Considering Overfilling to be a Non-Applicable Overpressure Scenario

Natalie Doe and Dustin Smith, P.E.

1. Introduction

The consequences of an overfilling overpressure scenario can result in increased risk to the facility when mitigated with pressure relief devices. This could occur due to many different root causes. In order for liquid overfilling to require overpressure protection from a relief device, the following must all be true:

1. The source pressure must be capable of exceeding the system MAWP. Since the relief device is supposed to be set at or below the system MAWP, if the relief device is set lower than the MAWP, a liquid release may occur at a lower pressure.
2. The flow of liquid through the system can be stopped by closing a valve on the system outlet or the loss of a discharge pump (etc). In general, system designers ensure that liquid flows can be stopped, so this is usually a given.
3. There are no acceptable administrative or instrumented controls in place to prevent the scenario.

When reviewing the consequences of an overpressure scenario, the designer must check to ensure that the overfilling event may also not occur during a larger plant upset (power failure, instrument air failure, or other global utility disruption). This would add a simultaneous load to the disposal system, which should be included in the disposal system design.

1.1 Overpressure Protection

The system designer should consider the root cause of the overfilling scenario to determine how to protect the system or eliminate the scenario. Relief devices are often used to prevent excessive vessel overpressure due to liquid overfilling. For many systems, overfilling is not expected to be the controlling case for relief device sizing; however, a review of incident history shows that many different systems have been overpressured by overfilling with liquid, resulting in relief. Therefore, when relief devices are used to provide protection for overfilling, it is important that proper consideration is given to the effluent handling system.

1. For a system with several pieces of protected equipment, consideration must be taken for the static head throughout the column to ensure equipment at grade is adequately protected. This is particularly an issue for low pressure tanks.
2. When systems overfill, there is the potential for a large amount of liquid to be released to the effluent handling systems. Unless liquid holding drums are sized for the potential liquid rate, there could potentially be an unplanned liquid release with significant consequences.

This paper will outline recent incidents and their consequences due to overfilling, and will overview methods to protect the vessels from overpressure and the system from the consequences of large liquid releases.

2. Overview of Recent Incidents

The following incidents from the past decade illustrate the consequences of overpressure due to overfilling and the handling of liquid releases.

2009, Bayamón, Puerto Rico

Per the CSB report, "Tank 409 overflowed with gasoline, resulting in a vapor cloud that encompassed 107 acres of the CAPECO tank farm." [1] The report also states that "Tank 409 overflowed for an estimated 26 minutes before the vapor cloud ignited. The CSB determined nearly 200,000 gallons of gasoline… rushed out of six vents in the tank." These six vents responded to the upset conditions to relieve the excess pressure in the tank; thus, the overpressure protection provided was sufficient to prevent a catastrophic vessel failure. The action of the "engineered" pressure relief devices for this scenario worked and then became the initiating event for this incident. The final result was that the company went bankrupt and 17 of 48 tanks were burned.

2008, Chesapeake, VA

Per the CSB report, "At about 2:20 pm, as the tank reached a level of 26.72 feet, a vertical split started midway up the shell and rapidly extended to the floor and roof of the tank on the side opposite the workers." [2] In this case overpressure protection to prevent catastrophic failure of the tank would not have worked because the tank was not "full". This incident could not have been protected for by pressure relief devices - only instrumentation, procedures or the like.

2005 Hertfordshire, England

Per the aforementioned CSB report, "Similar to the CAPECO incident, the vapor cloud explosion and multiple tank fires occurred after a tank was overfilled with gasoline." [1] Thus another incident of overpressure protection for the overfilling scenario working; as such, it operated as designed. The "engineered" overpressure mitigating system was the initiating event for an incident that caused more than a billion dollars' worth of damage to the surrounding commercial and residential property and injured 43 people.

2005 Texas City, Texas

Per the CSB report, "The incident occurred during the startup of an isomerization (ISOM) unit when a raffinate splitter tower was overfilled; pressure relief devices opened, resulting in a flammable liquid geyser from a blowdown stack that was not equipped with a flare. The release of flammables led to an explosion and fire." [3] The pressure relief devices opened, and prevented excessive overpressure of the ISOM tower. As such, the engineered pressure relief devices in this case also worked, preventing a catastrophic overpressure-related loss of containment, but the design for the disposal of the fluid created an additional hazard with significant consequences.

Many of these incidents involved tanks, but that is inconsequential as in each and every case either a relief device was insufficient to prevent overpressure, or the engineered design of the pressure relief device and disposal was the root cause for these scenarios. Not only do the pressure relief devices have to be designed to prevent loss of containment from overpressure, the disposal system has to be designed to ensure the effluent has a safe location to be stored or is adequately destroyed. This can be particularly difficult for liquid releases.

3. Means of Overpressure Protection

3.1 Relief Devices and Disposal

While relief devices are an acceptable method to protect from overpressure due to liquid overfilling, complete risk mitigation requires proper consideration of the ability of the disposal system to handle the liquid effluent. As mentioned previously, additional pressure due to static head should be considered when protecting multiple pieces of equipment. For column systems with relief devices located on the top of the column, this can have significant impact on associated equipment located at grade. It is common practice to perform overfilling relief device calculations at 10% overpressure rather than 16% overpressure when multiple devices are installed, in an attempt to account for the static head. For tall column systems, or for systems with a heavy relief fluid, this may not be sufficient to ensure the allowable accumulation on the equipment located at grade is not exceeded. The relief device set pressure may need to be lowered below the system limiting MAWP to ensure adequate protection for all equipment.

Additionally, the disposal system must be capable of handling the liquid flow from the relief devices. The disposal piping should be evaluated to determine if it can handle the weight of the liquid. A knockout drum must be incorporated as part of the disposal system to ensure liquid is not sent to the flare or vent stack. For large liquid releases, it may not be practical to size one knockout drum to obtain the required particle separation. Multiple knockout drums in parallel can be used to ensure adequate particle separation for these cases. Failure to size the knockout drum(s) correctly can lead to liquid being sent to a system which cannot handle it, which can have serious consequences. The CSB report which reviewed the Texas City incident [3] unduly criticized atmospheric blowdown drums; many of their preferred disposal systems, i.e. flare systems, have had similar incidents [4] with the authors aware of countless near misses from flare systems.

3.2 Overpressure Protection by System Design

The need to design a disposal system for the liquid effluent from relief devices that protect a system of equipment from overpressure by overfilling can be eliminated by designing the system such that relief devices are not needed. The acceptable way to do this is to ensure that the overfilling scenario is not credible. For vessels designed to ASME VIII, UG-140 (formerly known as code case 2211) states "A pressure vessel does not require a pressure relief device if the pressure is self-limiting… and this pressure is less than or equal to the MAWP of the vessel at the coincident temperature…" [5]. This can be achieved in many ways.

3.3 Equipment Design

A designer can utilize equipment design to ensure that the disposal system does not need to accommodate effluent from relief devices installed for liquid overpressure protection.

Example 1 – Pump Selection

Instead of feeding a system with a positive displacement pump, a centrifugal pump may be used that is not capable of exceeding the downstream system MAWPs. This is illustrated in Figure 1 below, as P-1 cannot exceed the MAWP of V-1. The defining quality of centrifugal pumps is that their flow will decrease with increased head. Therefore, as the pressure in the downstream system increases, the capacity of a centrifugal pump will decrease. Thus, pump selection can be an effective method of limiting the overfilling rate.

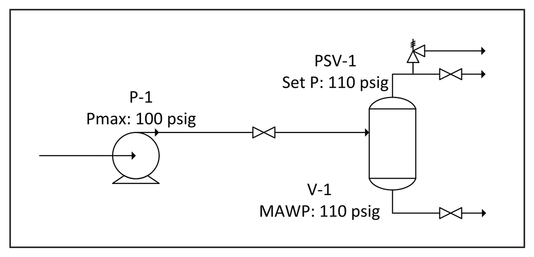

Figure 1: *Upstream sources incapable of overpressuring the system*

In contrast, positive displacement pumps are constant volume machines that are capable of maintaining high volumetric flow even at increased pressures. Therefore, alternative methods can be applied to protect from overpressure due to positive displacement pumps.

Example 2 – PRV Discharge to Process

If a relief device is installed on the pump instead of the vessel, the discharge piping can be routed to the pump suction. This allows for the liquid relief to be sent to process, rather than to a disposal system. However, the designer is cautioned that this will stop the forward flow of liquid so equipment upstream must be checked for this upset condition. An example is shown in Figure 2 below, as PSV-2A reduces the maximum feed pressure and eliminates the overfilling scenario on V-2.

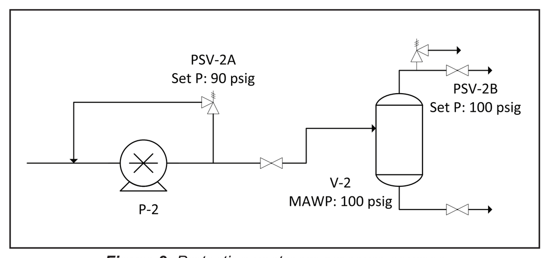

Figure 2: *Protecting upstream pressure sources*

In other cases, protecting for overfilling by pump selection or upstream protection may not be possible. Inventory controls may be utilized in these situations to ensure overfilling is not credible.

Example 3 – Inventory Controls

If possible, a designer can minimize the liquid inventory in a system. This is also a tactic in inherently safer process design. If the total liquid inventory of a system is insufficient to fill the vessel(s) vapor space then overfilling cannot occur. In this case overpressure does not occur irrespective of the maximum upstream pressure. An example of this is illustrated in Figure 3. The positive displacement pump (P-3) cannot overpressure the vessel (V-3) because the liquid inventory in the upstream tank (T-3) is less than the vessels vapor space.

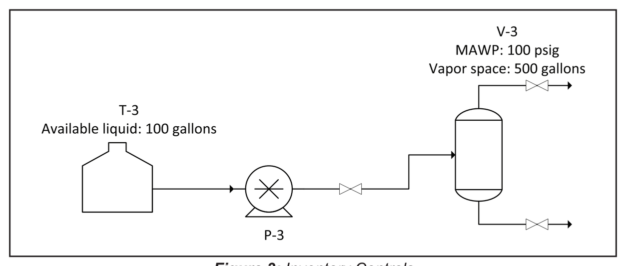

Figure 3: *Inventory Controls*

3.4 Instrumented Solutions

For installations where it is not practical to remove the credibility of the overfilling scenario by equipment design, safety instrumented systems (SIS) can be implemented. There are two ways to protect a facility from the effects of liquid effluent: remove the relief device entirely, or mitigate the consequences of the liquid effluent escaping from the disposal system.

Example 4 – Replace Relief Devices with Instrumentation

The system can be designed such that instrumentation is used instead of overpressure protection. A designer can find guidance in API STD 521 which states in Annex E that "High Integrity Protection Systems (HIPS) are designed to avoid overpressure incidents by removing the source of overpressure or by reducing the probability of an overpressure contingency to such a low level that it is no longer considered to be a credible case."[6] ASME VIII UG-140 allows for the use of these systems, provided that detailed description of the safety system is documented, and includes "the identification of all truly independent redundancies and a reliability evaluation… of the overall safety system" [5] The ASME requirements for these systems are further explored elsewhere [7]. Figure 4 below shows an example of a system protected by instrumentation. Three separate level taps are used to determine the liquid level in V-4. Two independent emergency shutdown devices (ESD), each with an independent controller, are used to shut off the feed on high liquid level. The redundancies expressed in this example would be integral to determining the safety integrity level (SIL) of this system.

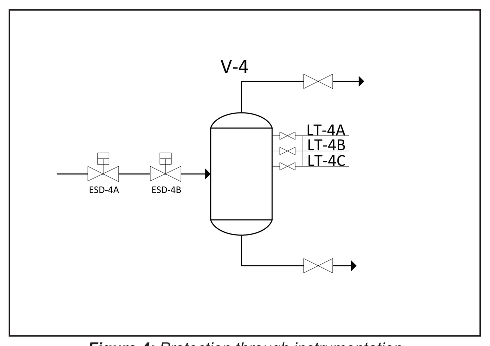

Figure 4: *Protection through instrumentation*

Example 5 – Add a Layer of Protection

Alternatively, the design of a SIS does not require that overfilling is mitigated to a point at which it cannot occur; rather, that the probability is low enough that the total system risk is at an acceptable level. Depending on the existing system, the most cost effective solution may be to mitigate the effluent system release with a SIS but rely on a the relief device to protect the equipment. Due to the uniqueness of each system a risk assessment (such as a LOPA) will be required to determine the reliability of the SIS. The designer may choose to put in a less reliable safety instrumented system in combination with an existing relief device, or the safety instrumented system may replace the relief device. As mentioned above, these redundancies are used to determine the safety integrity level (SIL) of the system. For most cases, a SIL-3 System is needed to remove the credibility of the overfilling scenario. However, a SIL-1 or SIL-2 system may be acceptable when reviewed in a risk analysis [such as Layers of Protection Analysis (LOPA)] to mitigate an incident caused by a release of liquid to the disposal system. Either way, a detailed risk assessment should be performed to determine the SIL rating required to mitigate the hazard [8]. An example of a SIS that could provide overfill protection would be level indicators independent of the process control instrumentation from a separate vessel tap feeding a dedicated PLC that triggers a shutdown valve to shut off the feed to the system on a high level alarm.

3.5 Operator Response to Mitigate Overfilling

For many facilities, a combination of instrumentation with an operator response is a reasonable mitigation of risk from overpressure. Research has shown the following factors tend to determine the reliability of operators to take the intended action [9][10]:

1. Trigger – there is a clear indication to the operator that something is wrong triggering the need to take action. It is unreasonable to assume that the operators would have mitigated the overfill scenario at Bayamón PR as they had no indication of level or procedures to know when the tank overfilled [1].
2. Time – Per the work performed by the NRC [9], an individual in a stressful situation with limited time to perform a moderately complex task has a 100 times likelihood of failing compared to the exact same task with sufficient extra time allotted for execution. Others, [10] have put the reliability of an operator completing a clearly understood task on which he/she is trained, with adequate time under stressful conditions, is equivalent to a SIL-III system.
3. Consequences – if the mitigation action causes (or is perceived to cause) a chain reaction that is worse than the failure being mitigated there may be reluctance to perform the action. Additionally, if the operator assumes (or is told) that they will be punished for stopping production, then the likelihood of following the procedure decreases greatly.
4. Training – without the knowledge and training to act, the probability that an action will be taken diminishes greatly, especially if the action is not obvious to the individual operating the facility.

As safety instrumentation systems can be complex and expensive, many facilities choose instead to take credit for operator response to high level alarms. There are several important factors to consider when taking these credits. API 521 4.4.7.3 [6] outlines several factors to consider when relying on level alarms:

a) Whether the level instruments used for safeguards against overfilling are on separate process taps from the process control system

b) Whether level instruments used for safeguards against overfilling are susceptible to the same common mode device failures as those used for the basic process control system.

c) Whether the programmable level transmitter is set to show a low or zero level when the level exceeds the instrument range

d) Whether an open system differential pressure cell is used that can show a false low level due to accumulation of liquid in the upper impulse line if it is overfilled or collects condensed liquid

e) Whether density changes due to temperature effects or composition changes impact readings from differential pressure transmitters

f) Whether the instruments are proven in use for the specific process applications

g) Whether the range of at least one of the level measurement(s) can indicate a valid level reading of the full range between the high critical alarm point and any shutdown or interlock point

h) Whether operating characteristics of the level measurement during off-design, start-up, and shutdown operations are considered in display of level, physical properties, setting alarms, trip points, operator training, and operating procedures

i) Maintenance and testing frequency required for the instrumentation

Even if all of these factors are considered, and the reliability of the operator is evaluated, it is important to analyze the risk associated with human error, and the operator not responding in the allotted time. As with instrumentation systems, relying on level alarms and operator response is not a guarantee overfilling will not occur; rather, it lowers the risk to an acceptable level.

Overfilling of low pressure tanks present a unique challenge as compared to pressure vessels. API has created a specific document to provide further guidance to protect for the overfilling of low pressure storage tanks [11].

Example 6 – Alarms with Subsequent Operator Response

As with Example 4 above, Figure 5 shows a vessel (V-6) with three independent level taps. These level taps are connected to two independent high level alarms (HLA). The designer performed a LOPA, and determined the operator can reliably address the alarm in 30 minutes. This is less than the fill time of V-6 from the time when the alarm sounds (1 hour), so credit may be taken for the operator actuating HV-6A and HV-6B to shut off the feed and prevent overfilling.

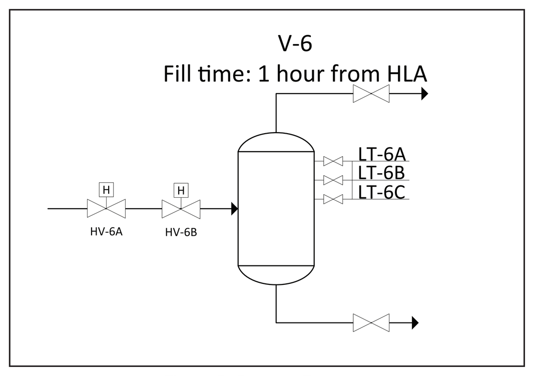

Figure 5: *Operator Response*

4. Conclusion

Liquid overfill can have serious safety and financial consequences, as seen in the recent incidents outlined in this paper. It is important for the designer to consider both the means to prevent overfilling, as well as methods to respond to an overfilling event. Appropriately designed relief devices and disposal systems are an acceptable method to react to an overfilling event. However, if this is to be the sole means of protection, careful consideration must be given to the large liquid effluent rate sent to the disposal system. Alternatively, the event may be prevented through the proper application of equipment design, instrumented solutions, alarms and operator response, or some combination thereof.

There are a large number of incidents involving overfilling that occurred despite the fact that the installed overfill protection reacted as designed. The protecting relief devices opened and were adequate to prevent overpressure of the overfilled vessel, but the disposal system was not designed for that case. The incidents mentioned in this paper resulted in billions of dollars' worth of damage, and even the bankruptcy of one company. When protecting for overfilling, it is imperative to consider the ramifications of allowing large liquid releases to occur. Overfilling protection design that encompasses consideration of all of the options presented above can prevent an incident with catastrophic consequences.

5. References

[1] U.S. Chemical Safety and Hazard Investigation Board. "Caribbean Petroleum Refining Tank Explosion and Fire" Available at: http://www.csb.gov/caribbean-petroleum-refining-tank-explosion-and-fire/. Accessed on 2/5/2016.

[2] U.S. Chemical Safety and Hazard Investigation Board. "Allied Terminals Fertilizer Tank Collapse" Available at: http://www.csb.gov/allied-terminals-fertilizer-tank-collapse/. Accessed on 2/5/2016.

[3] U.S. Chemical Safety and Hazard Investigation Board. "BP America Refinery Explosion" Available at: http://www.csb.gov/bp-america-refinery-explosion/. Accessed on 2/5/2016.

[4] HSE (Health and Safety Executive) (Eds.), 1997. The explosion and fires at the Texaco Refinery, Milford Haven, 24 July 1994. A report of the investigation by the Health and Safety Executive into the explosion and fires on the Pembroke Cracking Company Plant at the Texaco Refinery, Milford Haven on 24 July 1994, HSE Books, London.

[5] American Society of Mechanical Engineers, 2013 ASME Boiler & Pressure Vessel Code: Section VIII, Division I. s.l.

[6] API Standard 521, "Pressure-Relieving and Depressuring Systems," American Petroleum Institute, 6th ed., 2014.

[7] Smith, Dustin J. "Safety instrumented systems in lieu of pressure relief valves." Process Safety Progress 33.4 (2014): 345-349.

[8] A.E. Summers. "Overfill Protective Systems – Complex Problem, Simple Solution," 12th Annual Symposium, Mary Kay O'Connor Process Safety Center, October 2009.

[9] Blackman, Harold S., David I. Gertman, and Ronald L. Boring. "Human error quantification using performance shaping factors in the SPAR-H method." Proceedings of the Human Factors and Ergonomics Society Annual Meeting. Vol. 52. No. 21. SAGE Publications, 2008.

[10] Mannan, Sam, ed. Lees' Loss Prevention in the Process Industries: Hazard Identification, Assessment and Control. Vol. 1. Butterworth-Heinemann, 2004.

[11] API Standard 2350, "Overfill Protection for Storage Tanks in Petroleum Facilities," American Petroleum Institute, 4th ed., 2012.

Smith & Burgess
Process Safety Consulting
SmithBurgess.com