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SURGE MITIGATION IN A MARINE FUEL OIL TERMINAL

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ABSTRACT

Surge modeling of complex systems such as marine fuel oil terminals requires the use of accurate computer modeling techniques to help insure the best possible response to surge events. Various surge mitigation techniques can be pursued that often require information that manufactures rarely provide and have behavior that is problematic to replicate in a computer model. This paper provides guidance with one such device, the surge relief valve, and offers a case study in how they were used in conjunction with valve stroking to mitigate significant surge events at a terminal in the gulf coast region of the United States.

ABBREVIATIONS

MASP	Maximum Allowable Surge Pressure
SRV	Surge Relief Valve

1 INTRODUCTION

Transient modeling and analysis of hydraulic surges at marine terminals is one of the most important tasks to be completed when considering original construction, operational changes, or expansions to a terminal site. The potential damage from failure is high and the complex piping networks and specialty equipment used at these sites makes a detailed computer simulation necessary to capture how the system will likely respond to a transient event.

The marine terminal considered in this paper is in the gulf coast region of the United States and can import and export fuel oil from multiple connected pipelines or multiple ship docks. This ability to send and receive allows for more economic flexibility as production rates and prices vary globally but creates many complications for the engineer concerned with surge mitigation. For example, surge valve setpoints used for importing may not be appropriate for exporting as the pressure at the valve location will almost certainly be different upon a flow reversal. Other surge mitigation equipment sized for a specific case has the potential to cause a worse surge response if they are active during an unanticipated surge event for which they were not designed.

The marine terminal must be considered on a whole and one surge mitigation strategy for one situation may not be appropriate for the next. Often a strategy may work well, but can require the purchase, installation, and maintenance of costly and complex equipment. This paper considers a compromise between an increase in the amount of surge mitigation equipment, especially nitrogen backed surge relief valves, and the use of a dual rate closure similar to the valve stroking method from Swaffield and Boldy (1).

2 MODELING SURGE RELIEF VALVES

Modern surge relief valves (SRV) are complex pieces of engineering and it is important to accurately depict their dynamic behavior when incorporating them into a computer model of a hydraulic system. The required information that is needed to incorporate a surge relief valve into a computer simulation is:

1. Set Pressure – what triggers the valve to open? Typically, this is a high pressure that is 50 to 75% above line pressure.

2. Overpressure – the upstream pressure when the valve is just fully open

3. Blowdown pressure – the upstream pressure when the valve reseats itself. This is often the same as set pressure for conventional spring-loaded relief valves, but specialized SRVs with an isolated nitrogen plug cavity and varying exposed areas when open and closed, can result in the valve reseating at lower pressure than opening pressure. This is often referred to as overbalance.

   This can assist in preventing valve slam and secondary surge waves but is not a guarantee especially in complex systems where system interaction can result in rapid pressure changes that could result in lower pressure waves that force the valve to slam rapidly.

   This can be varied by the valve manufacture as it is a function of geometry and various sizes and area ratios can be purchased. By choosing the proper size and area ratio the SRV's pressure range when it is open can be controlled to a specified operating window. This is especially important for pipelines operating at high pressures near the maximum allowable surge pressure (MASP) and the valve may need to reseat at a higher pressure to prevent continuous flow through the SRV.

4. Opening rates – often this is very fast, on the order of 1 ms to 1000 ms, depending on valve size and differential pressure.

5. Closure rates – this is one of the more important, but harder to obtain pieces of information. Some nitrogen backed SRVs will have devices such as orifices and check valves that can be sized to control flow back into the nitrogen cavity behind the valve plug and slow the rate at which the valve re-seats, but others have no control devices and the pressure maintained in the plug cavity is nearly constant. This indicates that the valve would track the surge pressure and respond directly to pressure decay at the valve inlet. In other words, if a low pressure surge reaches the inlet of the open SRV and rapidly lowers pressure below blowdown pressure the SRV may slam and cause a secondary pressure wave near the magnitude of a Joukowski pressure spike if the closure rate on this newly established flow path is not controlled (2).

6. Flow Coefficient (Kv) – SRVs typically have a lower flow coefficient than other similarly sized valves and there are significant differences between manufactures. Be sure to know this as the valves resistance to flow will be a large factor in how effectively it can relief excess pressure. Oversized SRVs may relieve more pressure than required and are more prone to valve chatter.

7. Length and size of piping to and at the SRV skid – pipe period between the source of a pressure surge and the SRV directly impacts how effectively it will mitigate a pressure surge. Also, if the piping is incorrectly sized or too long, there may be too much resistance in the system to effectively redirect excess flow and pressure through the SRV.

8. Collection tank size, surface pressure, and fluid (liquid, gas, air) – These factors need to be accounted for to determine any additional resistance is provided by the tank surface pressure or hydrostatic pressure. This is also required to determine if the tank is large enough to maintain containment of the relieved fluid. If the tank is of the bladder style the amount of gas or precharge pressure will need to be known.

The marine terminal, including the SRVs, was incorporated into a computer simulation using a commercially available software product for surge analysis, AFT Impulse™ (3). It is important for the engineer to understand the software they are using and the specific behavior of the valves they are modeling. Below is a description of how the SRVs for this specific case were modeled after discussion with both the valve manufacture and the developers of the surge analysis software. This description is not intended to be used on all valves or all surge analysis software. The responsibility is on each engineer to understand the software they are using and the equipment they are modeling.

A specific set of three SRVs on a single skid in the marine terminal was modeled with the following properties:

1. Set Pressure – 928 kPa
2. Overpressure – 150% of set pressure or 1342 kPa
3. Blowdown pressure – 80% of set pressure due to overbalance or 763 kPa
4. Opening rate – there was no limit placed on opening rate
5. Closing rate – the valve closure rate was controlled to take at least 20 seconds to close from full open to full closed
6. Flow Coefficient – 3630 Kv
7. Length and size of piping to and at the SRV skid – varied for each SRV skid considered.

Note: All pressures throughout this paper are absolute and not reference to gage or atmospheric pressure.

In Figure 1 below the valve flow coefficient vs. inlet pressure can be seen. The valve will open once the set pressure is reached. The valve flow coefficient will then follow the Valve Kv curve as the pressure varies at the inlet of the valve. If the pressure reaches over pressure, the valve cannot open further and maintains the full open Kv until pressure drops below over pressure. As the pressure at the inlet of the SRV decays the valve will begin to close. If the pressure decays rapidly the valve could slam shut and cause a secondary pressure surge. The SRVs modeled considered a controlled closure rate that would prevent any closure rate of change faster than it would take the valve to close from full open to full closed in 20 seconds. In other words, the SRV was not allowed to close faster than 181.5

Kv per second. This resulted in a smoother and consistent relief response at the SRV. It is important to discuss this with the valve manufacturer before implementing this as a surge mitigation method. Be sure the valve will respond as modeled. If there is nothing to control the closure rate the likelihood of valve-slam is high and should be considered a risk.

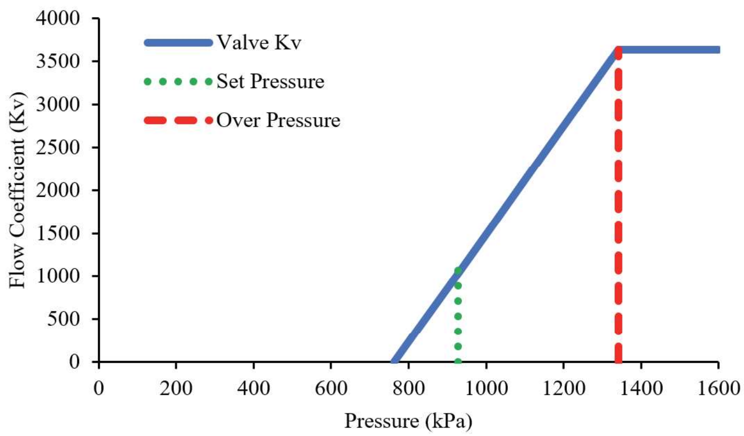

Figure 1: SRV flow coefficient vs. pressure

3 POTENTIAL MITIGATION METHODS

Several surge mitigation methods should be considered before selecting the appropriate one. All surge mitigation is based on one of two concepts: direct action or diversionary tactics. Direct action attempts to "contain increases in pressure within the system and to influence the behavior of the causes of the flow changes, such as valve or pump operations" (4). Diversionary tactics are "based on the concept of releasing surplus energy from the system or drawing needed energy into it" (4).

The simplest method of direct action for surge mitigation is to simply lower the steady fluid velocity. This can be done by either operating at a lower flow rate or increasing the diameter of the piping. Both options are often uneconomical for existing systems. Replacing already installed piping with larger diameter piping is a significant task and lowering flow rates can lead to costly delays and a lower overall turnaround of product.

Conventional spring-loaded relief valves were also considered as a diversionary tactic for this analysis. Depending on the source of a pressure surge and the system's response to a pressure drop when the valve opens, these relief valves can be a valid option. The marine terminal would not have been an ideal location for the valves given the relatively short runs of piping and many dead ends (the effect of dead ends needs to be considered during a transient analysis as they can be a source of large pressure spikes and drops as they behave as reflection points to pressure surges). The short runs and dead ends in the terminal indicated that the pressure response of the system would be quite complex with potential for sudden drops and spikes in pressure. If a sudden drop in pressure reaches a conventional spring-loaded relief valve it will likely slam closed and result in a secondary surge event caused by the sudden closure of the valve. This sudden closure can result in a surge larger than the original surge event's pressure.

Specially designed surge relief valves are another option that allow excessive pressure to be relieved by allowing high pressures to open an alternate flow path before an unacceptable critical pressure is reached. These devices can be always active and act as a last line of defense when all other flow paths are closed. They must be properly located and sized to be effective. They are also expensive pieces of equipment that often come in multiple sets on a skid and require a collection tank to gather the relieved fluid. The strategic placement throughout a system such as a marine terminal requires a detailed computer analysis that can consider all the cases and make a prediction of their behavior before they are installed. This option was selected, and multiple sites were sized and considered. The inclusion of five additional SRV skids was eliminated using the final surge mitigation method: a controlled valve actuation that allowed for a specific dual rate valve closure.

Another direct action that is often undertaken is the lengthening of valve closure times. This can be quite effective for specific systems and valves. For this solution to work the *effective closure time* of a valve must be longer than the pipe period or 2L/c, where L is length and c is wavespeed. Effective closure time depends on the valve's ability to control flow. For this paper, a valve is in its effective closure range once it has reduced total pipeline flow by over 1%. If the valve is significantly oversized or has minimal pressure drop the pipeline's fluid velocity will remain high until the valve is almost closed. If there is little change in flow because of the closing valve it can result in pressure spikes near the Joukowski pressure can occur even if the valve closure is longer than pipe period. This situation occurs if the effective closure time is shorter than pipe period and could be considered a 'rapid event' as described in Thorley (4). Often, effective closure times must be several times longer than pipe period to keep surge pressures within an acceptable level. Short effective closure times are especially true of low resistance valves such as gate valves that have high flow coefficient values and a steep flow coefficient change over time as they approach full closure. If a valve's resistance over a range of opening percentages has a significant effect on flow it will have a longer effective closure time and extending this valve's closure time will result in a lower surge response.

Dual rate or two stage closures for valve stroking are not a new idea to the pipeline industry as mentioned by Swaffield and Boldy in 1993 (1). The dual rate closure allows for the rapid closure of a valve through its non-effective closure range and extends the effective closure range. These ranges vary for each system and each valve, but a simple test run of a standard valve closure in a computer simulation can show when a perceptible amount of flow change occurs at the inlet of a valve. The amount of time it takes to reach the start of a valve's effective closure is inconsequential to system response; the only closure percentages that can effectively be extended occur after some perceptible amount of flow change occurs at the valve. Extending this effective closure time greater than pipe period will result in a lower pressure response lower than Joukowski pressure. It may be required to extend this several times greater than pipe period to maintain pressures within an acceptable range. This all greatly depends on operating velocities, the fluid in question, and the piping and equipment pressure ratings.

Typically, a Swaffield and Boldy closure profile considers an 80% reduction from full open flow coefficient in the first 20% of closure time. The final 20% of closure is then drawn out over the last 80% of closure time (1). This creates a longer amount of time the valve can effectively reduce the flow throughout the system and allows the momentum of the fluid to be slowly dissipated before the fluid is halted completely by a full closure of the valve. A hypothetical Swaffield and Boldy closure profile based on a valve in the marine terminal can be seen in figure 2 below. A standard closure profile for a 750 mm gate valve closing due to linear actuation of the valve stem over 75 seconds can also be seen. The final curve, or what was referred to as a dual rate closure during the analysis, shows the closure of the same gate valve, but fitted with a variably controlled actuator. The actuator would allow the valve to close following the standard closure but would begin to follow the Swaffield and Boldy curve once the two curves intercepted. This was a compromise to allow for a more realistic closure profile to be considered in the analysis as the valve would have to be closed faster than it could be actuated to initially follow the Swaffield and Boldy profile. However, the controlled actuation and extension of the final percentages of closure was obtainable.

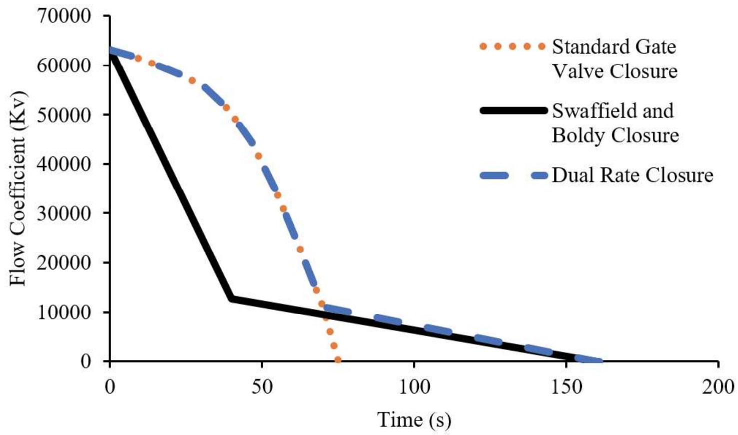

Figure 2: 750 mm gate valve closure profiles

4 THE MARINE FUEL OIL TERMINAL

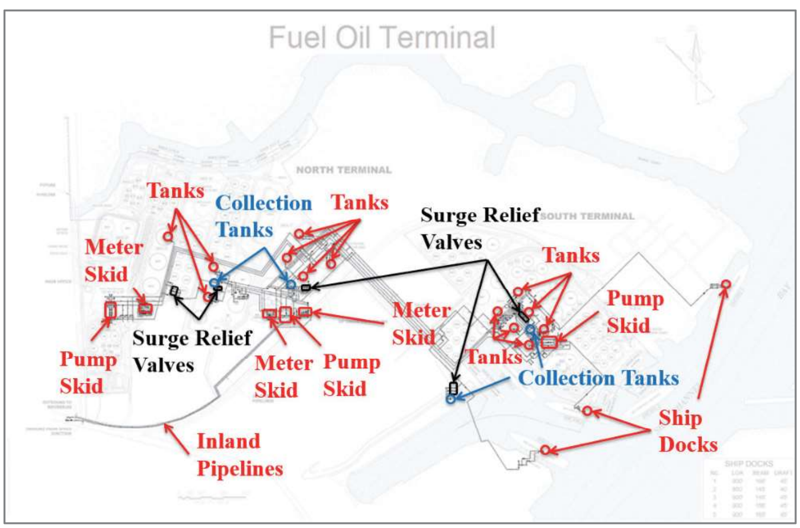

Figure 3: Gulf coast marine fuel oil terminal

Figure 3 above shows an overview of the terminal. It contains approximately 65 kilometers of piping in a few square kilometers of land. Within the terminal there are many storage tanks, meter skids, pumping stations, inland distribution pipelines, and ship docks. The terminal allows for the transfer and storage of various fuel oils. The terminal can transfer fluids from ship to shore, shore to ship, inland pipeline to shore, and shore to inland pipeline.

Creating a computer model that incorporates all significant piping, valving, pumping stations, and metering stations was a substantial undertaking. The final model consisted of approximately 800 unique piping elements and 700 component elements (valves, pumps, tees, flow meters, etc.). The other aspect of model building that occurred was the creation of over 100 unique operating cases that considered flow from each major tank area to each ship dock or pipeline and vice versa. Variations in flow rate, fluid composition, and surge mitigation methods were also included. A single flow scenario would consider a run of piping between 1,500 meters and 15,000 meters, a single valve movement with a specific closure profile, and determining if an SRV skid that would relieve pressure to a downstream collection tank filled with air at atmospheric pressure was required to maintain surge pressures within an acceptable range. Approximately 1/3rd of a meter of water is maintained in the collection tanks to keep the valves wet and prevent potential multi-phase flow complications.

5 HIGHLIGHTED CASES

Over 100 unique cases were considered as part comprehensive surge analysis of a marine terminal in the gulf coast region, and four of these cases are considered below. The cases have the following aspects in common:

1. Flow path from a tank, through a pumping skid, through a metering skid, through two parallel 600 mm lines, through a 900 mm mainline, a 750 mm gate valve, and a delivery point at a docked tanker. (Figure 4)
    a. All pipe is carbon steel with typical wavespeeds in the mainline of 1100 – 1200 m/s
2. A flow length of approximately 3,750 meters.
3. Crude oil with the following fluid properties:
    a. Specific gravity: 0.93
    b. Dynamic viscosity: 54 cP
    c. Bulk modulus 200,000 kPa
    d. Vapor pressure: 58.6 kPa
4. An initial flow rate of 1.312 m^3/s

The four cases have the following attributes that differentiate between them:

1. Case 1 - A standard 75 second valve closure with an SRV skid on the line
2. Case 2 - A dual rate 160 second valve closure with no SRV skid on the line
3. Case 3 - A dual rate 160 second valve closure with an SRV skid on the line
4. Case 4- A dual rate 160 second valve closure with an SRV skid on the line with no closure rates

A typical case that is often analyzed in marine terminals is an instaneous valve closure due to ship movement or other issues with blocked or ruptured hose on the ship. It is recommended that these types of cases be considered, but the scope of this study and paper only considered valve movements within the terminal.

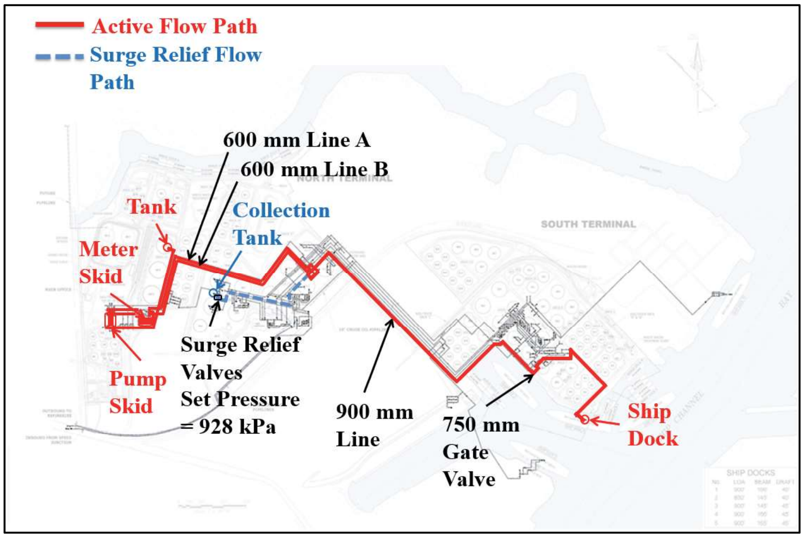

Figure 4: Active flow path and surge relief path for cases 1, 2, 3, and 4

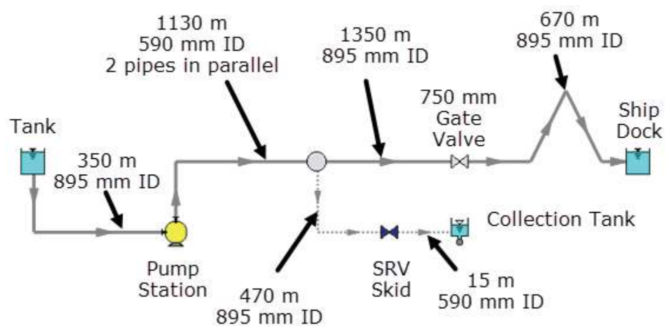

Figure 5: Simplified model view of flow path and relief line

The SRV skid had three 300 mm nitrogen backed pressure relief valves defined to behave as defined in section 2 above. The surge relief flow path consisted of primarily 900 mm piping and was approximately 470 meters long. Immediately downstream of the SRV skid was a collection tank that would accept the excess fluid discharged from the SRV's.

The four cases all shared a same steady-state operating pressure as the initial flow path and conditions were identical between them. However, they all demonstrate very different maximum pressures along the flow path (Figure 6). This is primarily a result of the standard closure being considered a rapid event. A rapid event can be defined as any transient event that occurs in a shorter amount of time than the pipe period (4). Pipe period can be defined as:

$$t_p = 2L/c$$

where:

t_p = pipe period
L = length of pipeline
c = wavespeed or celerity

For the flow path considered pipe period is approximately 7 seconds.

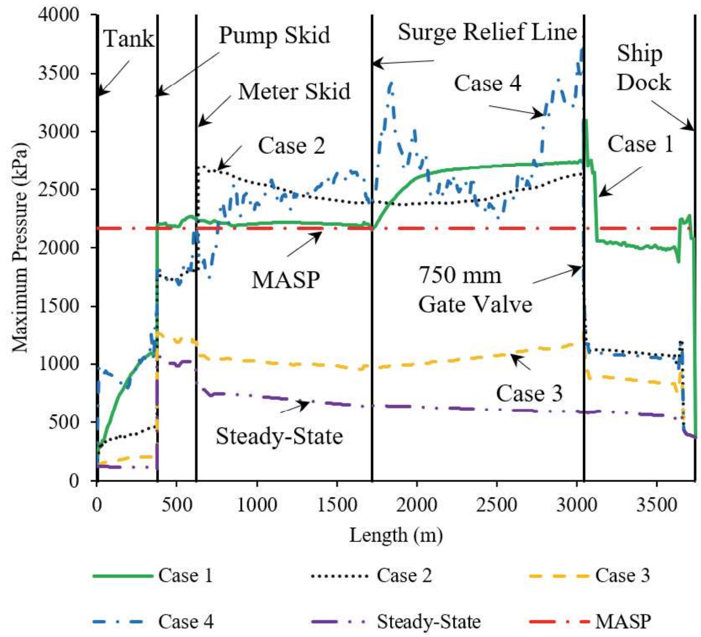

Figure 6: Steady-state pressure, maximum pressure envelopes, and maximum allowable surge pressure (MASP)

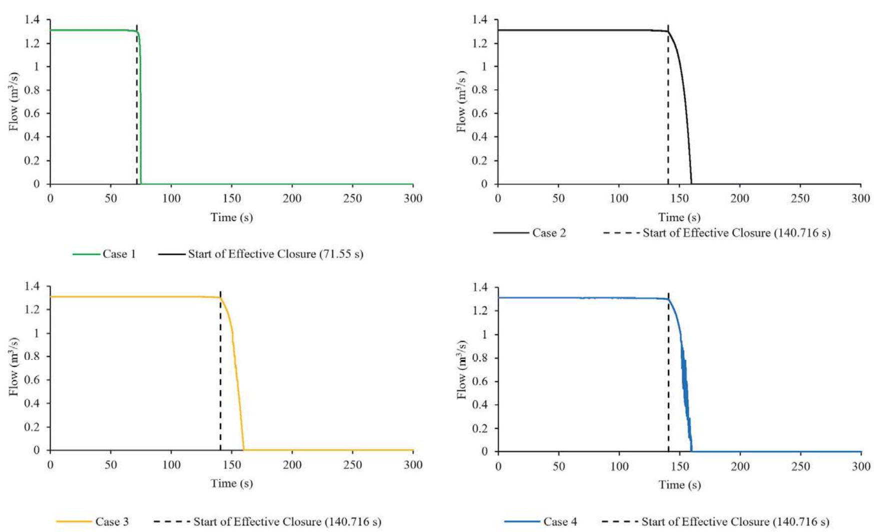

Figure 7: Flow at inlet of 750 mm gate valve

Figure 7 shows the flow at the inlet of the closing gate valve and the starts of the effective closures. Case 1 has a short effective closure time of 3.6 seconds, which is a shorter length of time than the pipe period of approximately 7 seconds. This results in the closure being considered a rapid event as defined by Thorley (4). Case 2, 3, and 4 have a longer effective closure times of 19.3 seconds. This allows time for the pressure rise to be communicated throughout the pipeline and interact with the system's boundary conditions and other active equipment such as the SRVs.

If a linear closure was extended to increase effective closure time to 19.3 seconds (same as dual rate) the closure would have to take approximately 400 seconds. This was a risk to the terminal and loading docks due to overfilling and unacceptable to the terminal owner. Other valves with better control such as a ball valve or equal percentage valve were also considered, but this is an existing system and the downtime and installation costs of adding hundreds of new valves far exceeded the costs of installing dual rate actuation.

Figure 8 shows the pressure rise at the inlet of the gate valve. Case 1 has a significant and rapid pressure rise very near Joukowski pressure. After the initial pressure rise, the corresponding pressure drop results in column separation and a few smaller pressure spikes against the inlet of the valve. Case 2 has a significant pressure rise and closes an upstream check valve that traps a high pressure between the closed gate and check valve. Case 3 would result in a pressure rise similar to case 2, but the longer closure gives time to allow the SRV skid to respond. This limits pressure rise at the valve and in the system to near the SRV setpoint. Case 4 responds similarly to case 3 at first, but the rapid closures on the new relief flow paths caused by an uncontrolled valve closure propagate high pressure waves throughout the system.

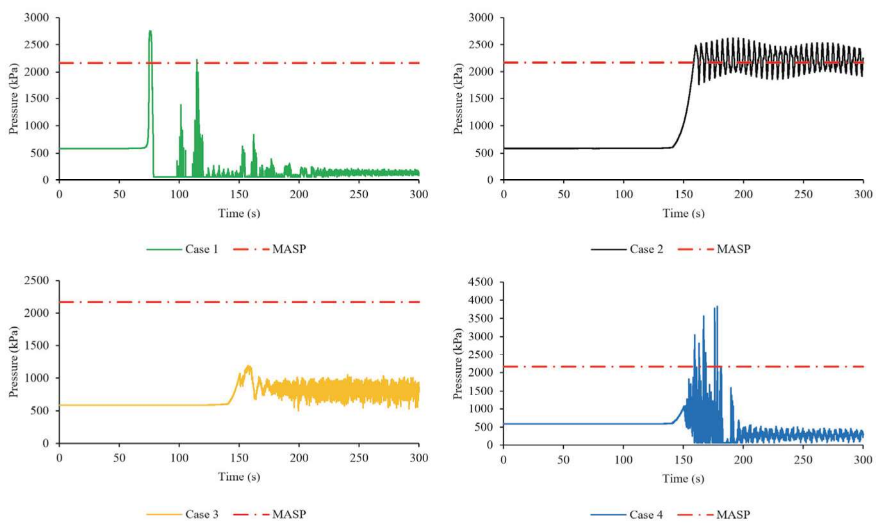

Figure 8: Pressure at inlet of 750 mm gate valve

Figure 9 shows the pressure drop at the outlet of the closing gate valve. Each case results in column separation, but the magnitude of the collapsing vapor cavity is more pronounce and exceeds MASP in Case 1.

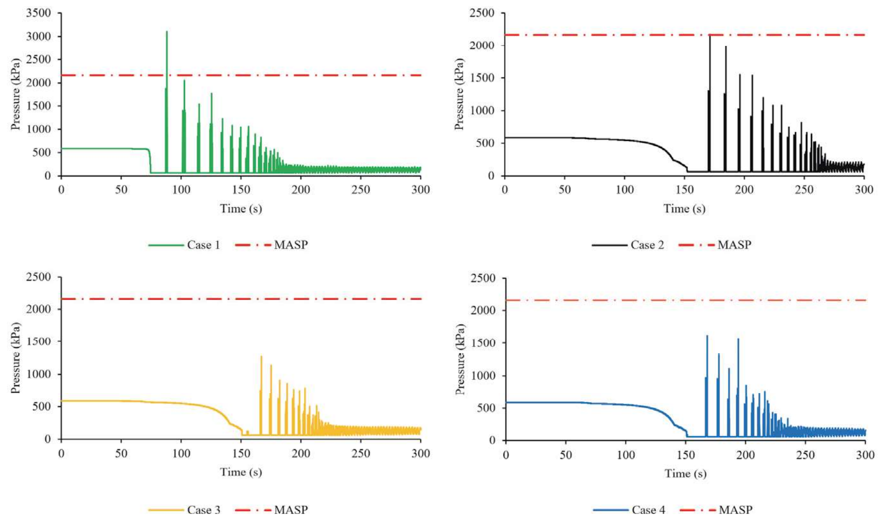

Figure 9: Pressure at outlet of 750 mm gate valve

Figure 10 show the pressure at the discharge of one pump (two in parallel have equivalent transient response). The pumps are equipped to shut down in the event of a discharge pressure greater than 1655 kPa. This occurs rapidly in case 1 and the pressure is lowered significantly. In case 2 a pressure rise also results in the pumps shutting down, but a high pressure is trapped by the pump check valves and nearby meter skid check valves that closed before the pump had shutdown. Case 3 had a limited pressure rise at the pumps because the SRV skid worked well at limiting the pressure rise throughout the system. This is an additional risk that must be considered as this simulation shows continuous flow into the collection tank. This result was determined to be sufficient by the terminal owner as they would have enough time to manually shutdown the pumps to prevent overfilling the collection tank if an event like this occurred. Case 4 shows the pump shutting down after pressure spikes from the rapidly closing SRV skid propagate throughout the system.

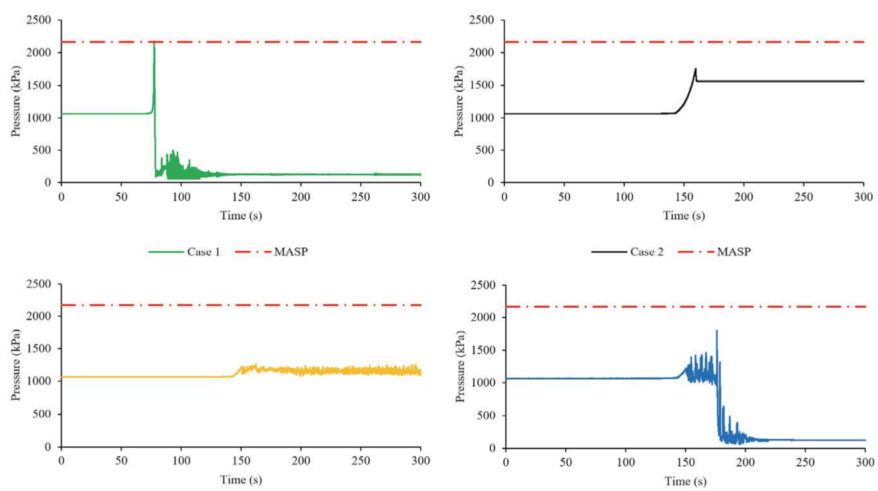

Figure 10: Discharge pressure at one pump

Figure 11 shows the flow at one pump (two in parallel have equivalent transient response). Case 1 has a rapid drop in flow once the high pressure shutdown setpoint is reached. Case 2 has a smoother transient response and flow is reduced to 0 rapidly. Case 3 shows some reduction in flow due to the closing gate valve, but a new flow balance is quickly established due to the pump not reaching the shutdown setpoint and continuous flow to the collection tank through the SRV skid. The pumps will need to be manually shutdown in this situation. Case 4 shows a more disrupted reduction in flow after the pump shutdown setpoint is reached.

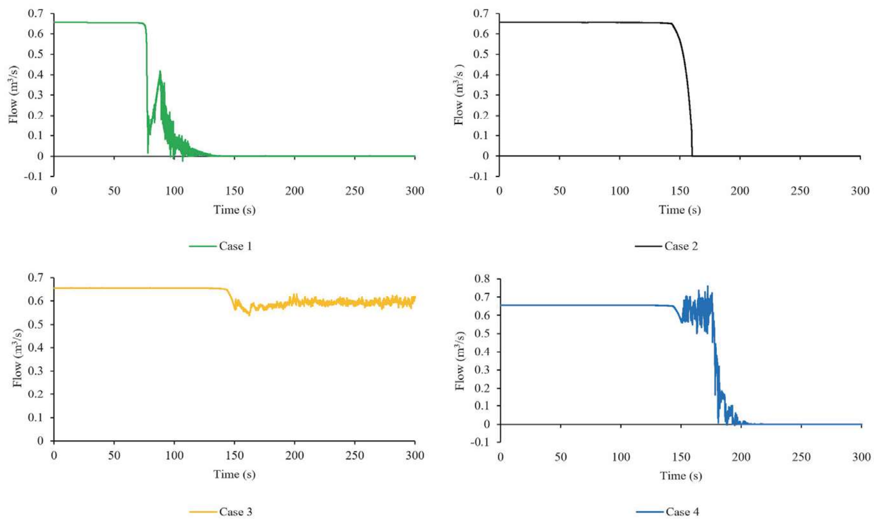

Figure 11: Flow at one pump

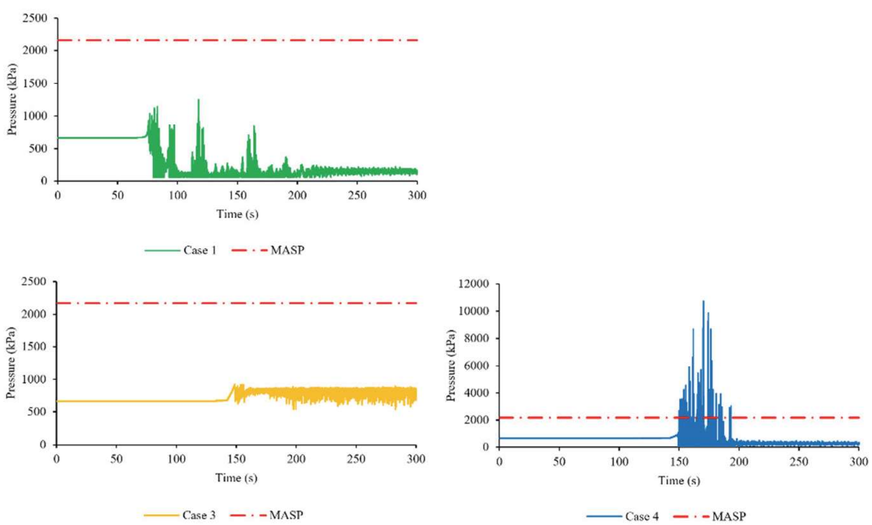

Figure 12: Pressure at inlet of one relief valve

Figure 12 above shows the pressure at the inlet of one relief valve (three in parallel have equivalent transient response). Case 1 and 3 have a controlled closure rate and limit pressure rise by preventing rapid closures on the relief flow path. Case 1 relief does not effectively protect the system however. The rapid gate valve closure is done closing before the transient pressure wave travel to the inlet of the SRV skid. Case 4 shows the results of relief valve chatter. This phenomenon is discussed by Thorley (4). The predicted pressure spikes after chattering has begun are likely inaccurate due to numerical noise caused by very rapid openings and closures of the valve. However, the first few pressure spikes near 4000 kPa are likely real and chattering would occur without control over valve closure time.

Figure 13 shows the flow at the inlet of one relief valve (three in parallel have equivalent transient response). Case 1 shows a rapid increase in flow as the valve open, but a controlled closure that prevents large spikes from being generate on the relief line. Case 3 shows a rapid increase in flow as the valve opens and stabilizes to a new flow as the pump fails to shutdown and a new flow path is established. Case 4 shows a significantly more chaotic response. The high pressure opens the valve, the rapid decrease in pressure as fluid is released rapidly closes the valve, the valve closure then causes a secondary surge wave on this new flow path, and this cycle continues.

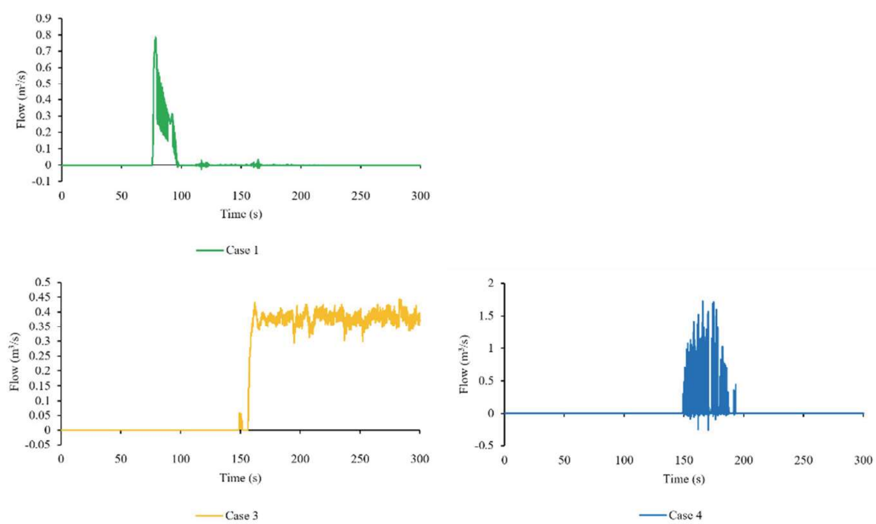

Figure 13: Flow at one relief valve

Figure 14 shows the accumulated volume of fluid at the collection tank. Case 1 and 4 have a finite amount of fluid that is acceptable for the size of the tank, but case 3 has continuous flow into the collection tank. This continuous flow must be stopped by manually shutting down the pumps to prevent overfilling the collection tank.

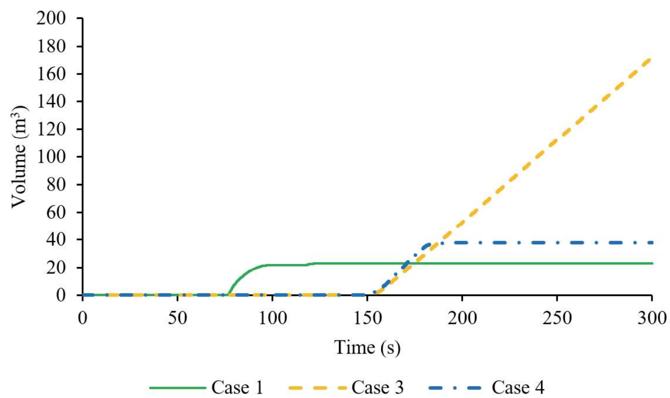

Figure 14: Accumulated volume at collection tank

6 CONCLUSION

Various mitigations methods can be used to prevent surge within marine terminals. Two methods, the installation of nitrogen-backed SRVs with a controlled closure rate and the use of a dual-rate valve actuation, are discussed within this paper. The use of both working together was successful at preventing pressure rising above the MASP. Finally, the use of dual rate closure and similar SRVs without a controlled closure rate is presented. Without the controlled closure the SRVs have a high potential to chatter. When this occurs rapid changes in pressure and flow occur. The primary concern is the rapid closure on this newly introduced flow path. When this occurs secondary surges greater than the primary surge caused by the closing gate valve can occur.

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