ioMosaic®
Minimizing risk. Maximizing potential.®

Bridging the 3 % Inlet Pressure Loss Rule Gap

An ioMosaic Corporation White Paper

G. A. Melhem, Ph.D., FAIChE
melhem@iomosaic.com

IOMOSAIC CORPORATION

Bridging the 3 % inlet pressure loss rule gap

Process Safety and Risk Management Practices

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

August 18, 2021

Contents

1 Introduction

Because the potential hazard of pressure relief valve instability (chattering) is already recognized, relief systems design basis documentation must demonstrate expected stable pressure relief valve (PRV) operation and performance for a multitude of credible scenarios. Historically, expected stable pressure relief valve performance has been demonstrated by showing that the irrecoverable inlet line pressure loss is less than or equal to 3 % of the pressure relief valve set pressure (3 % rule).

It is now widely known and recognized that the 3 % rule is not sufficient to guarantee pressure relief valve stability. It has been shown (through measurement, incidents, and modeling) that some installations with irrecoverable inlet pressure loss less than 3 % can be unstable while some installations with irrecoverable inlet pressure loss greater than 3 % can be stable. Numerous publications including research by Chiyoda [1], Pentair [2] and ioMosaic [3] showed that pressure relief valve instability leading to flutter and/or chatter is due to the coupling of the PRV disk motion with the quarter wave pipe/fluid mode frequency without resonance.

The American Petroleum Institute (API) and the Petroleum Environmental Research Forum (PERF) have cosponsored two major studies on PRV stability. The results of those studies have been incorporated into recent editions of the API 520 standard [4]. Recent editions of API 520 allow the user to perform an engineering analysis to demonstrate expected stable PRV performance for installations where the irrecoverable inlet pressure loss exceeds 3 %. One engineering analysis method described by API 520 is the force balance recommended by ioMosaic. The force balance is a simple method and should be used in conjunction with an estimate of the critical line length as also recommended by ioMosaic. This simple method is most applicable to simple piping geometries. Where complex piping geometries are encountered and/or inlet line lengths exceed the critical line length criterion, 1D dynamics is recommended by ioMosaic to demonstrate expected stable performance.

2 Compliance Requirements

Deficient process safety information (PSI) such as relief systems design basis documentation, process hazards analysis (PHA), and/or mechanical integrity (MI) violate the Federal Occupational Safety and Health Administration (OSHA) process safety management standard (PSM) Standard (29 CFR 1910.119) [5] and may also violate the General Duty Clause under the Occupational Safety and Health (OSH) ACT of 1970 (section 5(a)(1)).

When confronted with a potential PSM violation (e.g., inadequate PSI, PHAs and/or MI), OSHA may issue a citation under the PSM Standard or, in the alternative, under the OSHA General Duty Clause in the event that the PSM Standard does not apply or does not fully address the hazard(s). The General Duty Clause is a catchall provision that imposes an independent duty on operators/employers to provide a safe work environment. Specifically, it requires an operator/employer to provide a place of employment that is free from recognized hazards that are currently causing, or are likely to cause [should they occur] death or serious physical harm to . . . employees. Section 5(a)(2) of the ACT also requires that each employer "shall comply with occupational safety and health standards promulgated under this ACT".

A hazard is recognized where: (a) the employer has identified it; (b) it is known in the industry; or (c) it is blatantly obvious. Penalties under the General Duty Clause are the same as those issued under the PSM Standard. [1]

An employer knowledge of the hazard is key. The level of employer knowledge of the hazard can be a significant factor in determining if and to what extent a violation exists. If employer knowledge of the hazard is established, the level of that knowledge is considered in determining the classification of the OSHA citation(s).

OSHA violations can result in citations under one or more of the following classifications [2]:

Serious A violation is serious if death or serious physical harm (i.e., a substantial impairment to bodily function) could result from the violation. This classification carries a statutory maximum penalty of $ 13,653.

Willful A willful violation is one that is committed with either intentional disregard or plain indifference to the requirements of the PSM Standard. In other words, a hazard exists and the employer had an enhanced knowledge of the hazard or the regulatory requirement prohibiting it, and fails to correct it. Willful violations that cause death to an employee are subject to criminal sanctions, including imprisonment of up to 1 year. [3] This classification carries a statutory maximum penalty of $ 136,532.

Repeat A repeat violation occurs when the employer has been cited previously for violation of the same OSHA standard within a 5 year period. This classification carries a statutory maximum penalty of $ 136,532.

Other than Serious Conversely, a violation is non-serious if death or serious physical harm could not result from the violation. This classification carries a statutory maximum penalty of $ 13,653.

Failure to Abate This violation occurs when an employer fails to abate or correct the hazard within the required time frame after having been cited by OSHA. This classification carries a statutory maximum penalty of $ 13,653 per day beyond the original abatement date.

The severity of each OSHA penalty is determined by the gravity of the violation. Two factors largely determine the gravity of a violation: (1) the severity of the injury that could occur from the violation (i.e., high, medium, or low); and (2) the probability that the injury could result from the violation (i.e., greater probability and lesser probability). Other factors OSHA may consider include the size of the operator/employer, the operator's/employer's good faith, and the prior history of violations at the site. These factors, however, are not defenses to the underlying violations. [4]

[1] USC 654 (OSHA General Duty Clause); Occupational Health & Safety Law; Compliance and Practice 7.24-7.25.

[2] All monetary penalties amounts are adjusted annually based on inflation rates.

[3] USC 666 (Penalties); Trinity Indus., Inc., 504 F.3d 397 (3d Cir. 2007) (serious); OSHA Field Operations Manual Ch. 4-II-C-3(non-serious); J.A. Jones Constr. Co., 15 OSH Cas. (BNA) par. 2201(willful). In 2009, a bill known as the Protecting Americas Workers Act, was proposed in both the U.S. Senate (S.1580) and House of Representatives (H.R.2067) to increase OSHA civil penalties to $250,000 (maximum) per violation, and criminal penalties to up to 20 years for repeat deaths.

[4] USC 666(j) (criteria); OSHA Field Operations Manual Ch. 6-III-A (gravity).

3 History of the 3 % Rule

The most cited and acknowledged source of the 3 % rule is a study commissioned by API at the University of Michigan in 1948 [6]. This work considered pressure relief valves with a 4 % blowdown. The original 3 % inlet pressure loss rule included both recoverable and irrecoverable pressure loss. The following is an excerpt from the 1948 study (pages 72-73):

For a relief valve having approximately 4 per cent blow-down (that is, the valve will snap shut when the pressure has decreased to 4 per cent below the opening or set pressure), these recommendations are made:

1. *The pressure drop due to friction should not exceed 1 per cent of the allowable pressure for capacity relief.*
2. *The pressure drop due to the conversion of pressure to kinetic energy, commonly referred to as velocity head loss, should not exceed 2 per cent of the allowable pressure for capacity relief.*

The first component of pressure loss is identified in item 1 as irrecoverable frictional loss. The second component is identified as a dynamic and recoverable component. The 1948 report further confirms that the dynamic component can be dominant for some pressure relief valves with large beta ratios (nozzle to inlet line):

Large size nozzle-type relief valves will tend to have a velocity head loss in excess of the 2 per cent allowance for instances where the friction loss is satisfactory. This condition may result in chattering and it is advisable to consider the use of a larger diameter inlet pipe.

The above excerpts from the 1948 report are still true today. The dynamic pressure loss component can be recovered if the flow is arrested at the PRV disk surface as the PRV tries to close. It is clear that the original 3 % rule was meant to include both dynamic and irrecoverable frictional pressure loss.

4 Why 3 % Does Not Work all The Time

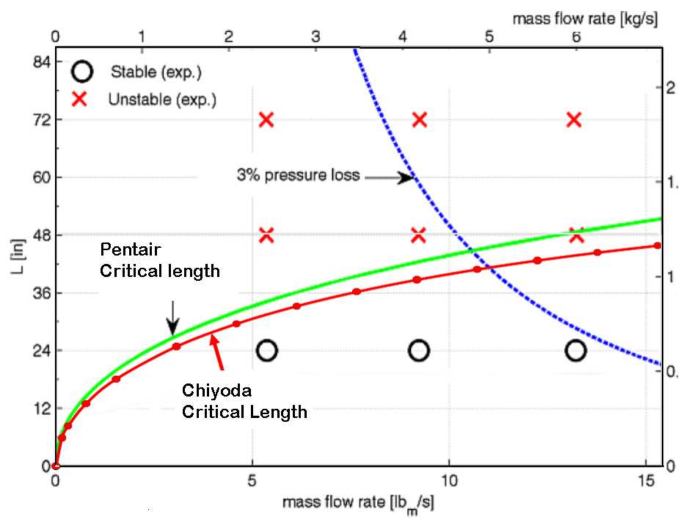
Sometime after 1948 the 3 % rule was adopted. Later, the rule was changed to apply to pressure relief valves with a nominal blowdown of 7 % where the requirement somehow became 3 % irrecoverable pressure loss only. There is an implicit assumption that the dynamic pressure component is always recovered for the 3 % rule to work as originally intended. We don't know exactly when the inlet pressure loss requirement was changed from total pressure loss to just irrecoverable pressure loss. But, the 1998 Edition of the CCPS Guidelines for Pressure Relief and Effluent Handling System states in section 2.4.2.2.1:

Note that the non-recoverable pressure loss from the vessel to the valve is less than the pressure drop, since the drop includes the change in velocity head from vessel to valve. This velocity head is recoverable (part of the lifting force on the disk), and thus is not included in the determination of inlet loss.

However, the dynamic pressure loss component can only be recovered at the disk surface (to keep the PRV open) by the returning reflected pressure wave from upstream if the PRV has not already fully closed. This means that the inlet line length has to be short enough to allow for the round trip travel time of the pressure wave to reach the disk surface before the PRV is fully closed. In other words, the round trip travel time has to be less than the closing time of the PRV. Therefore, the inlet line length cannot exceed a certain critical length value where the round trip pressure wave travel time is equal to the PRV closing time. This is called the critical line length. Normally the inlet line length should be less that 80 % of the critical line length to allow for uncertainties associated with flow rate and speed of sound estimates.

This places a strict limitation on the applicability of the 3 % rule to inlet lines where the acoustic length is less than 80 % of the critical line length, i.e. the returning pressure wave has to be recovered at the PRV disk surface before the PRV is fully closed. The 3 % rule as currently used cannot guarantee PRV stability if the inlet line is longer than 80 % of the critical line length.

Recent measurements and 1D dynamic modeling by several researchers confirm that the current 3 % rule is not sufficient to guarantee PRV stability. This is shown to the right. Pentair (also see [2]) test data is shown (open circles for stable behavior and X symbols for unstable behavior, 2J3 PRV, May 9th 2015, DIERS Meeting) along with Pentair analytical model predictions (green line). Additional data analysis (red line) is shown by Izuchi (also see [1]). As shown to the right, the 3 % rule only works when the inlet line length is less then the critical line length.



Methods for calculating the critical line length are available in several ioMosaic publications. The following references are suggested additional reading [3, 7, 8, 9, 10, 11]:

1. Analysis of PRV Stability in Relief Systems. Part I - Detailed Dynamics [3]
2. Analysis of PRV Stability in Relief Systems. Part II - Screening [7]
3. Analysis of PRV Stability in Relief Systems. Part III - How to Avoid the Singing Pressure Relief Valve Problem [8]
4. Analysis of PRV Stability in Relief Systems. Part IV - On the Estimation of Speed of Sound and Thermodynamic Properties for Fluid Flow and PRV Stability [9]
5. Analysis of PRV Stability in Relief Systems. Part V - Get a Handle on PRV Stability [10]
6. PRV Stability Inlet Line Critical Length. A Short Communication [11]

In particular, the Part V publication includes a video paper and several animations of PRV stability dynamics that illustrate the key concepts of PRV stability.

5 Why Do We Need to Bridge the 3 % Gap?

Our understanding of PRV stability is now much clearer but has not significantly changed since 1948. Despite our improved knowhow and widely accepted hazard recognition caused by PRV instability (3 % rule does not work all the time), standards making organizations such as ASME [12] and API still recommend and support its use for new and modified installations. Because the potential hazard is now widely recognized and can be significant especially for liquid and high pressure systems, the 3 % rule cannot continue to be used in its current form.

The underpinnings of the original 3 % rule are essentially the same as the recommended force balance highlighted in recent editions of API 520. The original 3 % inlet pressure loss rule was intended to include the dynamic component of pressure loss in the inlet line in addition to frictional loss. Because the dynamic component of pressure loss is more significant than frictional pressure loss (and is most significant for liquid flow), we cannot continue to use the 3 % rule with irrecoverable pressure loss only. The original 3 % rule (total pressure loss) provided for a 1 % margin between total pressure drop and blowdown.

6 How Do We Bridge the 3 % Gap?

We can bridge the gap between where we are now with the 3 % rule and where we need to get to. PRV stability for new and modified installations should be determined using a simple combined force balance/critical length method or using detailed 1D dynamics.

The recent publication of ASME Section XIII [13], rules for overpressure protection, requires that the inlet pressure drop and backpressure do not adversely affect the operation of the relief device without specifying any limits:

12.5 INLET PIPING (b) - The pressure drop through the upstream system to the pressure relief valve shall not reduce the relieving capacity below that required to prevent the pressure from exceeding its maximum allowed relief pressure or adversely affect the proper operation, including stability, of the pressure relief valve.

12.8 DISCHARGE PIPING (a) - The size of the discharge lines shall be such that any pressure that may exist or develop will not reduce the relieving capacity of the pressure relief devices below that required to properly protect the pressurized equipment, or adversely affect the proper operation of the pressure relief devices.

However, one should note that the current 3 % rule remains referenced in the non mandatory Appendix M-6 of ASME VIII [14]. Appendix M-6 clearly delineates recoverable and irrecoverable pressure losses but also fails to recognize that the recoverable losses must be considered as well. If a company elects to use this non mandatory Appendix for compliance, then the current 3 % still applies.

Companies that want to continue to use the 3 % rule in its current form using irrecoverable pressure loss should restrict its use. Either (a) use the current 3 % rule but only where the inlet line length is less than 80 % of the critical line length or (b) use the original form of the 3 % rule with the percent total pressure drop (dynamic and frictional) limited to percent blowdown (typically 7 %) minus 1 or 2 %. The total pressure drop method is essentially equivalent to the force balance described in API 520 [4].

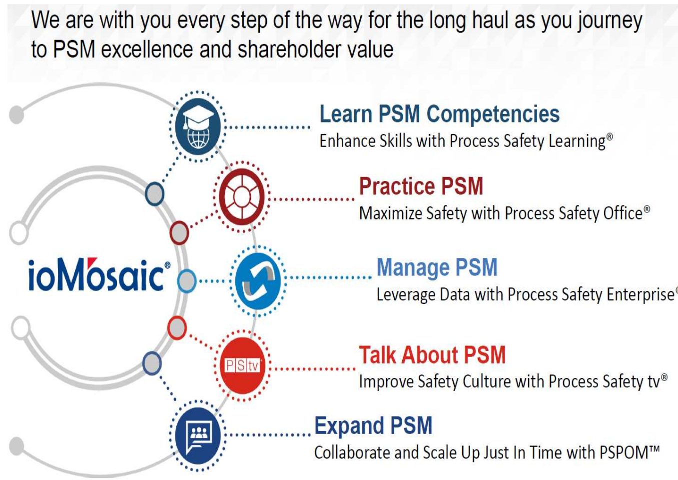
7 Conclusions and Recommendations

The current 3 % inlet line pressure loss rule should not be used unless the inlet line is shorter than the critical length (80 % of critical length). When using 3 % irrecoverable pressure loss as the sole criterion for PRV stability, the inlet line length must be less than the critical line length and the backpressure must be within tolerable limits. If the critical line length is not used, then the total percent pressure drop (frictional and dynamic) must be less than percent blowdown minus 1 or 2 percent.

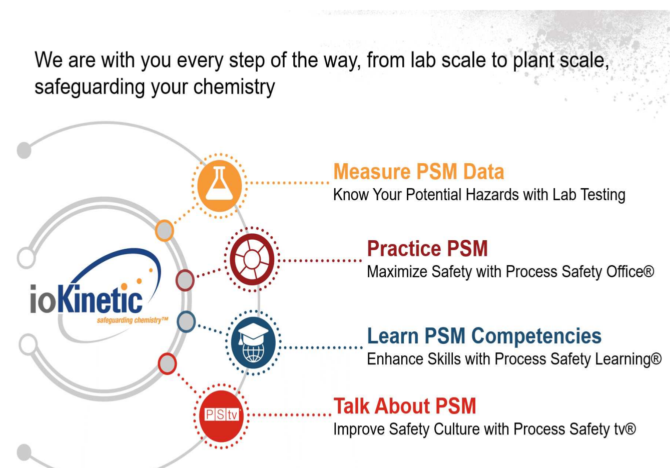
The 3 % rule should be replaced with the API force balance coupled with critical line length for simple piping geometries, where the inlet line length is less than the critical line length criterion. Detailed 1D dynamics should be used for complex piping geometries, especially where the inlet line length is greater than the critical line length.

How can we help?

In addition to our deep experience in process safety management (PSM) and the conduct of large-scale site wide relief systems evaluations by both static and dynamic methods, we understand the many non-technical and subtle aspects of regulatory compliance and legal requirements. When you work with ioMosaic you have a trusted ISO certified partner that you can rely on for assistance and support with the lifecycle costs of relief systems to achieve optimal risk reduction and PSM compliance that you can evergreen. We invite you to connect the dots with ioMosaic.



We also offer laboratory testing services through ioKinetic for the characterization of chemical reactivity and dust/flammability hazards. ioKinetic is an ISO accredited, ultra-modern testing facility that can assist in minimizing operational risks. Our experienced professionals will help you define what you need, conduct the testing, interpret the data, and conduct detailed analysis. All with the goal of helping you identify your hazards, define and control your risk.



Please visit www.iomosaic.com and www.iokinetic.com to preview numerous publications on process safety management, chemical reactivity and dust hazards characterization, safety moments, video papers, software solutions, and online training.

References

[1] Hisao Izuchi. Stability analysis of safety valve. In *10th Topical Conference on Gas Utilization*. AIChE, AIChE, 2010.

[2] C. J. Hos, A. R. Champneys, K. Paul, and M. McNeely. Dynamic behavior of direct spring loaded pressure relief valves in gas service: II reduced order modelling. *Journal of Loss Prevention in the Process Industries*, 36:1–12, 2015.

[3] G. A. Melhem. Analysis of PRV stability in relief systems. Part I - Detailed dynamics. *ioMosaic Corporation White Paper*, 2014.

[4] API 520. Sizing, selection and installation of pressure-relieving devices in refineries. Parts I and II, March 2020.

[5] C. Cunio and G. A. Melhem. A guide to the legal framework of the PSM standard for engineers. *Process Safety Progress*, 33(2):152–155, June 2014.

[6] N. E. Sylvander and D. L. Katz. The design and construction of pressure relieving systems. Technical Report Engineering Research Bulletin 31, University of Michigan, April 1948.

[7] G. A. Melhem. Analysis of PRV stability in relief systems. Part II - Screening. *ioMosaic Corporation White Paper*, 2014.

[8] G. A. Melhem. Analysis of PRV stability in relief systems. Part III - How to avoid the singing pressure relief valve problem. *ioMosaic Corporation White Paper*, 2014.

[9] G. A. Melhem. Analysis of PRV stability in relief systems. Part IV - On the estimation of speed of sound and thermodynamic properties for fluid flow and prv stability. *ioMosaic Corporation White Paper*, 2017.

[10] G. A. Melhem. Analysis of PRV stability in relief systems. Part V - Get a handle on PRV stability. *ioMosaic Corporation White Paper*, 2019.

[11] G. A. Melhem. PRV stability inlet line critical length. A short communication. *ioMosaic Corporation White Paper*, March 2021.

[12] ASME. Boiler and pressure vessel code. section VIII, rules for construction of pressure vessels, 2019.

[13] ASME. Boiler and pressure vessel code. Section XIII, rules for overpressure protection, 2021.

[14] ASME. Boiler and pressure vessel code. Section VIII, rules for construction of pressure vessels, 2021.

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

ioMosaic®

Minimizing risk. Maximizing potential.®

US Offices

New Hampshire (Salem) – *Headquarters*

Texas (Houston)

Minnesota (Minneapolis)

California (Berkeley)

International Offices

Kingdom of Bahrain (Al Seef)

United Kingdom (Bath)

Software Solutions

[Process Safety Enterprise®]

Centralize the process safety management lifecycle to accelerate business goals

[Process Safety Office®]

Identify, evaluate, and control process hazards with tools used by process safety consultants

[Process Safety Learning®]

Build your process safety competencies incrementally with online training

[Process Safety tv®]

View, share, and discuss PSM worldwide on a secure platform

Contact Us

www.ioMosaic.com

sales@ioMosaic.com

1.844.ioMosaic

About ioMosaic Corporation

Through innovation and dedication to continual improvement, ioMosaic has become a leading provider of integrated process safety and risk management solutions. ioMosaic has expertise in a wide variety of areas, including pressure relief systems design, process safety management, expert litigation support, laboratory services, training and software development.

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.

Our mission is to help you protect your people, plant, stakeholder value, and our planet.

Consulting Services

- Asset Integrity
- Auditing and Due Diligence
- Combustible Dust Hazard Analysis and Testing
- Facility Siting
- Fault Tree/SIL/SIS Analysis
- Fire and Explosion Dynamics
- Incident Investigation, Litigation Support and Expert Testimony
- Liquefied Natural Gas Safety
- Pipeline Safety
- Process Engineering Design and Support
- Process Hazards Analysis (PHA)
- Process Safety Management (PSM)
- Reactive Chemicals Evaluation and Testing
- Relief and Flare Systems Design and Evaluations
- Risk Management Program Development
- Quantitative Risk Assessments (QRA)
- Software Solutions
- Structural Dynamics
- Training

Laboratory Testing Services (ISO accredited)

- Chemical Reactivity
- Combustible Dust
- Battery Safety
- Specialized Testing