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CHAPTER 15

An LNG Import Terminal Whose Boil-Off Can Only Leave With Its Send-Out

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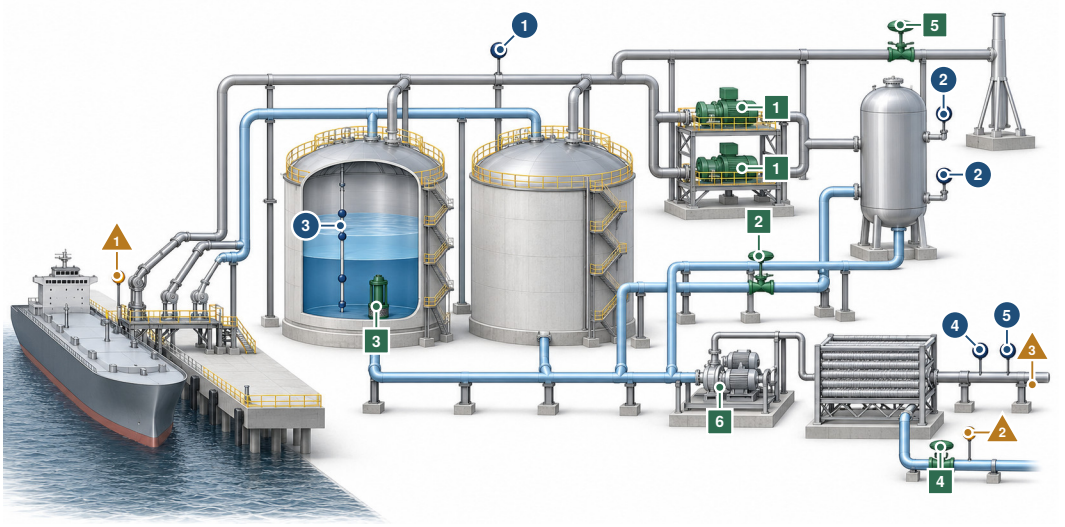
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CHAPTER 15

An LNG Import Terminal Whose Boil-Off Can Only Leave With Its Send-Out



The controller moves 1 two boil-off compressors, loaded and unloaded in stages
2 valve that sets how much LNG goes through the recondenser 3 in-tank pumps 4 seawater supply to the vaporizers
5 flare valve, opened by a high tank pressure 6 high-pressure pumps, which set the send-out

The controller reads 1 tank pressure in the shared vapor space 2 recondenser pressure and level
3 density profiler in a layered tank 4 send-out flow 5 gas temperature after the vaporizers

What disturbs it 1 the ship: displaced vapor and cargo flash 2 seawater temperature
3 the grid's nomination, which sets the send-out

Notice that the compressors' gas has one way out, into the recondenser, where the LNG on its way to the pipeline condenses it, so a low send-out leaves the boil-off in the tanks. Illustration, not to scale.

IN PLAIN TERMS Where the Gas From a Cold Tank Goes

The main idea. An import terminal stores liquefied natural gas in tanks so cold that a little of it boils all the time. Compressors push that gas into a vessel where the cold liquid leaving for the pipeline turns it back into liquid.

The challenge. The outgoing liquid can take back only a small share of its own weight. On a night of low demand the gas has nowhere to go, and more compressor power does not help. The tank pressure climbs until the gas must be burned at a flare.

Why it matters. Knowing the demand hours ahead lets the terminal lower the tank pressure before the night and keep the gas.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	This page, the Did you know? box at the end of the Introduction, the History box in Section 15.2, the Try it boxes in Sections 15.3.8 and 15.5, the second Did you know? box in Section 15.5.8, and Key points in Section 15.8. No equations.
Study	45 min	The whole chapter in order, stopping at the three pause points, then Exercises 1 to 12.
Practice	15 min	This page, Section 15.5 with Figure 15.4, Section 15.6 and Section 15.7 with its Open challenge box.

The control question The boil-off of an LNG import terminal can leave only by condensing into the LNG it sends out, so the outlet of an integrating tank pressure shrinks with a flow the market sets. How low can the send-out go before the tanks reach the flare, and how much of a low-demand night can a published nomination prepare the tanks for?

Learning objectives

- Compute the recondenser's capacity per kilogram of send-out from the subcooling and the heat each kilogram of boil-off must give up, and the minimum send-out that follows.
- Predict the rate of rise of the tank pressure from the vapor-space capacitance and the boil-off the recondenser cannot take.
- Explain why the compressors cannot rescue a low-send-out night, and how the recondenser override takes the load away from the pressure loop.
- Compare feedback alone, a preview of the published nomination and an MPC on flaring, compressor energy and boil-off.
- Judge the trade between tank pressure, cargo flash and compressor energy during a ship's unloading.

Prerequisites Sections 1.4.4 and 1.4.5 (inventories), 1.4.8 (selectors in external-reset form), 1.6.2 (the PI loops) and 1.6.4 (cases and data). Section 1.6.3 is needed only for the predictive controller. Chapter 11 for staged machines.

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See also Volume 6, Chapter 7 for inventory choices that decide where a rate change lands. Volume 4, Chapter 2 and Volume 4, Chapter 3 for protective overrides and limiter selection. Volume 3, Chapter 6 for feedforward that acts before feedback can.

15.1 Introduction

Two compressors that can move 20 t/h between them cannot hold the pressure of tanks that make 6.9 t/h of gas. In the generic terminal simulated here that happens every night the grid nominates 30 t/h. The compressors deliver the boil-off to a recondenser, where it condenses into LNG drawn from the tanks at −159.14 °C on its way to the high-pressure pumps, and the recondenser at 8 bar g saturates at −126.26 °C. Each kilogram of that LNG can absorb only its 32.89 K of subcooling, while each kilogram of compressed boil-off must give up 694.3 kJ, so the recondenser condenses at most 0.1658 kg per kilogram of LNG through it. At 450 t/h of in-tank pump flow that is 73.5 t/h. With the nomination ramped to 30 t/h, the recondenser fills 91.4 min into the case, its pressure override cuts the compressors to 4.5 t/h, and the tank pressure climbs 23.7 mbar an hour to the flare at 4.69 h.

A common belief holds that a gas inventory is limited by the machines that empty it, and the simulator is built to show it wrong. The vapor space of the tanks is an integrator, but the outlet that matters is a capacity proportional to a product flow set by the market, and the binding constraint moves from the compressors to the recondenser without any alarm on the compressors. The class is general. A refinery fuel gas header whose only consumers are its furnaces (Volume 11, Chapter 14), a digester whose biogas goes to an engine that follows the electrical load, a cooling system whose heat sink is a process stream, and a surge tank whose outflow is set downstream all integrate a surplus against a sink that another decision sets. Import terminals meet the problem in its plainest form, and their literature poses boil-off handling as a question of design and operation together [1–3].

DID YOU KNOW? A Tank Boils Away a Fraction of a Percent a Day

LNG storage tanks are typically designed so that less than 0.05 % of their content boils away a day, though the figure ranges from 0.02 to 0.1 %. Unloading a ship typically makes 8 to 10 times the boil-off of a tank at rest [4]. The in-leak of this chapter's tanks alone boils 0.082 % of two full tanks a day.

The published treatments of terminal boil-off are rigorous simulation-based optimizations and dynamic simulations of detailed process models, one of them built in a commercial simulator, which

a student cannot open or perturb [3, 5, 6], and the textbooks describe the equipment [7, 8]. This chapter works instead with a browser simulation of an LNG import terminal whose recondenser recomputes its capacity from the subcooling at every step. It quantifies how feedback, feedforward from a published nomination and a predictive controller manage a boil-off inventory whose sink is the send-out. The balances, the PI loops, the override and the MPC are standard. The measurements belong to one generic terminal at one seed, among them that the capacity per kilogram of send-out is $r/(1+r) = 0.1422$ with a minimum send-out of 49.6 t/h by hand and 50.0 t/h on the running model, and that a constant low tank pressure saves compressor energy while it raises the day's boil-off from 210.0 to 271.5 t through cargo flash. The model has 32 states, its tank and recondenser mass and liquid energy close to 3×10^{-5} kg and 3×10^{-4} kJ over a disturbed day, and its controllers read only instruments and published schedules. Each of its nine cases credits a learner only for a change of their own followed by the state it produces in the terminal.

Section 15.2 follows the domain, from boil-off handling to rollover. Section 15.3 sets out the terminal as modeled, and Section 15.4 its control layers: the pressure loop with its recondenser override, the staging, the boil-off observer, the preview and the MPC. Section 15.5 measures the nine cases and the graded day. Section 15.6 sets the hardware of a real terminal beside the model, Section 15.7 states the limitations, Section 15.8 draws the conclusions, and the exercises of Section 15.9 work through the cases.

15.2 Boil-Off, Recondensers and Rollover at Receiving Terminals

Natural gas crosses oceans as a liquid near −160 °C, and the gas-processing literature covers LNG as part of an international trade [7]. The receiving end of that trade stores the liquid, pumps it to pipeline pressure and vaporizes it. A handbook of the industry gives separate chapters to the operation of regasification terminals and to the process control and automation of LNG plants and import terminals [8]. No tank insulation is perfect, so the stored liquid boils continuously, and the gas that results has three possible destinations: compression into the export pipeline, recondensation into the send-out, or the flare.

Operating that choice has a literature of its own. A 2008 study optimized the operation of the boil-off compression process with a model of the boil-off rate of the storage tanks [9], and boil-off management at the Spanish terminals was surveyed in 2010 [1]. In the same year a simulation-based optimization over a regasification superstructure was posed to recover the boil-off made during ship unloading with the least energy, as a strategy for minimizing flare emissions at receiving terminals [3]. A 2012 dynamic study called the recondensation system one of the most important facilities at a receiving terminal, whose failure can cause boil-off loss or accidents, and improved its control algorithm by tracking recondenser pressure, liquid level and high-pressure pump suction pressure while the LNG and boil-off loads fluctuated [5]. A retrofit design of the boil-off handling process followed [2], and the boil-off generated at the jetty while ships load was simulated dynamically at export terminals, with less flaring as the aim [6].

The composition of stored LNG changes as it boils, because the lightest components leave first. A weathering model validated against industry data showed that heat ingress and boil-off release shift the liquid's composition and density over its storage, and that the nitrogen content governs the early boil-off through nitrogen's preferential evaporation [10]. A stratified tank adds a sharper hazard. Rollover is the sudden mixing of stratified layers, which can release large amounts of boil-off, and the History box at the end of this section tells its best documented incident and the first model to reproduce it [11, 12]. A 1997 study modeled the behavior of stratified LNG in storage tanks [13]. A 2014 review found no reliable model of industrial-scale rollover in the open literature, estimated a critical stability ratio from the 1997 data, and observed that the lumped models that describe La Spezia predict rollover too early at other incidents because they overestimate the mass transfer between the layers [11]. The handling literature adds that heat flowing into stratified layers equalizes their densities, and that a fall in the boil-off rate may be the only warning [14]. The simulator draws

Table 15.1 Variables by Role, Design Values With Tanks Half Full

Symbol	Role	Design	Range
p	CV, tank pressure (mbar g)	150	band 50–220
p_R, L_R	CV, recondenser (bar g, %)	8.0, 50	SP 6–10
F_{SO}	CV, send-out (t/h)	450	0–700
T_g	CV, gas temperature (°C)	5.00	≥ 1
D	MV, compressor load (t/h)	6.57	0–20
x_R	MV, LNG share to recondenser	0.0894	0–1
F_{LP}	MV, in-tank pumps (t/h)	443.4	0–700
F_{sw}	MV, seawater (t/h)	19,622	10–100 %
n	MV, compressors loaded	1	0, 1, 2
F_{nom}	DV, nomination (t/h)	450	0–700
Q_{unl}	DV, unloading rate (m^3/h)	12,000	0–14,000
T_{sw}	DV, seawater (°C)	15	0–30
M_v	state, vapor (t)	283.3	—
M_A, T_A	state, tank A	36.0 kt, −159.44°C	—
M_{vR}, M_R	states, recondenser (kg)	662, 8100	—
$\dot{m}_{bog}$	output, boil-off (t/h)	8.35	—
$\dot{W}_{max}$	output, capacity (t/h)	73.5	—

on this history in two places. Its recondenser carries the capacity that makes low send-out a flaring problem, and its rollover is a declared illustration of the mechanism rather than a model of any incident.

> **HISTORY 1971: A New Cargo Under an Old One**
>
> On 21 August 1971 a carrier discharged a new cargo into the bottom of a storage tank at an Italian terminal. The tank was already half full of LNG colder than the cargo, and the two liquids did not mix. They formed two layers of different density. About 31 hours after the transfer began, the layers mixed suddenly and the tank pressure rose fast. About 2,000 tonnes of vapor left through the tank's safety valves over a few hours and damaged its roof [15]. A 1983 model of the heat and mass transfer between the layers reproduced the documented time history and boil-off of that event [12]. A survey of the years 1970 to 1982 counted 41 rollover incidents in 22 plants and traced over half of them to new LNG loaded into a tank that already held some [15].

15.3 The Terminal as Modeled

The simulated terminal copies no real site. Its sizes, properties and thresholds are all teaching values. Two 160 000 m^3 full-containment tanks share one vapor space and one boil-off header at a design pressure of 150 mbar g. A ship unloads through a liquid arm into both tank roofs and takes part of the displaced vapor back through a vapor arm. Two 10 t/h compressors deliver the boil-off to a recondenser at 8 bar g, submerged in-tank pumps send LNG to it and around it, high-pressure pumps raise everything to 80 bar g, open-rack vaporizers warm the gas on seawater, and a flare valve opens on the tanks' pressure. The arrangement, the symbols of the equations and the values of two lesson instants are shown in Figures 15.1 and 15.2. Pressures in the tanks are gauge in mbar, those of the recondenser and send-out gauge in bar, flows in t/h and time in minutes.

The model integrates 32 states, listed by role with the other variables in Table 15.1. The physical states are the vapor mass M_v, tank A's liquid mass and temperature, tank B's upper and lower layers (mass, temperature, reference density), the recondenser's vapor and liquid, the compressors' net flow, the recondenser's LNG share, the in-tank pumps' flow, the send-out, the flare valve, the seawater flow, the gas temperature and the ship's cargo pumps. Thirteen running totals integrate the mass and energy that cross each boundary, so the balances can be checked exactly.

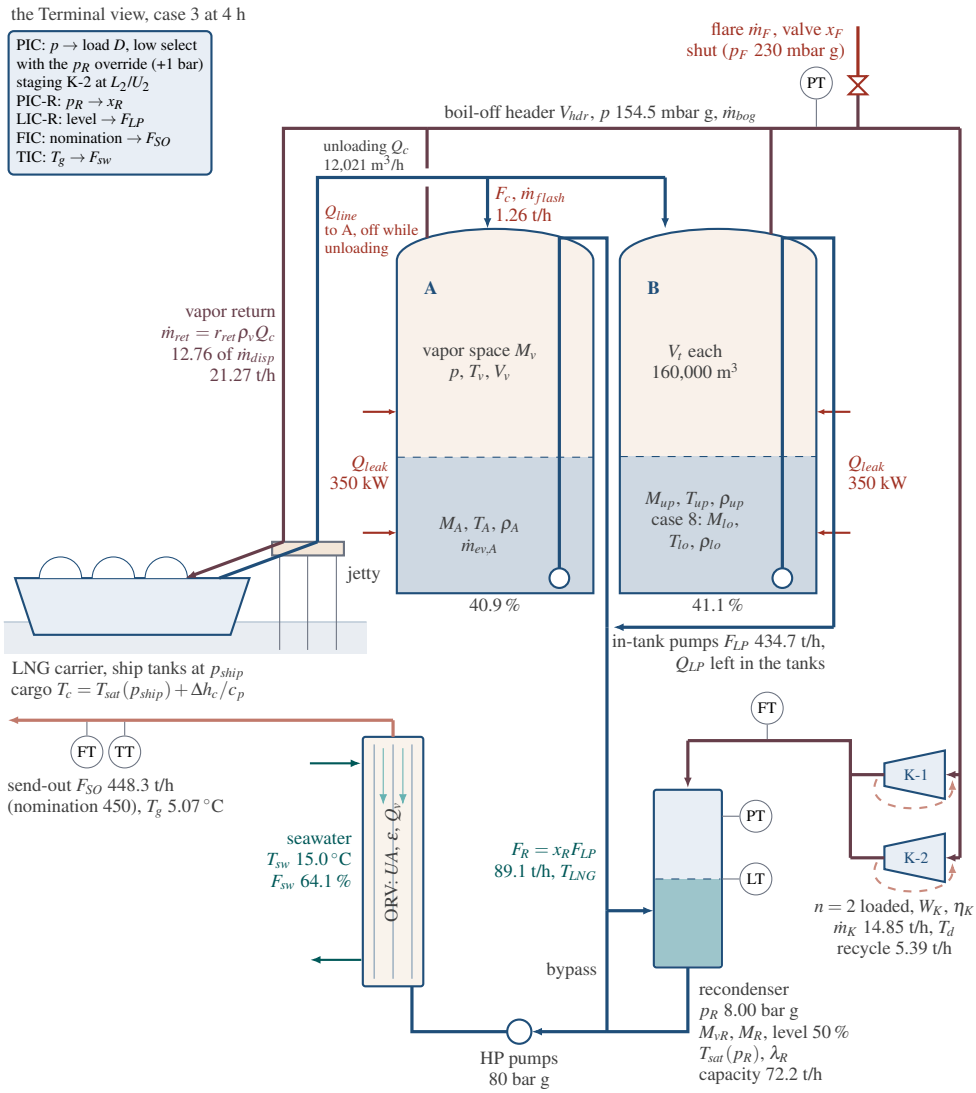


Figure 15.1 The terminal as modeled, drawn after the Terminal view of case 3 at $t = 4$ h, with every stream flowing: the ship unloading 12 021 m³/h into both roofs, the vapor arm taking back 12.76 t/h of the 21.27 t/h displaced, 1.26 t/h of cargo flash, both compressors loaded with 14.85 t/h to the recondenser and 5.39 t/h round their recycles, and 448.3 t/h sent out. The ship, the tanks and the header are drawn on top, and the compressors, the recondenser, the high-pressure pumps and the vaporizers below, with the flow from right to left. Flows in t/h. Process model only, not to scale.

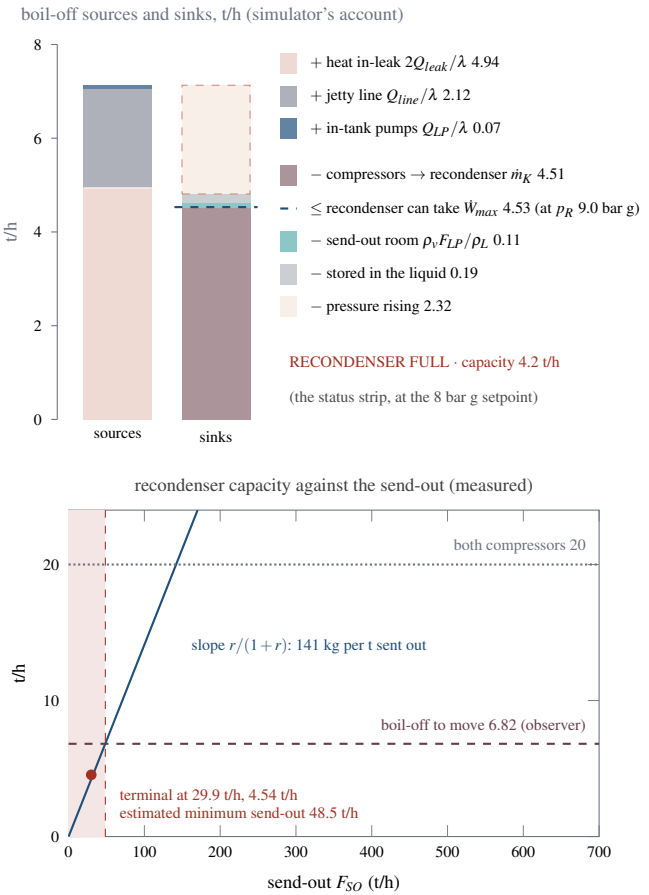


Figure 15.2 The Balance view of case 1 at $t = 4$ h, a night at 30 t/h. Top: the boil-off's sources against its sinks, the recondenser's limit of 4.53 t/h at 9.0 bar g as a dashed line across the sinks bar, and 2.32 t/h left as "pressure rising". Bottom: the measured capacity line (solid) with the terminal's point left of the estimated minimum send-out (thin dashed), under the boil-off to move (dashed) and both compressors' limit (dotted).

15.3.1 The Shared Vapor Space

Both tanks and the header hold one vapor mass at one pressure, so the vapor space is a single integrator, a gas inventory of the kind described in Sections 1.4.4 and 1.4.5, its volume set by the room the liquid leaves, as given in Equation (15.1).

$$\begin{aligned} \frac{\mathrm{d}M_v}{\mathrm{d}t} &= \dot{m}_{bog} - \dot{m}_{ret} - \dot{m}_K - \dot{m}_F - \dot{m}_{rel} \\ p = \frac{M_v R T_v}{\mathscr{M} V_v}, &\qquad V_v = 2V_t - \sum_k \frac{M_k}{\rho_k} + V_{hdr} \end{aligned} \tag{15.1}$$

where $\dot{m}_{bog}$ is the boil-off made by evaporation and flash, $\dot{m}_{ret}$ the vapor returned to a ship, $\dot{m}_K$ the compressors' net flow to the recondenser, $\dot{m}_F$ the flare, $\dot{m}_{rel}$ the relief valves, R the gas constant, $\mathscr{M}$ the molar mass, T_v the vapor temperature, V_t the capacity of each tank, V_{hdr} the header, and M_k, ρ_k the mass and density of each liquid layer. The capacitance $\partial M_v/\partial p$ is 243.6 kg/mbar with both tanks half full and 97.9 kg/mbar at 80 %, so a surplus of 1 t/h raises the pressure 4.1 or 10.2 mbar an hour.

Sharing the space means that a send-out drawn from either tank makes the same room, that unloading into both tanks squeezes one volume, and that a surge from one tank raises the pressure over both.

15.3.2 Saturation, Density and Evaporation

The LNG is one methane-rich lump. Its saturation line is Clausius–Clapeyron from a declared bubble point and its density falls linearly with temperature, as shown in Equation (15.2).

$$\frac{1}{T_{sat}(p)} = \frac{1}{T_b} - \frac{R}{\lambda \mathscr{M}} \ln \frac{p}{p_0}, \qquad \rho_k = \rho_{ref,k} - \beta\,(T_k - T_{ref}) \tag{15.2}$$

where T_b is the bubble point at $p_0 = 1.013\,25\,\mathrm{bar\,a}$, λ the latent heat, $\rho_{ref,k}$ a layer's reference density and $T_{ref} = 113.65\,\mathrm{K}$. At 150 mbar g the line gives −159.444 °C, a liquid of 449.92 kg/m^3 and a vapor of 1.7653 kg/m^3 at T_v. Heat that reaches a surface evaporates liquid there, and a weak exchange between the bulk and the surface lets a rising pressure store heat in the liquid, as shown in Equation (15.3).

$$\begin{aligned} \dot{m}_{ev,j} &= \frac{Q_{s,j} + h_S\,(T_j - T_{sat}(p))}{\lambda} \\ Q_{s,A} &= Q_{leak} + Q_{line}(1 - x_u) + Q_{LP,A} \\ Q_{LP} &= \frac{F_{LP}\,\Delta p_{LP}}{\rho_L}\left(\frac{1}{\eta_{LP}} - 1\right) \end{aligned} \tag{15.3}$$

where j is tank A or tank B's upper layer, Q_{leak} the in-leak per tank, Q_{line} the jetty line's recirculation heat, returned to tank A between ships and stopped while the ship's pumps run at fraction x_u, and Q_{LP} the in-tank pumps' losses, shared by the draw. Tank B's surface receives Q_{leak} less what a lower layer takes. At design the in-leak alone makes 4.941 t/h, 7.06 kg per kWh and 0.082 % of two full tanks a day, the line 2.118 t/h and the pumps' 182.5 kW 1.288 t/h, for 8.347 t/h of boil-off. The send-out's drawdown leaves room for 1.739 t/h, so the compressors move 6.574 t/h. Each liquid layer balances its mass and energy, as shown for tank A in Equation (15.4).

$$\begin{aligned} \frac{\mathrm{d}M_A}{\mathrm{d}t} &= \tfrac{1}{2}F_c' - d_A F_{LP} - \dot{m}_{ev,A} \\ M_A c_p \frac{\mathrm{d}T_A}{\mathrm{d}t} &= \tfrac{1}{2}F_c' c_p (T_c' - T_A) - h_S (T_A - T_{sat}) \\ &\quad - \dot{m}_{ev,A}\, c_p (T_{sat} - T_A) \end{aligned} \tag{15.4}$$

where F_c' is the cargo that stays liquid, $T_c' = \min(T_c, T_{sat})$ its temperature once it has flashed, d_A tank A's share of the draw (one half, or zero when the send-out is drawn from tank B first) and c_p the liquid heat capacity. Tank B's upper layer obeys the same balance plus the liquid an overturn lifts into it (Section 15.3.8).

15.3.3 Unloading: Displacement, Return and Flash

The cargo's volume squeezes the same volume of vapor, the ship takes a share of it back, and cargo warmer than the tanks' saturation flashes as it enters, as shown in Equation (15.5).

$$\begin{aligned} Q_c &= x_u Q_{unl}, \qquad F_c = \rho_L(T_c)\,Q_c \\ T_c &= T_{sat}(p_{ship}) + \Delta h_c / c_p \\ \dot{m}_{disp} &= \rho_v Q_c, \qquad \dot{m}_{ret} = r_{ret}\,\rho_v Q_c \\ \dot{m}_{flash} &= \frac{F_c\, c_p \max\left(0,\, T_c - T_{sat}(p)\right)}{\lambda}, \quad F_c' = F_c - \dot{m}_{flash} \end{aligned} \tag{15.5}$$

where Q_{unl} is the unloading rate, $p_{ship} = 150\,\mathrm{mbar}\,g$ the ship's tank pressure, $\Delta h_c = 0.3\,\mathrm{kJ/kg}$ the heat its pumps and the line add, and $r_{ret} = 0.6$ the share returned (the ship's own boil-off fills the

rest of its emptying tanks). The cargo pumps ramp over 30 min, and they begin to stop when the cargo left equals what the ramp down will still deliver, so a 140 000 m^3 cargo ends at 140 000 m^3. The cargo arrives 0.0857 K above the tanks' saturation at 150 mbar g, so at 12 000 m^3/h (5398 t/h) it flashes 3.18 t/h at 150 mbar g, and the flash falls by $F_c c_p (\mathrm{d}T_{sat}/\mathrm{d}p)/\lambda = 0.3995\,\mathrm{t/h}$ for each mbar the tanks run higher, reaching zero at 157.9 mbar g. This top-fill equilibrium flash is strong on purpose. A bottom fill would suppress part of it with the hydrostatic head. The two ship values are teaching values chosen so that a compressor trip during unloading can reach the flare.

15.3.4 Compressors

Each compressor is an on/off machine whose capacity scales with the suction pressure. What the load demand does not take goes round its recycle, and a loaded machine draws its full power, as shown in Equation (15.6).

$$\begin{aligned} W_K(p) &= W_{K,0}\,\frac{p}{p_{des}}, \qquad w = \frac{c_{p,v} T_v \left[(p_R/p)^{\kappa} - 1\right]}{\eta_K} \\ T_d &= T_v\left(1 + \frac{(p_R/p)^{\kappa} - 1}{\eta_K}\right), \qquad P_K = n\,W_K\,w \\ \tau_K \frac{\mathrm{d}\dot{m}_K}{\mathrm{d}t} &= u\,n\,W_K - \dot{m}_K, \qquad u = \mathrm{clip}\big(D/(nW_K), 0, 1\big) \end{aligned} \tag{15.6}$$

where $W_{K,0} = 10\,\mathrm{t/h}$ at $p_{des} = 150\,\mathrm{mbar}\,g$ in absolute terms, $\kappa = (\gamma - 1)/\gamma = 0.26$, $\eta_K = 0.75$, $c_{p,v}$ the vapor heat capacity, T_d the discharge temperature, n the number loaded and D the load demand. At design $w = 274.54\,\mathrm{kJ/kg}$ and a loaded machine draws 762.6 kW, 18.30 MWh a day, whatever its recycle. The discharge leaves at −15.21 °C.

15.3.5 The Recondenser and Its Capacity

The recondenser is in equilibrium. The LNG sent through it leaves saturated at its pressure, and the compressed boil-off it condenses is exactly what the subcooling of that LNG absorbs, as shown in Equation (15.7).

$$\begin{aligned} \dot{m}_{cond} &= \frac{x_R F_{LP}\, c_p \left(T_{sat}(p_R) - T_{LNG}\right)}{\lambda_R} = r\,x_R F_{LP} \\ \lambda_R &= \lambda_{R,lat} + c_{p,v} \max\left(0,\, T_d - T_{sat}(p_R)\right) \\ \frac{\mathrm{d}M_{vR}}{\mathrm{d}t} &= \dot{m}_K - \dot{m}_{cond}, \qquad \frac{\mathrm{d}M_R}{\mathrm{d}t} = F_{LP} + \dot{m}_{cond} - F_{SO} \\ p_R &= \frac{M_{vR} R T_{vR}}{\mathscr{M}\,(V_{RC} - M_R/\rho_{RC})} \end{aligned} \tag{15.7}$$

where x_R is the share of the in-tank pumps' flow F_{LP} sent through it, T_{LNG} the draw-weighted tank temperature plus 0.3 K of warming in the line, $\lambda_{R,lat}$ the latent heat at the recondenser's pressure, V_{RC} its volume, ρ_{RC} its liquid density and T_{vR} its vapor temperature. By hand from the declared constants, $T_{sat}(p_R) = -126.258\,^{\circ}\mathrm{C}$, $T_{LNG} = -159.144\,^{\circ}\mathrm{C}$, the subcooling is 32.886 K, $\lambda_R = 450 + 2.2 \times 111.05 = 694.31\,\mathrm{kJ/kg}$ and

$$r = \frac{3.5 \times 32.886}{694.31} = 0.16578, \qquad \frac{r}{1+r} = 0.14220. \tag{15.8}$$

With all the LNG through it ($x_R = 1$) the recondenser condenses rF_{LP}, and the condensate joins the send-out, $F_{SO} = (1+r)F_{LP}$, so its capacity per kilogram of send-out is $r/(1+r)$, as shown in Equation (15.8). Written on F_{LNG}, the LNG through the recondenser, the capacity would be r per kilogram. Written on the send-out it is $r/(1+r)$, which is why the plotted line has the slope 0.142 kg/kg and not 0.166 kg/kg. The engine at $t = 0$ of case 2 reproduces every figure above to the printed digit, and its condensed flow equals Equation (15.7), with the recondenser's enthalpy balance closing to machine precision, at every step of case 1. The in-leak and jetty line alone need

7.06 t/h moved, which divided by 0.1422 gives a minimum send-out of 49.6 t/h. A higher recondenser pressure condenses at a higher temperature: $r = 0.1737$ at 9 bar g and 0.1808 at 10 bar g, for 814 kW and 861 kW a machine. The capacity the operator reads on the status strip and the trend is the same formula from measurements at the pressure setpoint, while the Balance view's limit line is the simulator's capacity at the actual pressure. In case 1 at 4 h they read 4.21 and 4.53 t/h, the difference being the override's extra bar and not truth against measurement, because the capacity computed from measurements at the measured pressure reads 4.526 t/h.

15.3.6 High-Pressure Pumps and Vaporizers

The high-pressure pumps raise the mixed stream from p_R to $p_{SO} = 80\,\text{bar}\,g$ and leave their losses in it. Open-rack vaporizers are a lumped counter-current bank whose conductance grows with the seawater film, as shown in Equation (15.9).

$$\begin{aligned} T_{Lv} &= T_{HP} + \left(\frac{1}{\eta_{HP}} - 1\right)\frac{p_{SO} - p_R}{\rho_L c_p} \\ Q_v &= \varepsilon\, C_{min}(T_{sw} - T_{Lv}), \qquad UA = UA_0\left(\frac{F_{sw}}{F_{sw,0}}\right)^{n_{UA}} \\ \tau_V \frac{\mathrm{d}T_g}{\mathrm{d}t} &= T_{Lv} + \frac{Q_v}{F_{SO}\, c_{eff}} - T_g \end{aligned} \tag{15.9}$$

where T_{HP} is the flow-weighted temperature of the saturated recondenser outlet and the bypass, ε the counter-flow effectiveness at NTU $= UA/C_{min}$ and C_{min}/C_{max} with $C_g = F_{SO}c_{eff}$ and $C_{sw} = F_{sw}c_{sw}$, c_{eff} the effective heat capacity of the vaporizing LNG and $F_{sw,0} = 20\,000\,\text{t/h}$. At design the pumps take 2667 kW and warm the LNG 1.524 K, and 19 622 t/h of 15 °C seawater at $\varepsilon = 0.9409$ delivers 105.50 MW, 844 kJ per kilogram of gas, cooling the seawater 4.84 K.

15.3.7 Flare and Relief

The flare valve's flow is $\dot{m}_F = x_F W_F \sqrt{(p - p_0)/230\,\text{mbar}}$ with $W_F = 80\,\text{t/h}$, and it is fully open 40 mbar above its 230 mbar g set pressure, passing 86.7 t/h at 270 mbar g. The relief valves pass $k_{rel}\max(0, p - p_{rel})$ with $k_{rel} = 20\,\text{t/h}$ per mbar above $p_{rel} = 290\,\text{mbar}\,g$.

15.3.8 Tank B's Layers (Illustrative)

Case 8 gives tank B a denser lower layer that receives the floor's share of the in-leak and the walls' share in proportion to its depth, and has no surface. The upper layer weathers as it boils, and once the densities cross the lower layer overturns at a declared rate, as shown in Equation (15.10).

$$\begin{aligned} Q_{lo} &= Q_{leak}\left(f_{fl} + f_w \frac{M_{lo}}{M_{lo} + M_{up}}\right) \\ M_{lo} c_p \frac{\mathrm{d}T_{lo}}{\mathrm{d}t} &= Q_{lo}, \qquad \dot{m}_{lift} = k_{Ro} M_{lo} \\ M_{up} \frac{\mathrm{d}\rho_{ref,up}}{\mathrm{d}t} &= \tfrac{1}{2} F_c'(\rho_{ref} - \rho_{ref,up}) + w_W \dot{m}_{ev,B} \\ &\quad + \dot{m}_{in}(\rho_{ref,lo} - \rho_{ref,up}) \\ \dot{m}_{flash,L} &= \frac{\dot{m}_{lift}\, c_p \max\left(0, T_{lo} - T_{sat}\right)}{\lambda} \end{aligned} \tag{15.10}$$

where $f_{fl} = 0.15$ and $f_w = 0.60$, $w_W = 40\,\text{kg/m}^3$ per unit of the layer boiled off, $k_{Ro} = 1$ per hour applies once $\rho_{lo} \le \rho_{up}$, and $\dot{m}_{in} = \dot{m}_{lift} - \dot{m}_{flash,L}$ is the liquid that joins the upper layer. Tank B's pumps draw the lower layer while it lasts. The layers exchange no heat or mass across their interface, the mechanism that the rollover models of the literature integrate [11, 12], so this model shows the sequence and not the size or timing of a real event.

Table 15.2 Parameters and Defaults. A, Adjustable in the Advanced Panel. C, a Control on a Card. F, Fixed in the Source

Symbol	Meaning	Value Unit	
V_t, V_{hdr}	tank (each), header	160,000, 500 m^3	A
ρ_{ref}, β	LNG density, its slope	450, 1.4 kg/m^3, per K	A
c_p, λ	liquid heat capacity, latent heat	3.5, 510 kJ/(kg K), kJ/kg	A
$\mathcal{M}$, T_b	molar mass, bubble point	16.8, 112.0 kg/kmol, K	A
T_v	vapor-space temperature	133.15 K	A
Q_{leak}, Q_{line}	in-leak per tank, jetty line	350, 300 kW	A
h_S	bulk–surface exchange per tank	20 kW/K	A
Δp_{LP}, η_{LP}	in-tank pump head, efficiency	10, 0.6 bar, –	A
—	LNG warming to the recondenser	0.3 K	A
r_{ret}, p_{ship}	vapor returned, ship pressure	0.6, 150 –, mbar g	A
Δh_c, V_{cargo}	cargo heat, cargo	0.3, 140,000 kJ/kg, m^3	A
$W_{K,0}$, η_K, κ	compressor (each)	10, 0.75, 0.26 t/h, –, –	A
$c_{p,v}$, τ_K	vapor heat capacity, response	2.2, 0.3 kJ/(kg K), min	A
V_{RC}, V_{RL}	recondenser volume, at 100 %	80, 40 m^3	A
ρ_{RC}, T_{vR}	recondenser liquid, vapor	405, 165 kg/m^3, K	A
$\lambda_{R,lat}$	latent heat at p_R	450 kJ/kg	A
$F_{SO,max}$, η_{HP}	HP pumps	700, 0.75 t/h, –	A
UA_0, n_{UA}	vaporizer conductance	1935, 0.6 kW/K, –	A
c_{eff}, c_{sw}	vaporizing LNG, seawater	5.3, 4.0 kJ/(kg K)	A
$F_{sw,max}$, τ_V	seawater pumps, lag	30,000, 2 t/h, min	A
T_{min}	minimum gas temperature	1 °C	A
W_F, p_{rel}	flare valve, relief set	80, 290 t/h, mbar g	A
f_{fl}, f_w	lower layer's heat shares	0.15, 0.60 –	A
w_W, k_{Ro}	weathering, overturn rate	40, 1.0 kg/m^3, per h	A
$\Delta\rho_0$, ΔT_0	case 8 layer gap	0.35, 1.5 kg/m^3, K	A
p_{SP}, p_F	tank setpoint, flare	150, 230 mbar g	C
L_2, U_2	K-2 loads, unloads	95, 60 % of a machine	C
$p_{R,SP}$, $L_{R,SP}$	recondenser setpoints	8.0, 50 bar g, %	C
—	override above $p_{R,SP}$	1.0 bar	F
—	preview floor, ceiling margin	65, 30 mbar g, mbar	F

TRY IT IN THE APP 8 · Rollover in tank B (illustrative)

Load the case and press Run. Touch nothing. Watch the Tank B layer densities trend on the Tanks view as its two lines close. They meet at 21.34 h, the status strip reads ROLLOVER, the boil-off jumps to 97.9 t/h and the tanks reach 234.2 mbar g. The Flared tile ends near 3.84 t.

15.3.9 Instruments, Parameters and Numerics

The controllers read one packet. The tank pressure carries a 5 s lag and 0.3 mbar of noise, the recondenser pressure 2 s and 0.005 bar, its level 2 s and 0.2 %, the compressor discharge meter 5 s and 1 %, the in-tank pump, recondenser LNG and send-out meters 2 s and 0.3 %, the unloading meter 5 s and 0.3 %, the flare's ultrasonic meter 5 s and 3 %, the gas temperature 10 s and 0.1 K, and tank B's density profiler each layer to 0.02 kg/m^3. Every execution draws the same 18 deviates whatever the settings. The parameters are listed in Table 15.2. Every case begins at the steady state its settings imply, found by a fixed point between the pump losses and the condensate, with the vaporizer's seawater found by bisection. At $t = 0$ of case 2 every actuator and vaporizer derivative is under 0.0013 per minute and the vapor drift is zero, and after 15 min the pressure reads 149.92 mbar g. The classical fourth-order Runge-Kutta method advances the states in 2 s steps, the control layers run on a 6 s scan, and a logged row follows every 30 s, as the engine of Section 1.6.1 runs them. Over the suggested challenge with a compressor trip, the tanks' mass closes to 3.0×10^{-5} kg on 43.6 kt, the recondenser's to 6×10^{-8} kg and the liquids' energy to 3×10^{-4} kJ on 3.13 TJ. Halving the step leaves the flare onset of case 1 (281.50 min), the peak of case 4 (186.712 mbar g), the flared mass of case 6 (13.960 t) and the rollover of case 8 (1280.60 min, 97.913 t/h) unchanged, and moves the RECONDENSER FULL instants of cases 1 and 4 by 0.01 min.

15.3.10 Assumptions

The LNG is one lump with constant heat capacity and latent heat, and its boil-off is the same lump, while real boil-off is richer in nitrogen and methane [10]. Only tank B's declared layers weather. Against the NIST Chemistry WebBook's saturation table for pure methane, a fluid with a reference equation of state fitted to its vapor pressure and saturated densities [16], the declared line gives 146.89, 149.13 and 151.21 K at 8, 9 and 10 bar g against 146.90, 149.17 and 151.28 K, within 0.07 K at the recondenser. At 1 atm and 150 mbar g it sits 0.33 K and 0.34 K above pure methane, as an LNG lump should, and its slope at 150 mbar g is 0.010 79 K/mbar against 0.01097. The latent heat matches methane's 510.5 kJ/kg at 1 atm, while $\lambda_{R,lat} = 450$ is 6 % above methane's 423.2 kJ/kg at 8 bar g, and $c_p = 3.5$ against 3.48 kJ/(kg K). The vapor is an ideal gas at one temperature whose energy is not tracked. The recondenser is in equilibrium, so the subcooling left at the high-pressure pumps' suction is logged but their net positive suction head is not modeled, which is what bounds a low recondenser pressure in a real terminal. The vaporizers are one lumped bank without ice. The flare (230 mbar g), relief (290 mbar g), pressure band and 1 °C gas minimum are teaching values. Real ones come from the tank system's design code (EN 14620-1 or API 625, which cover refrigerated liquefied gas tank systems, with EN 14620-1 limiting design pressure to 500 mbar), its venting design (API 2000, normal and emergency venting) and the pipeline's gas quality specification.

15.4 Control Layers as Implemented

Within a physics step the control layers act first, the states advance next, and last the status flags latch and the challenge is scored. The control scan is $\Delta t_c = 6$ s, always on the packet. Every loop is the velocity-form PID of Section 1.6.2 used without derivative action, so Equations (1.16) to (1.19) apply with $\tau_D = 0$, a control period Δt_c, the back-calculation time $T_t = \tau_I$ and an output bias u_0 that carries a feedforward where a loop has one. A loop not driving its actuator tracks the one that is, so Manual to Auto, an architecture change and an MPC fallback are bumpless.

15.4.1 Tank Pressure, Override and Staging

The tank pressure loop (PIC) sets the load demand D in t/h, acting so that a higher pressure asks for more load, with $K_c = 0.5$ t/h per mbar, $\tau_I = 120$ min and an output of 0 to 20 t/h. Only this loop answers to the header's Manual/Auto switch. A recondenser high-pressure override, a PI on p_R at $p_{R,SP} + 1$ bar with $K_c = 5$ t/h per bar and $\tau_I = 2$ min, gives the most load the recondenser allows, and $D = \min(D_{PIC}, D_{OVR})$. The loop not selected tracks the selected output plus its own proportional term, the external-reset form of Section 1.4.8, and the override acts in Manual too, because it is protection. Volume 4, Chapter 2 treats a protective override on a compressor in depth. Two compressors stage on D in percent of one machine's capacity at the measured pressures, where Chapter 11 shares a load among three machines on one header. K-1 loads above 5 % and unloads below 1 %, K-2 loads above L_2 and unloads below U_2, each machine runs and rests at least 10 min and the sequencer allows one change a minute. The loaded machines pass D and recycle the rest. The flare valve opens in proportion above its set pressure, $x_F = \mathrm{clip}\big((p_m - p_F)/40\,\mathrm{mbar}, 0, 1\big)$.

15.4.2 Recondenser, Send-Out and Gas Temperature

The recondenser pressure loop (PIC-R) moves x_R, more LNG through the vessel for a higher pressure, with $K_c = 10$ % per bar and $\tau_I = 2$ min. The level loop (LIC-R) trims the in-tank pumps' flow around the measured send-out, $F_{LP,SP} = F_{SO,m} + \mathrm{PI}$, with $K_c = 2$ t/h per percent and $\tau_I = 20$ min. RECONDENSER FULL is declared when $x_R \geq 99.5$ % and the pressure is more than 0.2 bar above its setpoint. The send-out loop (FIC) moves the high-pressure pumps' speed toward the nomination, or a setpoint by hand, with $K_c = 0.3$ % per t/h and $\tau_I = 0.3$ min. The gas temperature loop (TIC) moves the seawater pumps between 10 % and 100 %, with $K_c = 5$ % per K and $\tau_I = 5$ min, and has its own Auto/Man switch.

15.4.3 Boil-Off Observer

The preview and the MPC need the boil-off, which no instrument measures. A two-state observer on the vapor balance estimates it from the measured pressure, compressor, flare and unloading flows and the room the measured send-out makes, as shown in Equation (15.11).

$$\begin{aligned} \hat{p}_{k+1} &= \hat{p}_k + \Delta t_c \frac{\hat{g}_k + d_m - \rho_v F_{LP,m}/\rho_L - \dot{m}_{K,m} - \dot{m}_{F,m}}{C_t} \\ &\quad + 2\zeta\omega\,\Delta t_c\,(p_m - \hat{p}) \\ \hat{g}_{k+1} &= \hat{g}_k + C_t\,\omega^2\,\Delta t_c\,(p_m - \hat{p}) \end{aligned} \tag{15.11}$$

where C_t is the vapor capacitance computed from the tank gauges and the declared capacity, in t/h per mbar/min, $d_m = (1 - r_{ret})\rho_v Q_{c,m}$ the displaced vapor the ship does not take back, $\omega = 0.1$ per minute and $\zeta = 0.8$, the error being taken after the prediction step.

15.4.4 Preview From the Published Nomination

The preview reads 12 hours of the published nomination $F_{nom}(t)$ and ship schedule in 10 min steps and adds up the boil-off that the recondenser and the compressors will not take, as shown in Equation (15.12).

$$\begin{aligned} e_i &= \hat{g} - \dot{m}_{flash,m} + s_i - \frac{\rho_v}{\rho_L} F_{nom,i} \\ &\quad - \min\left(0.9\frac{r}{1+r}F_{nom,i},\ 0.9\,n_{max}W_K\right) \\ m_{room} &= \max_j \sum_{i \le j} e_i\,\Delta\tau \\ p'_{SP} &= \mathrm{clip}\left(p_F - 30 - \frac{m_{room}}{C_v},\ 65,\ p_{SP}\right) \end{aligned} \tag{15.12}$$

where s_i is the published ship's displaced vapor and flash, r is computed from the measured LNG and discharge temperatures at $p_{R,SP}$, C_v is the capacitance in kg per mbar and the 0.9 derates the capacities. The PIC then follows p'_{SP} moved at most 1 mbar/min, and the measured unloading's boil-off enters as its bias u_0. The same idea, acting on a forecast before the demand arrives, plans the line pack of Chapter 12 before its evening peak.

15.4.5 Model Predictive Control

Every 5 min the MPC solves a quadratic program over 8 hours, 96 steps in 12 graduated move blocks, on the vapor space as the integrator it is, as shown in Equation (15.13).

$$\begin{aligned} p_{k+1} &= p_k + \frac{T_s}{C_t}(w_k - u_k) \\ w_k &= \hat{g} - \dot{m}_{flash,m} + s_k - \frac{\rho_v}{\rho_L}F_{nom,k} \\ \min\ & \textstyle\sum_k 0.01 w_p (p_k - p_{SP})^2 + w_{\Delta u}\sum_j \Delta u_j^2 \\ & \quad + 0.1 w_{pow}\textstyle\sum_k u_k + 10^3\|\varepsilon\|^2 \\ \text{s.t. } & 0 \le u_k \le n_{max}W_K, \quad u_{k-1} \le 0.95\frac{r}{1+r}F_{nom,k} + \varepsilon \\ & 65 - \varepsilon \le p_k \le p_F - 30 + \varepsilon \end{aligned} \tag{15.13}$$

where $T_s = 5$ min, u is the compressor flow and $w_p = w_{\Delta u} = w_{pow} = 1$ by default. A second state carries the last move so that the capacity bound applies step by step. The shared quadratic programming module of Section 1.6.3 solves it with Goldfarb and Idnani's dual algorithm [17]. Only the first move reaches the compressors, as industrial MPC implementations do [18], and any solve that is infeasible, not finite or outside its bounds returns the compressors to the tracked PIC. At the Advanced level the horizon, the move suppression and a multiple of the slack price can be changed.

Table 15.3 The Nine Cases

#	Case and events	Teaching point
1	Manual, tanks 80 %, nomination to 30 t/h over 0.5–1.5 h	low send-out means flaring
2	ship at 5000 m^3/h from 20 min, K-2 unloads at 90 %	hysteresis
3	tanks 30 %, ship at 12 000 m^3/h from 30 min	displacement and flash
4	tanks 75 %, nomination to 40 t/h over 0.5–2.5 h, back at 7 h	minimum send-out
5	seawater 15 to 4 °C over 1 h from 20 min	the vaporizers' limit
6	tanks 55 %, ship from 5 min, K-2 trips at 2 h	flare or not
7	tanks 70 %, nomination to 20 t/h from 5 to 11 h, loops	the nomination as preview
8	tank B stratified, 0.35 kg/m^3 and 1.5 K	rollover (illustrative)
9	Challenge: ship 2–14 h, night at 20 t/h from 18 h	the whole terminal

15.4.6 Three Models

The plant is Section 15.3. What a learner identifies is a capacitance (kg per mbar) and a capacity ratio (kg per kg of send-out). The controllers' models are the observer, the preview's running sum and the MPC's integrator, which know the declared properties exactly but neither the in-leak, the line heat, the bulk exchange nor tank B's layers. A test of the application perturbs those undeclared constants and finds the preview's and the MPC's decisions unchanged.

15.5 Nine Cases on the Running Engine

The cases are listed in Table 15.3. Every number below was measured by stepping the engine headless at the default seed 20261020 in the increments the page uses, along the path its sentence names. A second run of the measurement script printed an identical record, and each case logs an identical run when it is loaded first, picked after some other case, or reset (Section 1.6.1).

15.5.1 A Night the Compressors Cannot Fix

In case 1 the compressor load sits in Manual at the 6.60 t/h the evening needed and the nomination falls to 30 t/h. RECONDENSER FULL comes at 91.4 min, the override cuts the compressors to what a full recondenser condenses at 9.0 bar g, 4.53 t/h at 2 h and 4.51 at 4 h, while the tanks still boil 6.94 t/h at 4 h. The difference stays in a vapor space of 97.9 kg/mbar, the pressure climbs 23.7 mbar/h to 213.7 mbar g at 4 h, and the flare opens at 4.69 h. The balance at that instant is drawn in Figure 15.2. Switched to Auto at 2 h, the PIC asks for all 20 t/h, the override still holds the compressors at 4.49 t/h at 5 h, and the pressure passes 200 mbar g at 3.42 h just the same. A night at 60 t/h, above the minimum send-out, never fills the recondenser, whose capacity reads 8.90 t/h at 5 h. The lesson is that "low send-out means flaring" is a statement about the recondenser's capacity, and the compressors' 20 t/h never enters it.

Pause. Try Exercise 15.1 before reading on.

15.5.2 Staging and Its Hysteresis

Case 2 brings the boil-off to move to 9.02 t/h, just under one machine's 10.01 t/h. With K-2 loading at 95 % and unloading at 90 % it starts 10 times in six hours, each time pulling the pressure down until the demand falls below the unload threshold. Unloading at 60, 70 or 80 % it starts once and stays loaded, recycling a mean of 10.46 t/h between 2 and 6 h against 5.15, and the compressors use 7.52 MWh against 5.91. Each extra loaded hour costs about 0.76 MWh whether its gas is needed or not.

> **TRY IT IN THE APP 2 · Compressor staging and hysteresis**
>
> Load the case and run it to 6 h. Watch K-2 on the Terminal view and the K-2 starts tile: it starts 10 times. Set K-2 unloads below to 60 on the Staging card, press Reset and run again. K-2 now starts once and stays loaded, and the Compressor energy tile reads 7.52 MWh against 5.91 MWh. Fewer starts cost more power.

15.5.3 The Ship: Displacement, Return and Flash

In case 3 at 4 h, with the ship at full rate, the cargo displaces 21.27 t/h of vapor, the ship takes 12.76 t/h back and 8.51 t/h stays, against 1.26 t/h of cargo flash and a surface boil-off of 7.46 t/h. The compressors move 14.70 t/h, K-2 loads at 61 min, and the pressure peaks at 158.9 mbar g. The flash is the term the tank pressure controls. Held by the setpoint, the tanks flash 4.43 t/h at 146.9 mbar g, 1.26 at 154.8 and none at 158.6, 0.40 t/h per mbar between the first two as the hand derivation predicts. A setpoint of 200 mbar g removes the flash and lowers the boil-off at 4 h from 7.46 to 6.16 t/h, while the displaced vapor, a volume, stays. The ship's pumps begin to stop at 12.17 h with the 140 000 m^3 cargo in, and both tanks end 69.1 % full.

🕮 **Pause.** Try Exercise 15.2 before reading on.

15.5.4 The Minimum Send-Out and the Recondenser Pressure

Case 4 ramps the nomination to 40 t/h. RECONDENSER FULL comes at 149.3 min, at 42.4 t/h, and the pressure peaks at 186.7 mbar g at 7.03 h before the ramp back restores the capacity. At 4 h the capacity ratio computed from measurements is 0.1622 kg per kilogram of LNG and the boil-off to move 6.98 t/h, and the true minimum send-out is 50.0 t/h against the 49.6 t/h of Equation (15.8). Taken off the nomination at RECONDENSER FULL, a send-out of 50 or 55 t/h holds while 45 and 48 t/h refill the recondenser. A recondenser at 10 bar g raises the ratio to 0.1774 and cuts the peak to 173.6 mbar g, for 8.96 MWh of compressor energy against 8.59 over 9 h. Case 5 shows a different limit on the send-out. With the seawater cooled to 4 °C, SEND-OUT COLD comes at 76.3 min with the seawater pumps at 100 % and the gas at −0.03 °C, and the most the vaporizers warm to 1 °C is 416.8 t/h, 92.6 % of the nomination (420, 410 and 400 t/h give 0.91, 1.20 and 1.47 °C).

15.5.5 A Trip While the Ship Unloads

In case 6 K-2 trips at 2 h with the tanks at 157.4 mbar g, 72.6 mbar under the flare, and 13.18 t/h to move. K-1 alone takes 10.20 t/h, the pressure climbs 17.8 mbar/h in a vapor space of 219 kg/mbar, and the flare opens at 6.15 h, burning 13.96 t before the unloading ends. Of the boil-off, 8.64 t/h is displaced vapor the ship does not take back, the one source an operator can turn down. Slowing the ship to 7000 m^3/h at 2.2, 5 or 5.2 h keeps the tanks off the flare, with peaks of 159.9, 207.3 and 210.4 mbar g.

15.5.6 The Nomination as a Preview

Case 7 publishes a night at 20 t/h from 5 h. On the loops alone the pressure sits at 150 mbar g until the night, the measured capacity collapses from 73.52 t/h at 5 h to 2.65 at 6 h, and the flare opens at 9.12 h and burns 7.15 t, as shown in Figure 15.3. With the preview the setpoint holds 150 mbar g until 233.5 min, when the room the night needs passes what 150 mbar g leaves under the ceiling, and then falls 1 mbar/min. The pressure is at 98.1 mbar g at 5 h, bottoms at 60.0 mbar g at 5.90 h, and peaks at 196.9 mbar g, for 11.43 MWh against 10.19 over 12 h. The MPC, reading the same schedule, peaks at 199.8 mbar g for 11.30 MWh with no fallback in its solves.

15.5.7 Rollover, Declared and Illustrative

Case 8 opens with tank B's lower layer at 12.61 kt, 0.350 kg/m^3 denser than the upper one and 1.500 K over the surface's saturation, 129.8 t of boil-off stored. Before the rollover tank B boils 2.40 t/h at 6 h against 3.11 as one layer, the warning the handling literature describes [14]. The densities meet at 21.34 h with 7.87 kt below storing 92.4 t. The boil-off jumps to 97.9 t/h logged (99.9 t/h in the step it begins), the pressure reaches 234.2 mbar g and 3.84 t are flared. Only 53.1 t of the 92.4 t flashes, the rest staying in the liquid as the rising pressure lifts its saturation. The observer's estimate reads 7.7 t/h as the surge begins and peaks at 51.5 t/h 26 min later, the lag of a 0.1 min^{-1} observer. Drawn from tank B first, the send-out takes the warm lower liquid with it, the layers meet at 18.07 h with 4.59 kt storing 53.7 t, the surge peaks at 61.4 t/h and 203.4 mbar g, and nothing is flared. Every one

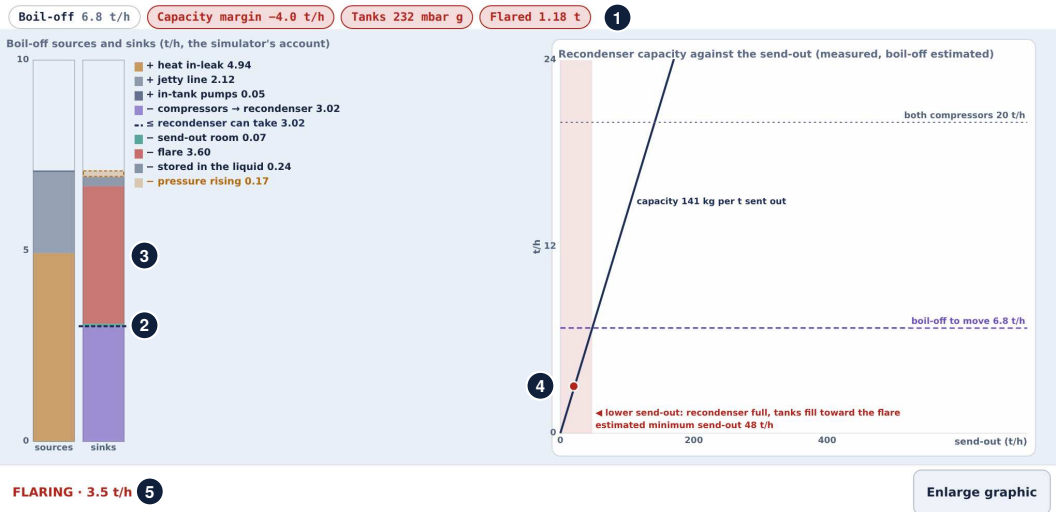


Figure 15.3 Case 7 as shipped on Loops (PI), $t = 9.5$ h, on the Balance view, light theme, cropped to the view. The status strip (5) reads FLARING · 3.5 t/h with the tanks at 231.9 mbar g against a setpoint of 150. The sources bar stacks 4.94 t/h of heat in-leak, 2.12 t/h from the jetty line and 0.05 t/h from the in-tank pumps, and the sinks bar stops the compressors at the recondenser's 3.02 t/h, its dashed line (2), with 3.60 t/h to the flare (3), 0.24 t/h stored in the liquid and 0.17 t/h as pressure rising. The plot puts the terminal (4) at the 20 t/h nomination, far left of the estimated minimum send-out of 48 t/h, under a boil-off to move of 6.8 t/h, and the capacity margin badge among the chips (1) reads −4.0 t/h, beside 1.18 t flared.

Table 15.4 Measured Cases at the Default Seed

Case	Configuration	Result
1	Manual, night 30 t/h	FULL 91.4 min, flare 4.69 h
1	Auto from 2 h	200 mbar g at 3.42 h, $\dot{m}_K$ 4.49 t/h
2	K-2 at 95/90 against 95/60	10 against 1 start, 5.91 / 7.52 MWh
3	setpoint 150 / 200 mbar g	flash 1.26 / 0 t/h, boil-off 7.46 / 6.16
4	minimum send-out	49.6 by hand, 50.0 measured
4	recondenser 8 / 10 bar g	peak 186.7 / 173.6, 8.59 / 8.96 MWh
5	seawater 4 °C	416.8 t/h reach 1 °C (92.6 %)
6	trip, as shipped / slowed	13.96 t / 0 t flared
7	loops / preview / MPC	7.15 / 0 / 0 t, 10.19 / 11.43 / 11.30 MWh
8	both tanks / B first	97.9 / 61.4 t/h, 3.84 / 0 t flared

of these numbers is a declared choice. The layers meet at 21.3, 37.1 and 47.3 h from gaps of 0.35, 0.70 and 1.05 kg/m^3, and from 1.40 kg/m^3 the send-out drains the lower layer before they meet. The overturn rate sets the surge, 53.4 t/h at 0.5 per hour with nothing flared and 183.9 t/h at 2 per hour with 11.45 t flared.

🕮 **Pause.** Try Exercise 15.3 before reading on.

15.5.8 The Graded Day

The challenge runs 24 h with both tanks 30 % full, a ship from 2 h whose pumps begin to stop at 13.67 h, and the nomination falling to 20 t/h from 18 h. Six targets are scored from the simulator's truth on every physics step: the pressure between 50 and 220 mbar g after 5 min, under 0.1 t flared, each hour's send-out within 2 % of that hour's published nomination, the gas at or above 1 °C, at most 30.6 MWh of compressor energy and at most 230 t of boil-off. A changed disturbance or model

Table 15.5 The Challenge Day at the Default Seed

Settings	p range (mbar g)	Flared (t)	Energy (MWh)	Boil-off (t)	Verdict
shipped, loops, K-2 50/40	135.6–231.9	6.61	33.08	190.8	fails
suggested, preview, 95/60	58.9–196.1	0	30.24	210.0	passes
preview, shipped staging	58.9–196.1	0	32.84	210.0	fails
loops, 95/60	135.6–231.9	6.61	28.07	190.8	fails
MPC, 95/60	64.7–196.7	0	29.75	218.4	passes
constant 70, 95/60	69.8–199.6	0	31.05	271.5	fails
constant 70, 95/80	69.8–199.6	0	28.93	271.5	fails
constant 92, 120/100	91.8–219.2	0	27.75	263.3	fails
preview, $p_{R,SP}$ 6 bar g	59.0–203.6	0	25.82	209.9	passes

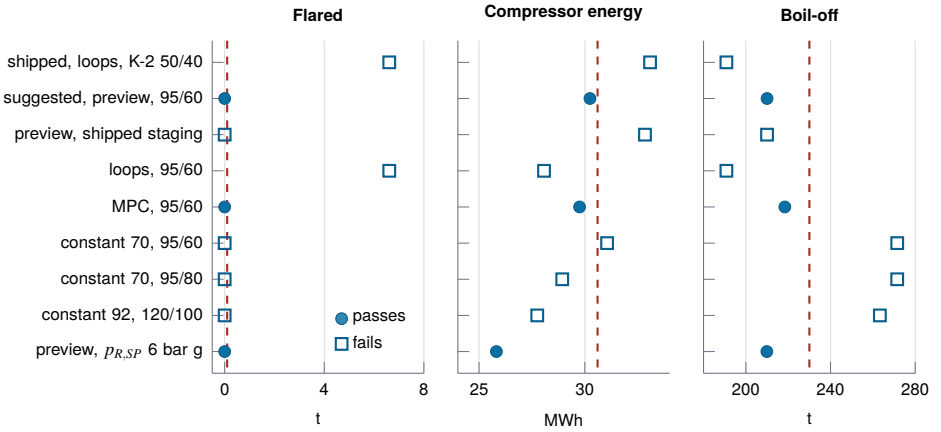


Figure 15.4 The challenge day of Table 15.5 as three dot panels, filled circles for the runs that pass and open squares for those that fail, with the day's limit as a dashed line: under 0.1 t flared, at most 30.6 MWh and at most 230 t of boil-off. Notice that no single panel sorts the runs: the loops fail on the flare, the shipped staging on energy and the constant setpoints on boil-off. The pressure range stays in the table.

parameter, or a press of the Ship button, marks the run "not graded". The outcomes are listed in Table 15.5 and the day is plotted in Figure 15.5. Figure 15.4 sets the table's flared mass, energy and boil-off against their limits.

As shipped, the pressure is still at 147.6 mbar g when the night begins, the night takes it to the flare at 22.16 h and 6.61 t burn, and K-2, loading above half a machine, runs all day for 33.08 MWh. The suggested settings, the preview with K-2 at 95 and 60 %, bank the tanks to 59.2 mbar g by 18 h and pass. Either change alone fails, the preview on power at 32.84 MWh and the staging on the flare. The MPC with the same staging passes at 29.75 MWh, and over seeds 0 to 4 and at half the step the suggested run uses 30.16 to 30.24 MWh and the MPC 29.72 to 29.80 MWh, every verdict unchanged.

The sixth target exists because energy could not separate two strategies. The energy counts loaded machine-hours, and a loaded machine draws slightly less at a lower suction pressure, so holding the tanks low all day costs nothing in energy. With K-2 unloading at 80 %, constant setpoints from 65 to 92 mbar g used 29.13 to 28.25 MWh, inside the budget and cheaper than the preview. Without the boil-off target they would pass. What a low tank pressure does cost is the cargo flash of Equation (15.5). At 70 mbar g the flash peaks at 27.27 t/h during the unloading against 4.38 t/h with the preview, and the day's boil-off is 271.5 t against 210.0 with the preview and 218.4 with the MPC, as Figure 15.5b shows. The 230 t budget sits 11.6 t above the MPC's worst seed and 33 t below the best constant setpoint. The Ship button is ungraded for a similar reason, because stopping the ship at 5 h with only

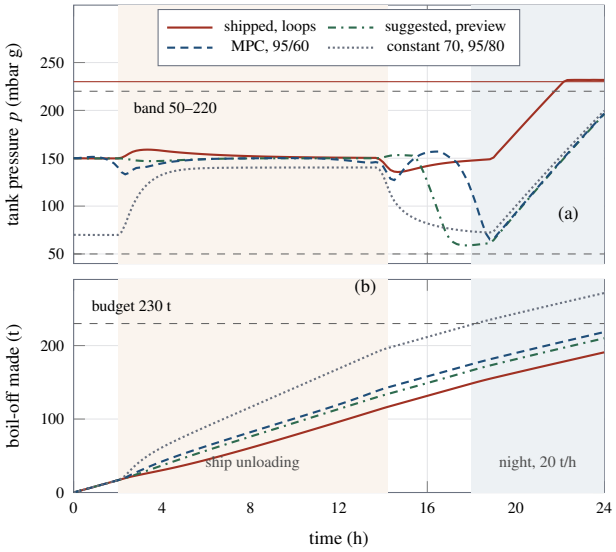


Figure 15.5 The challenge day under four strategies: the shipped loops (solid), the suggested preview (dash-dotted), the MPC (dashed) and the constant setpoint (dotted), with the ship's hours and the night shaded and labeled. (a) True tank pressure, with the judged band and the flare at 230 mbar g. (b) Boil-off made in the tanks since $t = 0$, against the 230 t budget, ending at 190.8 (shipped), 210.0 (preview), 218.4 (MPC) and 271.5 t (constant setpoint). The constant setpoint stays in the band without flaring but flashes cargo through the whole unloading.

36 000 m^3 in let the loops with K-2 at 95 and 80 % pass at 21.35 MWh.

> ✦ **DID YOU KNOW? The Two Cheapest Days Both Fail**
>
> From the simulator (Table 15.5). The two runs of the graded day with the least compressor energy both fail. The loops with K-2 at 95 and 60 % use 28.07 MWh but flare 6.61 t. A constant 92 mbar g with K-2 at 120 and 100 % uses 27.75 MWh but boils off 263.3 t. The suggested settings pass at 30.24 MWh.

One lever the target does not forbid is the recondenser setpoint. With the preview and the recondenser at 6 bar g the day passes at 25.82 MWh, 209.9 t and 59.0 to 203.6 mbar g, because a lower discharge pressure cuts the work per kilogram while the reduced capacity still covers the day. In a real terminal the high-pressure pumps' suction margin bounds that lever, and the model logs only the subcooling left there.

15.6 Technology in Practice

Figure 15.6 draws the loops of Section 15.4 with the hardware of a receiving terminal in place of the schematic's symbols.

What Measures It

The loops read a pressure transmitter on the shared vapor space, a pressure and a level transmitter on the recondenser, flowmeters on the compressors' discharge, the in-tank pumps, the recondenser's LNG, the send-out and the unloading line, a temperature element on the send-out gas, and an ultrasonic meter on the flare line. Tank B carries a density profiler. No instrument measures the boil-off itself, which the observer infers from the vapor balance. Each instrument model of Section 15.3, a lag and a noise level, stands for one of these devices. The flare meter's 5 s lag and 3 % noise, for example, are the ultrasonic meter below.

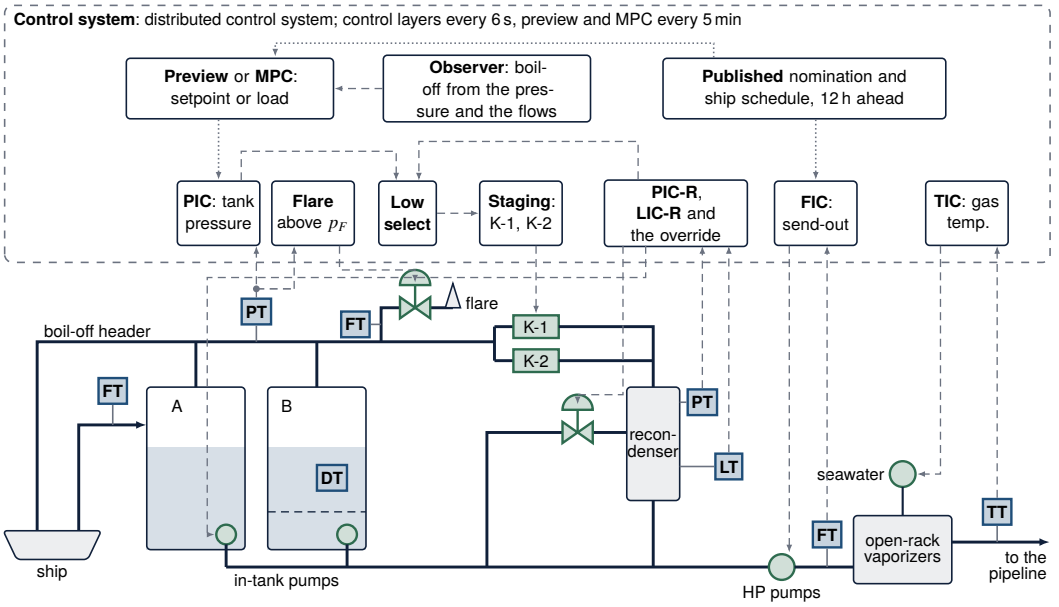


Figure 15.6 The loops of the terminal with their hardware. Lettered boxes are sensing devices with ISA letters: PT on the boil-off header and on the recondenser, LT on the recondenser, FT on the unloading arm, the flare line and the send-out, TT on the gas and DT, the density profiler, in tank B across its two layers. Green symbols are final elements: the in-tank pumps, the compressors K-1 and K-2, the valve that sets the recondenser's share of the LNG, the flare valve, the high-pressure pumps and the seawater pumps. Dashed arrows are signals, dotted arrows the published schedule and what the preview or the MPC writes. Notice that the compressors' load passes a low selector where the recondenser's override can cut it, and that no instrument measures the boil-off. Not to scale, and not a piping diagram.

> **TECHNOLOGY** **Sensor: The Ultrasonic Meter on the Flare Line**
>
> A transit-time ultrasonic flowmeter sends sound pulses between a pair of opposed sensors, with the flow and against it. The pulse carried downstream arrives sooner, and the flow follows from the two travel times in a form that does not depend on the speed of sound, so changes of composition, temperature or pressure have little effect. The meter also reports that speed of sound, a check that can reveal a fault in the sensors or their electronics. Several paths across the pipe are averaged where the velocity profile changes with the flow [19]. A flare is among the hardest services: almost no flow most of the time, a very large flow in an emergency, and a gas of varying composition. Multipath transit-time meters suit it, but their cost on large flare pipes limits them [19].

What Moves It

Five handles carry the control: the load of two on/off compressors, which recycle what the demand does not take, the share of the in-tank pumps' LNG sent through the recondenser, the in-tank pumps' flow, the speed of the high-pressure pumps and the seawater pumps of the vaporizers. Behind them stand the flare valve, which opens on the tank pressure once the handles have run out, as in case 1 at night and in case 8 at the rollover, and the tanks' relief valves above it.

TECHNOLOGY Final Element: The Flare and Relief Valves

Relief and safety valves open on the process pressure itself, with no signal from a controller. A relief valve opens in proportion to the overpressure. A safety valve, common in gas service, snaps fully open at its lift pressure and closes again only well below it, and the difference between the two pressures is its blowdown. In a pilot-operated valve a small pilot senses the pressure and sets the lift, so the setting is widely adjustable. An improper pilot setting played a role in a 1999 pipeline rupture, which shows why such settings need the same care as any instrument [19]. The chapter's flare valve opens in proportion over the 40 mbar above its set pressure, as a relief valve would, and its relief valves pass 20 t/h per mbar above 290 mbar g.

Where the Controller Runs

A distributed control system controls production within one location, and its supervisory and lower-level loops run with cycle times from milliseconds to minutes [20]. Control of a process plant is usually layered by time scale, with supervisory and predictive control acting in minutes and regulatory control in seconds [21]. The app's control layers run on a 6 s scan and its MPC every 5 min, so the chapter spans both of those layers. Its structure maps onto standard blocks: a pressure PI and a recondenser override PI into a low selector with external reset, a staging sequencer with hysteresis and minimum run and rest times, the recondenser's pressure and level PIs, a flow PI on the pumps' speed and a temperature PI on the seawater. The observer, the preview and the MPC sit above them as calculation blocks.

IN PRACTICE Before the Ship Pumps, Compare the Cargoes

United States rules for LNG plants require written transfer procedures. Before a transfer, personnel verify that the receiving tank has room for the cargo and that the incoming liquid, as it warms, will not overfill or overpressure it. For a bulk transfer into a partly filled tank they determine any difference in temperature or specific gravity between the incoming and the stored LNG and, if necessary, provide a means to prevent rollover. During the transfer they watch flow rates, liquid levels and vapor returns, and stop the flow by hand before overfilling or overpressure occurs [22]. Vaporization must keep the gas within the limits of the vaporizer and the downstream piping [23]. Cases 5, 6 and 8 rehearse three of these duties.

What Is Modernizing It

Three developments touch this chapter. The first is estimation. Soft sensors stabilize quality through online estimation and are used to validate online analyzers, and a survey of industrial applications names model maintenance as their most critical issue [24]. The boil-off observer of this chapter is a soft sensor of that kind, reading only pressures and flows. The second is predictive control, established in industry with only the first move applied [18], which the chapter's MPC follows on the published nomination. The third is design and operation studied together. A 2010 optimization recovered the unloading boil-off with the least energy as a strategy against flaring [3], and a 2012 dynamic simulation checked an improved recondenser control algorithm against fluctuating LNG and boil-off loads before its use at other terminals [5].

15.7 Limitations

The sizes, properties and thresholds were picked as teaching values for one self-consistent design, two tanks boiling 8.35 t/h at 150 mbar g beside a 450 t/h send-out, and none was fitted to a terminal. The LNG is one lump on a Clausius–Clapeyron line, within 0.07 K of pure methane at the recondenser but without composition or weathering outside case 8. The vapor space has one temperature, the recondenser is in equilibrium with no suction head modeled at the high-pressure pumps, the vaporizers are one bank without ice, and the cargo flashes at equilibrium as a top fill would. The rollover is illustrative. Its layers exchange nothing across their interface, its crossing time is set by the chosen initial gap and its surge by the declared overturn rate, so the case teaches the sequence and the remedy rather than a prediction.

The controllers know the declared properties exactly, and the observer lags a fast surge by tens of minutes. The compressors are on/off machines without load steps. The preview and the MPC read a perfect published schedule, and a nomination that changes after publication is outside the cases. The challenge grades boil-off because energy cannot separate a preview from a constant low pressure, and it leaves the recondenser setpoint free, which a real terminal's pump suction margin would not. All figures come from a single model at seed 20261020, the challenge alone being repeated over seeds 0 to 4 and at a halved step.

OPEN CHALLENGE **Measuring a Rollover Before Predicting One**

Industrial rollover incidents are rarely documented in the open literature, mainly because operating and commercial data stay confidential, and the report of the 1971 incident remains the most detailed record of a real event. Very little quantitative data exists. Progress, as a 2015 study set it out, means direct measurements of a rollover: the initial composition of each layer, its temperature and density against depth as they evolve, the boil-off rate, and the heat flux into the tank by position. Such measurements are costly, but the scale of the industry probably justifies them [15]. A model would then track the stability of the layers until its critical value is reached [11].

15.8 Conclusion

An LNG import terminal with a recondenser is a gas inventory whose outlet is a fraction of its product flow, and the simulator of this chapter logs the boil-off, the recondenser's capacity and the tank pressure beside the instruments and controllers that see them. The capacity is $r = 0.1658$ per kilogram of LNG and $r/(1+r) = 0.1422$ per kilogram of send-out, which puts the minimum send-out at 49.6 t/h by hand and 50.0 t/h on the running plant. A 30 t/h night fills the recondenser in 91.4 min and reaches the flare at 4.69 h whatever the compressors are asked to do. The ship's displaced vapor and its cargo flash of 0.40 t/h per mbar make the tank pressure a lever on the boil-off itself. Read from the published nomination, the preview passes the graded day at 30.24 MWh and the MPC at 29.72 to 29.80 MWh, while a constant low pressure flashes enough cargo to raise the day's boil-off to 271.5 t. The rollover is declared, with a chosen gap and overturn rate. A fuller model would add a multicomponent liquid with weathering, interfacial transfer between layers, the high-pressure pumps' suction margin, load-stepped compressors and an uncertain nomination. The simulator shows that the boil-off a terminal can take back is decided by the send-out it is asked to make.

KEY POINTS

- The tanks boil all the time, and the gas can leave only by condensing into the LNG the terminal sends out, so a night of low demand drives the tank pressure toward the flare.
- The recondenser takes at most 0.1422 kg per kilogram of send-out, so the minimum send-out is 49.6 t/h by hand and 50.0 t/h on the running plant.
- A 30 t/h night reaches the flare at 4.69 h whatever the compressors are asked to do.
- Read from the published nomination, the preview and the MPC pass the graded day, while a constant low pressure raises the day's boil-off to 271.5 t through cargo flash.

Where else this applies. A surplus integrated against a sink that another decision sets returns in Volume 11, Chapter 14, and a forecast acted on before the demand arrives in Chapter 12.

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15.9 Exercises

15.1 Concept check · 2 min

In case 1 the nomination falls to 30 t/h for the night. The two compressors can move 20 t/h, nearly three times the 6.94 t/h the tanks boil, yet the tank pressure climbs to the flare. Why?

(a) The pressure loop is in Manual, so the compressor load stays at the evening value

(b) The compressors' capacity falls with the suction pressure, so they lose their 20 t/h at night

(c) The recondenser condenses only a fraction of the send-out, and its override cuts the compressors to it

(d) The vaporizers cannot warm so small a send-out, so the high-pressure pumps return LNG to the tanks

15.2 Concept check · 1 min

In case 3 a ship unloads 12 000 m^3/h into tanks held at 150 mbar g. The tank pressure setpoint is raised to 200 mbar g before Run. What happens to the cargo flash and to the displaced vapor the ship does not take back?

(a) Both fall, because a higher pressure compresses the vapor the cargo displaces

(b) Both rise, because a higher tank pressure raises the cargo's arrival temperature

(c) The flash rises and the displaced vapor is unchanged, because warmer tanks boil more

(d) The flash stops and the displaced vapor, set by the cargo's volume, stays about the same

15.3 Concept check · 2 min

In case 8 tank B holds a denser, warmer lower layer. Before the layers roll over, which reading is the warning that the handling literature describes?

(a) Tank B boils less than it would as one layer, because the lower layer keeps the heat it receives

(b) Tank B boils more than it would as one layer, because the lower layer is warmer than the surface

(c) The tank pressure creeps up, because the lower layer vents its vapor into the shared space

(d) The observer's boil-off estimate jumps, because the observer reads tank B's density profiler

15.4 Theory and calculation · 6 min

The recondenser runs at 8 bar g, where the declared saturation line gives $T_{sat}(p_R) = -126.258\,^{\circ}\mathrm{C}$. The LNG reaches it at $T_{LNG} = -159.144\,^{\circ}\mathrm{C}$ with $c_p = 3.5\,\mathrm{kJ/(kg\,K)}$. The compressed boil-off arrives at $T_d = -15.21\,^{\circ}\mathrm{C}$ with $c_{p,v} = 2.2\,\mathrm{kJ/(kg\,K)}$, and the latent heat at p_R is $\lambda_{R,lat} = 450\,\mathrm{kJ/kg}$.

(a) Find the heat each kilogram of compressed boil-off must give up to condense, λ_R. *Checkpoint:* 694.3 kJ/kg.

(b) Find the boil-off condensed per kilogram of LNG through the recondenser, r, and per kilogram of send-out with all the LNG through it. *Checkpoint:* 0.1658 and 0.1422.

(c) The in-leak and the jetty line make 7.06 t/h of boil-off. Find the lowest send-out at which the recondenser can take it, and the capacity at a 30 t/h night. *Checkpoint:* 49.6 t/h and about 4.27 t/h.

15.5 Theory and calculation · 6 min

Case 1 opens with both tanks 80 % full. Each tank holds $V_t = 160\,000\,\mathrm{m^3}$, the header $V_{hdr} = 500\,\mathrm{m^3}$, and the vapor has $\mathscr{M} = 16.8\,\mathrm{kg/kmol}$ at $T_v = 133.15\,\mathrm{K}$, with $R = 8314.46\,\mathrm{J/(kmol\,K)}$.

(a) Find the vapor-space capacitance $\partial M_v/\partial p$ from Equation (15.1), in kg per mbar. *Checkpoint:* 97.9 kg/mbar.

(b) At 4 h the Balance view leaves 2.32 t/h of boil-off as "pressure rising". Find the rate of rise. *Checkpoint:* 23.7 mbar/h.

(c) The true pressure is 213.7 mbar g at 4 h. Estimate when the tanks reach the flare at 230 mbar g. *Checkpoint:* 4.69 h.

15.6 Theory and calculation · 5 min

A ship unloads 12 000 m^3/h, which is $F_c = 5398$ t/h of cargo, into tanks at 150 mbar g. The cargo arrives 0.0857 K above the tanks' saturation temperature, with $c_p = 3.5$ kJ/(kg K) and $\lambda = 510$ kJ/kg. Near 150 mbar g the saturation temperature rises 0.010 79 K/mbar.

(a) Find the cargo flash at 150 mbar g. *Checkpoint:* 3.18 t/h.

(b) Find how much the flash falls for each mbar the tanks are held higher. *Checkpoint:* About 0.40 t/h per mbar.

(c) Find the tank pressure above which the cargo no longer flashes. *Checkpoint:* 157.9 mbar g.

15.7 App challenge · 9 min

Load case 1, A night at low send-out (Manual), and change no setting. Run to 300 min at the default speed of 30 with the default seed and export the CSV file.

(a) Find the time of the first row with `rc_full` equal to 1 and of the first row with `flare_meas_tph` above zero. *Checkpoint:* 91.5 min and 281.5 min, within 0.5 min.

(b) In the row at 240 min read `truth_bog_tph`, `truth_comp_tph`, `truth_rc_capacity_tph` and `rc_capacity_tph`. *Checkpoint:* 6.94, 4.51, 4.53 and 4.21 t/h, within 0.02 t/h.

(c) Press the reload button, run at speed 5, pause at any time between 110 and 130 min, switch the header to Auto and run on to 300 min. Read `comp_load_req_tph` and `truth_comp_tph` at 300 min and the first row with `flare_meas_tph` above zero. *Checkpoint:* 20.00 t/h, 4.49 t/h and 281.5 min.

15.8 App challenge · 8 min

Load case 6, A compressor trip during unloading: flare or not. Use the default seed and speed 60, at which 12 h take 12 s.

(a) Run as shipped to 720 min. Read the Flared tile and, in the exported file, the first row with `flare_meas_tph` above zero. *Checkpoint:* 13.96 t and 369 min (6.15 h).

(b) Press the reload button and run at speed 10. Pause at any time between 2.2 and 5 h, set Unloading rate to 7000 m^3/h, and run to 720 min. Read the Flared and Peak pressure tiles. *Checkpoint:* 0.00 t flared, peak between about 161 and 208 mbar g.

15.9 App challenge · 9 min

Load case 7, The nomination as a preview. Run three times to 720 min at speed 60 with the default seed, choosing Tank pressure control before Run: Loops (PI), then Loops + nomination preview, then MPC on the compressors. For each run read the Flared, Compressor energy and Peak pressure tiles.

(a) Report the three runs. *Checkpoint:* Loops 7.15 t, 10.19 MWh, 233.0 mbar g. Preview 0.00 t, 11.43 MWh, 197.4 mbar g. MPC 0.00 t, 11.30 MWh, 200.1 mbar g.

(b) In the preview run, find in the exported file the first row with `p_sp_eff_mbarg` below 150 and the value of `truth_p_mbarg` at 300 min. *Checkpoint:* 233.5 min and 98.1 mbar g.

Accept an energy within 0.02 MWh and a peak within 0.5 mbar. Explain why the preview costs more energy than the loops.

15.10 Application area · 3 min

With the preview and K-2 at 95 and 60 %, the graded day passes at 30.24 MWh with the recondenser at 8 bar g and at 25.82 MWh with it at 6 bar g.

(a) Explain why the lower recondenser pressure saves energy and what it costs in capacity. *Checkpoint:* Less work per kilogram, smaller r.

(b) An engineer proposes to run a real terminal's recondenser at its lowest pressure for the same saving. Name the limit the model leaves out and the logged quantity that hints at it. *Checkpoint:* The high-pressure pumps' suction margin. The subcooling at their suction.

15.11 Application area · 4 min

A terminal engineer wants to use case 8 to decide how long a stratified tank may be held before its lower layer must be sent out.

(a) Which results of the case are set by declared choices rather than by physics the model resolves? *Checkpoint:* The crossing time and the surge.

(b) What can the case support, and which remedy does the app teach? *Checkpoint:* The sequence and the remedy. Tank B first.

15.12 Review the agent · 5 min

An AI assistant is asked how to pass the graded day of case 9 more cheaply than the preview and replies: "Keep Tank pressure control on Loops (PI), set the Tank pressure setpoint to 70 mbar g, K-2 loads above to 95 % and K-2 unloads below to 80 %. The low pressure leaves room for the night, so nothing flares, and a loaded compressor draws slightly less power at a lower suction pressure, so the day uses about 29 MWh, inside the 30.6 MWh budget and below the preview's 30.24 MWh. No forecast is needed." Find the flaw and say how you would check it.