SOLVING PRESSURE RELIEF VALVE AND PIPING CAPACITY PROBLEMS

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ABSTRACT

Engineers often uncover problems or inadequacies with pressure relief valve and relief system piping capacities that need creative and cost effective solutions. These problems may surface in many ways. For example, when attempting to close a HAZOP recommendation, it may be discovered that the pressure relief valve (PRV) capacity is inadequate. A debottlenecking study may reveal that a PRV is too small or backpressure is excessive. While updating process safety information (PSI), calculations for an installed PRV may indicate that PRV inlet piping pressure drop exceeds the 3% rule. Resolving inadequacies in pressure relief systems must be addressed to ensure this important safety system will perform its function during an emergency overpressure event, and to meet industry codes, standards and RAGAGEP. Increasing pipe sizes to solve capacity problems can be costly, so alternative, creative solutions are needed. In this paper, Trimeric Corporation explores practical solutions to solve PRV and inlet/outlet piping capacity issues. "Rules of thumb" commonly applied to pressure relief systems and ideas for avoiding piping rework are also discussed.

I. Introduction

Overpressure protection and pressure relief systems are subject to design iterations as a facility goes through phases for 1) overpressure scenario cause evaluation, 2) relief scenario flow rate (relief load) estimating, 3) preliminary design, 3) PRV selection and implementation, 4) changes to process requirements, and 5) Process Safety Management validation checks. Many relief system capacity inadequacies that arise can be resolved by understanding and leveraging the design interrelationships between the PRV and the inlet piping and outlet piping. This paper 1) explains common rules of thumb applied to PRV systems for initial design, and then 2) suggests practical ideas to solve PRV and piping capacity problems for existing installations without requiring major piping rework. The application is for overpressure protection of pressure vessels governed by American Society of Mechanical Engineers Boiler and Pressure Vessel Code Section VIII (ASME Code), and pertains to conventional, balanced bellows, and pilot-operated PRVs designed in accordance with American Petroleum Industry (API) standards API 520, 521, and 526. The API standard references in this paper are from the most recent versions issued (520 Part I 9th Ed., 520 Part II 6th Ed., 521 6th Ed., and 526 7th Ed.).

II. PRV Rules of Thumb Explained

Design of a pressure relief system that will perform and meet the requirements of each overpressure scenario identified can be complex. "Rules of thumb" for PRVs and relief system piping design provide useful starting assumptions for developing initial estimates for overpressure protection. Understanding the origins and application of the rules of thumb helps when navigating options for overpressure protection. The common rules of thumb are generally based on the design limitations of a conventional PRV, which has been the workhorse of the industry. The conventional PRV traditionally has been the most commonly encountered PRV type because it is simple, reliable, and cost effective.

It is important to understand the design differences between conventional, balanced bellows, and pilot-operated PRVs and their operating characteristics in order to properly apply the rules of thumb. While there are other factors to consider, the focus in this paper is on the different way each valve type is designed to respond to inlet pressure and pressure at the valve outlet (backpressure).

A conventional PRV is a spring-loaded valve, activated by inlet pressure and with a relief capacity and opening pressure directly affected by changes in backpressure. A balanced bellows PRV is designed to minimize the effect of backpressure as a closing force by adding a "bellows" to the conventional PRV design. The balanced bellows PRV design mitigates the effect of backpressure on the valve's relief capacity and opening pressure by isolating parts of the valve from the backpressure and thereby balancing the opening and closing forces. A pilot-operated PRV is a valve in which the major relieving device (main valve) is combined with and controlled by a self-actuated auxiliary pressure-relief valve (pilot). The pilot-operated PRV tolerates much higher backpressure than either the conventional PRV or balanced bellows PRV, and the opening pressure for the main valve is not affected by backpressure; however, its capacity may be reduced in some situations. When backpressure is higher than can be tolerated by a conventional PRV or when backpressure is variable due to multiple relief or vent sources that may be present in a closed disposal system (e.g., flare vent header), the design features of balanced bellows and pilot-operated PRVs may make them a better fit in certain process applications and help them operate with more stability than a conventional PRV.

A. API Preliminary PRV Sizing

"API preliminary PRV sizing" is more than a rule of thumb. It is an initial method for calculating and identifying a nominal PRV orifice for a required relief load. A nominal PRV orifice size may be chosen by 1) comparing PRV orifice areas calculated for each overpressure scenario relief load, 2) identifying the largest orifice area calculated, and 3) selecting the API nominal orifice area that exceeds the largest calculated orifice area. A capacity can be calculated for the nominal PRV orifice area selected and nominal PRV inlet and outlet connection pipe sizes can be identified. This information may be used for preliminary design of the PRV inlet and outlet relief piping. API standardization of nominal PRV orifice sizes, valve dimensions, and other characteristics allows the engineer to make an initial PRV nominal size selection that is consistent with the requirements of the ASME Code. API standardization provides a common basis to identify comparable PRVs from different manufacturers, thereby facilitating selection and specification of a manufacturer's PRV model suitable for an application with predictable valve performance and with the same physical dimensions for interchangeability in the piping system. Once a specific PRV model is selected, ASME Code and API require that the selected PRV and relief system piping capacity is verified to be sufficient for the application.

Individual PRVs are characterized by their discharge orifice area and their coefficient of discharge. API provides sizing equations to calculate the PRV orifice area required for a relief load based on a PRV's coefficient of discharge and the relieving fluid phase and thermodynamic characteristics. For a specific fluid and relieving condition, the relief load mass flow rate (W) through a PRV is proportional to the product of the PRV coefficient of discharge (K_d) and the PRV orifice area (A). As an example of this relationship, the API sizing equation for an ideal gas at critical flow through a PRV with U.S. conventional units is shown in Equation 1 (API 520 Part 1 Section 5.6.3).

$$A = \frac{W}{CK_dP_1K_bK_c}\sqrt{\frac{TZ}{M}} \qquad \text{Equation 1}$$

Where:

A required effective discharge area of the device, in^2

W required relief flow through the device, lb/h

C orifice factor that is a function of the ratio of the ideal gas specific heats ($k = C_p/C_v$), dimensionless (Equation 2)

$$C = 520\sqrt{k\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \qquad \text{Equation 2}$$

K_d effective coefficient of discharge (0.975 is API preliminary value for gases), unitless

P_1 upstream relieving pressure, psia
K_b capacity correction factor due to backpressure, unitless
K_c combination correction factor for installations with a rupture disk upstream of the PRV, unitless
T relieving temperature of the inlet gas or vapor, °R
Z compressibility factor, unitless
M fluid average molecular weight, lb/lbmol (g/gmol)

For the API preliminary PRV sizing method, API 520 Part I provides assumed "preliminary effective" values for the coefficient of discharge (K_d) corresponding to the fluid phase to be relieved and the appropriate sizing equation. API 526 provides a list of nominal "effective" orifice area values (A), and designates each size with a letter, D through T. A list of the nominal API effective orifice areas is shown in Table 1.

Table 1. Nominal Orifice Areas for API 526 PRVs.

API Letter Designation	Effective Orifice Area (square inches)
D	0.110
E	0.196
F	0.307
G	0.503
H	0.785
J	1.287
K	1.838
L	2.853
M	3.600
N	4.340
P	6.380
Q	11.05
R	16.00
T	26.00

The API preliminary effective coefficient of discharge value can be used to calculate a required effective orifice area for a relief load, using the appropriate API sizing equation and the particular fluid characteristics (phase, thermodynamic properties, and relieving conditions). The largest effective orifice area calculated considering all potential relief loads for the PRV is the minimum orifice area required for initial design, and determines the relief scenario PRV sizing case and required relief load. Comparing the minimum required "effective" orifice area to the API 526 list of nominal effective orifice areas allows selection of an API letter-designated orifice size.

Manufacturers use the API letter designations to identify actual valve models that will meet or exceed the API nominal PRV capacities and other API valve characteristics (note that there are exceptions). PRVs that meet the requirements of API 526 are commonly referred to as "API valves" and are listed in the manufacturer's literature with the API orifice size letter designation. Valves manufactured to meet API 526 standard dimensions by different manufacturers will be physically interchangeable. However, API 526 effective orifice areas are "nominal" values for use in preliminary sizing calculations - they are not actual orifice areas for any particular valve.

Once the engineer selects the actual PRV model for installation, PRV sizing calculations must be repeated for final sizing verification using the manufacturer's ASME Code capacity certified values for the "actual" rated flow coefficient of discharge and "actual" orifice (discharge) area. For example, the manufacturer's "actual" values would be substituted for the API "effective" values in Equation 1. This subsequent calculation step is the "ASME PRV sizing", and is required by the ASME Code to confirm that the actual PRV model and associated piping will prevent overpressure of the vessel. *API "effective" values and ASME "actual" values for the discharge coefficient and orifice area must not be mixed and matched in PRV sizing equations* (API 520 Part 1 Section 5.2.5).

1. 3% Rule for Inlet Piping

The "3% rule for inlet piping" is a design guideline to limit the pressure drop in the piping between the protected vessel and the pressure relief device to no more than 3% of PRV set pressure (in psig). The 3% rule allows the engineer to estimate inlet piping dimensions for preliminary design, and then confirm the adequacy of the design for the actual valve selected.

Except for modulating pilot-operated PRVs (as opposed to pop-action), inlet piping pressure drop is calculated using the "actual" rated capacity of the PRV for the fluid relieved rather than the required relief load. The PRV actual capacity often is significantly higher than the required relief capacity. The reason is due to discrete steps in API orifice size, which can be seen in is shown in Table 1.

Table 1. The required orifice in many cases is slightly larger than one of the nominal sizes, leading to a big step up in orifice area and corresponding capacity. For example, the increase in area between an "F" and "G" orifice is 64%.

Excessive pressure losses in the inlet piping can reduce the system's relieving capacity, can cause pressure in the vessel to exceed the protected vessel's ASME Code allowed maximum accumulated pressure, and cause valve instability, for example "chattering". Chattering is rapid opening and closing of the PRV, which can lead to reduced flow capacity, mechanical damage, and in the worst case, loss of containment.

Following the 3% rule provides a margin between the pressure at the PRV inlet when flowing and the PRV's typical reseating or closing pressure. "Blowdown" is the term used for the difference between the set pressure and closing pressure, and is typically 7 to 10% of set pressure (in psig). Inlet piping pressure drop (non-recoverable losses) must be less than blowdown to prevent rapid cycling open and closed or valve chatter. Table 2 provides an example to show how inlet piping pressure drop may cause chatter when greater than blowdown.

Table 2. Chatter Example for 3% and 10% Inlet Piping Pressure Drop

	Inlet Piping Pressure Drop LESS Than Blowdown	**Inlet Piping Pressure Drop GREATER Than Blowdown**
	No Chatter	**Chatter**
PRV Example		
Set Pressure	100 psig	100 psig
Inlet Piping Pressure Drop	3% of Set Pressure	10 % of Set Pressure
Approximate Pressure Drop	3 psi	10 psi
Blowdown	7% of Set Pressure	7% of Set Pressure
Blowdown	7 psi	7 psi
Reseating Pressure	93 psig	93 psig
PRV is Closed Preceding Overpressure Event		
Vessel Pressure	100 psig	100 psig
PRV Inlet Pressure	100 psig	100 psig
PRV Response	PRV Opens	PRV Opens
Inlet Piping Pressure Drop	~3 psig	~10 psig
Vessel Pressure	100	100
PRV Inlet Pressure	97	90
PRV Response	Stays Open Since Above Reseat Pressure	PRV Closes as Soon as Flow Established Since Below Reseat Pressure
Overpressure Event Continues…		
Vessel Pressure	100	100+ psig
PRV Inlet Pressure	97	100+ psig
PRV Response	Stays Open Since Above Reseat Pressure	PRV Re-Opens Immediately Since Above Set Pressure
PRV Will Close…		
PRV Inlet Pressure	≤93 psig	≤93 psig
Vessel Pressure	96 psig = 93 psig + 3psig	103 psig = 93 psig + 10psig
PRV Response	PRV Closes	PRV Closes
PRV Inlet Pressure = Vessel Pressure	96 psig	103 psig
PRV Response	Stays Closed Since Below Set Pressure	Re-Opens Immediately Since Above Set Pressure

There are some exceptions allowed to the 3% rule. For example, remotely sensed pilot-operated PRVs can be used when the inlet piping pressure drop exceeds 3% of the PRV set pressure (API 520 Part II Section 7.3.9). Previous revisions of API 520 allowed flexibility for higher inlet pressure drop if the owner conducted an "engineering analysis." The current revision of API 520 makes it clear that the 3% limit on inlet pressure drop really is a guideline and not a precise design criterion. The inlet piping pressure drop is just one of several factors that affect PRV stability and should not be relied on exclusively (API 520 Part II 7.3). A force balance calculation is the simplest method recommended by API to check PRV stability (API 520 Part II 7.3.6 d).

2. 10% Rule for Outlet Piping

The "10% rule for outlet piping" is a design guideline to limit the pressure drop in the outlet piping from a PRV, calculated at rated capacity, to no more than 10% of the PRV set pressure (in psig). The purpose of the guideline is to ensure that the pressure at the PRV outlet (backpressure) will not result in forces that close the PRV when it should be open, reduce the flow through the PRV, or otherwise adversely affect the operation of the PRV. During preliminary design, the 10% rule allows the engineer to perform conservative sizing for the PRV and disposal piping prior to selecting a specific PRV. The 10% rule is a simplification based on a conventional valve design, 10% allowable overpressure for a non-fire relief scenario, and zero pressure or constant pressure existing in the outlet piping when the PRV is closed. Selection of an appropriate PRV type includes careful consideration of the effect of backpressure on the operating characteristics of the valve.

The terminology used for backpressure in PRV sizing and piping pressure drop calculations can be confusing. An explanation of PRV "backpressure" terminology is helpful to understand design limitations placed on different PRV types. (Definitions are found in API 520 Part 1 Section 3.0.) The following bullet points and paragraphs explain PRV backpressure terminology and backpressure design considerations for conventional, balanced bellows, and pilot-operated PRVs to provide context for the 10% rule. Refer to API 520 Part 1 Section 5.3 for more details.

- *Accumulation* is the pressure rise above maximum allowable working pressure (MAWP) during discharge of a PRV, commonly expressed as a percentage of MAWP (psig). The maximum allowed accumulation is established by the ASME Code.

- *Overpressure* is the pressure increase above PRV set pressure, commonly expressed as a percentage of set pressure (psig).

- *Allowable overpressure* is established from the accumulation permitted by the ASME Code, and depends on the relationship between set pressure and MAWP; allowable overpressure % = (MAWP + accumulation – set pressure) / set pressure. Allowable overpressure is equal to the allowed accumulation when the set pressure equals MAWP; allowable overpressure is greater than accumulation when set pressure is below MAWP.

- *Backpressure* is defined as the pressure that exists at the outlet nozzle of a PRV as a result of the pressure in the disposal (discharge) system. Backpressure may be caused by pressure drop, flashing liquids, or pressure pre-existing in the disposal system.

- *Superimposed backpressure* is defined as the static pressure that exists at the outlet of a PRV before the valve opens. Superimposed backpressure is the result of pressure in the disposal system from other sources and may be constant or variable.

- *Built-up backpressure* is defined as the increase in pressure at the outlet of a PRV that develops as a result of flow after the PRV opens.

- *Total backpressure* (as referred to in this paper) is the sum of superimposed and built-up backpressures.

The 10% limitation on outlet piping pressure drop is actually a limitation on built-up backpressure. Superimposed backpressure is addressed separately through the PRV type selection or through spring set pressure compensation of a conventional PRV by cold differential test pressure (CDTP). Built-up backpressure greater than 10% is permitted for some relief scenarios, PRV installations, and valve types. The limitation for a conventional valve is that the built-up backpressure must not exceed the allowable overpressure. Therefore, built-up backpressure up to 21% may be acceptable for relief of a fire scenario; built-up backpressure up to 16% may be acceptable for installations that use multiple PRVs in parallel; and, when set pressure is below MAWP, built-up backpressure in excess of the typical 10%, 16%, and 21% may be acceptable. For example, assume MAWP = 100 psig, accumulation = 10% or 10 psi, and set pressure = 90 psig, then allowable overpressure = (MAWP + accumulation – set pressure) / set pressure = 22% of set pressure. Built-up backpressure could be acceptable up to 22%. For balanced bellows and pilot-operated PRVs, there is no built-up backpressure limitation and no CDTP correction for constant superimposed backpressure.

For a conventional PRV, excessive backpressure can increase the pressure required to open the valve, cause the valve to close too soon, cause the valve to chatter, and reduce the relieving capacity, any of which may lead to an unacceptable pressure rise in the protected vessel. Balanced bellows and pilot operated PRVs are typically used when built-up backpressure exceeds allowable overpressure (nominally the 10%) but total backpressure does not exceed approximately 50% of set pressure with little to no capacity reduction (consult manufacturer for backpressure correction factors). Capacity reduction will occur for compressible fluids when flow becomes sub-critical through the PRV. For balanced bellows and pilot-operated PRVs, set pressure is not affected by superimposed backpressure. The bellows itself is typically rated for a certain pressure and the engineer must be aware of this limitation to ensure that the bellows will not be damaged by excessive backpressure. Typical design backpressure limitations for the three considered PRV types are summarized in Table 3.

Table 3. Typical Backpressure Limits for PRV Types.

Backpressure	Conventional PRV	Balanced Bellows PRV	Pilot-Operated PRV
Built-up Backpressure	Valve not suitable if built-up backpressure > allowable overpressure.	(See total backpressure)	(See total backpressure)
Constant Superimposed Backpressure	Must compensate valve spring set pressure for constant superimposed backpressure by CDTP.	Valve is not compensated for constant superimposed backpressure. (See total backpressure)	Main valve is not compensated for constant superimposed backpressure (see total backpressure); Pilot valve may require CDTP pressure compensation or balanced bellows design.
Variable Superimposed Backpressure	Valve not suitable if variable superimposed backpressure is present.	(See total backpressure)	(See total backpressure)
Total Backpressure	Valve okay if all limits met for built-up and superimposed backpressures.	Valve okay for total backpressure up to 30% of set pressure; may be okay up to ~50% without capacity reduction; check with manufacturer for limitations & correction factors.	Valve lift unaffected by backpressure; check with manufacturer for limitations & correction factors; check for capacity reduction due subcritical flow.

III. Practical Solutions for Installed PRV and Piping Capacity Problems

A. Reduce or Eliminate the Relief Load

When the capacity of a PRV and associated piping are found to be inadequate for a particular relief load, take a closer look at the overpressure cause before increasing the PRV and piping capacity. Look for options to reduce the relief load so that the particular scenario is no longer greater than the PRV installed capacity, or to eliminate the scenario entirely as a PRV relief scenario by other means of protection. The four approaches to reduce or eliminate a PRV relief load that are discussed in this section include:

1) Define the Maximum Possible System Pressure,
2) Reduce the Source Pressure,
3) Install Mechanical Limiting Devices, and
4) Install Safety Instrumented System.

1. Define the Maximum Possible System Pressure

For relief scenarios such as heat transfer equipment failure, failure of automatic controls, and closed outlets, the flow rate of fluid that needs to be relieved by the PRV may be a function of the pressure upstream of the failed equipment or control element. PRV sizing is often done at an early stage in a project, and engineers completing the PRV sizing calculations may have used assumed, conservative values for the pressure source (e.g. MAWP, pump dead-head). In some instances it may be possible to lower the upstream pressure assumed in the relief load calculation and thus reduce the estimated flow rate of fluid that needs to be relieved. The key is to more rigorously define the maximum operating pressure of the system. More rigorously estimated relief loads ensure that a PRV is properly sized, and not oversized. This approach is discussed in the following example for the heat transfer equipment failure relief scenario caused by a heat exchanger tube rupture. The same rationale for determining the maximum possible system pressure can be applied to the failure of automatic controls and closed outlets scenarios for instances like gas blow-by into a low pressure system, high pressure let down valves into a lower pressure system, maximum suction pressure to centrifugal pumps and compressors, etc. In each instance, the engineer should research and select a reasonable maximum operating pressure to determine the appropriate relief load for the relief device.

Example: Heat Exchanger Tube Rupture

An existing facility has a closed loop refrigeration circuit that chills and liquefies process gas by evaporating ammonia at low pressure in a shell and tube heat exchanger. The facility was moved to a new location and, as part of the project, a Process Hazard Analysis (PHA) was held for the facility and the ammonia refrigeration system was reviewed carefully since it would fall under OSHA's Process Safety Management standard. During the PHA, the project team found that a relief scenario for tube rupture in the heat exchanger was not completed and generated an action item to complete a tube rupture calculation to estimate the relief load and check to ensure that the installed PRV had sufficient capacity. Figure 1 shows a simplified configuration of the equipment.

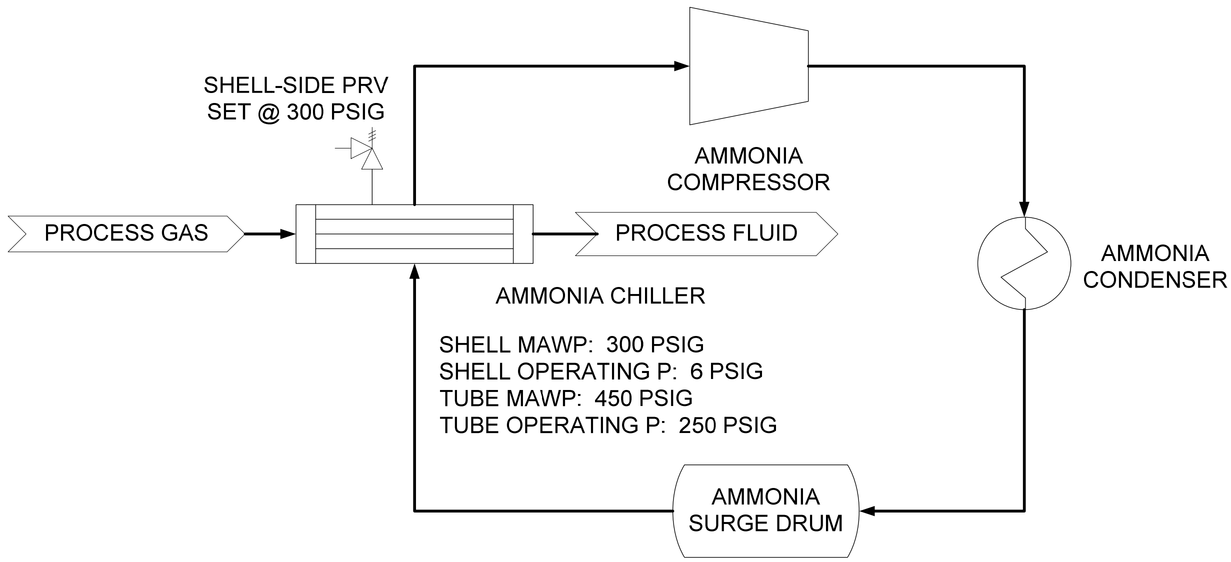

Figure 1. Process Schematic for Heat Exchanger Tube Rupture Scenario.

The refrigerant in the shell-side of the Ammonia Chiller operates at 6 psig while the process gas in the tube-side of the Ammonia Chiller operates at 250 psig, and as a result process gas will flow into the shell-side of the exchanger if a heat exchanger tube ruptures. The set pressure of the shell-side PRV is 300 psig.

A typical tube rupture calculation would use the MAWP of the high pressure side of the exchanger to calculate the flow through the ruptured tube, which in this case is 450 psig for the tubes. At a pressure of 450 psig, the installed PRV was unable to relieve the required amount of fluid. The operating pressure of the tube-side of the exchanger is significantly lower than the MAWP of the tube-side of the exchanger. Per API-521, "the use of maximum possible system pressure instead of MAWP may be considered as the pressure of the high-pressure side on a case-by-case basis." The question then becomes what is the maximum possible system pressure for the process gas in the tubes? In this example, the process gas is compressed from near atmospheric pressure up to the normal operating pressure of 250 psig. Using the normal operating pressure of 250 psig does not allow for any process upsets, unintended operation, etc. and should probably not be used as the maximum possible system pressure. However, the process gas compressor had a high discharge pressure shut down, and it is reasonable to use this high discharge pressure shut down value as the maximum possible system pressure since it is unlikely that the process would be operating above the compressor shut down pressure and the heat exchanger tube rupture would occur at the same time. In this example, the high discharge pressure shut down of the process gas compressor was set at 290 psig, which was below the MAWP of the shell-side of the exchanger. By defining the maximum possible system pressure as 290 psig, the tube rupture relief scenario was eliminated from consideration altogether for sizing the PRV since there would be no overpressure if a heat exchanger tube were to rupture given that the shell is rated for 300 psig.

2. Reduce the Source Pressure

Another option for eliminating a relief scenario from consideration for PRV sizing is to reduce the potential upstream source pressure by setting the upstream PRV at a low enough pressure to prevent the upstream source from over-pressuring the downstream equipment. This option may be attractive in low pressure systems such as sour water strippers or amine strippers where the columns may have MAWPs as high as 150 psig, but operate at 10 psig or less. In this situation, it may be feasible to set the PRV that protects the column at a lower pressure to protect equipment downstream of the column that has a lower MAWP. However, PRVs with a very low set pressure can be large and expensive, so there is a tradeoff to consider.

3. Install Mechanical Limiting Devices

A common problem with failure of automatic controls relief scenarios is an over-sized control valve that would result in a surge of fluid from a high-pressure system to a low-pressure system if it were to fail open. A well-sized control valve will be approximately 70% open for the maximum normal flow case, but it isn't uncommon to see this maximum flow case sized for 50% open or even lower in some circumstances. When the valve is equipped with equal percentage trim, the flow rate through the valve increases exponentially as the valve approaches a wide-open condition. The flow rate from a wide open control valve is often the PRV sizing relief load; thus an over-sized control valve can increase the size and cost of the downstream PRV, the size of the inlet and outlet piping for the PRV, and even the relief disposal system.

Several mechanical options may be available to limit the flow rate that needs to be relieved through the PRV from a wide open control valve, and are listed here in descending order of preference.

- *Install an Appropriately Sized Control Valve.* The most thorough and prudent solution to the problem of an over-sized control valve is to install an appropriately sized control valve. A well-sized control valve will not exceed 70% open for the maximum expected operating case.

- *Install a Restriction Orifice*. Install a restriction orifice upstream of the control valve that is being considered for failure wide open. The orifice should be placed upstream of the manual bypass loop around the control valve to also protect from inadvertent opening of the bypass valve. The orifice should be sized such that at PRV relieving conditions downstream the flow rate through the restriction orifice and the wide open control valve does not exceed the equivalent flow rate that the PRV can relieve. The restriction orifice should be stamped with the PRV tag number, and the purpose of the restriction orifice should be fully documented as safety critical for overpressure protection in documentation for the PRV and restriction orifice and on piping and instrument diagrams (P&IDs),

- *Install Mechanical Valve Stops*. Install mechanical stops in the control valve that will prevent the valve from opening more than a specified percentage to limit the wide open flow rate to less than the equivalent flow rate that the PRV can relieve. The purpose of the mechanical stops should be fully documented as safety critical for overpressure protection in documentation for the control valve and PRV, in the field, and on P&IDs.

- *Car Seal Control Valve Bypass Valve Closed*. In some cases, it may be appropriate to car seal closed the bypass valve around a control valve and remove the bypass valve flow rate contribution from the calculated relief load. Appropriate administrative controls must also be implemented. It is the responsibility of the owner to be sure sufficient written procedures, training, audits, and operating experience are in place to rely on administrative controls.

4. Install Safety Instrumented System

In some facilities, a PRV and even the relief disposal system (flare knock-out drum, flare tip, flare header, etc.) may be so under-sized that replacement with a larger device or multiple devices may not be practical. An example of this could be incorporating new, high pressure gas or oil wells into an existing gas treatment facility where the facility's capacity is essentially fixed but failure of the well's choke valve could result in very large flows of fluids to the facility at high pressure.

In this situation, and potentially others such as gas blow-by, the installation of a Safety Instrumented System (SIS), also called a High-Integrity Protection System (HIPS), in lieu of a PRV may eliminate the relief scenario for the PRV. An SIS is essentially a control system separate from the basic control system that runs the rest of the facility. The SIS's major function is to reliably execute automated shut downs that have a high safety impact and are instrumented and tested such that they are as reliable as a mechanical device such as a PRV. Figure 2 shows an example SIS that protects a low pressure vessel from overpressure by a high pressure source.

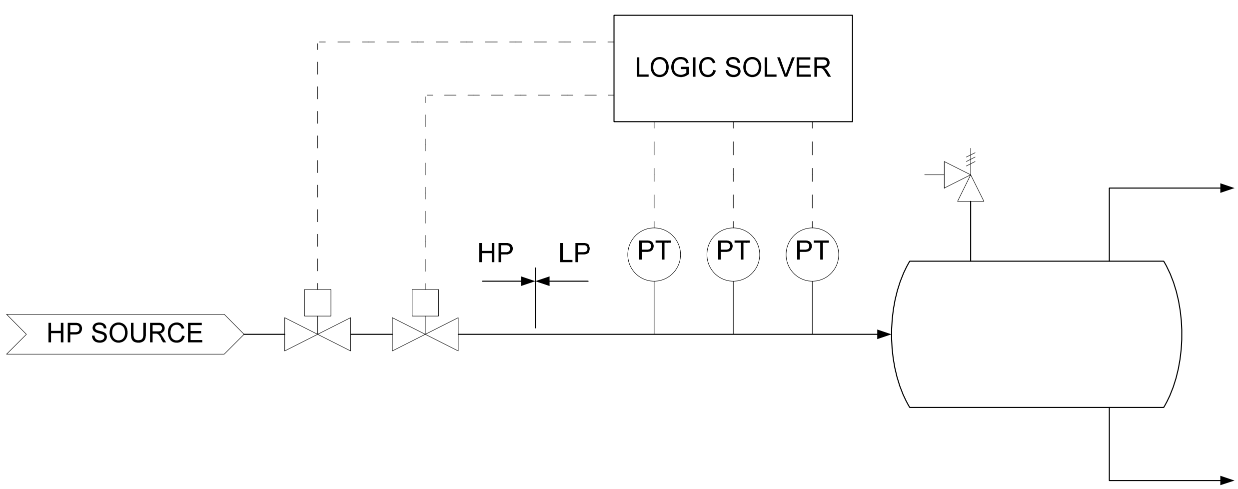

Figure 2. Example SIS for PRV Alternative.

The capital cost for an SIS for overpressure protection is relatively high with the redundant, high pressure rated valves rated for SIS service, multiple pressure transmitters rated for SIS service, and logic solver capable of a Safety Integrity Level of 3 (SIL-3). In addition to the high initial cost, there are strict and frequent testing requirements for an SIS. In the example shown in Figure 2, the SIS eliminates the HP Source as a relief scenario for the PRV protecting the vessel in question, and the PRV on the vessel no longer needs to be sized for that scenario. When the PRV and disposal system already exist and do not have extra capacity, it may be more economical to install the SIS rather than replace the existing PRV, associated piping, header, etc.

B. Change the PRV, Not the Pipe

The problems of undersized inlet piping, undersized outlet piping, or excessive backpressure can be challenging. Often these problems arise when validating a pressure relief system, or when making a change to a unit's capacity and disposal system piping modifications would be costly and potentially impact production. The good news is that there may be a solution that doesn't require increasing the pipe size. A change to the valve design selected may be a safe and cost effective option that is better than replacing pipe.

It is worth noting that the rated capacity of a selected PRV model typically exceeds the rated capacity calculated by API preliminary sizing. This may ensure adequate PRV capacity during selection, but can result in pressure drop that is too high in the inlet piping for the selected PRV. Since the valve capacity is proportional to the product of the coefficient of discharge and the office area, the ratio of the products of the API effective K_d and effective A to the ASME actual K and actual A provides a factor for the difference in capacity.

1. Problem: Inlet Piping Pressure Drop Limit is Exceeded

Except for remotely sensed pilot-operated PRVs, pressure relief valves are designed for inlet piping pressure drop that does not exceed 3% of set pressure. This is the "3% limit" discussed in the Rules of Thumb section. High inlet piping pressure drop is often difficult to resolve without replacing the pipe and/or fittings.

Some options to consider when confronted with pressure drop in the inlet piping that is greater than the 3% limit are listed in the following bullet points.

- *Restrict the Lift.* Some PRV designs have a conversion option to restrict the travel or lift when the valve opens. The valve's capacity may be reduced to as little as 30% of rated capacity. The valve will have the same body but a reduced flow capacity because of the restricted lift. Restricting the lift is a potentially low cost solution and is accomplished by installing a limit washer in the existing valve designed to achieve a specific capacity. This solution also "right sizes" the PRV while reducing the inlet piping pressure drop. The most recent revision of API 526 provides guidance for specifying a restricted lift.

- *Choose a Smaller PRV.* Replace the valve with a smaller one, multiple smaller valves that operate in parallel, or a different manufacturer's valve that has a lower rated capacity. This solution more closely matches the PRV rated capacity to the required relief load. Reduction of the rated capacity will in turn reduce the pressure drop calculated in the inlet piping (as well as the outlet piping). It may also reduce acoustic effects from rapid opening and closing.

- *Replace with a Modulating Pilot-Operated PRV.* Replace a conventional, balanced bellows, or snap-action pilot-operated PRV with a modulating pilot-operated PRV. Modulating pilot-operated PRVs are designed to relieve only the amount of flow needed to maintain the upstream pressure in the vessel at the PRV's set pressure. They open proportionally to the required flow. The main advantage of this device is that the amount of flow through the PRV and associated piping is limited to the flow rate required to protect the vessel. Therefore, the inlet piping pressure drop can be calculated for the maximum required relief load instead of the PRV's rated capacity, which will reduce the pressure drop.

- *Replace with or Convert to Remotely Sensed Pilot-Operated PRV.* A remotely sensed pilot-operated PRV utilizes tubing or other small bore piping to connect the inlet of the pilot assembly to the vessel instead of the inlet of the main PRV. This allows the pilot to sense the vessel pressure instead of the pressure at the main valve inlet after inlet piping pressure drop. The pilot will remain open, as well as the main PRV, even when the pressure drop in the inlet piping to the main PRV is greater than 3% and otherwise would have caused the pilot to close, which may have led to chattering or rapid cycling of the pilot. The capacity of the main PRV should be checked to be sure it has sufficient capacity at the higher inlet piping pressure drop. Consult the manufacturer for guidance on maximum remote sense distances.

- *Perform a Force Balance Assessment.* A documented engineering analysis for a PRV that has no history of chatter can be used by the owner to accept a PRV installation with inlet piping pressure drop greater than 3%. Consult API 520 Part 2 Section 7.3.6 for topics to consider for the engineering analysis. A simple force balance can indicate potential acceptability of the installation, as shown in Equation 3 and Equation 4:

    - Conventional PRV:

$$\text{total inlet pressure loss} + \text{built-up backpressure} \leq \text{overpressure} + \text{blowdown} \qquad \text{Equation 3}$$

    - Balanced bellows PRV:

$$\text{total inlet pressure loss} + 0.1 * \text{built-up backpressure} \leq \text{overpressure} + \text{blowdown} \qquad \text{Equation 4}$$

- *Convert a Conventional PRV to a Balanced Bellows PRV.* The simple force balance shows that the balanced bellows PRV will tolerate higher inlet losses than the conventional PRV.

- *Change the Blowdown.* Blowdown is the difference between actual set pressure of a PRV and the actual reseating pressure (in psig), expressed as a percentage of set pressure or in pressure units. For compressible fluids, the typical PRV reseat pressure is 7% to 10% below set pressure. Review the PRV's blowdown setting with the manufacturer to determine actual requirements for the valve design. Increasing the blowdown lowers the reseating pressure. When the blowdown is greater than the inlet piping pressure drop (non-recoverable losses), the chance of valve instability decreases. The manufacturer may be able test and/or set the blowdown to a better value for the service and to document it. Unfortunately, it is sometimes not economical or technically feasible to do a dynamic blowdown test that may be necessary to accurately set the blowdown.

- *Change the Upstream Rupture Disk.* Select a rupture disk with a capacity rating in combination with the PRV that is less than the capacity of the installed PRV and rupture disk. A caution is that the pressure drop associated with the rupture disk (K_r) may increase inlet piping pressure drop, and this tradeoff may be unacceptable.

2. Problem: Outlet Piping Capacity is Undersized

PRV outlet piping is commonly a tail pipe to atmosphere or a lateral to a closed disposal system that may include a common vent header, vent stack, flare, or other treatment system. The flow rate that must be handled by the outlet piping is a function of the PRV type selected. All PRVs except for modulating pilot-operated PRVs require tail pipe or lateral piping designed to flow at the PRV's rated capacity. The rated capacity is the flow rate of the fluid through the PRV at relieving conditions when the PRV is wide open or at full lift. (However, the common vent header piping may be sized based on the required relief loads as opposed to the rated capacities of the PRVs.) By definition, the rated capacity will be higher than the required relief load used to size the PRV, and for some PRVs, it may be significantly higher. So, the problem of undersized outlet piping may be solved by looking at options to reduce the amount of flow that the tail pipe or lateral must be designed to move by changing an aspect of the PRV design.

- *Reduce The Valve Capacity.* Restricting the lift of the installed PRV or replacing the PRV with a smaller valve, multiple smaller valves in parallel, or a different manufacturer's valve may reduce the rated capacity of the valve sufficiently as previously discussed for inlet piping pressure drop. Reduced PRV capacity, in turn, will reduce the pressure drop calculated in the outlet piping.

- *Replace with a Modulating Pilot-Operated PRV.* Replace a conventional, balanced bellows, or snap-action pilot-operated PRV with a modulating pilot-operated PRV, as previously discussed for inlet piping pressure drop. The flow rate used in the outlet piping design for this type of valve is the required relief rate, not the rated capacity. Therefore, the outlet piping backpressure can be calculated for the maximum required relief load instead of the PRV's rated capacity, which will reduce the pressure drop.

- *Change the Upstream Rupture Disk.* Select a rupture disk with a capacity rating in combination with the PRV that is less than the capacity of the installed PRV and rupture disk. A caution is that the pressure drop associated with the rupture disk (K_r) may increase inlet piping pressure drop, and this tradeoff may be unacceptable.

- *Reduce the Set Pressure.* For vapor relief, a lower set pressure typically reduces the capacity of the valve. A caution is that the inlet piping pressure drop will increase due to the lower pressure (lower vapor density), and this offset may be unacceptable.

3. Problem: PRV Backpressure is Too High

The problem of high backpressure could be related to undersized outlet piping (see previous section), but there are potential solutions that do not involve reducing the backpressure, but instead, modifying the PRV design to operate properly at the high backpressure.

High pressure at the PRV outlet may result from many situations. When tail pipes or laterals do not have sufficient capacity, excessive backpressure can build up when the PRV opens. In a closed disposal system, a common relief scenario cause (i.e., a pool fire or utility outage) will raise backpressure to all connected PRVs. Increases to the vent header load from de-pressuring or maintenance activities may raise the superimposed backpressure on all connected PRVs (pressure that exists when a PRV is closed). Flashing liquids downstream of a PRV will increase the vapor load in the disposal piping and this also increases the backpressure. When a unit is debottlenecked and the PRV size is increased, the PRV built-up backpressure will increase.

The potential solutions to manage high backpressure that are discussed in the following list are intended for individual PRVs experiencing high backpressure, but the ideas may also be useful to a closed system with multiple PRVs. Any solution to be implemented that results in higher backpressure should include a check to ensure the pressure rating for all components in the relief system will tolerate the higher pressure.

- *Specify CDTP*. For conventional PRVs discharging to a closed system, the cold differential test pressure (CDTP) should be specified to account for constant superimposed backpressure. This is always a first step to address backpressure. The CDTP compensates for the constant superimposed backpressure by reducing the spring force required to keep the PRV closed. Some owners will compensate for low amounts of variable superimposed backpressure as well; the caution is to ensure that the operating pressure is sufficiently below the set pressure so that the PRV will not open when the force of the variable superimposed backpressure is not present.

- *Check Allowable Overpressure:* Conventional PRVs are limited to built-up backpressure that does not exceed the maximum allowable overpressure. If the total backpressure limit was based on the 10% rule or did not consider that the set pressure was below MAWP, a higher total backpressure may be acceptable because the allowable overpressure may be a higher value. As covered in the 10% Rule for Outlet Piping section, built-up backpressure up to 21% of set pressure (in psig) may be acceptable for relief of a fire scenario; built-up backpressure up to 16% may be acceptable for installations that use multiple PRVs in parallel; and, when set pressure is below MAWP, built-up backpressure in excess of the typical 10%, 16%, and 21% may be acceptable. Bear in mind that the PRV must be fully open at overpressure equal to10% of set pressure.

- *Convert Conventional PRV to a Balanced Bellows PRV.* A balanced bellows PRV is designed to handle higher backpressures. For API preliminary sizing for vapors and gases, a balanced bellows valve is assumed to have full capacity with total backpressure up to 30% of set pressure (K_b = 1.0). The manufacturer's backpressure capacity reduction curves must be checked, but it is common to handle backpressure up to about 45% of set pressure for vapors and gases with little capacity reduction, and even higher backpressure when the capacity is compensated by selecting the appropriate K_b. For API preliminary sizing for liquids, a balanced bellows is assumed to have full capacity with backpressure up to 15% of set pressure (K_w = 1.0). Many conventional valves can be converted with a bellows kit installed by a certified repair shop or by the manufacturer.

- *Replace Installed PRV with a Pilot-Operated PRV.* Conventional or balanced bellows valves may be replaced with a pilot-operated valve. These valves are designed for high backpressure applications.

C. Sharpen the Pencil

Pressure relief work often requires making simplifying assumptions when evaluating relief scenario causes and quantifying relief loads. Owners are well served to have robust engineering standards that include the philosophy behind their overpressure protection strategy, risk tolerance criteria, and specific guidance for applying industry codes, standards, and recognized and generally accepted good engineering practices (RAGAGEP) in owner's facilities. Many engineers tend to make overly conservative assumptions when there is a lack of owner guidance and when the owner's risk tolerance is not clearly understood. A consequence of overly conservative assumptions may not be a safer system, but potentially a less stable or less reliable system, and definitely a more costly one. Well defined engineering standards and other guidance helps engineers refine assumptions appropriately.

1. Refine Assumptions

Closed outlets is a typical relief scenario to consider for the discharge side of centrifugal pumps. A common, but conservative, assumption is to use the pump dead-head pressure for determining if overpressure is credible. The cause of the closed outlet or blocked flow could be far downstream from the pump, with heat exchangers or other pressure vessels between the pump and the blocked flow point. Elevation changes also impact the maximum pressure at the relief device. It is possible in some cases to eliminate the relief scenario by taking into account the frictional and static pressure losses between the pump and the relief device. At the very least, the required relief rate could be reduced by accounting for pressure drop between the pump discharge and the PRV, and then moving further back on the pump curve.

Figure 3 shows a recent application where Trimeric completed relief sizing validation for the PRV that was located on a vaporizer system. The pump's rated discharge pressure was well above the MAWP of the vaporizer vessel due to the distances and the equipment between the pump and the vaporizer. As a result, blocked flow that resulted from a closed valve downstream of the vessel was a cause for overpressure. As a first pass, Trimeric checked the pump's flow rate at the relief pressure but found that the valve was undersized for that flow and that it would be necessary to do a more thorough analysis in an effort to reduce the required relief load.

A hydraulic analysis was completed from the pump discharge to the PRV to determine the pressure drop through the equipment between the pump discharge and the vaporizer vessel. Each control valve was assumed to be wide-open since the natural response of the flow control loop would be to go wide open as the flow rate dropped and the pressure control valve was normally operated in manual mode at 100%. Height differences between the pump and the vessel were considered in the hydraulic analysis as well. Accounting for this pressure drop characterized the system curve more completely, which in turn showed that the pump would operate at a point further back on the pump curve and thus reduced the required relief load.

A better approach during original facility design would have been to design the entire system MAWP for the pump dead-head pressure to avoid having a relief device. In this case, the pump dead-head pressure was almost 150 psi greater than the equipment MAWP due to a legacy design decision, so there was an incentive to install a PRD instead of redesigning the equipment.

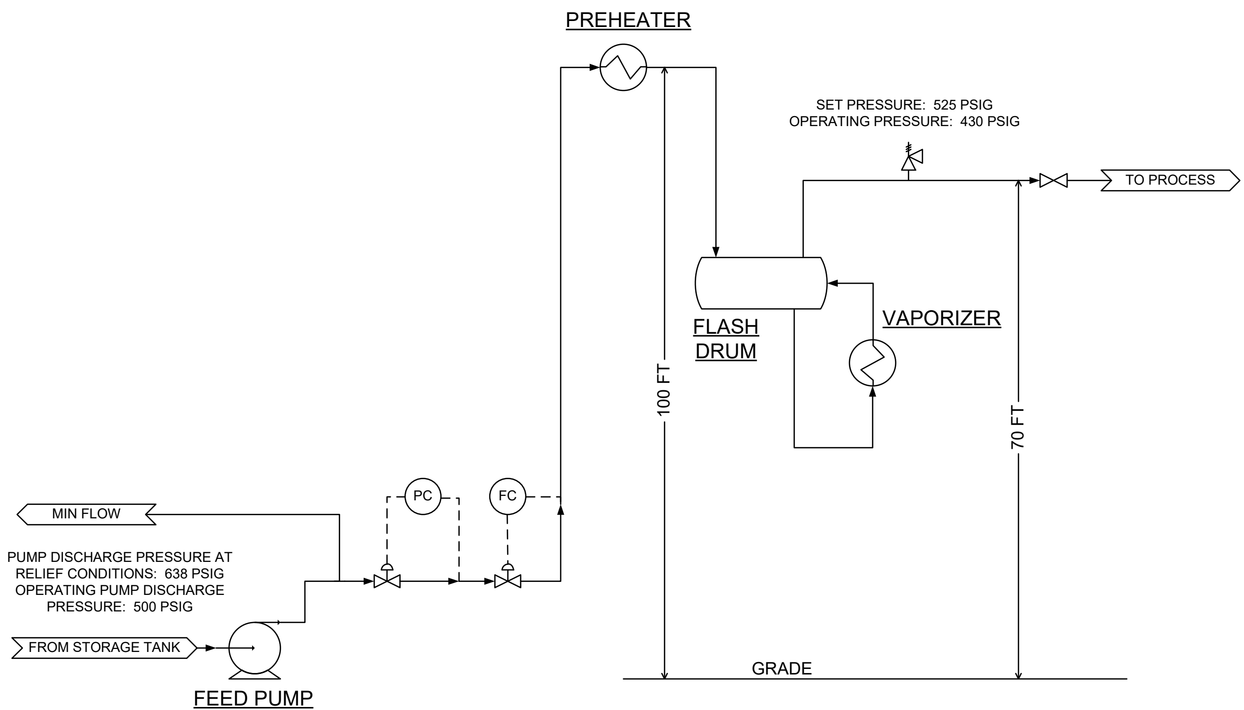

Figure 3. Simplified Process Diagram for Closed Outlets Scenario.

2. Check and Validate

Commercial process modeling software often is used to estimate the pressure drop in PRV inlet and outlet piping, as well as any vent headers; so that pressure drop calculations are updated automatically when operating conditions change. Trimeric resolved one case that appeared to have both inlet and outlet pressure drop above the API guidelines by carefully checking the calculations before reporting the unfavorable results to the client. An error was discovered in the reducer fitting "K-values" in the process modeling software that resulted in higher calculated pressure drop. Trimeric entered standard K-values for the reducers in the software package, and both the inlet and outlet pressure drop estimates fell within the API guidelines. The pressure drop estimates with the standard K-values were double-checked using "old-fashioned" spreadsheet and paper methods to confirm that the lower pressure drop values were correct.

Another area worth a closer look is the tools employed in the performance of pressure relief work. Equations provided in industry standards and in commercial simulation software should always be checked and used with care to ensure that the underlying limitations are understood and that boundaries are not exceeded. Pressure drop due to fittings may not be consistent from one software package to another, for example.

The default equations for pressure drop calculations in commercial process modeling software may or may not be appropriate for the process system of interest. The fluid type (compressible, incompressible, or non-Newtonian), flow regime and phase (laminar, transition, turbulent, two-phase, slug, etc.), and process conditions will determine which correlations and property sets are most appropriate for a given process system. Particular attention should be given to the fluid property calculation methods for supercritical fluids and non-ideal liquid mixtures. The properties calculated using the software package should be verified against literature data. It may be possible to eliminate excessive pressure drop or insufficient PRV relief capacity by selection of more precise fluid properties (but this can go the other way, too!).

Note that the 3% and 10% rules of thumb discussed previously for PRV inlet and outlet pressure drop, respectively, should include only the "non-recoverable" pressure losses. The static head losses for liquid relief cases are considered to be "recoverable" and are not included in the pressure drop calculation.

3. Refine the Fire Case Required Relief Load

The pool fire relief scenario often is the sizing case for PRVs and is the only credible case in some instances. There are multiple assumptions that must be made to estimate the required relief rates from pool fire cases. The heat input to a process unit from a pool fire depends, among other factors, on the classification of flammable material that is burning, the surface area of equipment exposed to the heat, the type of insulation (if any) on the equipment, and the type and capacity of fire protection systems in service.

The most direct approach to reduce the required relief rate from a fire case is to avoid it entirely by eliminating the fuel source from the process unit. Facilities may develop a plot plan showing areas where pool fires are and are not possible to avoid overly conservative assumptions.

The API 521 correlations for heat input from a pool fire generally assume that the flammable material is a hydrocarbon with an assumed heat of combustion. There are correction factors that can be applied to reduce the heat generated by the fire if the fluid is not a hydrocarbon, for example, alcohols or other oxygenated organics. Annex A of API 521 provides adjustment factors for non-hydrocarbon fires.

Credit may be taken for reduced heat input to the process fluid if the equipment and piping is insulated. The correction factors for insulation depend on the insulation material and the fastener type. Credit also may be taken for reduced heat input to the process fluid if fire protection systems such as water deluge are available for the equipment and piping exposed to the fire. The fire protection systems <u>may not</u> be used to eliminate the fire case by assuming that the fire is extinguished, only to reduce the heat input.

IV. Conclusion

Relief systems can be complex and squeezing out additional capacity in an existing system is not always easy. This paper presented ideas and items to examine more closely and potential changes to resolve pressure relief system capacity problems without major piping replacement. Reducing a relief load or eliminating an overpressure relief cause proactively prevents the need to increase relief system capacity. Whether by refined assumptions and better system definition or by physical changes to instrumentation or equipment, preventing or eliminating a potential overpressure situation is almost always preferred. When piping pressure drop is too high or backpressure is excessive for a PRV installation, examining ways to leverage the interrelationship between the PRV type, PRV capacity, and relief system inlet/outlet piping hydraulic design requirements can avoid the need to increase relief system piping sizes. Changing the PRV to a different type, model, size, capacity, or specifying the PRV characteristics differently can make the PRV a better match for the required relief load and installed inlet/outlet piping and header systems, and may avoid costly piping and equipment replacement and facility downtime.

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