning, 1.0 % per millimeter and 30 min, the valve goes wide open, the rag top peaks at 1487 mm and the current at 1.48 A, but the slug goes straight to the wastewater plant and the oil in the brine peaks at 99 mg/L instead of 75. An offshore separator makes the same trade between averaging and tight interface tuning in Volume 10, Chapter 6.

2.6.6 The Challenge and What It Does Not Price

The challenge runs 12 h with the heavier crude from 3 h and the slug at 8 h. Its target is the true salt at 1 PTB or less on average and 2 PTB or less at every analyzer sample, the BS&W at 0.2 % or less on average, the oil in the brine never above 200 mg/L, and no grid trip. The BS&W is judged as an average because even the suggested run exceeds 0.2 % for 125 min, with a peak of 0.306 %, during the switch and the slug. The variants appear in Table 2.5, and Figure 2.4 draws the same rows as bars.

As shipped, the unit runs the heavier crude on the design crude's settings, its BS&W averages 0.57 % from 240 to 480 min, its rag passes 400 mm by the time the slug arrives, and the grid trips at

Table 2.6 Paired Mean Quality and Time Above 0.2% Water Over 0–720 min, Seed 20261012

Case	Law	Salt (PTB)	BS&W (%)	$T_{B>0.2}$ (min)	ESC reports	ESC hold (min)	Trip (min)
Salt map	Fixed	0.6704	0.1041	0.0	0	0.0	—
	RTO	0.5425	0.1761	0.0	0	0.0	—
	ESC	0.6006	0.1317	0.0	48	0.0	—
Heavier crude	Fixed	1.3825	0.5290	646.0	0	0.0	—
	RTO	1.8305	0.2538	651.2	0	0.0	—
	ESC	1.4504	0.6137	648.8	7	609.7	715.8
Water slug	Fixed	0.6678	0.1082	0.0	0	0.0	—
	RTO	0.5704	0.1794	44.4	0	0.0	—
	ESC	0.6678	0.1082	0.0	0	720.0	—
Challenge, shipped chemistry	Fixed	4.6441	2.0285	526.0	0	0.0	493.3
	RTO	1.5441	0.2456	531.6	0	0.0	—
	ESC	4.6349	2.0332	526.9	18	451.2	493.2
Case E	Fixed	0.8304	0.1146	287.9	0	0.0	—
	RTO	0.6718	0.1375	62.8	0	0.0	—
	ESC	0.7842	0.1295	195.0	48	0.0	—

493.3 min, 13.3 min into the slug, with the rag top 394 mm below the grid. With the trip disabled the current would have reached 3.80 A. The suggested settings pass with 0.819 PTB on average, a worst sample of 1.374 PTB, 0.173 % of water, at most 94 mg/L of oil in the brine and a peak of 2.20 A. The optimizer holds 1.44 bar on the design crude at 15 ppm, and from 240 min on it keeps the setpoint between 0.69 and 0.94 bar. The trim adds nothing at the samples reported at 15 and 135 min, which find the rag at 57 and 49 mm, below its target. The sample drawn at 4 h and reported at 255 min finds 115 mm and takes the dose to 36.1 ppm, and the next, at 375 min, finds 181 mm and takes it to the 60 ppm limit. The rag then levels at no more than 237 mm, and the slug lifts its top to 1533 mm, 417 mm below the grid. The suggested settings pass at seeds 1 to 5 as well, with 0.778 to 0.852 PTB.

That passing run depends on the sample at 4 h. On daily samples the trim acts once, at 15 min, on a sample drawn before the switch, adds nothing, and the run reproduces the optimizer at a fixed 15 ppm to the digit. On 8 h samples the first useful sample comes too late and the run misses at 1.027 PTB. With the earlier version of the trim, both variants passed at the default seed, because the stored integral action raised the dose on the first sample, and they missed at most other seeds. The target also sets no chemical budget. Of the fixed ratios tried, 10, 15, 20, 25, 30, 40 and 60 ppm, the smallest that passes is 30 ppm, with 0.810 PTB and 0.197 % at every seed tried, while 25 ppm misses only on the BS&W, 0.213 %. The suggested settings average 40.0 ppm, a third more chemical than that fixed ratio, because the trim keeps adding while the heavier crude's rag stays above its target. The challenge therefore rewards holding the rag thin and the specifications met, and it does not reward the optimizer or the trim for saving chemical.

2.6.7 Measured Learning After a Crude Switch

Case E starts at 0.9 bar and 30 ppm, switches crude at 360 min, and runs to 720 min. Fixed pressure, the commissioned map optimizer (RTO) and ESC use the same chemistry, seed 20261012, instrument noise and events. The first ESC tuning candidate is frozen for every case. Other cases retain their shipped fixed pressure and dose. Each comparison reloads the case before selecting its law, retaining the same initial pressure and dose. Table 2.6 uses full-duration true outlet quality integrals, not analyzer averages. Post-trip field-off operation is included. The unchanged challenge verdict instead stops its accumulation at the trip, explaining its shipped 1.141 PTB in Table 2.5 versus 4.6441 PTB over the complete comparison window.

In case E, ESC reduces mean salt from fixed pressure's 0.8304 to 0.7842 PTB, but RTO achieves 0.6718 PTB. Time above 0.2 % BS&W is 287.9, 195.0 and 62.8 min, respectively, as shown in Figure 2.5. Mixing-valve travel is 131.30, 140.95 and 171.69 percentage points on the existing logged-sample metric. All three have zero valve saturation, current-alarm time and trips. With $k_g = 0$, probing alone gives 0.8461 PTB, so perturbation has a measurable cost. A hindsight fixed 1.2 bar

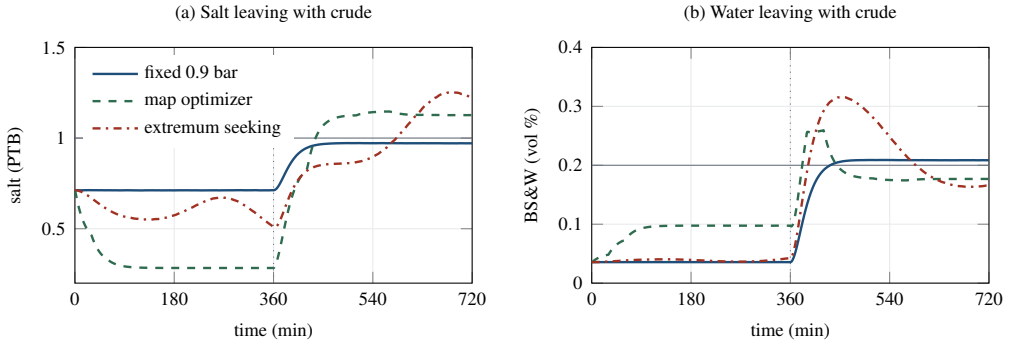


Figure 2.5 Outlet quality through the crude switch in case E. Both panels show simulator truth for evaluation, not ESC information. Fixed pressure is the solid line, the map optimizer dashed and extremum seeking dash-dotted. Thin gray horizontal lines mark the 1 PTB salt and 0.2% water specifications, and the dotted vertical line marks the 360 min switch. All three laws share the full 720 min window, 30 ppm dose and initial 0.9 bar.

gives 0.5978 PTB, but exceeds the water specification for 333.2 min. Neither this pressure nor extra chemical is credited as learned information. Seeds 1–3 retain ESC's salt loss to RTO. The center reaches 1.074 13 bar at the switch and 0.765 23 bar at the end, still moving 0.120 bar over the last 120 min. Two probing cycles establish no optimum-acquisition time. At 720 min, instantaneous ESC salt is 1.2223 PTB, versus fixed pressure at 0.9712 PTB and RTO at 1.1265 PTB.

ESC loses both quality measures to fixed pressure on the heavier-crude case, holds for 609.7 min, and trips at 715.8 min. The water-slug case's initial reported 350 mm rag holds it throughout. Matching the suggested challenge chemistry gives ESC 0.8126 PTB and 0.2762 %, versus RTO's 0.8191 PTB and 0.1731 %. ESC misses the water target while the suggested run with the optimizer still passes. The policies differ. ESC uses a soft water penalty and 0.3–2.5 bar projection, while RTO prioritizes feasible predictions on its 0.3–2.0 bar grid and knows the declared assay. The comparison therefore tests the implemented information and constraint policies rather than equal mathematical optimizations.

Independent state integration verifies all 15 primary rows. Halving the physics step preserves their salt rankings, with a largest change of 0.001 12 PTB. Replaying 7201 controller packets through independent filter recurrences differs by at most 1.78×10^{-15}. A quadratic fixture checks finite-filter demodulation to 4.44×10^{-16}, not plant-gradient accuracy or convergence. Computation includes every ESC call and history update. One sample in the Chrome browser at 1 min/s measures 9.091 µs per call over 22 calls and one fresh report, using 0.009 08 % of a core.

2.7 Technology in Practice

The model of Section 2.3 gives each loop a named instrument and an ideal valve. Figure 2.6 draws the same loops with the hardware a refinery installs in their place.

What Measures It

The interface is read by a capacitance probe through the top of the vessel. The probe answers to the electrical character of whatever wets it, between a value for oil and a value for water, and with a rag present it reports an approximate, averaged position [21]. That averaged position is the share κ of Equation (2.11), and the lag τ_{LT} and noise σ_I of the same equation are the model's whole account of the transmitter. The mixing pressure drop is read by a differential pressure transmitter with one line to each side of the valve.

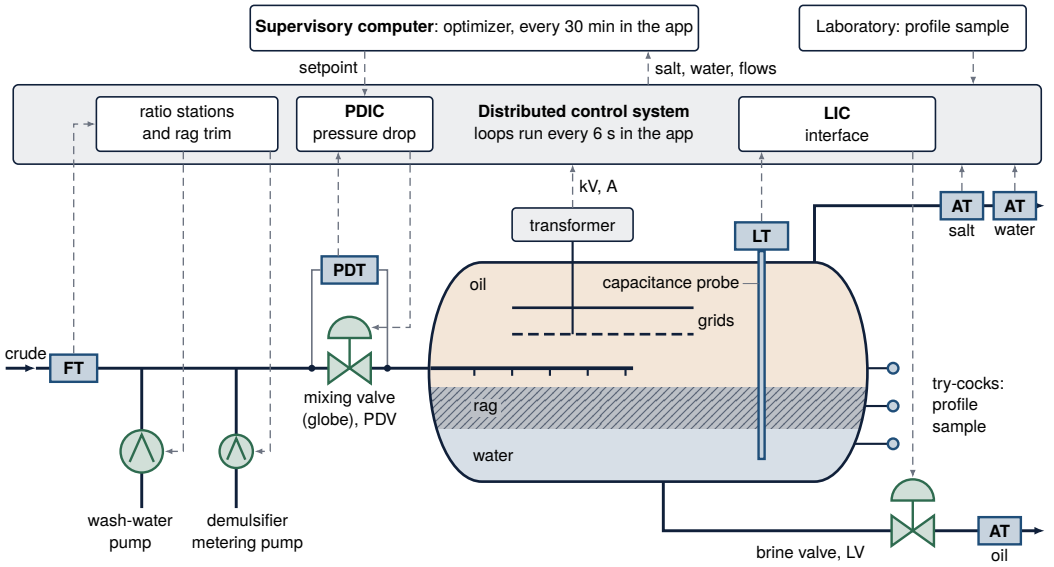


Figure 2.6 The loops of the desalter with their hardware. Lettered boxes are sensing devices, namely the flow transmitter (FT), the differential pressure transmitter (PDT), the level transmitter (LT) on the capacitance probe and the analyzers (AT). Valve and pump symbols are final elements. Dashed arrows are signals. The regulatory loops run in the distributed control system, and the optimizer above it writes only the pressure-drop setpoint. Notice that the level transmitter is the single path from the vessel to the brine valve, so its error passes to the water unseen. Not to scale, and not a piping or safety diagram.

> **TECHNOLOGY** **Sensor: Capacitance Interface Probe**
>
> A capacitance probe measures the electrical character of the fluid that touches it. As the interface rises along the rod, the measured capacitance moves from its value in oil, 0% of the range, to its value in water, 100% [21]. The contrast is large, a relative permittivity of about 2.1 for oil against 80 for water [22]. A probe with a single electrode needs temperature compensation and cannot locate more than one interface [22]. It fails in three ways. A new feedstock or a rag changes the electrical properties, and the change reads as a move of the level. A coating of solids can disable the rod. Any repair needs a shutdown, because the rod sits in the process [21]. On a trend the first failure is a steady reading over a moving interface, as in case 7.

What Moves It

The mixing valve is commonly a globe valve, and spray nozzles or static mixers may premix the water ahead of it [2]. The model's brine valve is linear in flow and its mixing valve follows the square law of Equation (2.10), each behind a short lag. The wash water and the demulsifier are moved by pumps, which the ratio stations set from the metered crude flow.

> **TECHNOLOGY** **Final Element: Globe Valve With a Pneumatic Actuator**
>
> A globe valve regulates flow with a movable plug and a fixed ring seat, and the shape of the plug sets how flow follows lift, as quick opening, linear or equal percentage [23]. The usual actuator is pneumatic. Air in a sealed flexible chamber works against a pre-compressed spring and moves the stem. The spring also decides whether the valve fails open or closed when the air is lost, and that choice is made by asking which position is safer for the process [23]. A pneumatic actuator answers with a delay [23], which the model carries as a lag of 0.1 min on each valve (Table 2.2). The mixing valve cannot be throttled far. At 15 % open its drop at design flow is already 11.2 bar, and the manual station stops there.

Where the Controller Runs

A refinery runs loops of this kind in a distributed control system. In such a system a supervisory level sends set points to distributed controllers, and these act on the process through its actuators from the feedback of its sensors [24]. Loops at the two levels cycle in times from milliseconds to minutes [24]. The app executes its controllers every 6 s and its optimizer every 30 min, inside that range. The interface controller, the pressure-drop controller, the ratio stations and the rag trim would sit in the distributed controllers. The optimizer and extremum seeking would sit in the supervisory level, since each only writes the pressure-drop setpoint.

> **IN PRACTICE** **The Salt Number, the Heat and the Interface**
>
> The salt figure an operator works to comes from a laboratory test, ASTM D3230. It infers chlorides from the electrical conductivity of the crude over 1.0 to 150 PTB, and it is used to judge both whether a crude needs desalting and how well the desalter works [25]. In service the crude is heated to between 150 and 350 °F, as far as its vapor pressure allows [3]. At the interface, an industry question-and-answer panel recorded in 2016 that capacitance probes and floats give a general position but little about the width of the interface or its growth, and that knowing both lets operators adjust the demulsifier ahead of an upset [26].

What Is Modernizing It

Three developments bear on this chapter. The first is the profile instrument, which replaces one reading with a measurement at many heights. One kind is a vertical array of low-energy gamma sources facing arrays of detectors, which gives the density at each height. Another is a capacitance sensor of 64 segmented electrodes [22]. A profile read in real time [21] would show the bias κt_r of Section 2.4 continuously, where the simulated unit sees it only at each profile sample. The second is the electrode. Recent electrocoalescers all use insulated electrodes to prevent the short circuit that the grid trip guards against [8]. The third is the network. In many modern systems the control system is interfaced with the corporate network to give the business a view of production [24], which makes the security of the control network part of the design of every loop that runs on it.

2.8 Limitations

The sizes and correlations describe a typical single-stage desalter on a 500 m^3/h crude unit, chosen so that the design point closes, and none was fitted to a vessel. The separation, rag, grid and oil-in-brine laws are synthetic, so where the salt optimum lies, how thick the rag grows and at what gap the grid trips are reasonable sizes for teaching and not forecasts for a particular vessel, crude or chemical. The model has one oil zone, one rag and one water layer, a fixed temperature of 130 °C, no second stage and no handle for temperature, so a truly heavy crude cannot be brought to specification here. Given the heavier assay's solids and asphaltenes at API 22.3 (919 kg/m^3 and 2.9 mPa s) and dosed at 60 ppm, no pressure drop brings the BS&W to 0.2 % and the least salt anywhere on the map is 1.40 PTB, where a refiner would raise the desalter's temperature. The demulsifier never overdoses, and the probe's rag share $\kappa = 0.5$ is a constant where a real probe's response depends on the emulsion it sits in.

> **OPEN CHALLENGE** **Seeing Both Faces of the Rag**
>
> A 2006 review called the accurate measurement of several interfaces in one vessel a challenge, and reported that for lack of it separators were run by trial and error [22]. Each established instrument misses the emulsion in its own way. Displacers and differential pressure cannot detect it, ultrasound has difficulty with it, and a nucleonic gauge finds the midpoint of a diffuse band but not its depth [21, 22]. Ten years later some refiners had moved to nuclear gauges on desalters and were still evaluating them [26]. Progress would be a profile reliable enough for a loop to hold the true water and the rag top apart, which case 7 does by hand from a two-hour sample.

The optimizer's model is the plant's own correlation with the commissioned parameters, so it meets model error only through unmeasured free water, the probe and a changed parameter, and its biases learn only on steady data. The trim acts on samples alone, and the challenge prices neither chemical nor wastewater, so a fixed 30 ppm meets the target that the suggested architecture was designed for. The grid trip reads the truth and freezes the run rather than model a restart, and the disturbances arrive as scheduled steps and pulses.

ESC's sampled washout and low-pass filters do not remove process lag, crude-change transients or clipping bias. The known analysis delay is aligned by timestamp, but no dynamic phase compensation is fitted. Protective holds can consume all 720 min, and bounded commands do not guarantee a feasible product or prevent a later trip. The measured objective prices water excess in PTB equivalents rather than dollars.

2.9 Conclusion

A crude desalter is a level loop under a hazard, wrapped around a mixing valve whose best setting moves with every crude, and this simulator computes the salt map, the rag, the probe's reading and the grid current together from a twenty-state model whose ledgers close to round-off. On the design crude the salt is least at 1.29 bar, 0.54 PTB, the BS&W reaches its specification at 1.36 bar and has a minimum of its own at 0.57 bar, and on the heavier crude at 5 ppm no pressure drop meets the specification, so demulsifier decides which curve exists and the mixing valve where to sit on it. A probe that reads half the rag lets a loop on its setpoint drop the water from 750 to 632 mm while the brine turns oily, and correcting the reading without lowering the setpoint lifts the rag into the grid. The challenge passes with the optimizer, a rag trim acting from the sample drawn at 4 h and 15 ppm, at 0.819 PTB, and equally with a fixed 30 ppm, because it sets no chemical budget. Model-free extremum seeking lowers the mean salt of case E from fixed pressure's 0.8304 to 0.7842 PTB, while the map optimizer remains stronger at 0.6718 PTB, and two probing cycles establish no time to find the optimum. The correlations are synthetic and the temperature fixed. A fuller model would add desalter temperature as a handle, a second stage with recycled water, a demulsifier that can overdose and a chemical budget in the challenge. The simulator shows that a loop on its setpoint is only as right as the instrument it reads.

KEY POINTS

- Mixing harder washes out more salt only up to a point. Past it the water drops are too small to settle, so the best setting lies in between and moves with every crude.
- The demulsifier decides which salt curve exists, and the mixing valve where to sit on it.
- A probe that reads half the rag lets a loop on its setpoint lower the true water while the brine turns oily.
- Correcting the reading without lowering the setpoint lifts the rag into the grid.
- A loop on its setpoint is only as right as the instrument it reads.

Where else this applies. The same kind of interior optimum is held in Chapter 13, the trade between averaging and tight interface tuning returns in Volume 10, Chapter 6, and a sensor that misleads its loop in Volume 5, Chapter 12.

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2.10 Exercises

2.1 Concept check · 2 min

On the design crude at 5 ppm of demulsifier, the salt left in the desalted crude falls from 1.69 PTB at 0.6 bar of mixing pressure drop to 0.54 PTB at 1.29 bar and rises again to 0.89 PTB at 2.0 bar. What makes the salt rise again above the optimum?

(a) The analyzer's delay makes the reading lag the mixing, so the rise is an artifact of sampling

(b) Harder mixing contacts more brine but shears the water into drops too small for the field to recover

(c) Harder mixing heats the crude by valve friction and thins the oil past the best viscosity

(d) Harder mixing throttles the wash water pump, so less wash water reaches the crude's brine

2.2 Concept check · 2 min

In case 7 the interface loop holds the probe reading on its 1000 mm setpoint while the rag grows by 100 mm. The probe counts half of the rag as water ($\kappa = 0.5$) and has no offset. What happens in the vessel?

(a) The true water rises 50 mm and the rag top rises 150 mm

(b) The true water stays put and the rag top rises 100 mm, because the loop holds the water

(c) The true water falls 50 mm and the rag top rises 50 mm, with no error on the loop

(d) The true water falls 100 mm and the rag top stays put, because the loop holds the rag top

2.3 Concept check · 2 min

Three hours after the switch to the heavier crude at 5 ppm, the least BS&W anywhere on the salt map is 0.216 %, at 0.40 bar. Which change can bring the desalted crude within the 0.2 % specification?

(a) Lowering the mixing pressure drop to the 0.3 bar end of its range

(b) Raising the mixing pressure drop to 1.5 bar to contact more of the brine

(c) Selecting Loops + optimizer with its BS&W limit at 0.18 %

(d) Raising the demulsifier ratio from 5 to 30 ppm and waiting for it to act

2.4 Theory and calculation · 7 min

The vessel is a horizontal cylinder 3.6 m across and 24 m long, the interface stands near 1.25 m, and one percent of brine valve passes 0.6 m^3/h. The crude charge is 500 m^3/h.

(a) Find the width of the interface, its area and the integrating gain of the water layer in millimeters per hour per percent of valve. *Checkpoint:* 3.43 m, 82.3 m^2 and 7.29 mm/h per percent.

(b) With a proportional-only interface loop at $K_c = 0.3$ % per millimeter, find the closed-loop time constant, and the integral time at which a PI loop with this gain is critically damped. *Checkpoint:* 27.4 min and 110 min.

(c) The wash water rises from 5 to 7 % of the crude. Find how far the brine valve must open for good and the offset the proportional-only loop holds. *Checkpoint:* 16.7 points and 55.6 mm.

2.5 Theory and calculation · 6 min

In case 7 the probe reads $h_I = h_w + \kappa t_r$ with $\kappa = 0.5$ and no offset, the interface setpoint is 1000 mm and the lower grid is at $h_g = 1950$ mm. The rag starts 500 mm thick.

(a) With the reading on its setpoint, find the true water, the rag top and the gap from the rag top to the lower grid. *Checkpoint:* 750 mm, 1250 mm and 700 mm.

(b) The rag grows to 735 mm with the reading still on its setpoint. Find the same three heights. *Checkpoint:* 632.5 mm, 1367.5 mm and 582.5 mm.

(c) A profile sample finds the reading 282 mm above the water, and the reading is corrected by it with the setpoint left at 1000 mm. Find the rag thickness the bias implies and the rag top once the loop holds the water itself at 1000 mm. What setpoint keeps the rag top where it was before the correction? *Checkpoint:* 564 mm, 1564 mm (a 386 mm gap) and about 718 mm.

2.6 Theory and calculation · 7 min

The transformer drives the lower grid with an open-circuit tap $V_{tap} = 27\,\mathrm{kV}$ through a reactor $R_s = 2.0\,\mathrm{kV/A}$, and $V = V_{tap}/(1 + R_s G)$, $I = GV$ (Equation (2.8) with full supply). On the dry design crude the conductance is $G = 0.040 + 2.0\,\mathrm{e}^{-(h_g - h_t)/\lambda}$ in amperes per kilovolt with $\lambda = 100\,\mathrm{mm}$.

(a) At design the rag top is 660 mm below the grid. Find G, the grid voltage and the current. *Checkpoint:* 0.0427 A/kV, 24.87 kV and 1.063 A.

(b) Find the gap at which the current reaches the 3.0 A trip. *Checkpoint:* $G = 0.1429\,\mathrm{A/kV}$, a gap of 297 mm.

(c) Find the voltage and the current with water at the grid (a gap of zero), and compare the current with the reactor's limit. *Checkpoint:* 5.31 kV, 10.84 A against 13.5 A.

2.7 App challenge · 9 min

Open case 2, "The interface loop on an integrating level", at the default seed, and run each part to 480 min at 60 min per second (about 8 s a run). Export the CSV file after each run. The setpoint steps from 1250 to 1350 mm at 60 min, and the wash water from 5 to 7 % at 240 min.

(a) Run as shipped, proportional only. Average `interface_meas_m` minus `interface_sp_m` over 200 to 240 min and over 420 to 480 min, and average `brine_valve_cmd_pct` over the same two windows. *Checkpoint:* −0.2 mm and 55.3 mm (within 2 mm), valve 42.4 and 59.2 % (within 0.3 points).

(b) Reload the case, set Interface integral time to 60 min before Run, and run again. Give the average error over the last hour and the overshoot of the reading above 1350 mm between 60 and 240 min. *Checkpoint:* −1.0 mm and 28 mm (within 3 mm).

(c) Repeat with 30 min. Give the overshoot, and say why the setpoint step left no offset in part (a) while the wash step did. *Checkpoint:* 39 mm (within 3 mm).

2.8 App challenge · 9 min

Open case 7, "The rag fools the interface instrument", at the default seed and the shipped settings (heavier crude, a 500 mm rag, interface setpoint 1000 mm, profile samples every 2 h). Export the CSV file after each run.

(a) Run to 480 min at 20 min per second (24 s). In the CSV file, read the true water (`truth_water_interface_m`) at 0 and 480 min, and the rag (`truth_rag_m`) and the reading (`interface_meas_m`) at 480 min. Find the first row in which the oil in the brine (`oil_in_brine_mgL`) passes 200 mg/L. *Checkpoint:* Water 750 to 632 mm, rag 735 mm, reading within the probe's noise of 1000 mm, oil in brine past 200 mg/L at 192 min.

(b) Reload the case, run at 5 min per second, and pause between 195 and 210 min. Set Interface reading to Corrected by profile, leave the setpoint at 1000 mm, and run on at 20 min per second. Read `interface_correction_m` just after the switch, and the time the grid trips. *Checkpoint:* A bias of 282 mm, and a trip between 255 and 268 min.

(c) Reload, pause in the same window, correct the reading and set the setpoint to 850 mm. Run to 480 min and read the true water, the oil in the brine and the peak grid current. *Checkpoint:* Water 852 mm (within 3 mm), 106 mg/L, peak 2.65 A and no trip.

2.9 App challenge · 8 min

Open the challenge, case 9, at the default seed. Each run lasts 12 h of plant time, about 2.4 s at 300 min per second, and stops at 720 min with its verdict.

(a) Run as shipped. When does the grid trip? *Checkpoint:* At 493.3 min, during the slug.

(b) Reload, set the Demulsifier ratio to 25 ppm before Run, and run. Read the verdict's average salt and average BS&W. *Checkpoint:* 0.84 PTB and 0.213 %: missed on the BS&W alone.

(c) Reload and repeat at 30 ppm. Then reload, reveal the suggested settings (optimizer, rag trim, 2 h samples, 15 ppm) and run. Compare the two passing runs on the average of `demulsifier_ppm` in the CSV file. *Checkpoint:* 0.81 PTB and 0.197 % at 30.0 ppm, 0.82 PTB and 0.173 % at 40.0 ppm.

2.10 Application area · 3 min

The raw crude of this chapter carries 10 PTB of salt. A current account of the process puts the refinery's target near 1.5 PTB and quotes about 90 % removal for one stage and 99 % for two.

(a) Find the salt left by one stage and by two at those removals, and compare them with the simulated unit's 93.3 %. *Checkpoint:* 1.0 PTB, 0.1 PTB and 0.67 PTB.

(b) Name two ways in which salt left in the crude harms the units downstream. *Checkpoint:* Hydrochloric acid in the overhead, and scale or poisoned catalyst.

2.11 Application area · 3 min

A slug of 50 m^3/h of free water arrives for 30 min, as in case 8. The brine valve passes at most 60 m^3/h and normally runs near 26 m^3/h.

(a) At least how much of the slug must the layer store, even with the valve wide open at once? *Checkpoint:* About 8 m^3.

(b) The averaging tuning sends at most 42.4 m^3/h of brine with 75 mg/L of oil and lets the current reach 2.45 A. The tight tuning sends 60 m^3/h with 99 mg/L and holds the current at 1.48 A. Which would you choose when the grid alarm matters more than the wastewater plant, and what does it cost? *Checkpoint:* The tight tuning, at the cost of the brine surge.

2.12 Review the agent · 5 min

An AI assistant reviewing case E writes: "Extremum seeking needs no model, so it cannot be misled by a wrong salt map. After the crude switch at 360 min it will find the new optimum faster than the map optimizer, and it should replace the optimizer in the challenge." Find the flaw and say how you would check the claim with the app.