Pressure Relief Device Inlet Pressure Loss – A Primer

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Abstract

The API and ASME guidelines and standards for emergency relief systems both state that total non-recoverable inlet pressure losses between protected equipment and a spring-loaded relief valve should be limited to 3% of the relief valve set pressure. Inlet pressure losses above this limit may experience ‘chatter,’ which can lead to damage of equipment, valves, and piping. The API standards allow for inlet pressure loss beyond 3%, with a proper engineering analysis. Consistent with the performance-based nature of these guidelines, operating companies can define what a proper engineering analysis is and often such an analysis can be experience based. The requirement for inlet pressure loss, be it 3 % or higher, is not sufficient to guarantee pressure relief valve (PRV) stability.

This issue is a hot topic which is currently being debated within industry and regulators. Regulatory authorities in the United States have recently imposed fines on companies which had relief valves which did not comply with these criteria. The outcome of these discussions will have widespread implications affecting most petrochemical companies.

This paper presents a summary of the history and application of the 3% rule, and presents practical mitigation options for companies trying to follow this rule. It will benefit anyone involved in safety and pressure relief systems.

How a Spring-Loaded Relief Valve Works

Spring-loaded relief valves are one option for providing overpressure protection to process equipment. They are self-actuating valves which open at a predetermined pressure in order to protect a vessel or system from excess pressure by venting fluid from that vessel or system.

Spring-loaded relief valves are available either as conventional or balanced bellows, and are available in a variety of sizes.

The basic components of a spring-loaded relief valve include an inlet nozzle connected to the vessel or system to be protected, a movable disk which controls flow through the nozzle, and a spring which controls the position of the disk. Under normal system operating conditions, the pressure at the inlet is below the set pressure and the disk is seated on the nozzle, preventing flow through the nozzle.

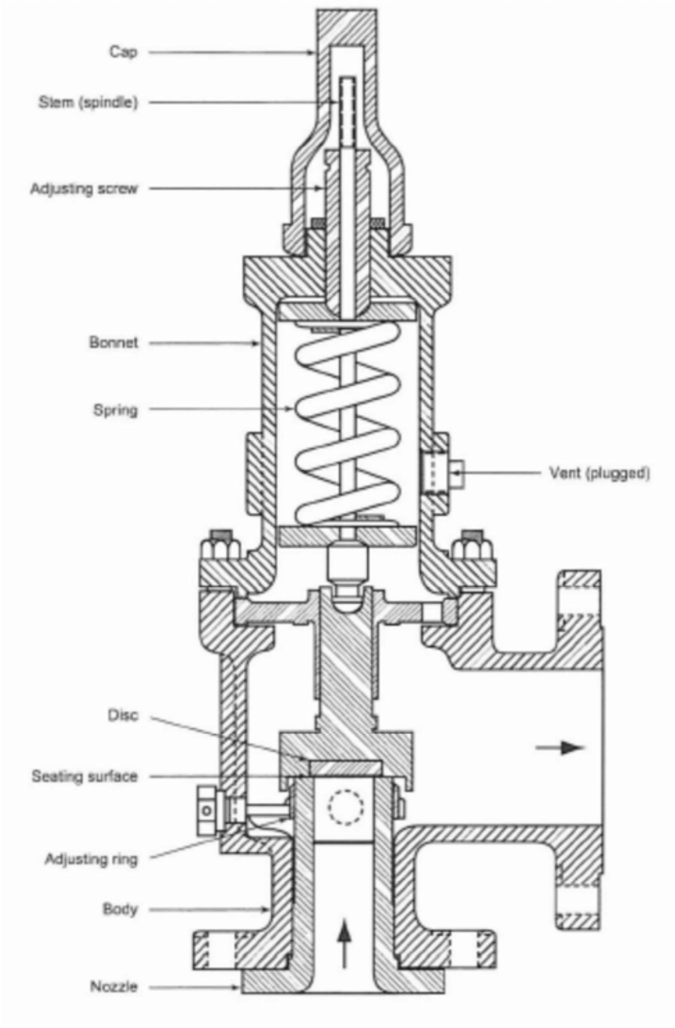

Figure 1: Basic Components of a Conventional Relief Valve (Source: API Standard 520 Part 1, Figure 1)

Spring-loaded relief valves operate on a snap-action basis, meaning that the valve will 'pop' open when a specific pressure is reached. Without this feature, the relief valve would lift gradually and uncertainly. Figure 2 shows the typical main stages of a relief valve actuation, which are described below. It should be noted that the opening and closing characteristics of a relief valve can vary. The manufacturer flow curves should be consulted if available.

Stage 1 – Closed: Inlet pressure is below relief valve set pressure. The relief valve remains closed, with no flow through the valve.

Stage 2 – Simmering: As pressure increases within the protected system, the inlet pressure increases to equal the relief valve set pressure. This is where the inlet (system) pressure exactly matches the closing force exerted by the relief valve spring pushing downward. As the inlet pressure continues to rise, the valve disk starts to lift, releasing a small amount of fluid.

Stage 3 – Pop Opening: This is where the snap-action comes into effect. Sufficient fluid has entered the relief valves huddling chamber so that the inlet pressure is acting on a larger area, thereby producing a significant force greater than the spring force pushing downward. This is enhanced by the reaction force of the kinetic energy of the fluid passing through the huddling chamber. The resulting effect is that the valve snaps open with a positive movement, forming a larger flow area for the fluid and giving a quick, but controlled, release of overpressure.

Stage 4 – Reseating: As overpressure is released and the system pressure starts to decrease, the relief valve will close under the effect of spring pressure. This process is known as blowdown. The pressure at which the valve reseats is controlled by the blowdown ring.

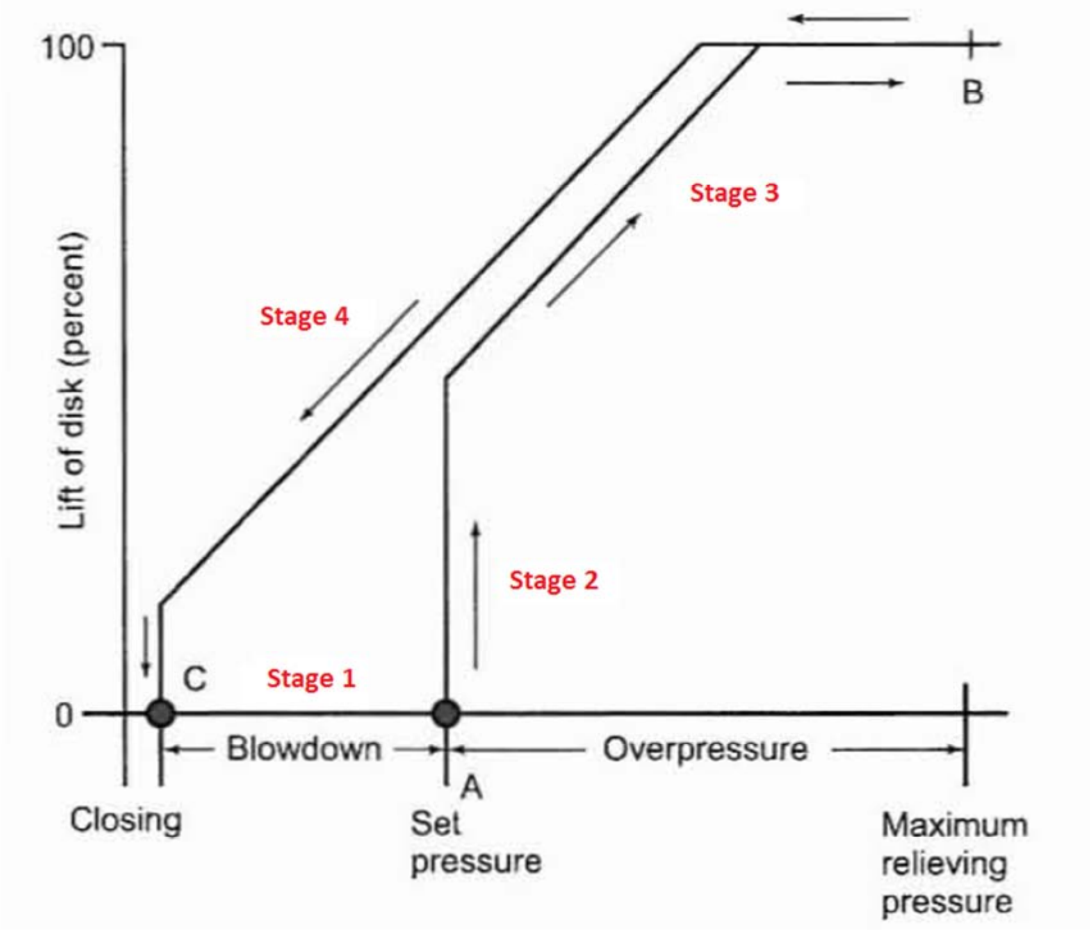

Figure 2: Main Stages of a Relief Valve Actuation (Source: API Standard 520 Part 1, Figure 6)

Chatter

Chatter is an undesirable situation, where there is an abnormal, rapid, reciprocating motion of the movable parts of a PRV, in which the disk contacts the seat.

Possible consequences of chatter include reduced flow capacity, increased pressure accumulation in the vessel, damage to the valve seating surfaces, and mechanical failure of valve and piping with consequent loss of containment of process fluids.

Chatter can be caused due to the following reasons:

1. Oversized pressure relief valve
2. Inlet piping has excessive length or fittings
3. Inlet piping is undersized, therefore starving flow to the relief valve
4. Outlet piping has excessive length
5. Outlet piping is undersized for relief valve
6. The blowdown adjusting ring may be set too high

Chattering relief devices are known to contribute to process safety incidents. In 1976, the API conducted a survey of chatter incidents recorded by their member companies. The responses they received spanned fourteen (14) companies and covered thirty nine (39) facilities. Table 1, below, summarizes the findings:

Table 1: API Relief Valve Chatter Survey Findings

Size of Relief Valve	Incidents	Leaks/Failures
3/4 x 1	1	0
1 1/2 x 2 1/2	1	1
1 1/2 x 3	1	1
2 x 3	3	1
2 1/2 x 4	2	0
3 x 4	9	4
4 x 6	16	6
6 x 8	7	5
Unknown	2	1
Total:	**42**	**19**

Four (4) of the leaks/failures listed in the above table were known to have led to fires. Probably the most notable known process safety incident which arose from relief valve chatter was the 1978 Conoco Commerce City Refinery fire, where piping in a propane/butane splitter system failed. It was found that the inlet pressure loss of the relief valve on the overhead line exceeded 5%, and that the relief valve inlet line was not well supported to handle acoustic or flow induced vibration. The incident resulted in three fatalities, and up to 25% of the facility was destroyed.

The History of the 3% Rule

When it comes to pressure safety valves (PSV), the “3% rule” has been the target to avoiding chatter. It is assumed that when irrecoverable inlet pressure losses are limited to less than 3% of the set pressure, that a properly set and sized PSV will operate stably and chatter free ensuring protected systems stay within their allowable accumulation limits.

Both the American Petroleum Institute’s (API) RP-520 Part II, 5th Ed (2003), Section 4.2.2 and the American Society of Mechanical Engineers (ASME) Section VIII, Div. 1 (2005 Ed), Appendix M-6(a), are both considered recognized and generally accepted good engineering practices (RAGAGEPs).

API RP 520, Section 4.2.2 states the following for spring-loaded relief valves:

> “When a pressure-relief valve is installed on a line directly connected to a vessel, the total non-recoverable pressure loss between the protected equipment and the pressure-relief valve should not exceed 3 percent of the set pressure of the valve.”

Additionally, API RP 520, Section 4.2.2 also states:

> “An engineering analysis of the valve performance at higher inlet losses may permit increasing the allowable pressure loss above 3 percent.”

However, guidance is minimal regarding what such an engineering analysis might entail.

Additionally, the American Society of Mechanical Engineers (ASME) Section VIII, Div. 1 (2005 Ed), Appendix M-6(a) states:

> “The nominal pipe size of all piping, valves and fittings, and vessel components between a pressure vessel and its safety, safety relief, or pilot operated pressure relief valves shall be at least as large as the nominal size of the valve inlet, and the flow characteristics of the upstream system shall be such that the cumulative total of all nonrecoverable inlet losses shall not exceed 3% of the valve set pressure.”

Notably, both of these documents are ‘non-mandatory’, but both are considered RAGAGEPs.

The approach to inlet pressure drop has changed progressively with updates of pertinent codes and standards. Consideration of inlet pressure loss can be traced over the following time period:

1955 – API Recommend Practice 520, First Edition. The first edition did not provide guidance or limits related to inlet pressure loss.

1963 – API Recommended Practice 520, Part II, First Edition. Inlet pressure loss was limited to 3% of set pressure.

1986 – ASME Sec VIII (non-mandatory Appendix-M) incorporated language limiting PRV inlet pressure drop to 3% of set pressure.

1994 – API 520, Part II, Fourth Edition introduced wording to allow inlet pressure losses to exceed 3%, when supported by an engineering analysis.

The original guidance regarding inlet pressure loss was based on research conducted by the University of Michigan, which was sponsored by the API. Sylvander and Katz published, *"The Design and Construction of Pressure Relieving Systems"* in the University of Michigan Press in 1948, which stated:

> "If an excessive pressure drop occurs through the inlet piping, the valve tends to close prematurely. ... This action results in what is commonly referred to as "chattering."
>
> "For a relief valve having approximately 4 percent blow-down (that is, the valve will snap shut when the pressure has decreased to 4 percent below the opening or set pressure), these recommendations are made:
>
> > The pressure drop due to friction should not exceed 1 percent of the allowable pressure for capacity relief.
> >
> > The pressure drop due to the conversion of pressure to kinetic energy, commonly referred to as velocity head loss, should not exceed 2 percent of the allowable pressure for capacity relief."

It should be noted, that the combined 3% pressure loss limit was based on a 4% blowdown, which was typical for relief valves in the 1940s. Additional guidance was published in 1963 by E. Jenett supporting the API introduction of 3% inlet pressure drop based on a 5% blowdown typical for PRVs in the 1960s (providing a 2% margin).

Over time, the typical blowdown setting of a relief valve has increased from 4% in the 1940s to 7% used in today's industry. On that basis, the argument could be made that the 3% inlet pressure loss value could be increased.

However, it should be noted that limiting a relief valve's inlet pressure loss to 3% of the set pressure may not necessarily guarantee stable operation. Recent test results of 18 relief valves with 3 different inlet line lengths showed "unstable" operation for 5 tests, when the inlet pressure drop was less than 3% of the set pressure. These 5 tests covered 3 different relief valves.

Additionally, inlet pressure losses exceeding 3% of the set pressure do not necessarily result in chatter. The same test results showed "stable" operation for 11 tests where the inlet pressure drop was greater than 3% of the set pressure. Additional test results showed that a 6R10 relief valve did not exhibit instability with measured inlet losses at 6.1% of set pressure.

Discussions have often focused around maintaining a safety margin between the inlet pressure loss and blowdown (often suggesting a value of 2%). Test results showed stable operation for 4 tests with a margin of less than 2% between the measured blowdown and inlet pressure loss. Conversely, three of the tests resulted in unstable operation with a margin greater than 3%. To complicate the subject of blowdown and maintaining a "suitable" margin, it can be difficult to test and verify reseat pressures.

The above experiments can lead to the following conclusions:

- Limiting the irreversible inlet pressure drop to 3% of the set pressure does not guarantee that a relief valve will behave in a stable manner

- Exceeding 3% of the set pressure does not mean that a relief valve will chatter
- Maintaining a reasonable margin between inlet losses and blowdown is difficult to verify (and inconclusive regardless)

There are many well-researched publications and presentations that put forward additional considerations to ensure safe operation and are well summarized in the DIERS, *"Interim Research Report on Safety Relief Valve Stability and Piping Vibration Risk – 2003–2012."* It is clear that in addition to irreversible inlet pressure drop, the entire picture of relief valve stability and safe operation should consider several factors including, but certainly not limited to:

- Acoustic length of inlet and discharge lines
- Body bowl choking
- Piping vibration risk
- Backpressure
- Relief line geometry
- Free-draining piping
- Oversized pressure safety valves (PSVs)
- Restrictions in the relief path
- Mass of moving PSV parts
- Relief valve trim (liquid versus vapor)
- Relief valve action (pop versus modulating)

In conjunction with these developments, rigorous software tools such as SuperChems™ Expert can incorporate the latest complex modeling techniques to analyze relief system installations, including everything from acoustic affects to a relief valve's dynamic response to system re-pressurization. Furthermore, explicit guidance regarding what constitutes an engineering analysis to evaluate PSV installations is anticipated in the 6th edition of API RP-520, Part II.

When considering pressure losses that are only marginally above 3% of the set pressure, it is important to consider the overall risk. Modifying piping or changing relief valves, which necessitate procedures for shutdowns, start-ups, and hot work on pipe and vessels, may increase the overall risk associated with the system, as well as potentially incurring injury to those conducting the work.

While it may be difficult to ensure the stable operation of a relief valve, a detailed analysis of the entire installed system can be performed to catch conditions that may lead to chattering. The "3% Rule" is a historically sound guideline, but the irreversible inlet losses are only part of the story; relief system designers must consider several other factors to determine if an installation is truly adequate and safe.

Mitigation Options

As stated above, the "3% Rule" is a historically sound guideline which has recently been enforced by OSHA during their National Emphasis Programs (NEP). However, many facilities will find themselves struggling to comply with this requirement.

In fact, studies have shown that a significant portion of installed relief valves may exceed the 3% rule:

- One study found that 1,072 relief valves in a 13,049-item sample pool exceeded 3% inlet pressure loss (8.2%)
- Another study found that 64 relief valves in a 550-item sample pool exceed 3% inlet pressure loss (12%)

For relief valves whose inlet pressure losses exceed 3%, there are a number of mitigation options available to address this issue. Options include:

1. Avoid turns, elbows, and sharp area reductions in inlet and outlet lines.
2. Use long radius elbows.
3. Use rounded nozzles at the equipment connection to the relief valve piping
4. Use multiple valves with staggered set pressures when the lowest required contingency rate is less than 25% of the highest rate
5. Use larger inlet piping. Some valves are inherently problematic. Enlarged inlet pipe diameter is almost always required for:
   a. 4P6, 6R8, 6R10 and 8T10
   b. Installations with three-way valves
   c. All relief valves used in series with rupture disks
   d. 1.5H3, 2J3, 3L4, and 6Q8 with shut-off valve, and L/D=5
6. If you cannot enlarge the inlet piping:
   a. Install a smaller relief valve or use a restricted lift valve
   b. Install a different type of relief valve (for example, a pilot valve)
7. Ensure your relief valve calculations accurately consider all of the above, and use accurate field-verified data!

Conclusions

The “3% Rule” is a historically sound guideline, which is considered RAGAGEP within industry. Users should also be aware of the “engineering analysis” clause referenced in API RP 520, Part II, which can permit inlet piping losses to exceed 3%.

It must be recognized that relief valve installations with less than 3% inlet line loss can still experience chatter. Conversely, relief valve installations with inlet pressure loss exceeding 3% can function without chattering.

When considering the adequacy of relief valve installations, a range of criteria including pressure losses should be considered.

The issue is currently generating a lot of discussion within industry working groups, and hopefully further clarification will be provided in future editions of RAGAGEP guidelines and standards.

References

"Sizing, Selection, and Installation of Pressure Relief Devices in Refineries," 8th Edition, API Standard 520, Part I (2008).

"Sizing, Selection, and Installation of Pressure Relief Devices in Refineries" 5th Edition, API Recommended Practice 520, Part II (2003).

"Pressure-relieving and Depressuring Systems" 5th Edition, ANSI/API Standard 521 (ISO 23241) (2007)

"Guidelines for Pressure Relief and Effluent Handling," 1st Edition, AIChE/CCPS (1998)

"Analysis Identifies Deficiencies in Existing Pressure Relief Systems," Berwanger, P.C., R A. Kreder, W. Lee; Process Safety Progress Volume 19, Number 3 (2000)

"Interim Research Report on Safety Relief Valve Stability and Piping Vibration Risk 2003 – 2012," AIChE/DIERS (2012)

"A Review of PRV Chatter Incidents," Otis, B., API 520 Subcommittee Meeting (2011)

"Relief Device Inlet Piping: Beyond the 3 Percent Rule," Smith D., J. Burgess, C. Powers; Hydrocarbon Processing (2011)

"The Design and Construction of Pressure Relieving Systems," Sylvander, N., D. Katz; Engineering Research Institute (1948)