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Analysis of PRV Stability In Relief Systems

Part V – Get a Handle on PRV Stability

An ioMosaic White Paper

G. A. Melhem, Ph.D., FAIChE

melhem@iomosaic.com

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authored by
Georges A. MELHEM, Ph.D., FAIChE

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Contents

1 3 % Inlet Pressure Loss Does not Guarantee PRV Stability

There is general agreement that the 3 % inlet pressure loss rule (IPL3) is not sufficient to guarantee PRV stability and does not work all the time. This is confirmed by recent findings from actual PRV stability measurements and dynamic modeling [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15].

IPL3 only considers irrecoverable pressure loss. IPL3 assumes that the fluid dynamic pressure is ultimately recovered at the disk surface as the PRV is closing. This recovery of fluid dynamic pressure can keep the PRV open, even at reduced lift. But this is only possible if the inlet line length is less than the ”critical length”. In other words, the returning pressure wave can keep the PRV open before the PRV reaches full closure only if it can get there before the PRV closes. One might even argue that as long as the ”total” wave/dynamic pressure drop in the inlet line is less then PRV blowdown, the PRV can operate in a stable manner, even at reduced lift. The pressure wave travel time depends on the speed of sound of the fluid/pipe system and the presence of any acoustic barriers.

This creates a predicament for spring loaded pressure relief valves users and manufacturers worldwide. Although we now know that IPL3 is not sufficient to guarantee PRV stability, new facilities and modifications to existing facilities continue to be designed with IPL3 requirements for stable PRV operation. Despite recent advances and confirmations of how and why different PRV instability mechanisms occur, industry standards and guidelines continue to consider IPL3 as a sufficient requirement for PRV stable operation because of only historical legacy. There are installations where PRVs will be unstable despite an IPL of 3 % or less. The opposite is also true where PRVs will be stable with an IPL in excess of 3 %. Simple and dynamic PRV stability analysis can and should be used to confirm that PRV installations are stable, whether they are designed to meet the 3 % IPL requirement or other company specific requirements.

This white paper illustrates important concepts associated with PRV stability through the use of one dimensional (1D) fluid dynamics and a single degree of freedom (SDOF) representation of a spring loaded pressure relief valve. SuperChems™ Enterprise, a component of Process Safety Office® is used to perform the detailed 1D flow dynamics throughout the paper. A primary objective of this work is to provide the reader with a clear understanding of how and why PRV instability occurs through animation of key concepts, flow variables, and PRV lift under a variety of scenarios, configurations, and conditions.

This paper is the fifth installment in a series of white papers written by this author on the subject of PRV stability [16, 17, 18, 19, 20].

2 Additional PRV Stability Analysis is Required

Most operating companies calculate fluid IPL using simplified steady state methods. In many instances such methods only use the momentum equation to establish the flow hydraulics. Additionally, IPL requirements are sometimes evaluated at 16 or 21 % overpressure.

First, we should confirm that any identified stability or instability by such simple steady state methods is real. Coupled mass, momentum, energy, PVT, and phase equilibrium equations should be used. This can be important because, for example, the change of density with respect to pressure (temperature and quality also) for steady state flow imputes/implies a specific value of the mixture speed of sound. Systems handing fluids that have high speeds of sound (hydrogen for example), can tolerate longer inlet lines and more pressure drop [1]. Where numerous relief scenarios are considered for emergency relief with different fluids, PRV stability has to be evaluated for those scenarios where the speed of sound is different and scenario dependent.

The discharge piping backpressure also impacts PRV stability because it alters the force balance on the PRV disk. Steady state methods assume the discharge piping is initially packed with fluid. As a result higher backpressures are calculated than would actually be developed which reduces PRV disk lift. If the discharge line is initially empty or at a lower pressure before relief starts, it has to be filled as the PRV lifts. Therefore more flow can be achieved and sustained, especially if the PRV can be pushed into full lift before the discharge piping is filled.

Excessive inlet pressure loss may be tolerable if we can show that the PRV has sufficient flow capacity at reduced stable lift and if we can demonstrate that it can operate stably at those conditions:

1. Confirm the inlet piping geometry, pipe surface roughness, and the actual inlet velocity head loss used to represent the inlet line / vessel connection. Smooth round inlet nozzles have low resistance to flow as do pipes with low surface roughness.
2. Confirm the steady state hydraulics using more detailed methods such as SuperChems for DIERS, SuperChems for DIERS Lite, or SuperChems Expert. These tools solve all the required flow equations simultaneously and provide higher quality and more accurate answers for IPL, speed of sound, sound power level by segment, and fluid properties. This is especially important for complex and long piping geometries.
3. Establish the steady state IPL at 10 % overpressure. The PRV has to go through 10 % overpressure first on the way to 16 or 21 % overpressure where higher IPL can be tolerated. IPL losses can be up to 1 % less at 10 % overpressure than at 21 % overpressure. IPL losses should be calculated without the derating factor of 0.9 built into the API flow area or the ASME discharge coefficient values.
4. Establish the critical inlet line length. If the actual physical inlet line length is less than the critical inlet line length at full or reduced PRV lift (required relief rate), the PRV can operate in a stable manner at reduced or full lift.
5. Use the full implementation of the Melhem force balance [21, 17] method (SuperChems for DIERS or Expert) in conjunction with relief requirement and critical line length to confirm if PRV stability is an issue. If the PRV has sufficient capacity at reduced lift, and the inlet line is less than the critical line length at such reduced lift, then further analysis is not needed.
6. Establish how long it takes to repressure the system by performing a dynamic analysis on the pressure source. If the repressurization time is much longer than the PRV opening/closing time, then further analysis may not be needed. This is typical of fire exposure scenarios on large vessels. It may take several minutes for the PRV to reopen if the PRV has sufficient

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[1] As long as the reduced flow capacity of the PRV still meets or exceeds the relief requirement

relief capacity. In these situations, cycling is more likely since all spring loaded PRVs exhibit some small instability during opening and/or closing.

7. If all the above checks fail, and the actual inlet line length is longer than the critical line length, perform 1D PRV dynamics to identify which mode of instability may be triggered, especially for liquid packed systems. SuperChems Enterprise provides 1D PRV dynamics tools for all types of flow and complex piping arrangements, including liquid, vapor, supercritical, and multiphase.

These checks and additional PRV stability analysis can yield effective risk reduction, i.e. risk reduction where it is really needed. Unnecessary and costly piping and/or vessel modifications, especially for existing systems, can increase risk instead of reducing risk.

3 It's All About the Pressure Waves

In order to get a good understanding of what causes PRV instability, we need to first understand what happens to pressure, velocity, and vapor quality as flow is introduced into a piping system or when flow is stopped out of a piping system. The transient details associated with pressure waves as the system tends to steady state are not immediately obvious in steady state analysis. They are critically important for the assessment of PRV stability, especially for liquid systems.

We will build our case for PRV instability by examining first what happens when flow is introduced quickly into a pipe. We then explore what happens when the flow is stopped. This is essentially what occurs when a PRV opens and closes. The rapid opening and closing of a PRV accelerates and decelerates the fluid in the relief piping similar to what happens when one opens or closes a valve rapidly which causes pressure upsurge and downsurge (water hammer). Rapid introduction of flow into a liquid packed system will create higher reflected pressures at the PRV disk and causes the PRV to higher initial lift. The time required to reach the disk depends on the length of the inlet line and the speed of sound of the pipe/fluid system.

Rapid opening and closing of a pressure relief valve (disk motion) can couple with recurring expansion and compression pressure waves in the inlet/discharge line to cause instability (flutter or chatter). The travel time of the pressure waves relative to the response time of the valve (or PRV) is very important. If the round trip time is much shorter than the valve closing time, the PRV will flutter as the returning compression wave will keep it open at some reduced lift. If the travel time is much longer than the valve response time, the valve will close and then open at a later time. Depending on how long that is (length of inlet line), the valve will be cycling at either high or low frequency. If the pressure wave round trip time is about the same as the valve response time, opening and closing will occur continuously at that frequency. That is called chatter or instability for a PRV.

Before we use an actual SDOF representation of a PRV, we build our case for understanding instability by using a regular valve that opens linearly and closes linearly over a specific time interval for different types of fluids.

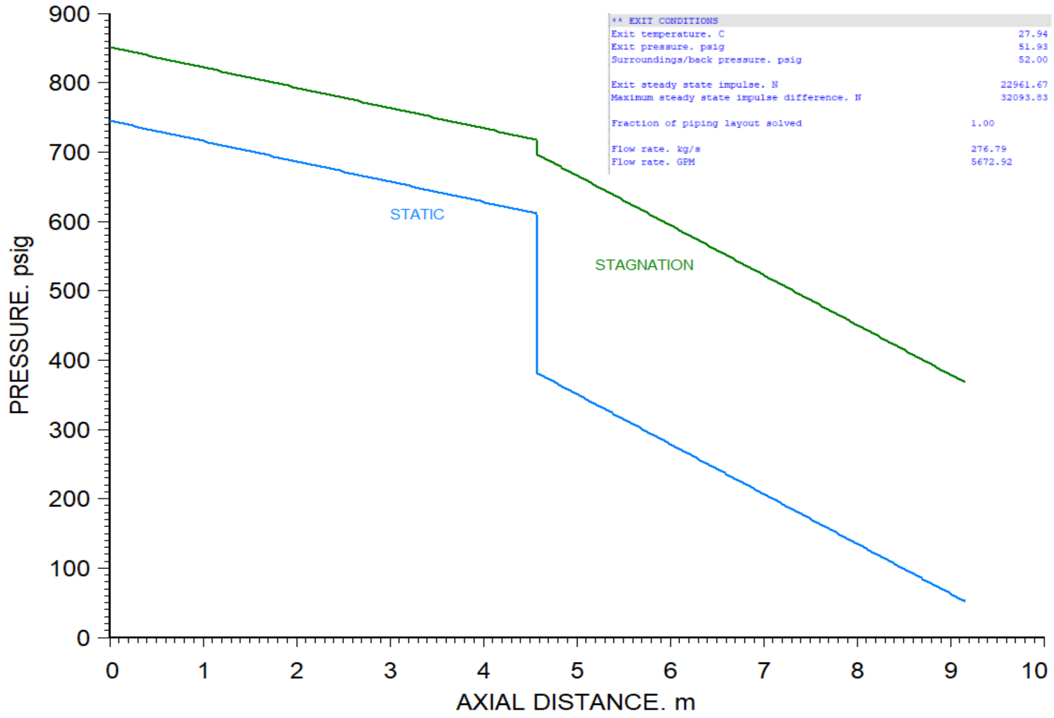
4 What Happens When Flow Starts?

We consider the flow of a hydrocarbon liquid [2] into a open piping system consisting of a 4 inch segment (L = 15 ft) followed by a sudden contraction into a 3 inch pipe segment (L = 15 ft). The upstream stagnation pressure is 851 psig and the downstream backpressure is 52 psig. A steady state estimate of flow yields the pressure profile vs. axial distance shown in Figure 1. The steady state flow rate is calculated at 276.8 kg/s along with a flow impulse ($PA + mu$) of 22,962 N.

The same analysis is conducted using the 1D flow dynamics modules of SuperChems Enterprise. The upstream boundary condition of stagnation pressure allows for the pressure to increase from 52 psig to 520 psig in 5 milliseconds and then to 851 psig in 10 milliseconds. The 3 inch line has an ideal full port valve which starts to open in 10 milliseconds and becomes fully open in 20 milliseconds. The animated pressure-time history in the piping system is shown in Figure 2.

It is interesting to note that the steady state flow rate reached by the 1D flow dynamics is the same as the steady state pipe solution estimate as shown in Figure 4. However, the steady state estimate of pressure does not provide any insight into how the pressure behaves as the liquid is introduced into the piping system and as the valve opens. As shown by Figure 2, a pressure upsurge and downsurge is exhibited before steady state is reached in approximately 350 milliseconds. We also note that the dynamic reaction force loading on the piping system is significant and goes to zero as steady state is reached as shown in Figure 3.

Figure 1: Pipe steady state liquid flow solution following valve opening - pressure



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** EXIT CONDITIONS
Exit temperature. C                                    27.94
Exit pressure. psig                                    51.93
Surroundings/back pressure. psig                       52.00

Exit steady state impulse. N                        22961.67
Maximum steady state impulse difference. N          32093.83

Fraction of piping layout solved               1.00

Flow rate. kg/s                                276.79
Flow rate. GPM                                 5672.92
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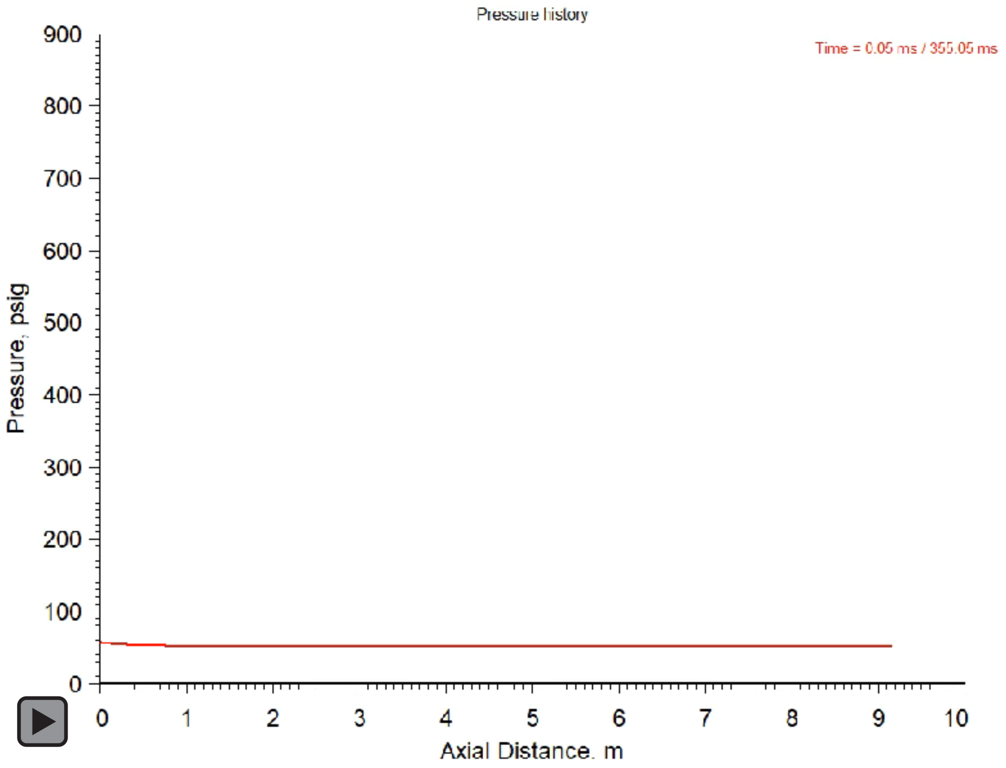
[2] specific gravity = 0.86, viscosity = 3cp, speed of sound = 1178 m/s, vapor pressure = -5 psig at ambient temperature

Figure 2: Pipe liquid flow 1D dynamics following valve opening - pressure [Animation]

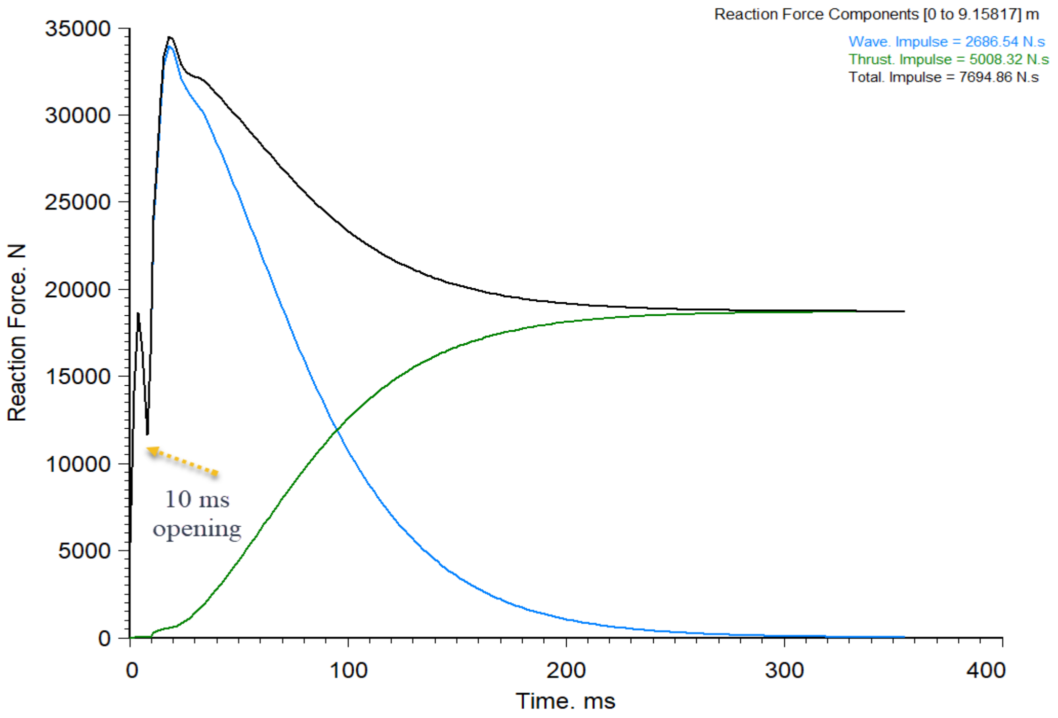


5 What Happens when Flow is Stopped?

We continue the above solution by instructing the same full port valve to close linearly in 20 milliseconds starting at 350 milliseconds. The animation in Figure 5 illustrates what occurs as the valve closes and the flow out of the piping stops. Very large upsurge and downsurge pressure waves (12,250 psig and -5.9 psig) are created due to the closure of the valve and the the conversion of dynamic pressure as the flow is arrested. Liquid column separation occurs during the downsurge phase which leads the shocks when the vapor is collapsed during the returning upsurge phase. The pressure surge following valve opening/closure is consistent with industry experience that chatter in liquid services causes more damage to piping and piping components.

The magnitude of pressure wave is much larger for liquids than vapors and two-phase fluids because liquids are only slightly compressible. Vapor systems exhibit the same behavior with smaller upsurge and downsurge pressures. The speed of sound in vapor and two-phase fluid/pipe systems is lower than the speed of sound in liquids. In highly subcooled systems, such as typically encountered in ethylene service, the pressure drops quickly to saturation and is then is followed by two-phase flow.

Figure 3: Pipe liquid flow 1D dynamics following valve opening - reaction force components



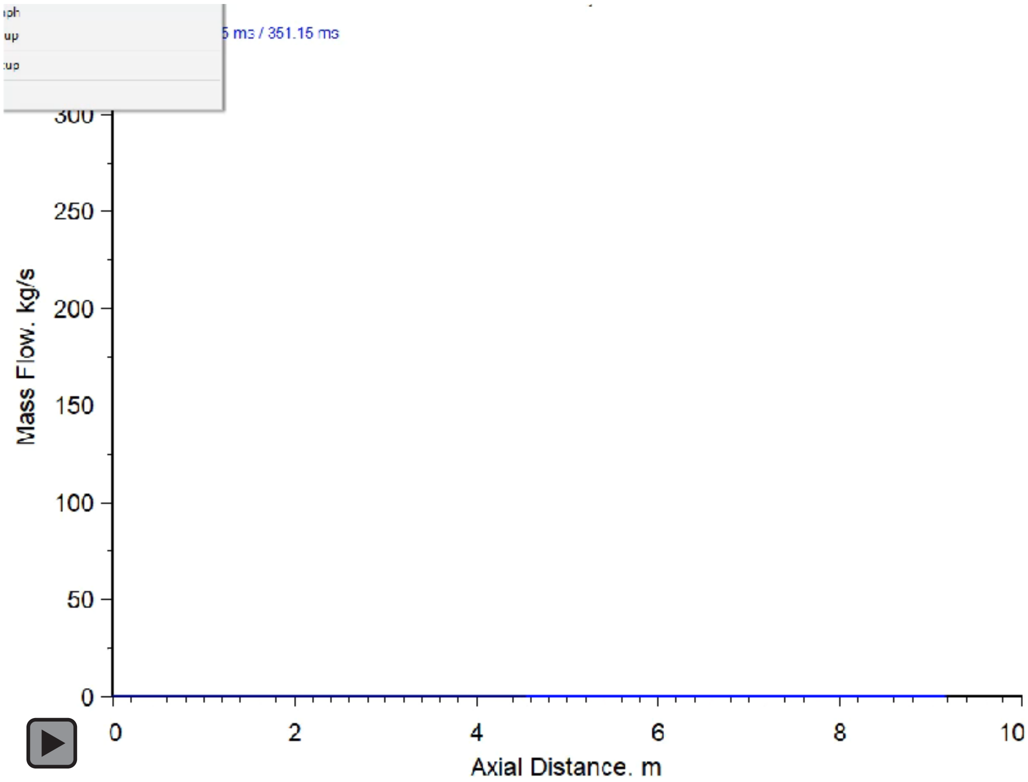
6 PRV Stability vs. Inlet Line Length for a Liquid System

We illustrate the impact of inlet line length on a liquid system equipped with a 4L6 PRV set to open at 15 barg. The liquid has a density of 725 $\mathrm{kg/m^3}$ and the fluid/pipe speed of sound is set at 850 m/s. Upstream conditions for the simulation are set at 10 % over the set pressure. Figure 6 illustrates the impact of inlet line length on PRV disk lift (maximum lift = 0.78 in, critical lift = 0.50 in).

The 3 m inlet line length case shows a stable behavior as illustrated in Figure 7. The 7 m inlet line length case shows chatter, a severe form of instability, because the inlet line length is approximately equal to the critical line length. See Figure 8. We note that the PRV lift reaches maximum lift and then full closure at the same frequency as the PRV opening/closing time. During the chatter event, even if the PRV and piping components survive the dynamic reaction force loads, the PRV flow capacity is reduced essentially by half. The 15 m inlet line length case shows a stable PRV at a longer length than the critical length.

Finally, at a much longer inlet line length of 76 m, a stable condition is reached with some instability during opening. This is shown in Figure 9.

Figure 4: Pipe liquid flow 1D dynamics following valve opening - mass flow [Animation]



7 PRV Stability vs. Inlet Line Length for a Vapor System

Similar behavior is illustrated for all vapor or gas systems. We show the case of a relief system that consists of several large 6R8 PRVs installed on a common header with closed ends. The relief discharge lines of all the PRVs are also connected to a common discharge header.

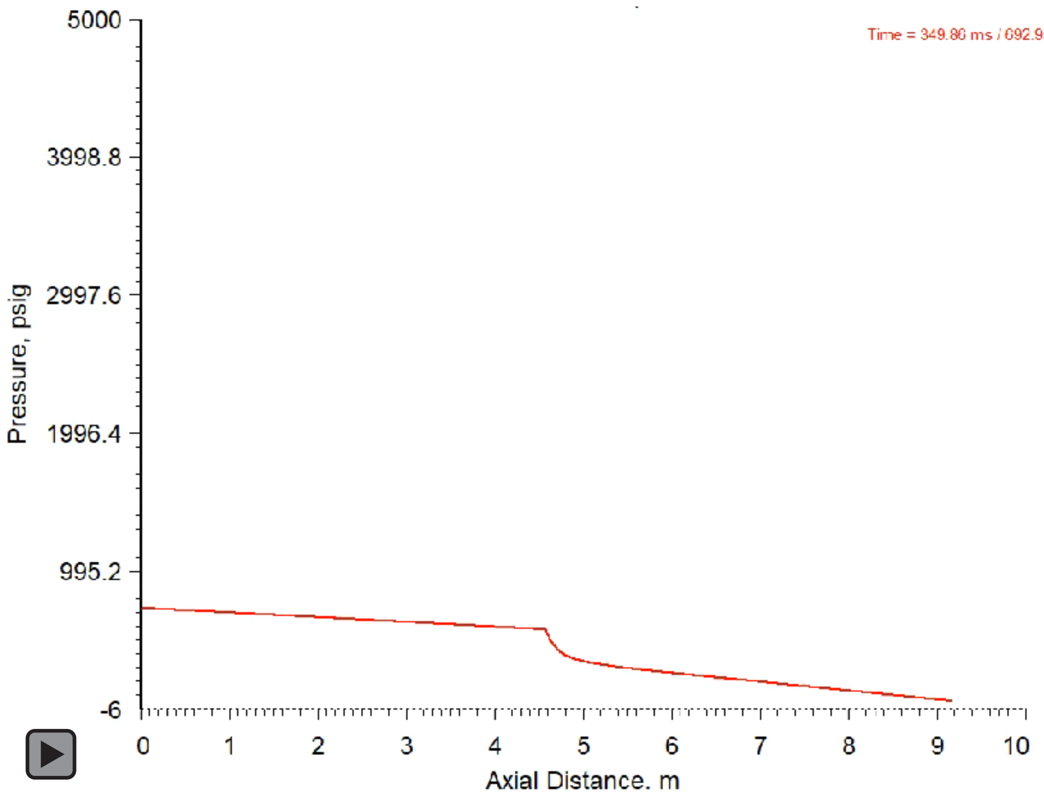
Figure 10 illustrates the pressure-time dynamics in the common inlet and discharge headers as all the PRVs open and close. This installation shows unstable behavior. The common inlet header length is too long and the PRVs have too much capacity.

Figure 11 illustrates the same pressure-time dynamics in the common inlet and discharge headers as all the PRVs open and close. This installation shows stable behavior because the inlet header is made shorter and the number of PRVs was reduced by one PRV.

8 PRV Stability Methods

Screening and detailed dynamics methods exist for the evaluation of PRV stability. The screening method that is gaining wide use and recognition is the ”force balance” method proposed by Melhem [17] and referenced in API520 part II [21] as a reasonable engineering analysis method that can be used for IPL in excess of 3 %. The API screening method does not currently include the critical line length criteria although Appendix C describes PRV inlet acoustic line limits. The API

Figure 5: Pipe liquid flow 1D dynamics following valve closure - pressure [Animation]



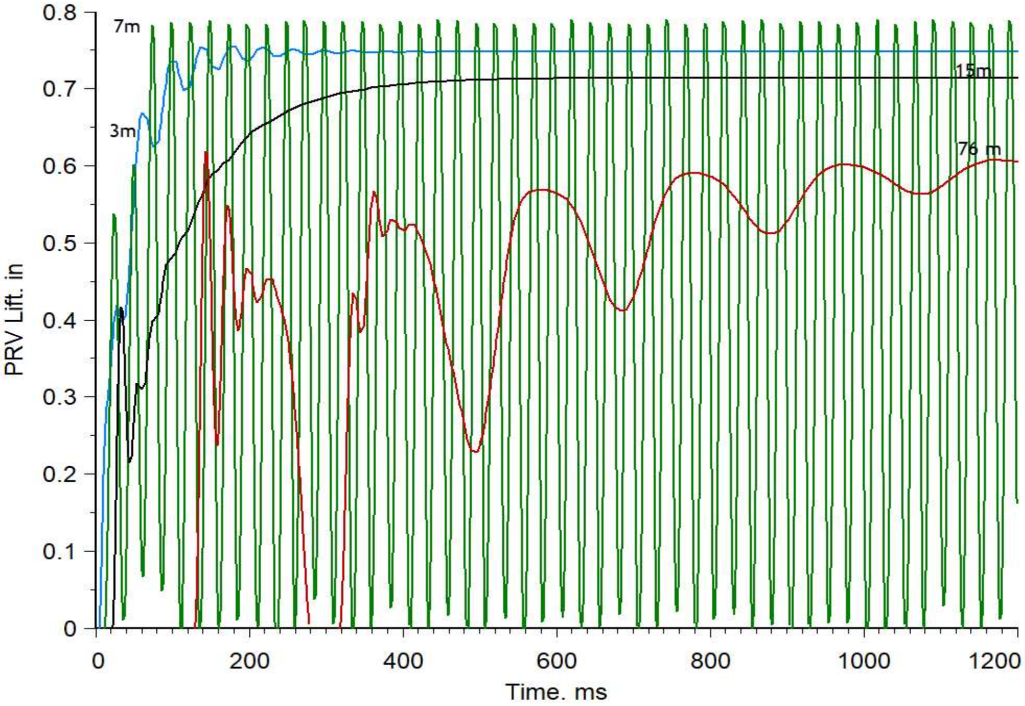
screening method requires a user specified value of blowdown and PRV opening/closing time. The screening method is limited in use and does not address complex inlet and discharge pipe geometries very well. Inlet pipe lengths well in excess of the critical line length may not be addressed properly by the screening method even for simple pipe geometries.

For simple pipe geometries where the inlet line is less or equal to the critical line length, screening methods can quickly identify relief systems installations that may be at risk. These methods tend to be conservative, especially for liquid systems, and benchmark well against detailed PRV dynamics estimates.

Detailed PRV dynamics method exist for the evaluation of complex piping arrangements for all types of flow including vapor, liquid, two-phase, supercritical, and subcooled flows. ioMosaic has developed and validated such methods for relief systems including vessels, and the associated relief systems (inlet line, PRV, and discharge line) as shown in some of the animations presented in this paper. Detailed dynamics are extremely useful when analyzing systems with very long inlet lines, systems packed with liquid or high pressure fluid, and where multiple PRVs are involved.

PRV Dynamics methods can provide insight into how long it takes to fill the discharge pipe, how the discharge pipe can continue to flow during PRV cycling or chatter, whether the rapid cycling is likely to damage PRV bellows, if air or other fluids can be ingested into the discharge line during a downsurge, retrograde and phase changes during wave phenomenon for pressure upsurge and downsurge, i.e. vapor bubble collapse and liquid column separation, how the system volume/capacitance can influence PRV stability, how acoustic reflection points associated with area

Figure 6: Impact of inlet line length on 4L6 PRV lift for liquid flow



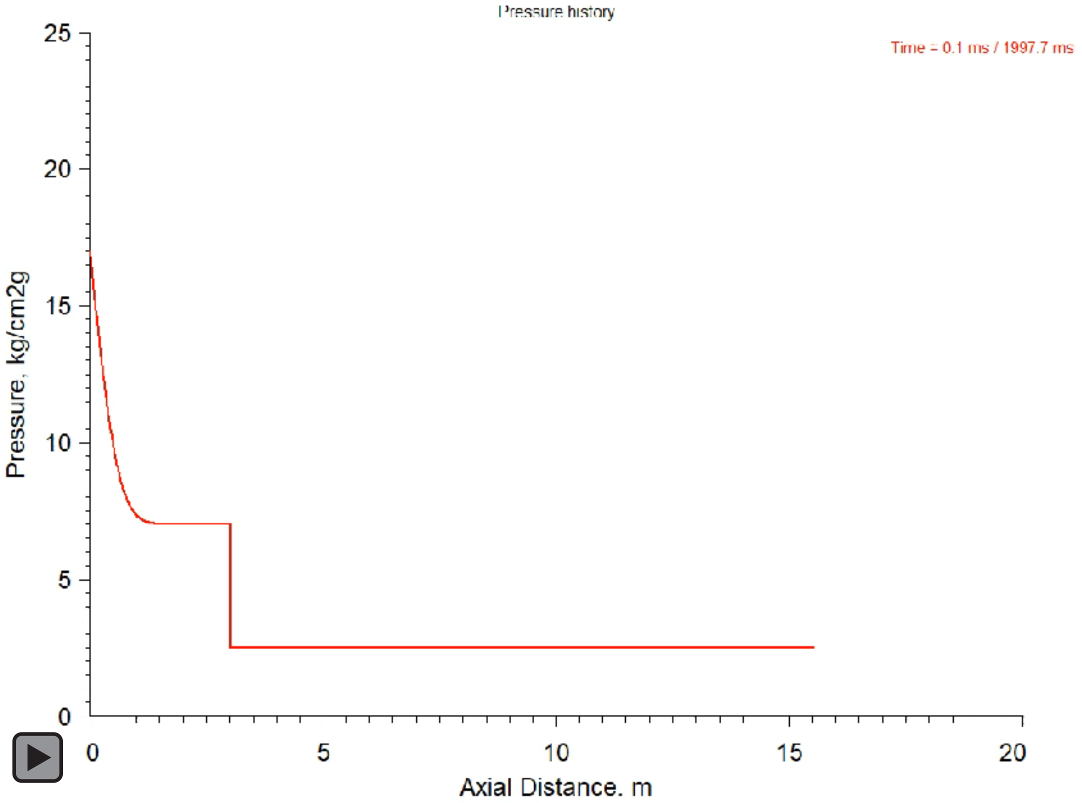
changes impact PRV lift, how pressure rise rate at the source influences PRV lift, flow capacity of PRVs at reduced lift, intraction between multiple PRVs with different set points, how rapid pressure drop from small volumes can sometimes outpace PRV closing and as a result the PRV will close at much lower pressure than the actual blowdown pressure (dynamic blowdown), etc.

Piping transient loads and reaction forces are byproducts of any PRV stability dynamics analysis and are specific to actual piping locations and segments. Duration of the loads are easily obtained and can be provided to structural engineers to assess the piping systems structural integrity during expected rapid cycling of PRVs in liquid or high pressure service. Most importantly, detailed dynamics methods provide a better and more realistic estimate of the actual mass flow for downstream equipment sizing and hazard analysis.

Both simple and detailed PRV stability methods require information about PRV opening/closing time and blowdown. SDOF models can be used to calculate the opening/closing time and to also indicate what blowdown is implied by the SDOF model parameters (see Figure 12). The model parameters can be calculated using available data on stable PRV lift at specific backpressure or overpressure as shown by Melhem [16, 17].

Although PRVs are damped to some extent as shown by Darby [7, 8, 9] (0.2 to 0.8 critical damping factor), SDOF models can be biased to be conservative (no damping) and to also yield a specific blowdown. SDOF models can developed for conventional PRVs or PRVs with bellows. Note that bellows can increase the spring stiffness and can also fail or be damaged due to excessive cycling (1000 to 5000 cycles). SDOF models are therefore PRV model and geometry specific. One can also develop a pressure vs. lift curve by direct measurement where warranted.

Figure 7: Pressure vs. time history for 3 m inlet line [Animation]



9 Conclusions

We have demonstrated using 1D dynamics how PRV instability can occur because of the interaction of pressure waves with the PRV disk motion. Examples were provided using SuperChems Enterprise to illustrate the risk reduction and cost reduction benefits and insight that can be provided using detailed PRV stability dynamics. The methods provided by SuperChems for screening and/or detailed dynamics can ensure effective risk reduction, i.e. risk reduction where it is really needed. Unnecessary and costly piping and/or vessel modifications, especially for existing systems, can increase risk instead of reducing risk. PRV stability analysis should be the method of choice regardless of the value of steady state irrecoverable inlet pressure loss.

Figure 8: Pressure vs. time history for 7 m inlet line [Animation]

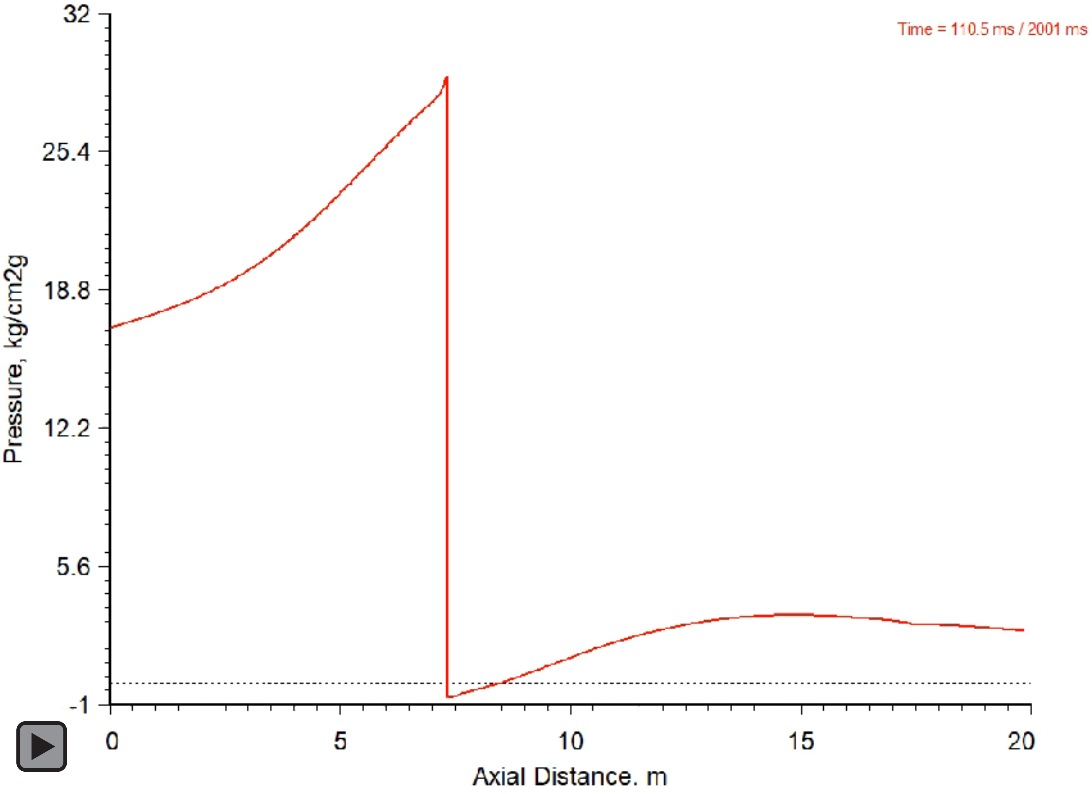


Figure 9: Pressure vs. time history for 76 m inlet line [Animation]

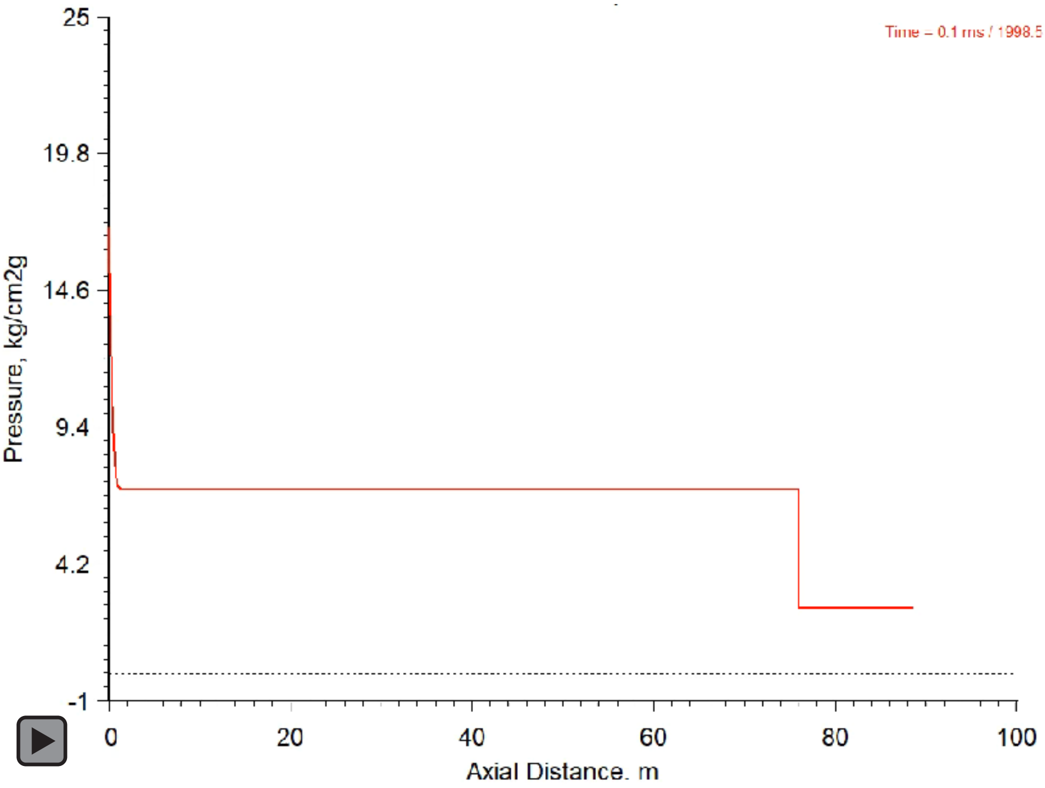


Figure 10: Pressure vs. time history for multiple large PRVs on a common manifold [Animation]

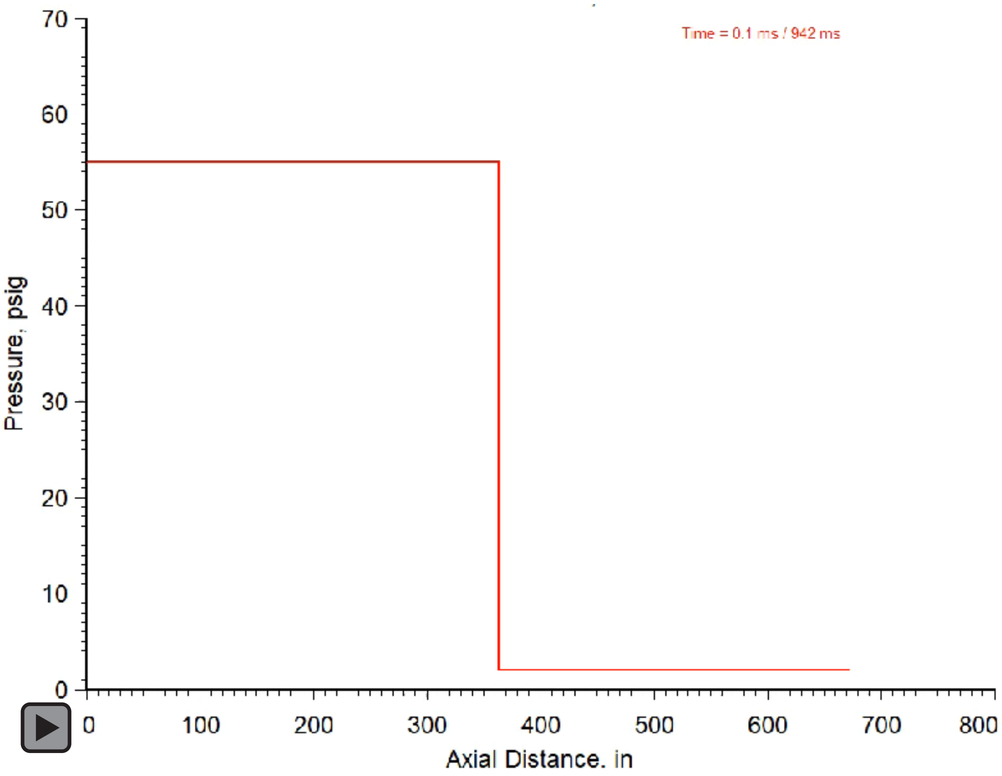


Figure 11: Pressure vs. time history for multiple large PRVs on a common manifold with shorter length and one less PRV [Animation]

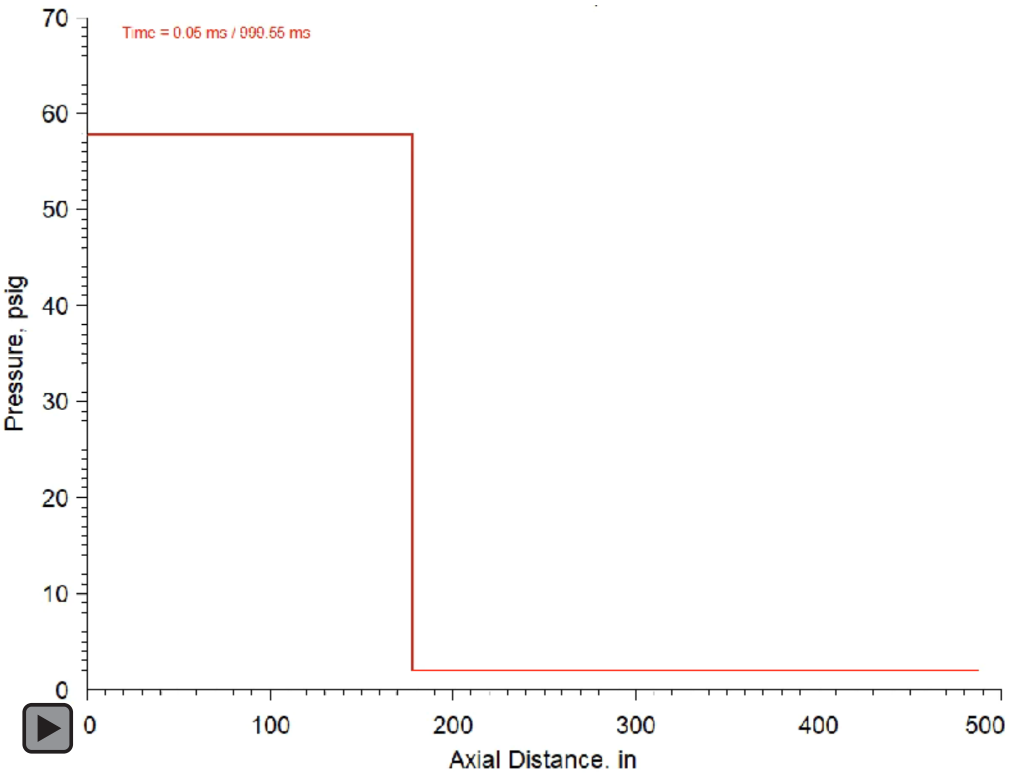
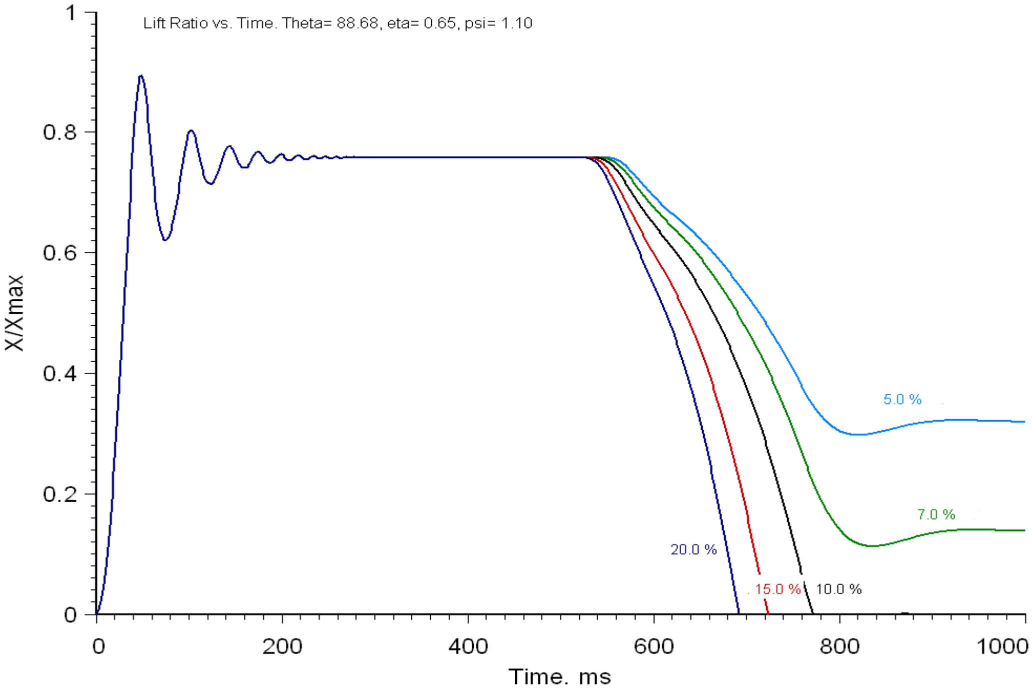


Figure 12: SDOF model implied blowdown for a 6R8 PRV in vapor service



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About the Author

Dr. Melhem is an internationally known pressure relief and flare systems, chemical reaction systems, process safety, and risk analysis expert. In this regard he has provided consulting, design services, expert testimony, incident investigation, and incident reconstruction for a large number of clients. Since 1988, he has conducted and participated in numerous studies focused on the risks associated with process industries fixed facilities, facility siting, business interruption, and transportation.

Prior to founding ioMosaic Corporation, Dr. Melhem was president of Pyxsys Corporation; a technology subsidiary of Arthur D. Little Inc. Prior to Pyxsys and during his twelve years tenure at Arthur D. Little, Dr. Melhem was a vice president of Arthur D. Little and managing director of its Global Safety and Risk Management Practice and Process Safety and Reaction Engineering Laboratories.

Dr. Melhem holds a Ph.D. and an M.S. in Chemical Engineering, as well as a B.S. in Chemical Engineering with a minor in Industrial Engineering, all from Northeastern University. In addition, he has completed executive training in the areas of Finance and Strategic Sales Management at the Harvard Business School. Dr. Melhem is a Fellow of the American Institute of Chemical Engineers (AIChE) and Vice Chair of the AIChE Design Institute for Emergency Relief Systems (DiERS).

Contact Information

Georges. A. Melhem, Ph.D., FAIChE
E-mail. melhem@iomosaic.com

ioMosaic Corporation
93 Stiles Road
Salem, New Hampshire 03079
Tel. 603.893.7009, x 1001
Fax. 603.251.8384
web. www.iomosaic.com

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As a certified ISO 9001:2015 Quality Management System (QMS) company, ioMosaic offers integrated process safety and risk management services to help you manage and reduce episodic risk. Because when safety, efficiency, and compliance are improved, you can sleep better at night. Our extensive expertise allows us the flexibility, resources, and capabilities to determine what you need to reduce and manage episodic risk, maintain compliance, and prevent injuries and catastrophic incidents.

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