Pressure-Relief System Design

Unexpected high-pressure situations can be relieved with a proper relief-system design

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Pressure relief systems are vital in the chemical process industries (CPI) for handling a wide variety of situations. They are used to prevent pressurization above a system's design pressure; for venting during an unusual or emergency situation; and for normal depressurization during a shutdown, as examples. In some cases, such as when noncombustible gases including steam, air and nitrogen are used, venting into the atmosphere may be an option. In other cases, such as those typically encountered in the hydrocarbon sector, elaborate systems for the disposal of vented gases may be required.

This article describes some of the causes of overpressurization, the types of valves and rupture disks that are available and some of the components needed for a pressure relief system. Example calculations are given, as well as a list of installation considerations.

Causes of overpressurization

An overpressurization may result from a single cause or a combination of events. Typically, not all causes will occur simultaneously. In case of an external fire in vessels that predominantly handle vapors, such as knockout drums, there may be a rapid temperature rise in the metal accompanied with a rise in pressure due to expansion. In case of external fire in vessels that contain liquids, there will be a rise in pressure as the liquid vaporizes. Pressure may also rise abruptly due to thermal expansion when a blocked-in pipeline or other equipment containing a liquid is heated. Relieving pressure under these situations is essential to prevent failure. It is also required in systems where a continuous flow of vapor or liquid is suddenly stopped by a downstream blockage.

While a full description of the various causes of overpressurization is beyond the scope of this article, details are provided by API [*1*]. The following is a partial list:

- Blocked outlet
- Failure of control valve
- Cooling water failure
- Power failure
- Instrument air failure
- Heat-exchanger-tube failure
- External fire

Safety relief valves

There are several types of safety relief valves available on the market, including the following.

Conventional: Conventional pressure-relief valves are susceptible to back pressure. Such valves are not recommended when the total back pressure exceeds 10% of the set pressure. For systems operating at pressures close to atmospheric or at low pressures, the limit of 10% is rarely achieved. Therefore, these valves find application mainly in high-pressure systems, or in systems that relieve to the atmosphere (for example, steam and air).

Balanced bellows: Balanced pressure-relief valves are used when conventional pressure-relief valves cannot be used because of the reasons mentioned above. Such valves are not susceptible to back pressures as high as 50% of set pressure. The valve opening is independent of the back pressure. At higher back pressures, these valves will still relieve at the set point, but with a reduction in capacity. Therefore, it is recommended that if balanced pressure-relief valves are to perform as rated, the back pressure should be limited to about 50% of the set pressure.

Pilot operated: In such valves, the main pressure-relief valve opens through a pilot valve. Pilot operated valves are used in the following circumstances: 1) The pressure-relief-valve set pressure is lower than 110% of the operating pressure and 2) when high back pressures are applicable. The opening of the valve is independent of back pressure.

Rupture disks

A rupture disk is a pressure relieving device that is used for the same purpose as a relief valve, but a disk is a non-reclosing device — or in other words, once it is open it will not close. This means that whatever is in the system will continue to vent until stopped by some form of intervention. The following are the applications of rupture disks [*3*]:

For quick action: Rupture disks are very fast acting. Therefore, they are used in cases where relief valves may not be fast enough to prevent a catastrophic failure. Some engineers prefer to use rupture disks to prevent heat-exchanger-tube ruptures because they are concerned that pressure relief valves would be too slow to prevent pressure build-up scenarios.

To prevent plugging of relief valves: In certain processes, the process fluid contains solid particles that may cause blockage within a relief valve, rendering it useless. In such cases, a rupture disk is normally used upstream of the relief valve. Purified terephthallic acid plants (PTA) is a typical application example.

Handling highly viscous liquids: In systems handling highly viscous liquids, such as polymers, depressurization through a relief valve may be too slow for a given situation. A rup-

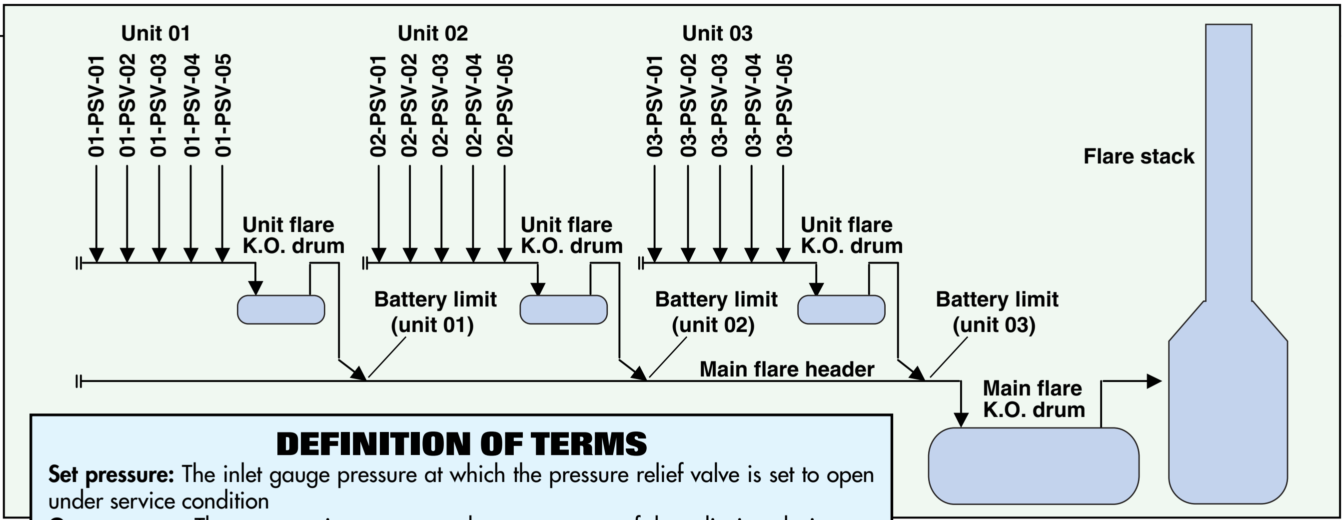

FIGURE 1. A network of flare headers may be used in a complex process

DEFINITION OF TERMS

Set pressure: The inlet gauge pressure at which the pressure relief valve is set to open under service condition
Overpressure: The pressure increase over the set pressure of the relieving device expressed as a percentage
Relieving pressure: The sum of the valve set pressure and the overpressure
Superimposed back pressure: The static pressure that exists at the outlet of a pressure relief device at the time the device is required to operate. It is the result of the pressure in the discharge system coming from other sources and may be constant or variable
Built-up back pressure: The increase in pressure in the discharge header that develops as a result of flow after the pressure relief device opens
Back pressure: The pressure that develops at the outlet of a pressure relief device after the pressure relief device opens. It is the sum of the superimposed and the built-up back pressures

Abbreviations

P_1	Pressure at pipe inlet, kg/cm^{2}a	M_w	Gas molecular weight, kg/kmol
P_2	Pressure at pipe outlet, kg/cm^{2}a	f	Moody's friction factor
W	Gas flowrate, kg/h	k	Ratio of specific heats, C_p/C_v
Z	Gas compressibility factor	a	Absolute pressure, as in kg/cm^{2}a
T	Gas temperature, K	g	Gauge pressure, as in kg/cm^{2}g

ture disk is the preferred choice.

Loss prevention: In systems handling low-molecular-weight hydrocarbons, there is always a chance that some material will pass through the pressure relief valve into the flare system — leading to material loss. In such cases, a rupture disk is normally used upstream of the relief valve.

For economic reasons: Many process industries use exotic materials, such as titanium and Hastelloy C. In these cases, rather than having a pressure relief valve made of Hastelloy C, it may be cheaper to have a rupture disk made of Hastelloy C followed by a stainless-steel pressure-relief valve.

PRESSURE RELIEF SYSTEMS

Open and closed systems

In cases where non-hazardous fluids are used, such as steam, water and air, a typical pressure-relief system consists of several pressure relief valves that discharge through short tail pipes to the atmosphere. These systems are termed *open disposal systems*.

When hazardous fluids, such as hydrocarbons are in use, the tail pipes are connected to a common flare header, which is ultimately routed to a flare stack where the hydrocarbons are burned. In many cases, the fluid relieved is toxic or flammable. In such cases, it is mandatory to discharge the gases through a *closed disposal system* such as the flare. The flare system converts the flammable vapors to less objectionable compounds by combustion.

Components of closed systems

Pressure-relief valve-outlet piping: The flare system starts with outlet pipes from the various pressure relief valves of a unit. These valves are piped together to a common unit-flare header, which is routed to the unit-flare knockout (K.O.) drum.

Unit flare header: Discharge pipes from the pressure relief valves in individual units are connected to the respective unit-flare headers. These headers are either connected directly to the main flare header, or are routed to the flare K.O. drums, which in turn are connected to the main flare header (Figure 1) with a recommended minimum slope of 1:500. All unit flare headers are continuously purged from the upstream end towards the respective K.O. drums to avoid ingress of air into the system. Fuel gas, or inert gases, such as nitrogen are typically used as purge gas.

Unit-flare knockout drum: In cases where the discharge from a unit is expected to contain appreciable quantities of liquids, especially corrosive, fouling and congealing liquids, a unit-flare K.O. drum of a suitable size is mandatory. Another reason for requiring such a drum may be that it is not feasible to have all headers continuously slope toward the main-flare K.O. drum. In this case, the unit flare headers are sloped toward the unit-flare K.O. drums. The vapors from these drums are then routed to the main flare header [2].

Unit-flare K.O. drums are sized to separate particles in the range of 300–600 microns, and hold liquid discharge for 5–10 min from a single source. The liquid collected in these drums should preferably be drained by gravity to the blowdown drum. If a congealing type of liquid is likely to be discharged, the drums should be heat traced or provided with steam coils [2].

Main flare header: The main flare header receives discharge through individual unit-flare headers, or through unit-flare K.O. drums. The flare header should not have pockets and should be free draining toward the nearest K.O. drum, typically with a slope of 1:500.

Although flare headers are normally sized based on pressure drop,

TABLE 1. RELIEF LOAD SUMMARY		
	Relief load, kg/h	
Relief Valve Tag No.	Cooling water failure	External fire
PSV-01	12,870	13,453
PSV-02		6,750
PSV-03	10,536	9,872
PSV-04	14,076	8,970
PSV-05		5,783
PSV-06	12,960	11,423
PSV-07	15,052	6,432
PSV-08		5,764
PSV-09	16,732	8,976
PSV-10		7,432
PSV-11	13,422	5,133
PSV-12		9,984
Total load	95,648	

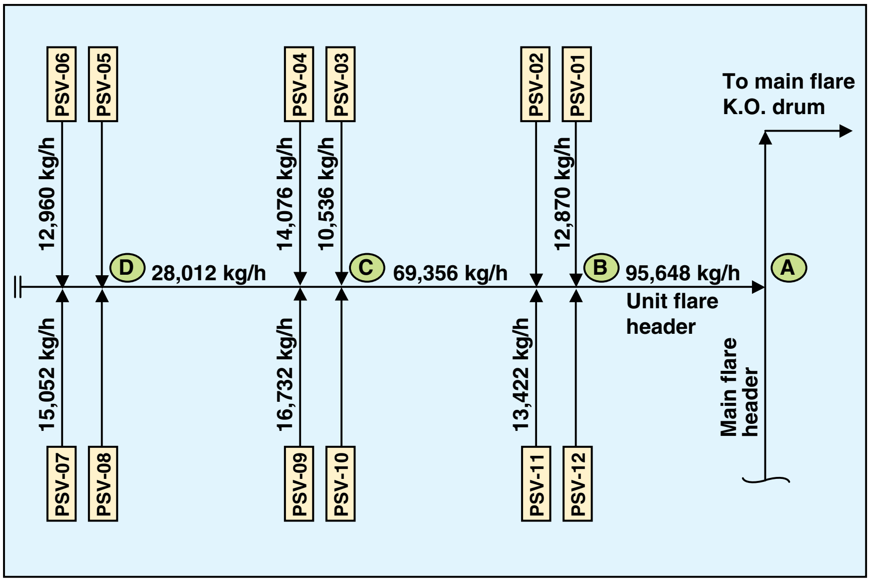

FIGURE 2. This sketch of a typical flare system is used as the basis for the sample calculations explained in the given example

velocity cannot be ignored. A Mach number in the range of 0.2–0.5 is recommended. The third criterion that should be checked is the change in density of flare gases along the length of the flare header. In many cases where flare discharges are at high temperatures, the flare gases cool down due to the length of the flare header. This leads to an increase in density and, correspondingly, a decrease in flowrates. Therefore, while estimating pressure drops in such flare lines, it is a good idea to divide the header into sections and estimate pressure drops separately.

Main-flare knockout drum: In addition to the unit-flare K.O. drum, a main-flare K.O. drum close to the flare stack should be provided. This takes care of condensation in the header that results from atmospheric cooling. Similar to the unit-flare K.O. drums, these drums are also sized to separate out liquid droplets of 300–600 microns in size, and for holdup of 20–30 min [*1*] of liquid release. Pumps are installed with the K.O. drum to transport any collected liquid to a safe location. The pumping capacity should allow the liquid holdup to be emptied in 15–20 min. When congealing liquids are in use, the drums should be provided with steam coils [*2*].

Seal drum: Seal drums are located close to the flare stack or are sometimes integral with the flare stack. These drums protect against flame flashback from the flare tip. The seal drum should have a diameter of at least two times the flare pipe diameter [*1*].

Flare stack: Flare stacks are usually elevated structures designed to burn flammable vapors.

Relief system piping

Inlet piping: The inlet piping from the protected equipment to the pressure relief valve should be sized to prevent excessive pressure loss that can cause chattering with consequent reduction in flow and damage to seating surfaces. The recommended practice is to limit the total pressure drop in the inlet piping to 3% of the safety-valve set pressure [*1*]. The piping is designed to drain towards the protected vessel.

Discharge piping: In case of overpressurization in a vessel, the relevant pressure-relief valve will start to open at the set pressure. At this moment, the downstream pressure at the valve is the superimposed back pressure of the system. The valve keeps opening as the pressure builds up. The resultant flow creates a built-up back pressure on the discharge pipe. As long as the built-up back pressure is less than the overpressure after the valve opens, the valve will remain open and perform satisfactorily. If however, the built-up back pressure develops at a rate greater than the overpressure, it will tend to close the valve. Therefore, proper sizing of discharge pipes is very important in such systems.

Discharge piping and manifolds are sized for the contingency that produces the largest relief load. Pipe sizing is carried out by working backward from the battery limit of the unit flare header up to the outlet of individual, pressure safety valves. The superimposed back pressure of the flare header at the battery limit is defined. Thereafter, based on the relief loads, pressure drop calculations are carried out to arrive at the back pressure of the individual, pressure relief valves. In the course of the calculations, two parameters are checked for compliance:

- The Mach number at each pipe section should not exceed 0.5
- The back pressure at each safety valve should not exceed 30–50% of the set pressure

The isothermal flow equation based on the outlet Mach number is given by API [*1*]. This method calculates pressure buildup backward up to the outlet of relief valves, thus avoiding the need for trial and error methods:

$$\frac{fL}{D} = \frac{1}{(M_2)^2} \times \left(\frac{P_1}{P_2}\right)^2 \times \left[1 - \left(\frac{P_2}{P_1}\right)^2\right] - \ln\left(\frac{P_1}{P_2}\right)^2 \quad \textbf{(1a)}$$

or,

TABLE 2. FLARE DISCHARGE PIPING CALCULATIONS														
Segment	Set pressure	Line size	Line size	Flowrate	Pressure P_2	Density	Roughness factor	Pipe length	No. of tees	No. of valves	No. of elbows	Pressure P_1	Pressure P_1	% of set pressure	Mach no.
	kg/cm²g	m	in.	kg/h	kg/cm²a	kg/m³	mm	m				kg/cm²a	kg/cm²g		
A to B		0.30	12	95,648	1.5000	4.2899	0.1	15	0	1	0	1.6234	0.5904		0.4004
B to PSV-01	5.0	0.10	4	12,870	1.6234	4.6428	0.1	30	0	1	3	2.7780	1.745	34.9	0.4480
B to PSV-11	5.0	0.15	6	13,422	1.6234	4.6428	0.1	30	0	1	3	1.8282	0.7952	15.9	0.2077
B to C		0.25	10	69,356	1.6234	4.6428	0.1	15	0	0	0	1.7528	0.7198		0.3863
C to PSV-03	5.0	0.15	6	10,536	1.7528	5.0129	0.1	30	0	1	3	1.8712	0.8382	16.8	0.1510
C to PSV-04	5.0	0.15	6	14,076	1.7528	5.0129	0.1	30	0	1	3	1.9616	0.9286	18.6	0.2017
C to PSV-09	5.0	0.15	6	16,732	1.7528	5.0129	0.1	30	0	1	3	2.0449	1.0119	20.2	0.2398
C to D		0.20	8	28,012	1.7528	5.0129	0.1	15	0	0	0	1.8111	0.7781		0.2258
D to PSV-06	5.0	0.15	6	12,960	1.8111	5.1796	0.1	30	0	1	3	1.9832	0.9502	19.0	0.1797
D to PSV-07	5.0	0.15	6	15,052	1.8111	5.1796	0.1	30	0	1	3	2.0417	1.0087	20.2	0.2088

$$\frac{fL}{D}=\frac{1}{\left(M_2\right)^2}\times\left[\left(\frac{P_1}{P_2}\right)^2-1\right]-\ln\left(\frac{P_1}{P_2}\right)^2 \quad \textbf{(1b)}$$

The Mach number at the outlet of each pipe section is given as follows [1]:

$$M_2=3.293\times10^{-7}\times\left(\frac{W}{P_2D^2}\right)\left(\frac{ZT}{kM_W}\right)^{0.5} \quad \textbf{(2)}$$

In the next section, a solved example illustrates the procedure.

EXAMPLE

An extractive distillation plant has twelve safety valves. There are two major relief scenarios: cooling water failure and external fire. Table 1 summarizes the relief rates under these two conditions. The governing case is the cooling water failure because it occurs plant wide. External fire occurs only at localized areas and the relief loads come from only a couple of safety valves. Hence, we will consider the cooling water failure case here. For simplicity, we will assume that set pressures of all safety valves are 5.0 kg/cm² g.

The flare network is divided into segments as shown in Figure 2. Segment 1 is a section of the flare header between the battery limit A and point B. Likewise, segment 2 is a section of the flare header between points B and C. Let us assume a superimposed back pressure at point A of 1.5 kg/cm² a.

Piping between points A and B

Data

Flowrate: 95,648 kg/h (Table 1)
Pressure at point A, P_2: 1.5 kg/cm²a
Molecular weight of vapor, M_w: 86
Temperature of vapor: 100°C
Straight length of pipe : 15 m
Number of elbows: 0
Number of valves: 1
Number of tees: 0
Compressibility factor: 0.95
Ratio of specific heats, C_p/C_v: 1.4
Viscosity: 0.000009 kg/m s

Roughness factor, ε: 0.0001m (0.1 mm)
Pipe diameter, D (assumed): 0.30 m (12 in.)

Calculations

Density of vapor: PM_w/ZRT = 4.2899 kg/m³

Volumetric flowrate: 95,648/(4.2899 x 3,600) = 6.193 m³/s

Velocity in pipe: 6.193 x 4/(π x (0.30)²) = 87.61 m/s

Reynolds number, N_{Re}: 0.30 x 87.61 x 4.2899/0.000009 = 12,528,371

Outlet Mach Number, M_2: 3.293 x 10⁻⁷ (95,648/(1.5 x 0.30²)) x (0.95 x 373/1.4 x 86)^0.5 = 0.4003

Fanning's friction factor (to be solved by iteration):
$1/\sqrt{f} = -4\log[\varepsilon/(3.7D) + 1.256/(N_{Re}\sqrt{f})]$ = 0.0038

Moody's friction factor: 4 x 0.0038 = 0.0152

Equivalent length: 17.8 m
fL/D: 0.0152 x 17.8/0.3
Using Equation (1b), P_1/P_2 is calculated to be: 1.08226
P_1: 1.08226 x 1.5 = 1.6234 kg/cm²a
Hence, the pressure at point B is 1.6234 kg/cm²a

Piping between point B and PSV-01, 1st trial

Data

Set pressure of PSV-01: 5.0 kg/cm²g
Flowrate: 12,870 kg/h (Table 1)
Pressure at point B, P_2: 1.6234 kg/cm²a
Molecular weight of vapor M_w: 86
Temperature of vapor: 100°C
Straight length of pipe: 30 m
Number of elbows: 3
Number of valves: 1
Number of tees: 0
Compressibility factor: 0.95
Ratio of specific heats, C_p/C_v: 1.4
Viscosity: 0.000009 kg/m s

Roughness factor, ε: 0.0001m (0.1 mm)
Pipe diameter, D (assumed): 0.08 m (3 in.)

Calculations

(*detailed steps not repeated*)

Density of vapor: 4.6428 kg/m^3
Volumetric flowrate: 0.7700 m/s
Velocity in pipe: 153.186 m/s
Reynolds number, N_{Re}: 6,321,901
Outlet Mach number: 0.6998
Fanning's friction factor: 0.0052
Moody's friction factor: 0.0208
Equivalent length: 40.65 m
P_1/P_2: 2.67214
P_1: 4.3380 kg/cm^2a

Hence, the back pressure at PSV-01 is 4.3380 kg/cm^2a, or 3.3050 kg/cm^2g.

The ratio of the back pressure to the set pressure for PSV-01 works out to 66.10% which is more than that recommend for balanced bellow-type valves. In addition, the Mach number is 0.6998, which is greater than the recommended limit of 0.5. Therefore, we need to increase the line size in the stretch between B and PSV-01. Let us now select a line size of 4 in. for the second trial.

Piping between point B and PSV-01, 2nd trial

Data

Set pressure of PSV-01: 5.0 kg/cm^2g
Flowrate: 12,870 kg/h
Pressure at point B, P_2: 1.6234 kg/cm^2a
Molecular weight of vapor, M_w: 86
Temperature of vapor: 100°C
Straight length of pipe: 30 m
Number of elbows: 3
Number of valves: 1
Number of tees: 0
Compressibility factor: 0.95
Ratio of specific heats, C_p/C_v: 1.4
Viscosity: 0.000009 kg/m s
Roughness factor, ε: 0.0001m (0.1 mm)
Pipe diameter, D (assumed): 0.10 m (4 in.)

Calculations

(*detailed steps not repeated*)

Density of vapor: 4.6428 kg/m^3
Volumetric flowrate: 0.7700 m/s
Velocity in pipe: 98.03 m/s
Reynolds number, N_{Re}: 5,057,041
Outlet Mach Number: 0.4480
Fanning's friction factor: 0.0049
Moody's friction factor: 0.0196
Equivalent length: 43.31 m
P_1/P_2: 1.71121
P_1: 2.7780 kg/cm^2a

Hence, the back pressure at PSV-01 is 2.7780 kg/cm^2a, or 1.745 kg/cm^2g.

The ratio of the back pressure to the set pressure for PSV-01 is 34.90%, which is acceptable. The Mach number is 0.4480, which is also within acceptable limits.

A summary of parameters and calculation results is given in Table 2.

INSTALLATION FEATURES

Correct installation of relief valves and the associated relief system is very important for their proper operation during upsets to ensure the safety of personnel and the plant. Some useful guidelines follow:

- Pressure relief valves should be connected to the vapor space of the protected equipment
- The inlet line should be self draining back to the process vessel. This is to prevent accumulation of liquid that can corrode or block the system. Likewise, the outlet line from the pressure relief valve should be self-draining to the flare header. To meet this requirement, it is recommended that relief valves are installed at a high point in the system (Figure 3)
- For reliable overpressure protection it is best to install pressure relief valves without any isolation valves. However, pressure relief valves sometimes do not reseat properly and start to leak. Therefore, in many cases, two safety valves are installed to allow replacement of relief valves that are leaking while the plant is in operation. This also facilitates testing and servicing of relief valves regularly without interrupting plant operations
- Whenever two pressure relief valves are installed as mentioned above, isolation valves are provided for each relief valve (Figure 4). This is to facilitate isolation of the "A" valve for maintenance while taking valve "B" online when required. In such cases, a ¾-in. bleeder valve with an isolation valve is recommended in between the isolation valve and the pressure relief valve. This is needed because when the "A" valve has been isolated, the section between the isolation valve and the pressure relief valve is still at the operating pressure of the column. The bleeder is used to depressurize this section before the valve is removed from the line, otherwise it could be an unsafe condition for maintenance personnel [*4*]
- Whenever two pressure relief valves are provided, it is mandatory that a mechanical interlock system is installed between the respective isolation valves to ensure that one of the isolation valves is open at all times. This is to eliminate operator error, which might mistakenly create a situation where both the isolation valves are in the closed position, leading to unavailability of either of the relief valves for any particular equipment
- Pressure relief valves in steam, water or air service are connected to the atmosphere through a short vertical pipe. To keep this pipe free from liquid accumulation, a small weep hole is drilled at the lowest point of this pipe
- Whenever a rupture disk is installed upstream of a pressure relief valve, it is important to have a pressure indicator in the section between the

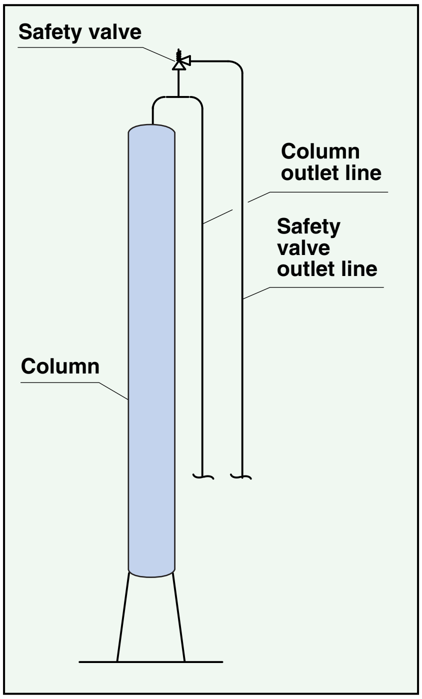

FIGURE 3. In order to make relief valves self-draining to the flare header, it is recommended that they be installed at a high point in the system

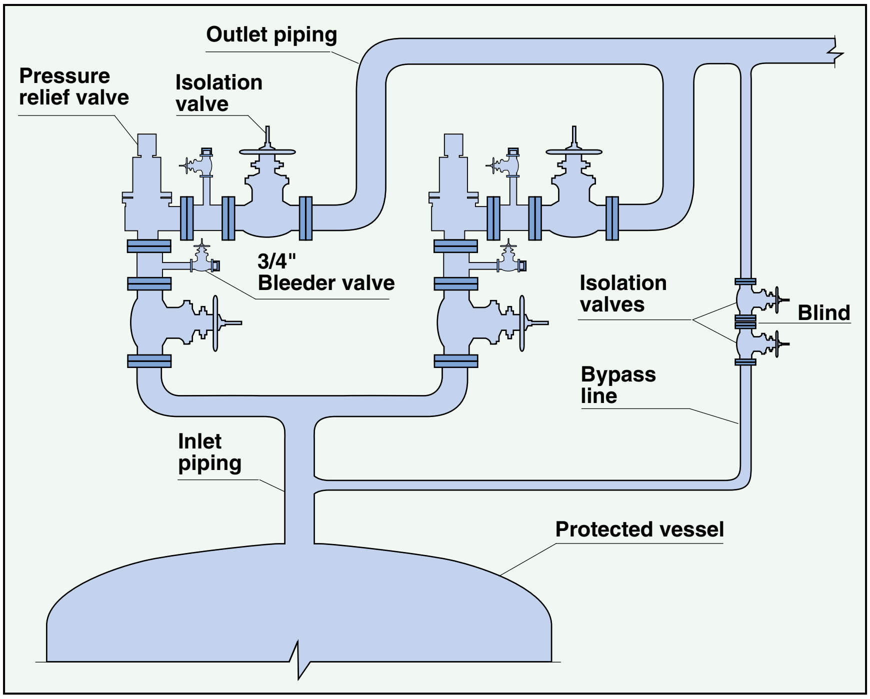

FIGURE 4. When two pressure relief valves are used, isolation and bleeder valves are needed to prevent an unsafe condition

two (Figure 5). The reason for this is that in case of a pin-hole leak in the disk, vapors from the protected equipment would pass through to the section between the disk and the safety valve. After some time, the pressures upstream and downstream of the disk would be the same and the disk would never burst

- The unit and the main flare header should slope towards the main, flare-header K.O. drum. This is to ensure that condensed vapors, if any, do not back up and accumulate immediately downstream of the safety valves ■

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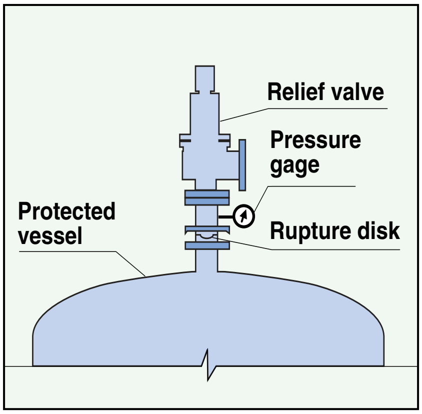

FIGURE 5. When a rupture disk is installed upstream of a pressure relief valve, a pressure indicator is needed between the two

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