Assessment of Operators' Response Time on Safe Operation of Distillation Columns: A Process Dynamic Analysis

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Dynamic simulation has been instrumental in delivering solutions to ensure safety and controllability of process plants. In this work, dynamic simulations were performed as a follow up of a Layer Of Protection Analysis (LOPA) study for two existing distillation columns. Cooling water and reflux failures were considered as the event scenarios. Models were developed and run in iCON-Symmetry v2020.3 environment, considering all related data taken from as built documents. In Column C-1, cooling water failure event leads to the high-high pressure alarm at about 7 min, followed by opening of its five PSVs simultaneously at about 2 min afterwards. Liquid level in the reflux drum drops quickly due to its flow control setup and the reflux pump is shut off about 5 min afterwards. Reflux failure case for this Column C-1 only increases the pressure by about 0.4 bar and hence, all PSVs remain close. This is mainly attributed to the huge capacity of the condenser and the volume of the column itself. In Column C-2, the high-high pressure alarm alerts the operator after at about 3-4 min, while its three PSVs open within about 1-2 min afterwards. Its more rapid overpressure situation is caused by the reduced reflux flowrate (level-controlled) as well as the presence of vapor fraction in the feed. The reflux pump is shut off at about 9 min after the PSVs open. Its reflux failure case is less severe compared to its cooling water failure. Nonetheless, the pressure does increases significantly and the PSVs open at about 9-10 minutes. Overall, it is shown that all PSVs have been sized adequately to cater for the cooling water failure as the worst-case scenario, as recorded in the document of relief load calculations. In addition to this, even though operators on the field do not have sufficient time to react, operators in the control room, however, can quickly push the safety switch on the control board to isolate the columns. Thus, the operating procedure is updated accordingly so that the operator has to push the switches within two and one minutes after the alert of high-high pressure alarms for Column C-1 and C-2, respectively.

Keywords: Process Dynamic Simulation, iCON Symmetry, Layer of Protection Analysis, Distillation Column, Process Safety Valves, Set Points, Control Loops, Cascade Control, Cooling Water Failure, Failure Events, Reflux Failure, Relief Load Calculations, Process Flow Diagram, Piping & Instrumentation Diagram, Hazard Studies, Process Data Sheets,

Introduction

There are several safety studies for typically conducted during the life cycle of industrial plants, either qualitatively such as Hazard Identification (HAZID) or Hazard and Operability (HAZOP) study or quantitatively such as Layer Of Protection Analysis (LOPA) or Quantitative Risk Assessment (QRA) [1]. In relation to these studies, use of dynamic process simulation models has been found to help better safety studies. It also has been acknowledged as a tool that complements traditional safety studies to provide a deeper analysis [2] and to discover, among others, possibility of runaway reactions performed during HAZOP studies for cases like ammonia and propylene glycol [3]. Dynamic simulation has been used as well in addressing over-engineering, setting Independent Protection Layer (IPL) accurately, and verifying human factors [4].

In terms of plant operations, dynamic operator training simulation has been applied to prepare operators in achieving safe operation in various process plants [5,6]. Operational safety is also strongly related to controllability of chemical processes. In this regard, some applications in operational safety with model predictive control in an ammonia plant [7] and typical feedback control in a methyl isocyanate process [8] have been conducted. Furthermore, safety studies for operational improvements are enhanced via dynamic process simulations have been very well reviewed by Ahmad et.al. [9].

One way to utilize dynamic process simulation from process safety point of view is to calculate operators' response time. IEC-62682 [10] defines (operator) allowable response time as maximum time between the annunciation of the alarm and when the operator takes corrective action to avoid the consequence. Furthermore, definitive value of response time varies within industries, such as from 7 minutes for moderate frequent incidents on nuclear industries [11] to 8 minutes 49 seconds on UK fire and rescue services [12]. As a benchmark, EEMUA 191 [13] proposes 10 minutes as "very likely to be acceptable" for operator response time.

In this work, LOPA studies on two distillation columns in a refinery complex in Malaysia have shown some concerns during several over pressure scenarios, namely reflux and cooling water failures. These concerns revolves around whether the installed Pressure Relief Valves (PSV) were adequately sized and whether the operators had sufficient time to isolate the columns as part of their operating procedure. To evaluate this situation, dynamic simulation models were developed in iCON-Symmetry v2020.3 environment. The objective was to evaluate time durations for operators to respond if the overpressure scenarios occur. During this study, various process situations were also observed such as the decrease of reflux drum level, reboiler temperature, the operability of hot bypass valve, and all control loops behavior during the events. Furthermore, to prevent chattering of the PSV, all of them were set at the same set pressure, new set pressures were recommended.

Methodology

Work methodology consists of (1) developing dynamic simulation models for both columns independently using iCON® Symmetry Process Simulation Software 2020.3, (2) developing event scenarios based on the cause-and-effect matrix of the columns during the

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overpressure scenarios, (3) running and visualizing the simulation results to evaluate the time required from the start of the event to the opening of the PSV.

Selected thermodynamic model is Advanced Peng Robinson since the columns to be simulated are light gases, primarily ethane, propane, and propylene.

Sources of information are obtained from Process Flow Diagram (PFD), Piping & Instrumentation Diagram (P&ID), Process Data Sheets (PDS) for all units relevant for the simulation, e.g., column, condenser, reflux drum, reflux pump, reboilers, Cause & Effect Matrix (CEM), PSV Relief Load Calculation Sheet, Data Sheet for Safety Relief Instrument, Data Sheet for Control Valve, and Process Control Narratives.

In this work, it is assumed that there are no additional hazards expected such as support and structural damages due to the relief force of PSVs while they are opening and closing.

Results and discussion

Case Study 1

A snapshot of the relevant process flow diagram for this C-1 column is shown in Figure 1. The column C-1 is heated by three reboilers. Two of them are using Pump Around (PA) streams from an upstream Fluid Catalytic Cracking (FCC) distillation column, while the other one is using steam. In this column, the steam reboiler (E-2) is controlling the temperature of tray 32. The steam supply is cut off when the column pressure is reaching 20.5 barg. There are five PSV (PSV-1A/…/1E) installed and they will open at 21.3 barg. The column operates at maximum 18.3 barg, as indicated in the figure. The size of the unit operations, their elevations, and control configurations of the system are considered. In this column, the reflux flowrate is flow-controlled, while the distillate is operated by the level control of the reflux drum (V-1). There is no controller around the condenser, E-1.

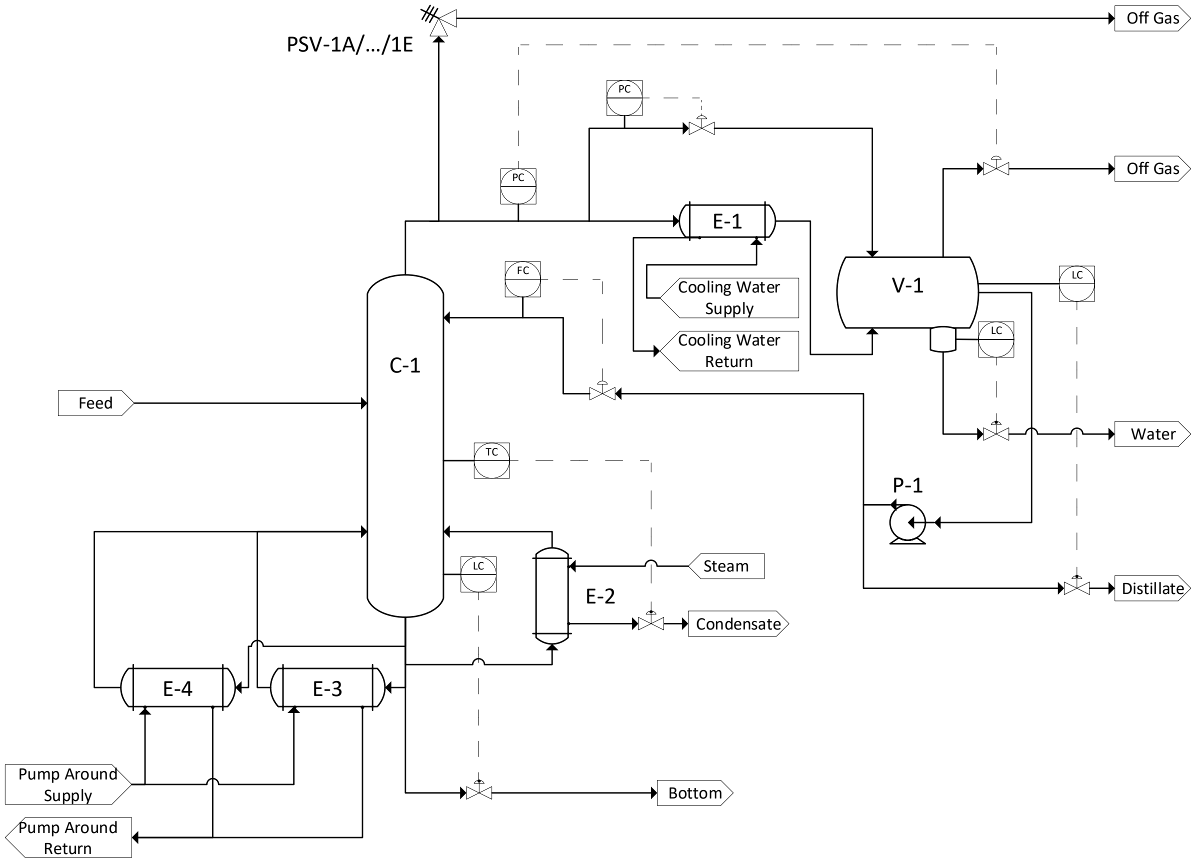

Figure 1. Simplified Process Flow Diagram for C-1

In this simulation, the cooling water failure event starts when the simulation time reaches 500 s. It can be seen in Figure 2 that, as the cooling water condenser fails (long-dotted line showing the condenser duty drops to zero), the uncondensed vapor enters the reflux drum, which then pressurizes the column (solid line) and increases the temperature throughout the column. The steam reboiler (E-2) is still supplying some energy (short-dotted line), regulating the temperature in stage 32. Its duty reduces since the temperature in stage 32 increases. When the pressure reaches 20.5 barg, this steam reboiler is cut off in about less than 7 min. The pressure keeps increasing because the other two reboilers using the PA streams are still supplying the energy to the column.

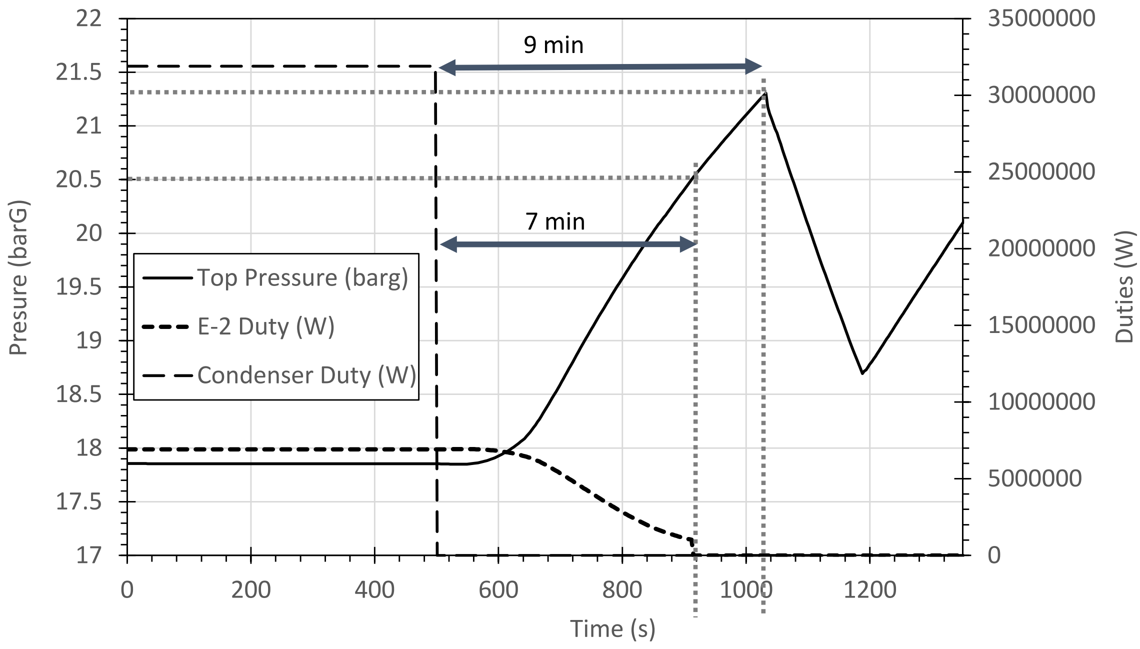

Figure 2. Column C-1 top pressure, reboiler, and condenser duties during cooling water failure

When the pressure reaches 21.3 barg, all five PSVs (PSV-1A/…/E) open at the same time at about less than 9 min, releasing the vapor, and hence, reducing the pressure of the column, as seen in Figure 2. It is also important to note that the resulting temperature increase in the condenser is still below the design temperature of the condenser. Hence, the material integrity in the condenser is preserved. Nonetheless, operators in the control room should be aware of this situation and be reminded to isolate the column as part of their operating procedure.

After the pressure of the column drops, the PSVs close, all while the feed keeps coming and the PA reboilers (E-3 and E-4) are still supplying energies, the pressure increases again, and the cycle continues. The graph showing the opening of five PSVs simultaneously is shown in Figure 3.

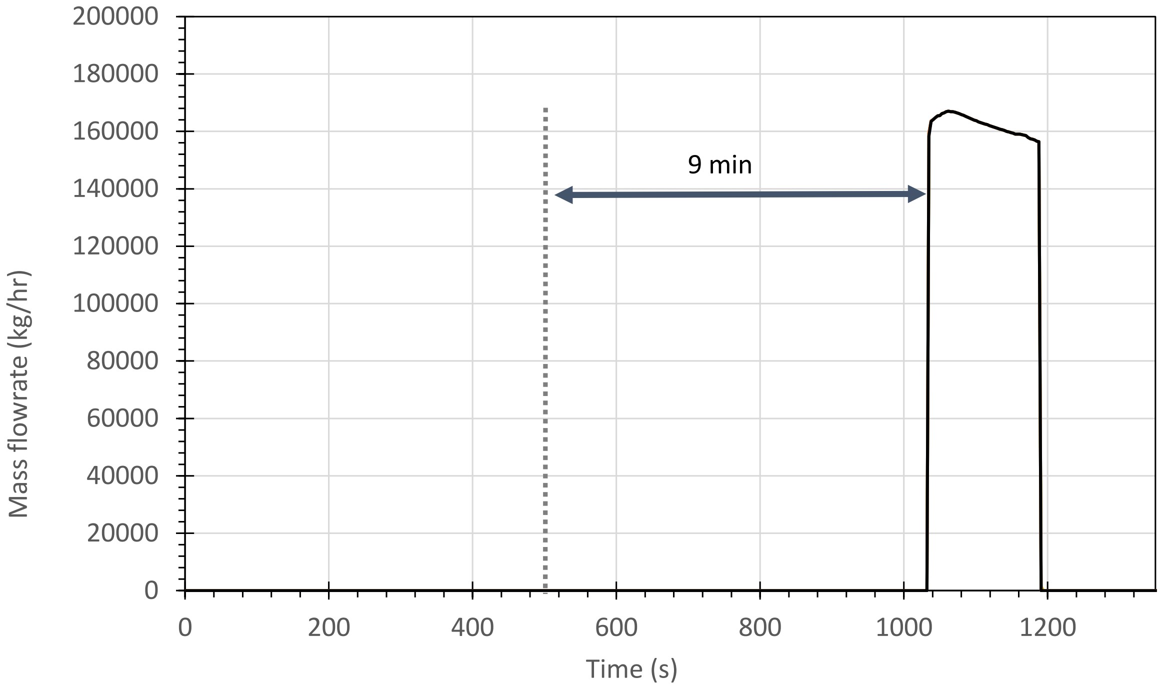

Figure 3. All five PSV open simultaneously during cooling water failure

During this situation, when the pressure of the column increases, the hot bypass valve closes while the valve to the flare opens. This is seen in Figure 4 (valve opening is on the left vertical axis). The same cycles of pressure going up and down are also shown here from the perspective of these valves (pressure values are on the right axis).

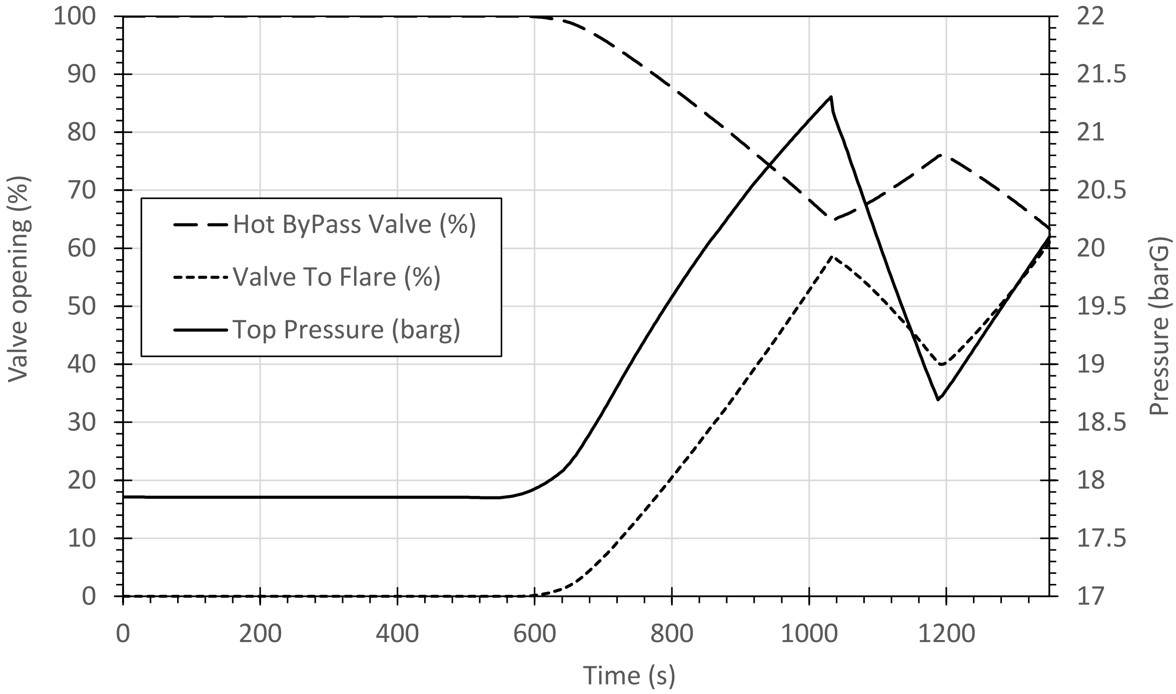

Figure 4. Hot bypass valve and valve to flare in column C-1 during cooling water failure

As mentioned before in this Column C-1, the reflux flowrate is flow controlled. Hence, when the cooling water fails, there is no more liquid coming into the reflux drum, while the reflux stream is still at its set point. Thus, the level in the reflux drum drops quickly after an increase of about 10% (from normal level of 50%). When the reflux drum reaches 30%, (the limit for the pump safety switch low low), the reflux pump is stopped (See the solid line in Figure 5, right axis). This is just about 14 min after the cooling water failure or just 5 min after the PSVs open. Hence, for consistency in visualizations, all the previous graphs are stopped until this point in time.

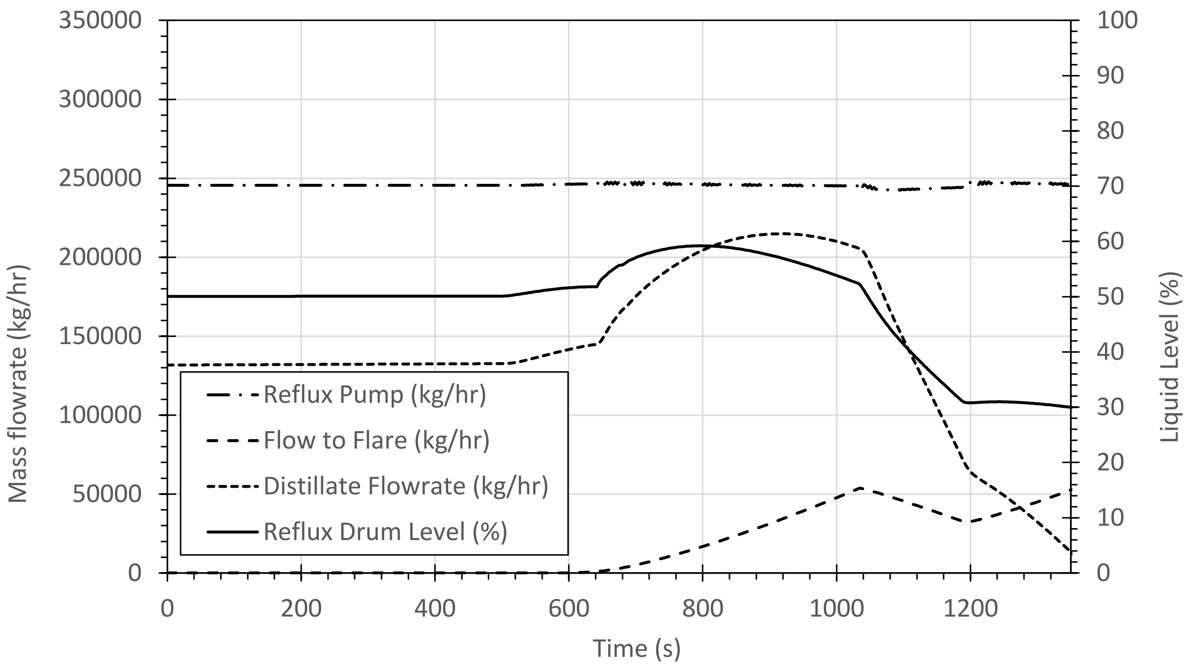

Figure 5. Column C-1 flowrates and reflux drum level during cooling water failure

As a summary of this cooling water failure case, the high-high pressure reading happens at 7 minutes, which then stops the steam reboiler, and the PSV pops up after 9 minutes of the incident. In the current safeguarding scenario, the high-high pressure alarm in the column will alert the operators. This, however, is not considered as an independent protection layer. Thus, based on the discussion with the plant people, the operating procedure will be updated that the operators will have to isolate the column within two minutes after the high-high pressure alarm.

On the reflux failure case, the reflux control valve is closed at 500 s. The pressure of the column increases only slightly (max about 0.4 bar). This is due to the big capacity (max 31.9 MW) of the fully functioning condenser (Figure 6) as well as the huge volume of the column (~ 1100 m^3). The condenser is designed to cater the maximum duty of the three reboilers. Hence, all vapor generated is fully condensed, mitigating the pressure increase. This slight increase of pressure is also visible through the slight increase of temperature throughout the column. Hence, the steam reboiler also reduces slightly as shown in the figure.

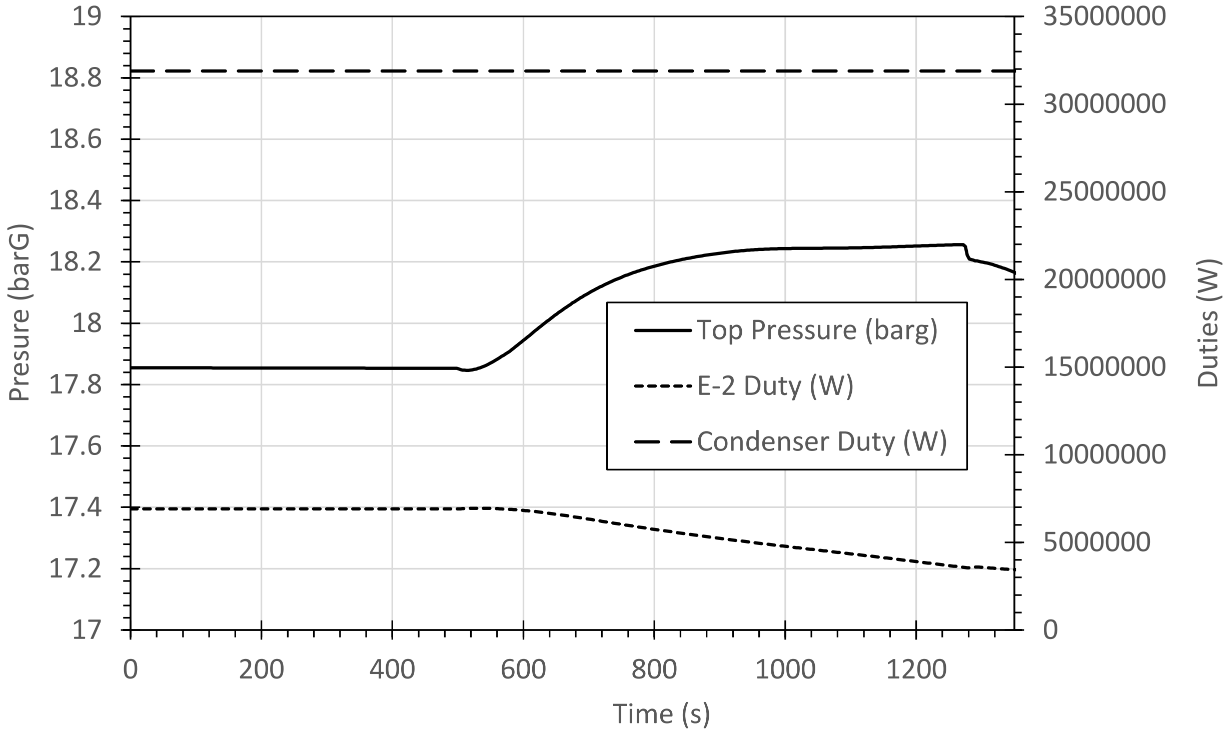

Figure 6. Column C-1 top pressure, reboiler, and condenser duty during reflux failure

From a different perspective, when the reflux flowrate is unavailable, liquid traffic in the column drops. More significant drop is seen in the enriching section for obvious reason. In the stripping part, only the liquid feed travels down the column to the reboiler. Hence, there is a lower liquid flowrate to the reboiler, which is boiling at a relatively constant boiling temperature. Consequently, a lower amount of vapor is produced from the reboiler (due to the assumption of fixed duty in the reboilers). This vapor is in contact with the liquid feed, thus reducing its capacity to pressurize the big column (~ 1100m^3). Therefore, the column pressure does not increase significantly.

In the bottom part of the column, due to lower liquid traffic, the reboiler return temperature increases until maximum temperature of 174°C (Figure 7). This is the maximum incoming temperature of the PA stream from FCC. The reboiler (E-3 and E-4) design temperature itself is 190°C. Hence, the reboiler is still within its safe design limit. The time taken to reach this maximum temperature of the reboiler is about 14 minutes, as shown in Figure 7. To have a consistent visualization throughout the graphs, all plots are stopped when the reboiler temperature reaches this 174ºC.

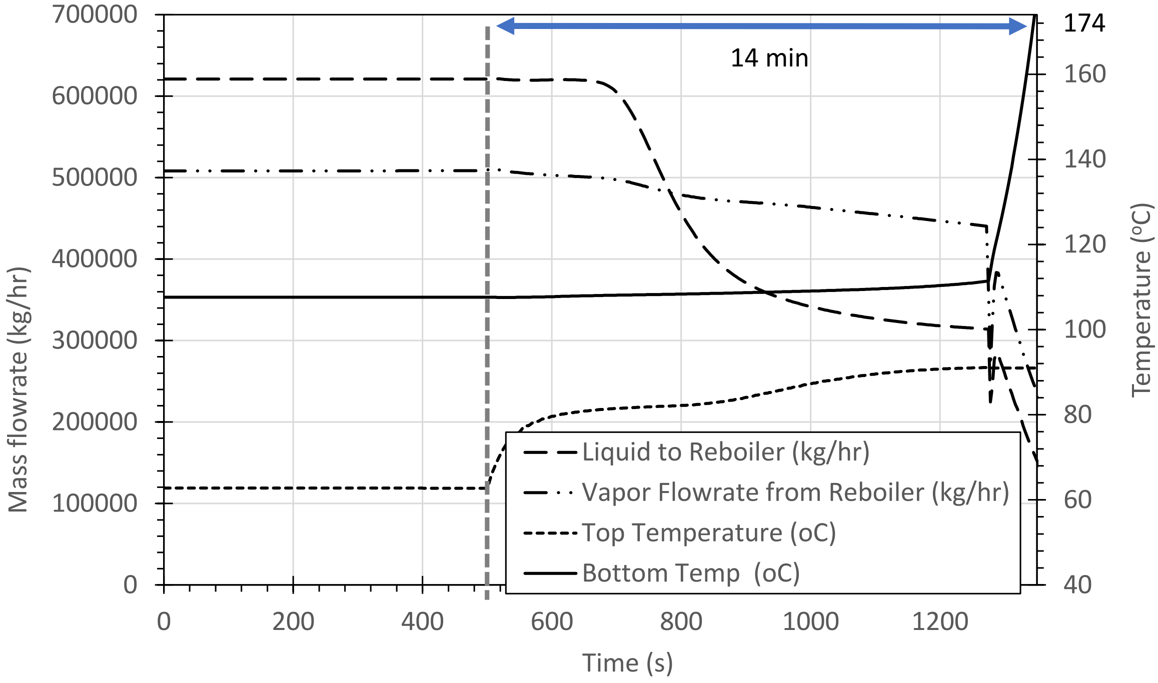

Figure 7. Column C-1 temperature and flowrates to reboiler during reflux failure

Since this slight increase of pressure is still within the operating pressure of the column (max 18.3 barg), the hot bypass valve is still fully opened since its set point is 18.3 barg in this simulation. Nonetheless, due to this slight increase in the column pressure, the valve to flare hardly opens. This is shown in Figure 8.

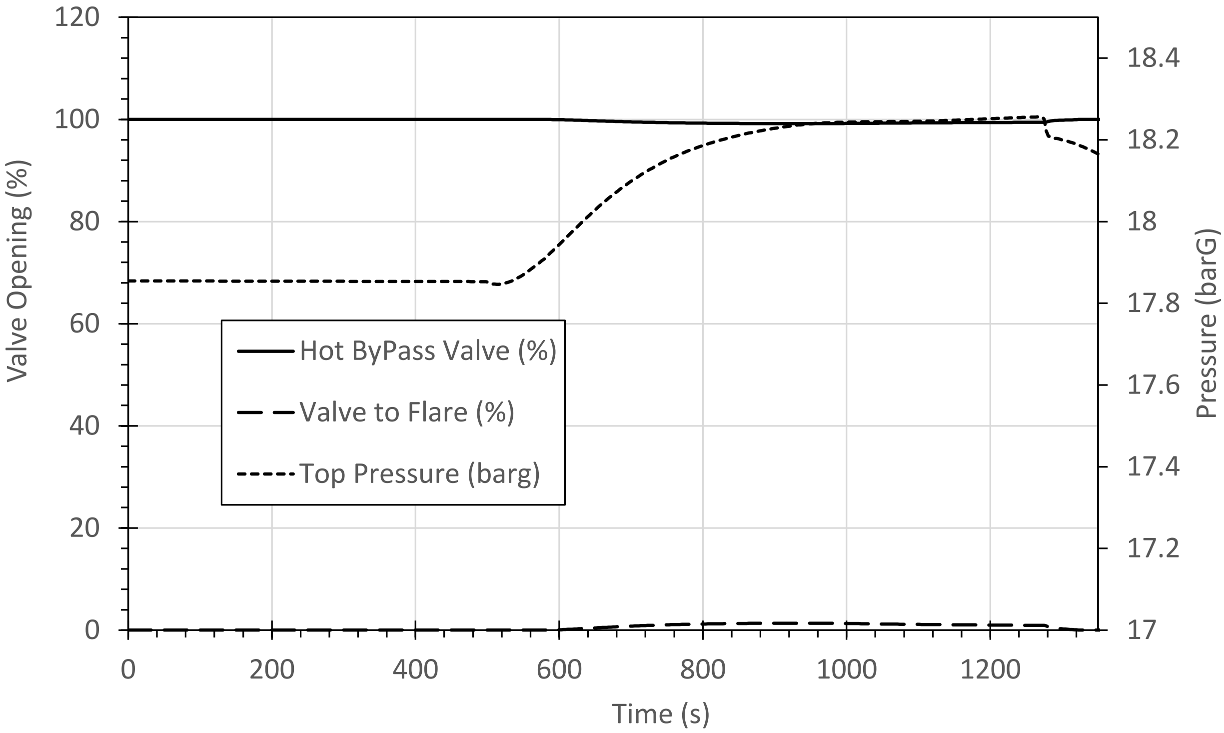

Figure 8. Hot bypass valve and valve to flare of column C-1 during reflux failure

Figure 9 shows that when the pump is off (no reflux), the liquid level in the reflux drum increases, which then increases the distillate flowrate.

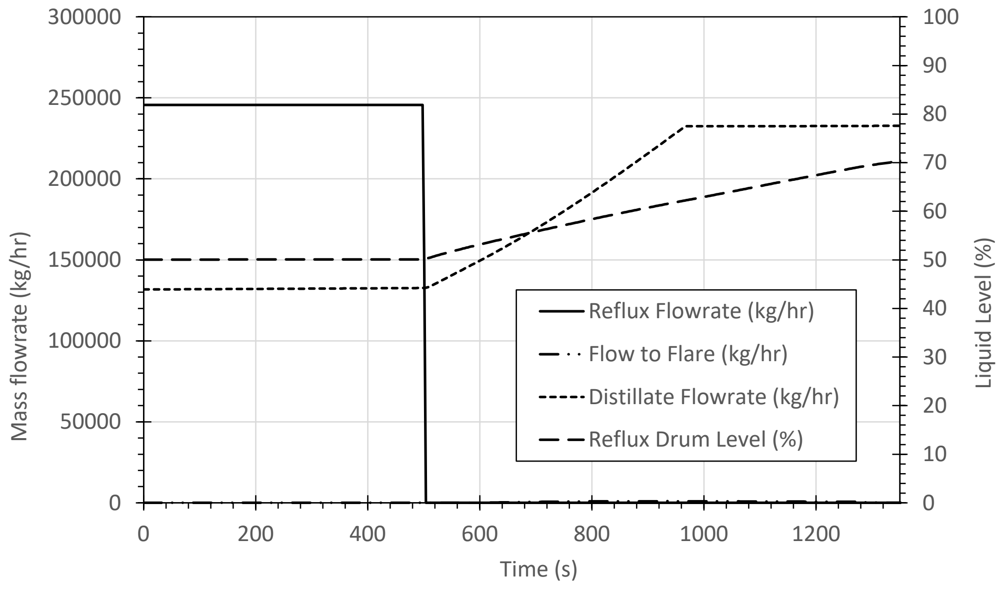

Figure 9. Column C-1 associated flowrates during reflux failure

Nevertheless, this reflux failure case does not lead to an unsafe situation where an overpressure can occur, in contrast to the cooling water failure case. The pressure only increases by about 0.4 bar and hence, all PSVs remain close. Thus, as the operating procedure has been updated in accordance with the cooling water failure scenario above, this reflux failure case is considered to be already taken care of.

Case Study 2

The same snapshot from the process flow diagram for the column C-2 is shown in Figure 10. The feed is the distillate of column C-1. It has a similar feature regarding the setup of the reboilers. Two reboilers (E-7 and E-8) are using PA streams from the upstream FCC unit, while one reboiler (E-6) is using steam. If the column pressure reaches 24.5 barg, the steam is cut off. There are three PSVs installed here, and they will open if the pressure reaches 25.3 barg. In this column, there is no liquid distillate stream other than off gas and condensed water. All liquid is sent back to the column as reflux. Its flowrate is controlled by the level of the reflux drum in cascade control.

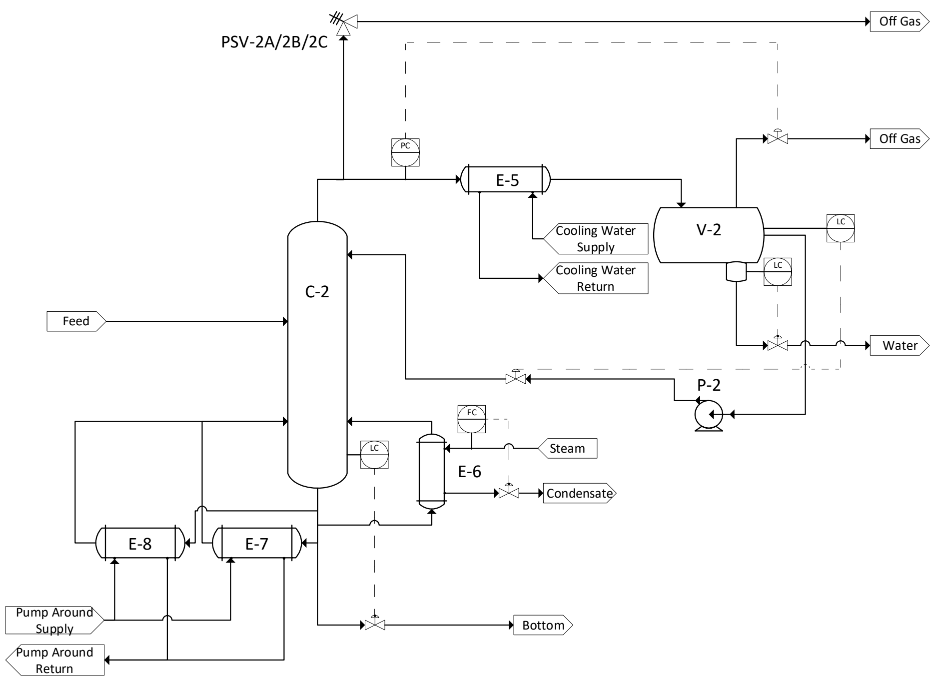

Figure 10. Simplified Process Flow Diagram for C-2

Compared to the column C-1, in this column C-2, all controllers are in cascade mode (e.g. column pressure – off gas flowrate, reflux drum level – reflux flowrate, column bottom level – bottom flowrate). There is no controller around the condenser (E-5) as well, like in column C-1.

In the case of column C-2 cooling water failure event, when the cooling water fails at 500 s, the uncondensed vapor enters the reflux drum, and thus pressurizes the column (shown in Figure 11). Top pressure increases until it reaches the setpoint of 24.5barg, then the steam reboiler E-6 is cut off (in less than 4 minutes). The pressure keeps increasing since the Pump Around reboilers (PA) E-7 and E-8 are still supplying energy. All three PSV (PSV-2A/2B/2C) set point is reached (25.3 barg) and subsequently the valves open after about 5 minutes. See both Figure 11 and Figure 12.

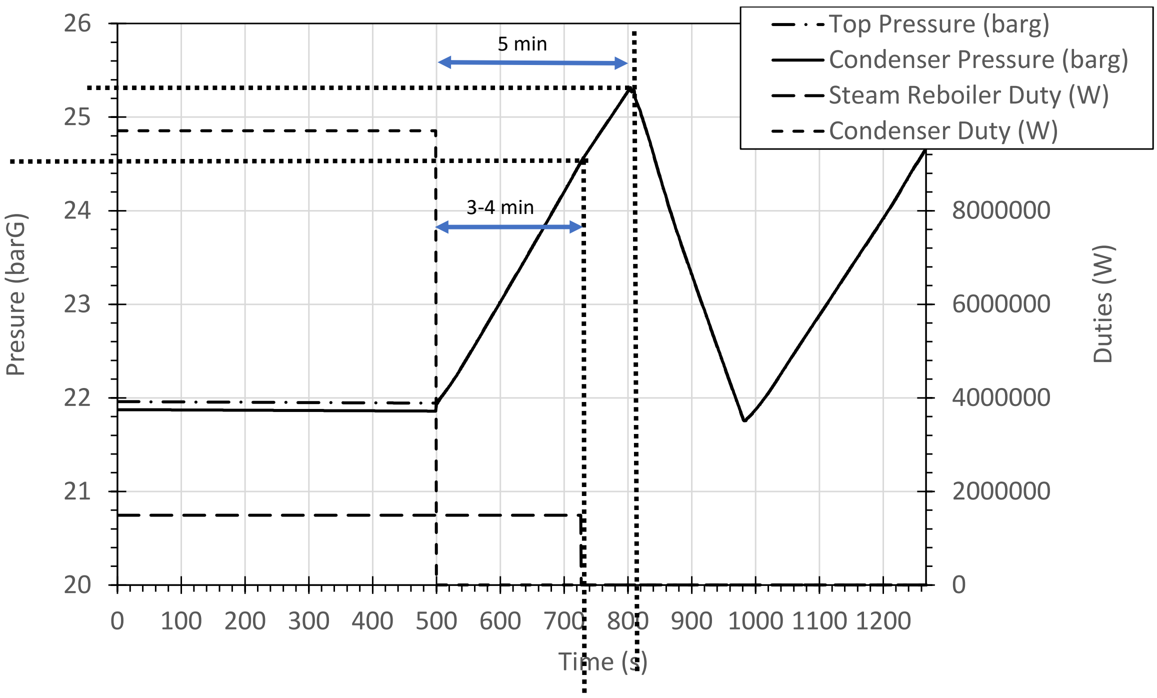

Figure 11. Column C-2 pressure and duties during cooling water failure

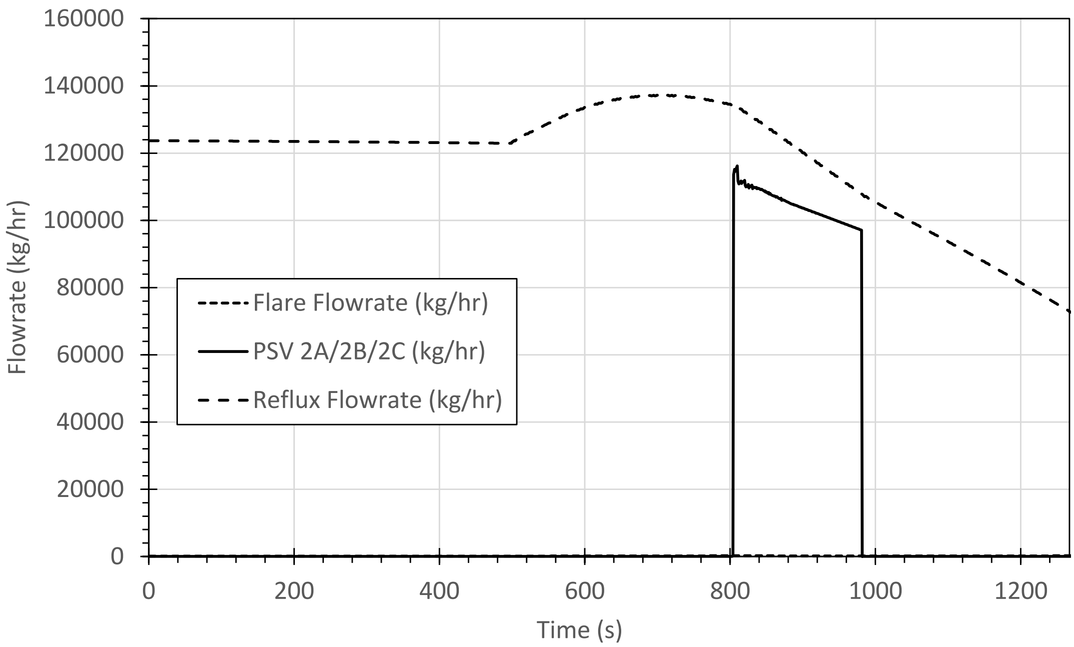

Figure 12. Flowrate of Column C-2 during cooling water failure

This available time for operators to respond for column C-2 is almost half of that for column C-1. This could be due to the presence of vapor (7-8%) in the feed and the reflux flowrate is controlled by the level in the reflux drum (V-2). This additional vapor from the feed and the reducing reflux flowrate, pressurizing the column C-2 faster.

When the reflux drum reaches 30%, (the limit for the pump safety switch low low), the reflux pump is stopped (See short-dotted line in Figure 13).

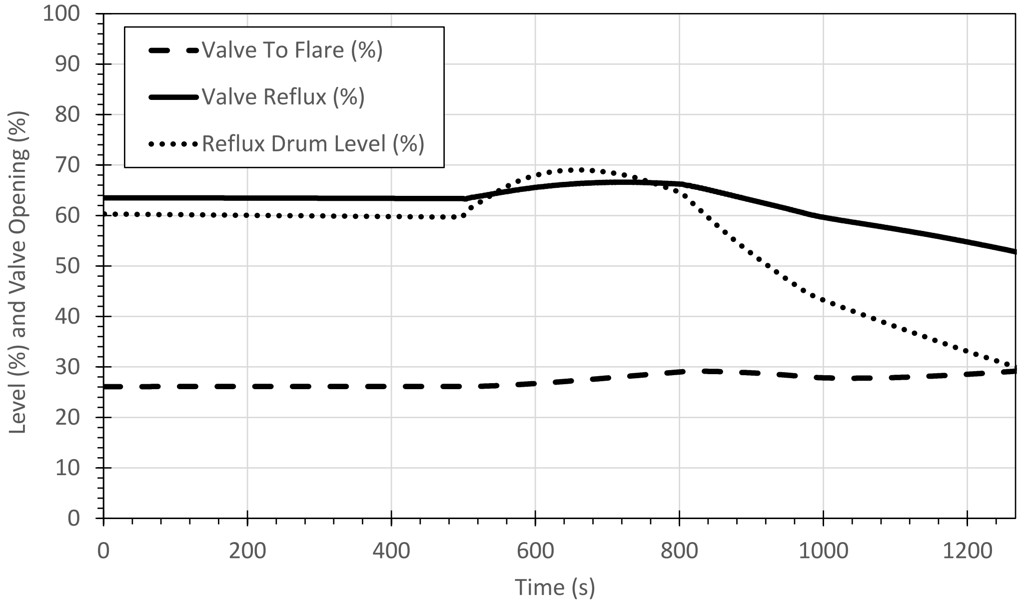

Figure 13. Column C-2 valves and reflux drum level during cooling water failure

For this cooling water failure case of this Column C-2, the high-high pressure alarm happens at 3-4 minutes, which then stops the steam reboiler, and the PSV pops up about 1 minute after this alarm. Based on the discussion with the plant people, the operating procedure for this column will also be updated that the operators will have to isolate the column within one minute after the high-high pressure alarm. The fact that the PSVs have been designed to cater for this relief adds to the argument that no further protection layer nor additional operators' response is necessary.

In the reflux failure case for the column C-2, reflux flowrate is stopped due to control valve failure at t=500 s, leading to the increase in the pressure of the column (see Figure 14 and solid line in Figure 15). Condenser is still operating (normal duty 9.7 MW) and it condenses vapor that comes in.

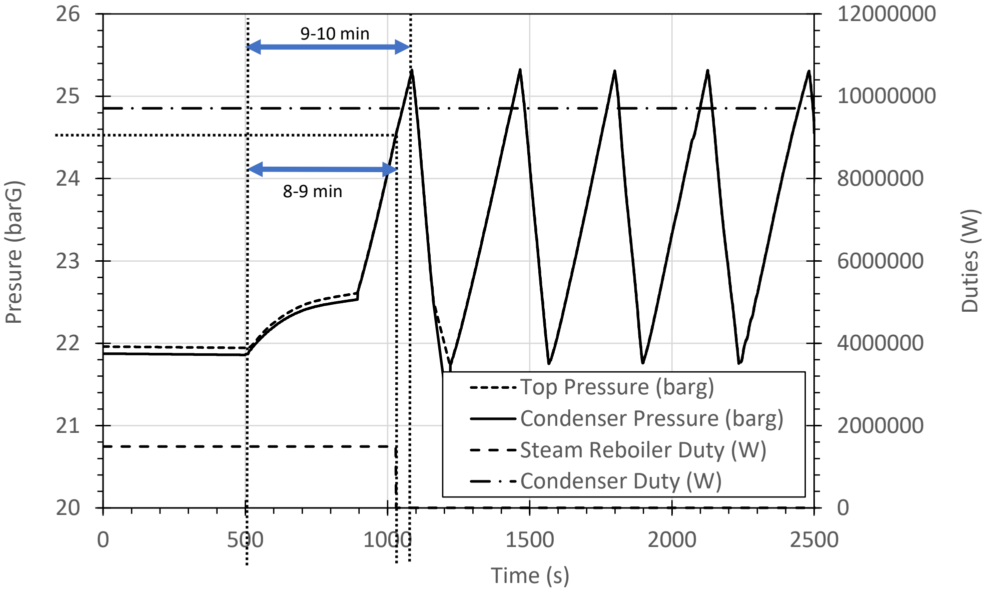

Figure 14. Column C-2 pressure, reboiler, and condenser duties during reflux failure

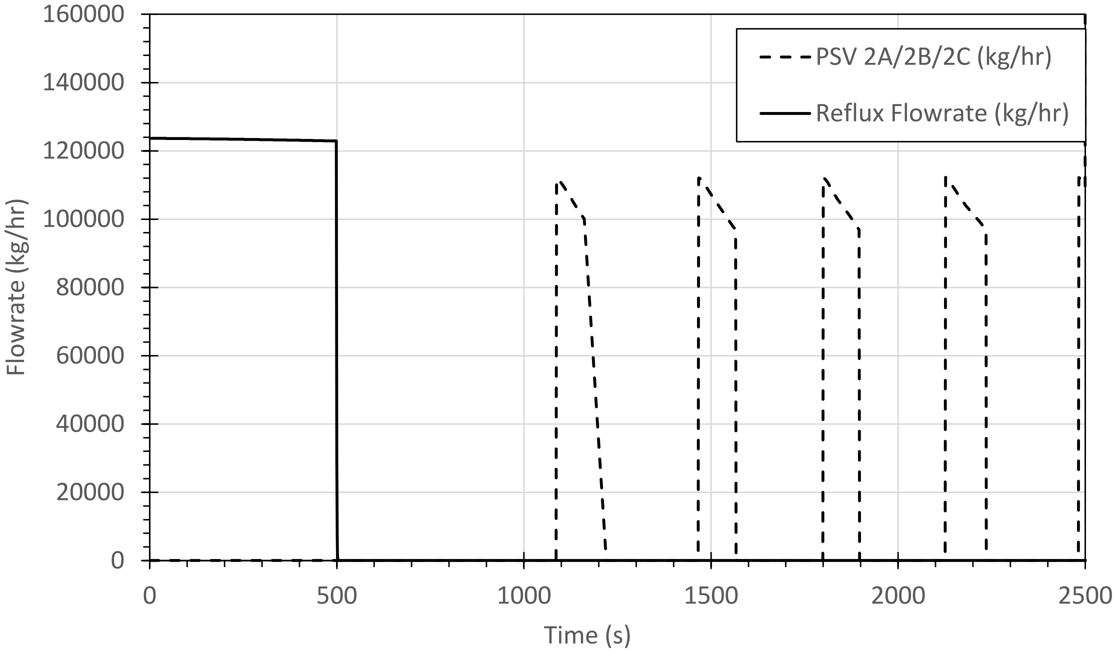

Figure 15. Flowrates of column C-2 during reflux failure

Due to the valve closure and the continuous condensed liquid coming in, the liquid level in the reflux drum increases (Figure 16). The pressure of the column reaches somewhat slowly. When the reflux drum level reaches 100%, the column pressure increases drastically (Figure 14). Due to this rapid pressure increase, the steam reboiler is shut off at 8-9 min after the reflux fails. The PSVs finally open after just 1 min after the steam reboiler is shut off.

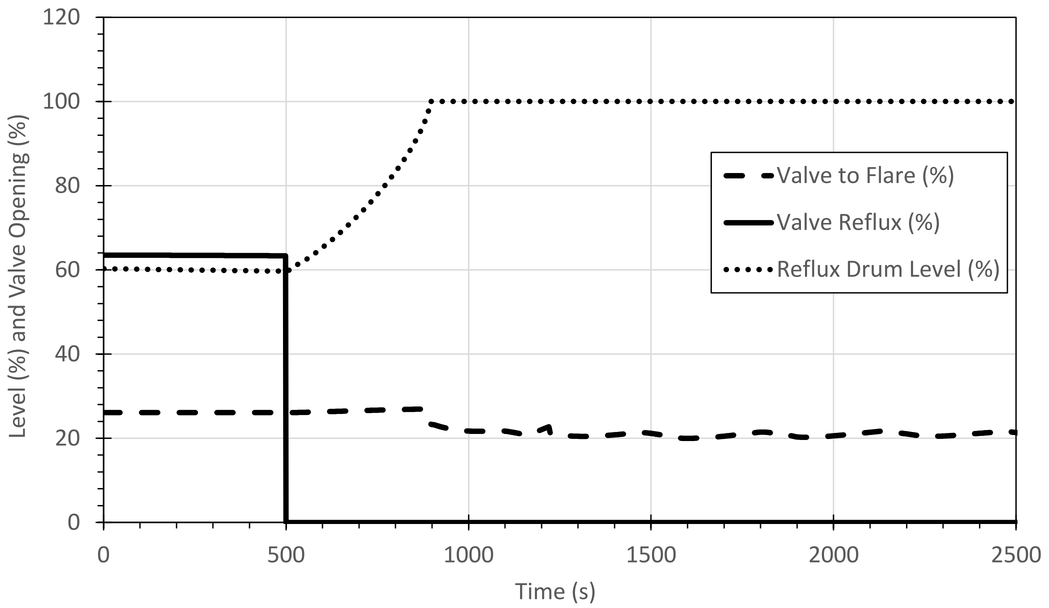

Figure 16. Valves and reflux drum level for column C-2 during reflux failure

In this reflux failure case of column C-2, the pressure of the column increases significantly to reach the set point of the PSVs compared to that of column C-1. The PSVs open at about 9-10 minutes. Nonetheless, this scenario is less severe compared to the cooling water failure case. However, the available timing is very similar to the cooling water scenario of Column C-1. Hence, the same update of the operating procedure for this column is also implemented.

Case Study 3

When the simulation of column C-1 was left running for some time, due to their same set pressures and continuous feed and energy from upstream, all five PSVs open and close repetitively (see Figure 17). This phenomenon is known as chattering which can damage the PSVs.

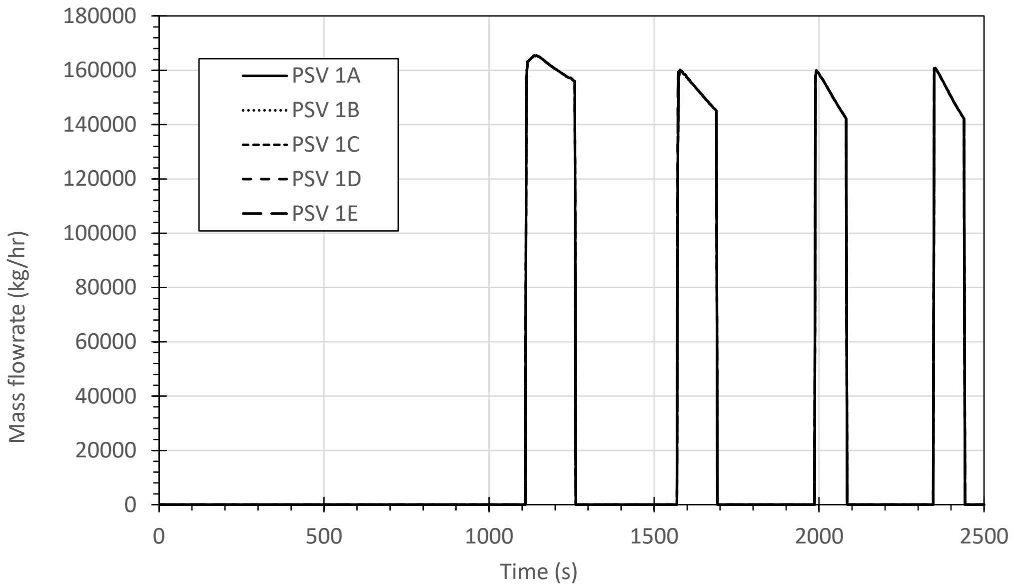

Figure 17. Cyclic PSV openings for the base-case

To reduce the possibility of chattering, different (staggered) set pressures need to be applied to the PSVs [14]. Table 1 shows the base-case set pressures and two other options where some of the PSVs are set at a lower pressure. Option 1 consists of one PSV set at 97%, three at 100%, and one at 10%. Option 2 uses two PSVs set at 97% and the remaining three stays at 100%.

Table 1. Variation of PSV set points (barg)

PSV No	Base-case	Option 1	Option 2
PSV 1A	21.3	20.7	20.7
PSV 1B	21.3	21.3	20.7
PSV 1C	21.3	21.3	21.3
PSV 1D	21.3	21.3	21.3
PSV 1E	21.3	22.4	21.3

Figure 18 shows the results of applying the two set options on the pressure profile of the column. In this analysis, the worst-case scenario which is the cooling water failure is used. It can be seen that the pressure profile of the basecase fluctuates a lot. Option 1 with one PSV opens at 97% does not seem to be able to reduce the column pressure completely. The pressure still goes up until it reaches the 100% set pressure where three PSVs open simultaneously and manage to quickly reduce the pressure. On the other hand, Option 2 with two PSVs open at 97% is able to reduce the set pressure and bring it to the original value and when these two closes, the pressure rises again. And the cycle continues, but it is much less frequent than the base-case.

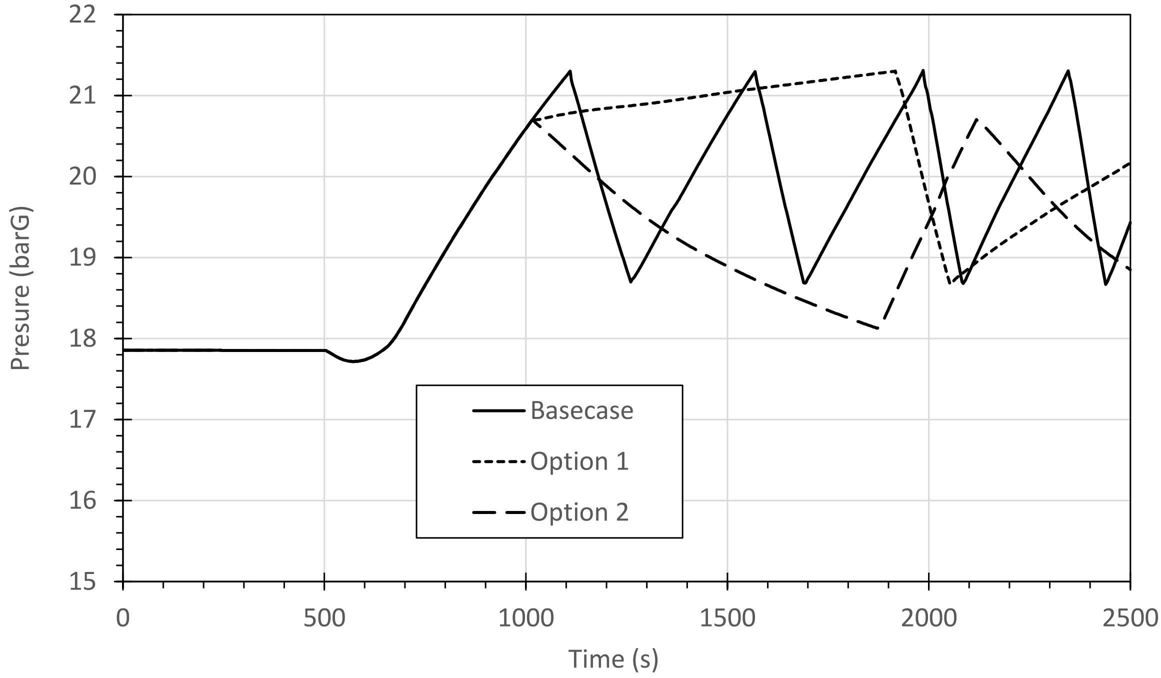

Figure 18. Top pressure of the column (barg) for various PSV set points

From this analysis, the last PSV does not seem to be necessary as the pressure can be safely maintained below the set pressure. Hence, it can be concluded that in fact four PSVs are sufficient for this column C-1. For Option 2, two PSVs are in fact sufficient to release the pressure buildup due to the worst-case scenario. Figure 19 and Figure 20 show the movement of the PSVs for Option 1 and Option 2, respectively.

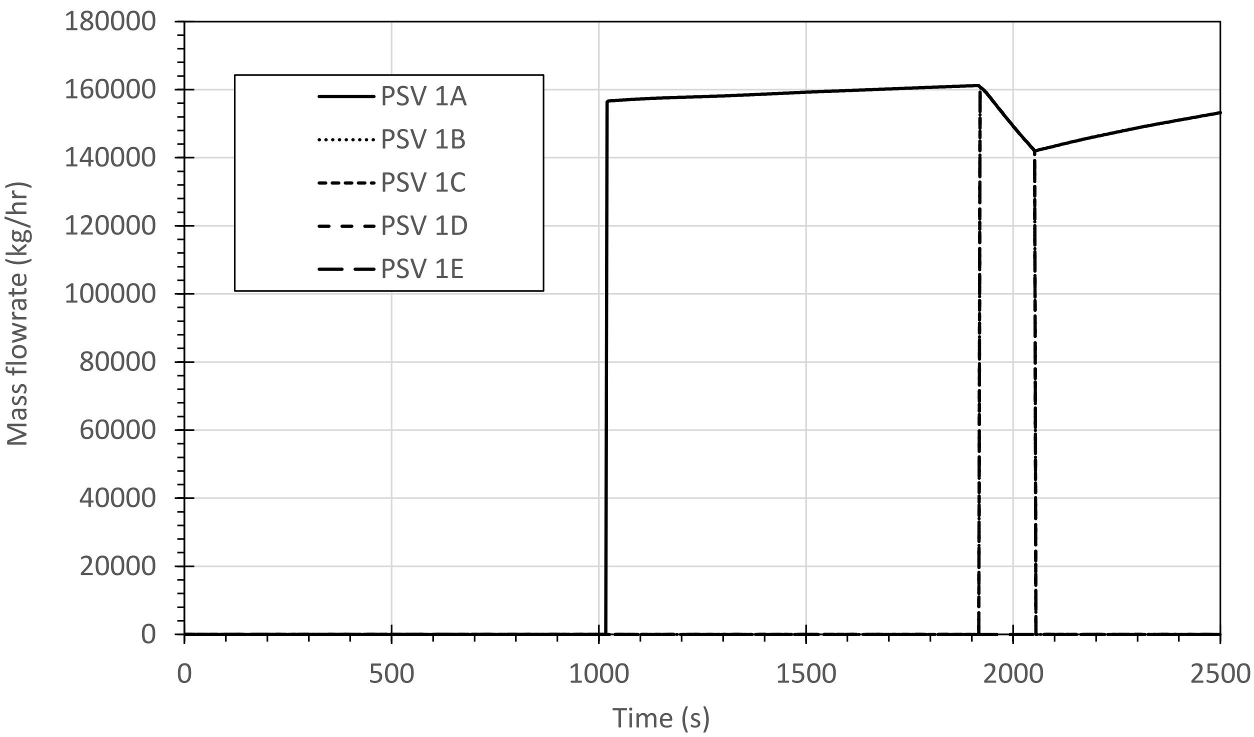

Figure 19. PSV openings for Option 1

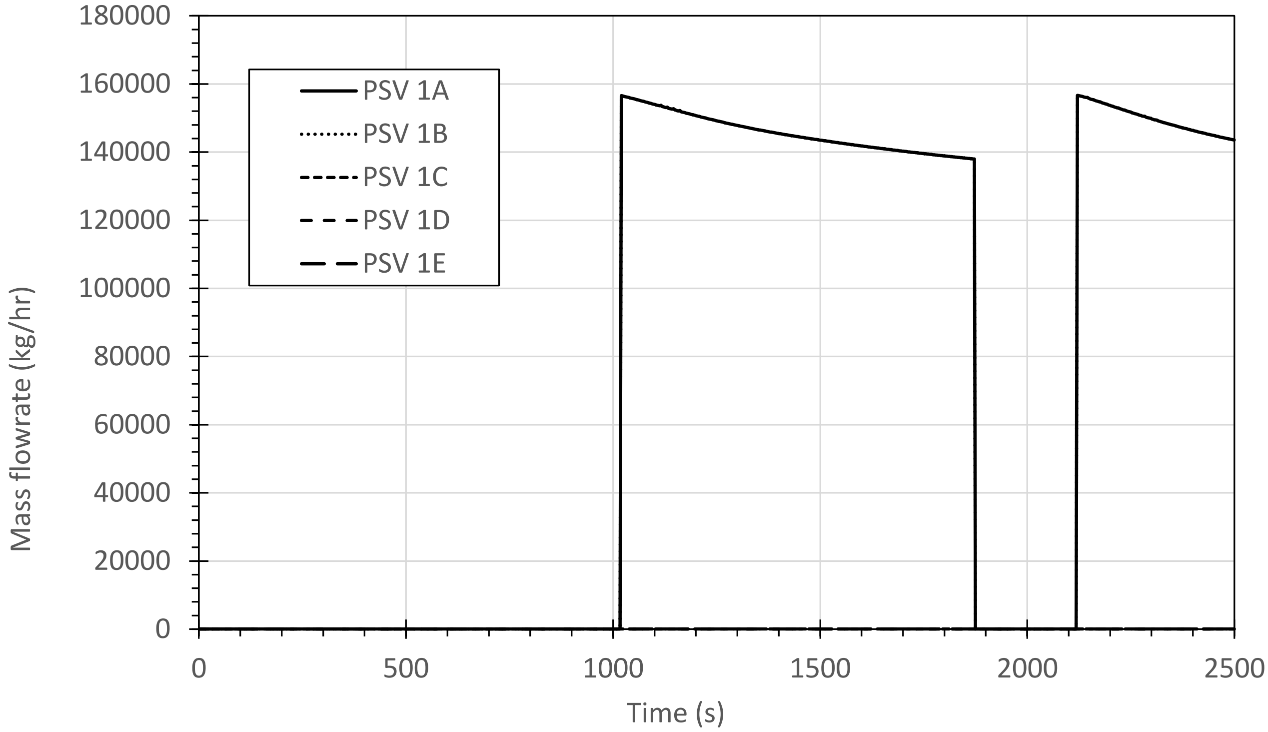

Figure 20. PSV openings for Option 2

Conclusion

Dynamic simulation models have been successfully utilized to evaluate two overpressure scenarios, namely cooling water and reflux failures, in two distillation columns. In the first column C-1, the cooling water failure event leads to high-high pressure alarm in about 7 min, which then closes the steam reboiler, and then followed by the opening of its five PSVs at the same time at about 2 min afterwards. Liquid level in the reflux drum drops quickly due to its fixed flow control setup and the reflux pump is shut off about 14 min after the cooling water fails. Reflux failure case of column C-1 does not lead to an unsafe situation where an overpressure can occur. The pressure only increases by about 0.4 bar and hence, all PSVs remain close. This is mainly attributed to the huge capacity of the condenser and the volume of the column itself. In this event, the temperature of the reboilers reach maximum temperature of the PA stream at about 14 min, while still being under the safe design limit of the reboiler.

In the cooling water failure event of Column C-2, the high-high pressure alarm that closes the steam reboiler happens at about 3-4 min, while its three PSVs open within about 2 min afterwards. Its more rapid overpressure situation is caused by the reduced reflux flowrate (level-controlled) as well as the presence of vapor fraction in the feed. The reflux pump is shut off at about 14 min after the cooling water fails when the level reaches 30% low-low limit. Reflux failure case of column C-2 is less severe compared to its cooling water failure. Nonetheless, the pressure of the column does increases significantly and the PSVs open at about 9-10 minutes. In all cases, it is seen that the PSVs have been sized adequately to cater for the cooling water failure as the worst-case scenario, as recorded as well in the document of relief size load calculations.

Additionally, through varying set pressures of the parallel PSVs, it can be seen that a reduced number of PSVs is sufficient to cater the worst-case overpressure scenario. The current operating procedure is updated to make sure that the operators push the isolation switch buttons for both columns shortly after the corresponding high-high pressure alarm triggers them.

Acknowledgements

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