

Sizing Pressure-Relief Devices

DANIEL A. CROWL
MICHIGAN TECHNOLOGICAL UNIV.
SCOTT A. TIPLER
THE DOW CHEMICAL COMPANY

Although relief devices may never be activated, they must be designed and sized to function correctly every time they are necessary. This article provides an introduction to sizing pressure-relief devices for liquid and vapor service.

A pressure-relief device protects process equipment from the hazards of high (or low) pressure in a process. It operates by opening at a designated pressure and ejecting mass from the process. The ejected mass contains energy — the removal of the energy reduces the process pressure.

A previous article in *CEP* (1) provided a basic overview of pressure-relief systems. That article stressed the importance of properly locating, selecting, designing, and maintaining pressure-relief devices to ensure that they operate when their service is required.

This article follows up with an introduction to sizing pressure-relief devices to ensure that they function properly. More detailed information on relief sizing is provided in Refs. 2–4.

Relief device basics

The purpose of relief sizing is to determine the proper discharge area of the relief device and diameter of the associated inlet and outlet piping. If the relief device is undersized, high pressure and equipment failure may result. If the relief device is oversized, the relief may become unstable during operation (1), which may damage the relief device and cause it to fail. In addition, the cost of an oversized relief system will be higher than one of the correct size.

It is important to note that the pressure-relief system might never be used, but it must operate effectively every time it is required. Process operators must have confidence that the pressure-relief system is designed, sized, and

maintained properly. Special considerations that impact the operability, such as plugging, must be addressed.

There are many different ways that high (or low) pressure can be created in a process. For instance, high pressure may result from the failure of a control valve, a reaction that is out of control, thermal expansion of a liquid, or even an external fire. Each possible cause of overpressure is referred to as a scenario. All potential overpressure scenarios must be carefully identified, characterized as credible or non-credible, and documented prior to sizing the relief system.

Two-phase relief discharge. The mass discharged through the relief system is typically a gas, liquid, or a combination of both. A combination of gas and liquid is called two-phase flow, and its release is a frothy discharge similar to the discharge from a soda can that has been shaken and then opened.

Two-phase sizing is considered only for those devices that two-phase fluid enters. For example, if liquid propane enters a relief device and partially vaporizes so that two-phase flow occurs in the tailpipe, only the tailpipe should be designed for two-phase flow. Two-phase relief is common in reactive relief systems and systems with foamy or viscous materials. The required relief area for two-phase flow is typically two to ten times the area for single-phase flow. Two-phase relief-device design is more difficult than single-phase design (2, 4); experts with specialized knowledge should perform two-phase relief design. This article discusses only the sizing of relief devices for single-phase flow — either all gas or all liquid entering the relief device.

Design and sizing terms and definitions

The primary parameter used to characterize a pressure vessel is the maximum allowable working pressure (MAWP). The MAWP is the maximum allowable pressure at the top of a vessel at a designated temperature. This designated temperature is known as the maximum allowable working temperature (MAWT). The MAWT is important because as the temperature increases, the MAWP decreases, since the strength of the metal is reduced. In addition, at very low operating temperatures (approximately -20°F), embrittlement may be an issue. The vessel nameplate typically includes the MAWP, MAWT, and the minimum design metal temperature (MDMT). The MAWP, MAWT, and MDMT must not be exceeded under non-emergency operating conditions.

The set pressure of a relief device is the pressure at which the device operates. For spring-operated relief valves, small amounts of leakage start to occur at 92–95% of the set pressure.

A relief device's overpressure is the pressure increase over its set pressure, usually expressed as a percentage of the set pressure. Pop-acting relief valves do not immediately open completely (to 100% lift). Sufficient overpressure is necessary to achieve full lift. ASME-certified relief valves

are required to reach full rated capacity at 10% or less overpressure. Relief valves are code-certified by the National Board of Boiler and Pressure Vessel Inspectors. Code certification involves conducting flow tests under conditions specified in the ASME code.

The pressure vessel accumulation is the pressure increase above the MAWP, usually expressed as a percentage of the MAWP. When the relief device is at the MAWP, the overpressure and accumulation are equal.

Backpressure is the pressure downstream of the relief device. It includes the constant superimposed backpressure and the built-up backpressure due to the discharge of fluid from the relief device through the downstream piping and/or treatment system.

ASME Boiler and Pressure Vessel Code Section VIII requirements

Figure 1 summarizes the ASME Boiler and Pressure Vessel Code (BPVC) Section VIII (6) requirements for pressure vessels and relief systems. The left side of the figure shows code requirements for pressure vessels, while the right side shows code requirements for typical relief devices. The entire figure is relative to the MAWP, which is assigned the arbitrary value of 100%.

As shown in Figure 1, the relief device's maximum allowable set pressure is equal to the vessel's MAWP. This applies to vessels protected by a single relief device. However, if the vessel is protected by multiple relief devices, then one relief device must be set no higher than the MAWP but the others can be set as high as 105% of the MAWP.

Typically, relief devices are set to open at the MAWP. The expected maximum operating pressure should be low enough to prevent relief device activation during routine operations. The difference between the set pressure and the maximum operating pressure is known as the operating margin. The required operating margin depends on the type of relief device and the pressure control capability of the process.

The allowable accumulation for pressure vessels protected by a single relief device is 110%, as shown in Figure 1. The exception to this is fire exposure scenarios, for which the allowable accumulation is 121% of the MAWP. When multiple relief devices are used for non-fire scenarios, the allowable accumulation is 116%.

| Pressure Vessel | | Typical Relief Valve |
|---|------|--|
| Maximum allowable accumulation pressure, fire sizing | 121% | Maximum relieving pressure, fire sizing |
| Maximum allowable accumulation pressure, multiple reliefs | 116% | Maximum relieving pressure, multiple reliefs |
| Maximum allowable accumulation pressure, non-fire sizing | 110% | Maximum relieving pressure, single relief |
| Maximum allowable working pressure (MAWP) | 100% | Maximum allowable set pressure, multiple reliefs |
| Typical maximum allowable operating pressure | 90% | Maximum allowable set pressure, single relief |

▲ **Figure 1.** The ASME Boiler and Pressure Vessel Code Section VIII sets out requirements for standard pressure vessels (left) and the relief valves protecting them (right) as a percentage of the maximum allowable working pressure (MAWP).

The relief design procedure

Figure 2 is a flowchart for the pressure-relief design procedure.

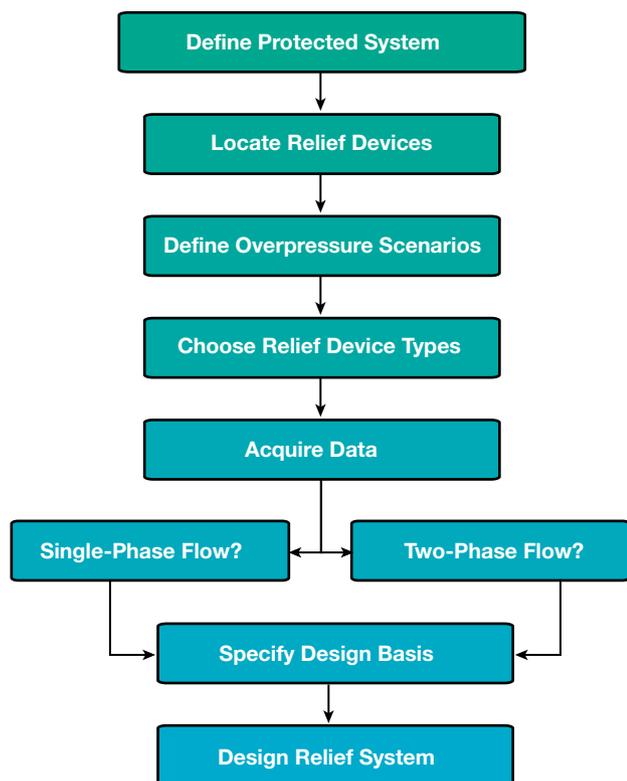
Define the protected system. The first step in the design procedure is to define the protected system and understand the operation of the process. The protected system may include several pieces of equipment. For example, if a relief

Back to Basics

is provided on the top of a distillation column, it may protect the column, reboiler, condenser, and accumulator. The design procedure is more complex for processes involving connected equipment with different pressure ratings. The relief designer needs to have a good understanding of the operation of the process in order to assess the overpressure protection needs.

Locate the relief devices. Next, determine where overpressure protection may be needed. The codes and standards set different requirements for different types of equipment. For example, all pressure vessels must be protected from overpressure per ASME code. Protection may also be needed for other equipment in the process where damage or personnel injury can be caused by excessive pressure. Table 1 contains general guidelines on where relief devices are required, although there are likely to be other special cases in any process where they may be necessary.

Low-pressure storage tanks require both vacuum- and pressure-relief devices, since these vessels typically are not designed for full vacuum. Relief devices for these tanks are designed only for vapor relief and not for liquid discharge due to overfilling — instrumentation and/or procedural safeguards are used to mitigate the overfilling scenario.



▲ **Figure 2.** The relief-device sizing procedure involves these steps.

Pumps can be an overpressure hazard to downstream equipment. All positive-displacement pumps should be reviewed as a potential source of overpressure. Normally, the relief device on a pump discharges to the inlet side of the pump — either to the pump suction pipe or to the suction vessel. Routing to the suction vessel is recommended to reduce the risk of dangerous heating of the fluid caused by liquid recirculating through a blocked pump.

Overpressure hazards of process lines are sometimes overlooked. Any blocked liquid-filled line poses a risk of overpressure if the fluid can be heated by ambient temperature or sun exposure. Heat-traced liquid-filled lines typically require a relief device or an open outlet to allow for liquid expansion. Long lines (*i.e.*, more than about 300 ft) that are not in continuous service generally need protection from liquid thermal expansion, as do loading and transfer lines and other lines that extend beyond the battery limit (*i.e.*, the property line). Finally, lines with a history of overpressure, for example as indicated by gasket blowout, generally require a relief device.

The coolant side of a heat exchanger may or may not require a relief device, depending on the service. Maintenance isolation valves are typically present on the coolant lines. Therefore, if the valves are closed and the coolant side is exposed to heat from the hot side of the exchanger, damage might occur. However, piping systems such as cooling water lines are seldom isolated in an operating plant, even when the plant is down. If the coolant side is drained whenever the exchanger is isolated, then a relief may not be required.

Table 1. These general guidelines provide advice on where relief devices are required.*

| |
|--|
| All pressure vessels require overpressure protection. |
| All low-pressure storage tanks require pressure and vacuum relief for normal operation (<i>e.g.</i> , pumping in and out, tank breathing caused by temperature changes). Tanks must also be protected from any emergency events that could create an abnormally high venting load (<i>e.g.</i> , fire exposure, procedural failure during line blowing, etc.). |
| Positive-displacement pumps, compressors, and turbines require relief devices on the discharge side for deadhead protection. |
| Segments of liquid-filled piping that have a high risk of overpressure due to thermal expansion (<i>e.g.</i> , unloading lines) should have relief devices. |
| Piping that can be overpressured due to process control failure (<i>e.g.</i> , high-pressure steam letdown control into a low-pressure steam header) need relief devices. |
| A vessel jacket is usually considered a distinctly separate pressure vessel, and requires its own overpressure protection. |

* This list is not exhaustive.

Batch chemical reactor example. Figure 3 depicts a batch chemical reactor in a pilot plant. A positive-displacement pump is used to load the vessel contents. Cooling coils inside the reactor control the reaction temperature, and a reflux condenser provides additional temperature control. In this example, relief devices may be required at four locations to provide overpressure protection:

- on the reactor itself to protect the reactor vessel and the process side of the reflux condenser from overpressure
- on the cooling water coils inside the reactor; if hot liquid is pumped into the reactor while the cooling water valves are closed, the liquid inside the tubes will expand and likely damage the tubes
- on the coolant side of the reflux condenser, because hot vapors from the reactor can cause the water to expand and create overpressure if the coolant valves are closed
- on the pump outlet, as closing the outlet side valve may damage the pump and the discharge piping.

Define the overpressure scenarios. For each piece of process equipment, there are typically multiple scenarios that may result in overpressure. An up-to-date piping and instrumentation diagram (P&ID) is essential for identifying these potential scenarios. Reference 3 discusses the most common causes of overpressure for different types of process equipment.

When evaluating scenarios, consider modes of operation other than normal operation, such as startup and shutdown.

Once the potential scenarios have been defined, the next step is to determine which are credible scenarios. A

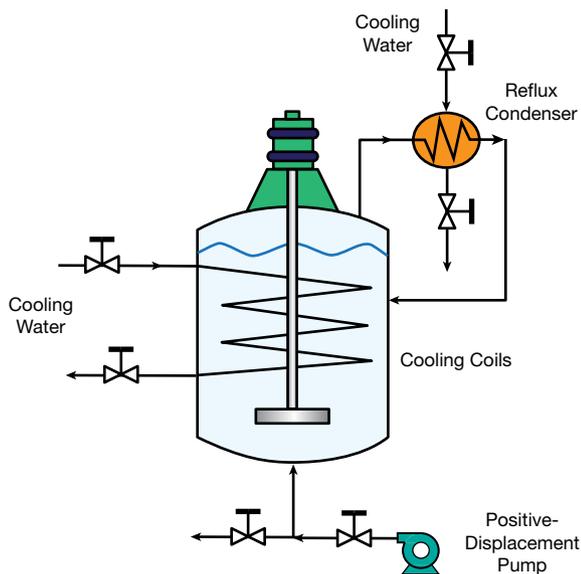
credible scenario is typically one that involves a single failure. Scenarios that require multiple independent failures are typically not considered when sizing individual relief devices. Credibility is based on risk, which is a function of probability and consequence. Formal hazard-identification procedures, such as layers of protection analysis (LOPA), hazard and operability (HAZOP) analysis, fault-tree analysis (FTA), or failure modes and effects analysis (FMEA), can be used to assess risk.

Most relief-system designs involve compromises. A particular relief device might work fine for the primary design (*i.e.*, controlling) scenario, but pose a performance risk for other scenarios. An example of this is a relief valve that is sized for a vapor scenario but must also work effectively in a liquid scenario. The liquid scenario will often present some mechanical instability risks, which must be tolerable to the plant owner (*e.g.*, it may require lower pressure to reclose in liquid service).

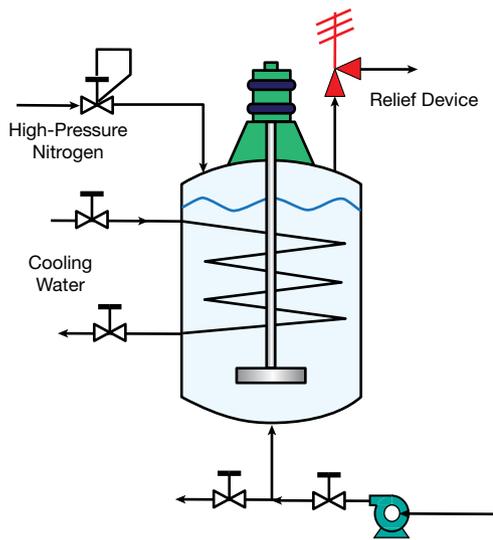
It is possible that no causes for overpressure can be identified for a particular piece of equipment in the process. The ASME Boiler and Pressure Vessel Code Section VIII (6) requires all pressure vessels to have protection from overpressure regardless of whether there are any credible overpressure scenarios. In such cases, a relief device is typically installed to meet the code requirements. Even if no credible scenarios exist, a small relief device is good insurance against overpressure.

Mixing vessel example. In Figure 4, a mixing vessel's relief valve is shown in red. This vessel has four potential overpressure scenarios:

- The nitrogen regulator could fail, exposing the vessel to



▲ **Figure 3.** This batch reactor requires relief devices in four locations: on the reactor itself, on the cooling water coils, on the coolant side of the reflux condenser, and on the pump outlet.



▲ **Figure 4.** A mixing vessel with a high-pressure nitrogen supply system (whose relief valve is shown in red) is subject to several overpressure scenarios.

Back to Basics

the pressure of the nitrogen supply system.

- A leak could develop in the cooling water coils, exposing the vessel to the pressure of the coolant system, or possibly resulting in a reactive scenario if the process materials react with the coolant.
- A procedural failure could cause the pump to continue operating while the vessel outlet is closed, exposing the vessel to the discharge pressure of the pump.
- The vessel could be exposed to fire, which may heat the vessel's contents and result in overpressure.

Note that these are scenarios only for the mixing vessel. Scenarios would also need to be identified for all other pressure vessels in this process (which are not included in Figure 4).

Choose the type of relief device. The next step is to select an appropriate relief device for the specific application, because the sizing calculations depend on the type of relief device selected.

There are many different types of relief devices. The most common are spring-operated relief valves, balanced spring-operated relief valves (balanced using a bellows or balanced piston), rupture discs, pilot-operated relief valves, and rupture-pin relief devices. Combinations of these devices may also be desirable (*i.e.*, a rupture disc located under a relief valve). Details on these different types, and the advantages and disadvantages of each, are discussed in Refs. 2 and 5. One must have a good understanding of the process in order to select the right type of relief device for that process.

Rupture discs and buckling-pin-type relief devices do not reclose after activation. Therefore, they should not be the first choice for most applications. Preference should be given to reclosing relief devices for both safety and reliability.

The routing of the relief device effluent will also influence the selection of the type of relief. If the device discharges to the atmosphere, then a conventional spring relief valve is generally the best and most economical choice. If the discharge is routed to a containment (*e.g.*, pipe or vessel) or treatment (*e.g.*, scrubber or flare header) system, then a balanced or pilot-operated relief valve is more appropriate due to the backpressure from the downstream system.

Acquire data for relief-device sizing. The next step in the relief-design procedure is to acquire the data needed to determine the required relief flowrate and required relief area for each scenario. For example, a control valve failure scenario requires knowing the control valve's flow coefficient and the upstream pressure. If the overpressure is caused by a centrifugal pump, then the pump curve and the size of the impeller are needed to calculate the flowrate.

To calculate the required relief area, physical property

data such as heat capacity, density, heat of vaporization, and vapor pressure are typically needed.

Determine whether single- or two-phase flow is likely.

At this point in the relief-design process, a determination must be made as to whether the material entering the relief device will be single-phase or two-phase flow when the device is at its relieving pressure. If a chemical reaction is involved, two-phase flow is very likely. During a fire exposure, two-phase flow is possible, but not likely unless the fluid is inherently foamy, contains surfactants, or has a high liquid viscosity. The superficial velocity in a narrow-diameter vessel may also result in two-phase flow, if the velocity is too high to allow for vapor-liquid disengagement.

Determine the design basis for the device. Adequate information is available at this point to determine the design basis for the relief device. The design basis includes the mass discharge rate through the device and operating information for the relief device, such as the relief set pressure, overpressure, and superimposed backpressure, to name a few. For rupture discs, the burst temperature is also important.

The scenario that requires the largest area, rather than the one with the highest mass flowrate, is the controlling case for device sizing. Liquid relief scenarios commonly have the highest mass flowrate, but they are generally not the controlling scenarios when vapor scenarios also exist.

Relief device sizing

The American Petroleum Institute's Recommended Practice for Sizing, Selection, and Installation of Pressure-Relieving Systems in Refineries, API 520 Part 1 (3), is the most widely used manual for sizing relief devices in the chemical process industries.

The objective of the relief sizing calculation is to determine the required relief area for the relief device. Almost every relief device installation has its own unique design issues and special considerations that will impact the relief sizing calculations. The procedure outlined in the flowchart provided in Figure 2 must be followed to identify these issues. The procedure described in this article is a generic sizing procedure and covers sizing calculations only for conventional spring-operated devices in liquid and gas (vapor) service.

Sizing for liquid service

For a spring-operated pressure-relief device in liquid service, the sizing procedure requires, at a minimum, a specification of the design basis. This includes the volumetric discharge flowrate through the relief device, the set pressure, and the overpressure. For a balanced-bellows relief valve, the backpressure must also be known.

For liquid service, the sizing calculation is based on the fundamental equation for liquid discharge through an orifice (2):

$$u = K_d \sqrt{\frac{2g_c \Delta P}{\rho}} \quad (1)$$

where u is the average discharge velocity of the fluid through the relief orifice (in units of distance/time); K_d is the effective discharge coefficient (unitless); g_c is the gravitational constant (distance-mass/force-time²); ΔP is the pressure drop across the orifice (force/area); and ρ is the density of the fluid (mass/volume). The unitless discharge coefficient, K_d , is normally provided by the valve manufacturer. It can also be obtained from the ASME National Board of Boiler and Pressure Vessel Inspectors for code-certified devices. For preliminary sizing, a value of $K_d = 0.65$ is assumed.

The volumetric flow of liquid, Q (volume/time), is equal to the discharge velocity (u) multiplied by the orifice area (A). Substituting and solving for the area gives:

$$A = \frac{Q}{K_d \sqrt{2g_c}} \sqrt{\frac{\rho}{\Delta P}} \quad (2)$$

A working equation with fixed units is derived from Eq. 2 by replacing the density with the specific gravity (ρ/ρ_{ref}) and using water as the reference material, and making the appropriate substitutions for unit conversions. The result is Eq. 3:

$$A = \left[\frac{\text{in.}^2 (\text{psi})^{1/2}}{38.0 \text{ gpm}} \right] \frac{Q}{K_d} \sqrt{\frac{\rho/\rho_{ref}}{\Delta P}} \quad (3)$$

where A has units of in.², Q has units in U.S. gal/min, and ΔP has units of psi.

Equations 1–3 model liquid discharge through an orifice with fully turbulent flow. Equation 3 must be adjusted for the viscosity of the fluid; a fluid with a higher viscosity requires a larger orifice. Equation 3 must also be adjusted for backpressure if a balanced-bellows relief valve is selected.

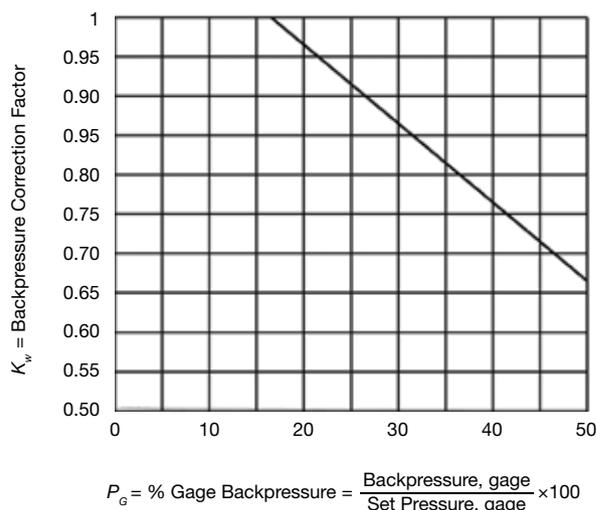
Incorporating these adjustments into Eq. 3 results in the following equation:

$$A = \left[\frac{\text{in.}^2 (\text{psi})^{1/2}}{38.0 \text{ gpm}} \right] \frac{Q}{K_d K_w K_v} \sqrt{\frac{G}{P_1 - P_2}} \quad (4)$$

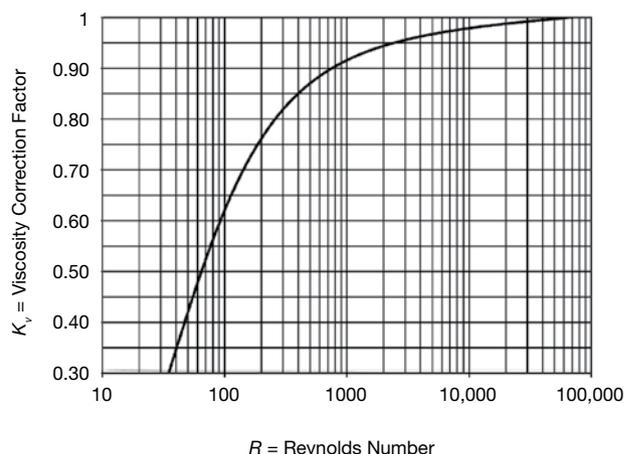
where K_w is the adjustment factor for backpressure (unitless); K_v is the adjustment factor for viscosity (unitless); G is the specific gravity of the liquid referenced to water at 70°F, which is equal to ρ/ρ_{ref} ; P_1 is the upstream relieving pressure (gauge pressure), which is the set pressure plus allowable overpressure; and P_2 is the total backpressure (gauge pressure).

For conventional relief valves in liquid service, use $K_w = 1.0$. For balanced-bellows relief valves in liquid service, K_w must be obtained from the manufacturer. For preliminary sizing, K_w can be determined from Figure 5.

K_v is the unitless viscosity correction factor and can be determined from Figure 6. The viscosity correction factor is a function of the fluid's Reynolds number. As the Reynolds number decreases (*i.e.*, the liquid becomes more



▲ **Figure 5.** Use this diagram to determine the backpressure correction factor, K_w , for balanced-bellows relief valves in liquid service. The figure is drawn using the equation $K_w = 1.1165 - 0.01(P_G)$ for $P_G > 17$ and data from Ref. 3.



▲ **Figure 6.** Use this diagram to determine the viscosity correction factor, K_v , for both conventional and balanced-bellows relief valves in liquid service. The figure is drawn using the equation $\ln K_v = 0.0857 - 0.9541/\ln R - 35.571/R$ and data from Ref. 3.

Back to Basics

viscous), the value of K_v decreases, and a larger relief area is required.

For a Reynolds number greater than 16,000, viscosity correction is not needed (*i.e.*, $K_v = 1.0$). However, in order to calculate the Reynolds number, the relief area must be known. This may require solving Eq. 4 by trial and error. In this case, first assume a viscosity correction factor of $K_v = 1.0$ and calculate the relief area, then calculate the Reynolds number. In most cases, the Reynolds number will be much greater than 16,000. However, if the Reynolds number is less than 16,000, use Figure 6 to determine a new viscosity correction factor, and calculate a new relief area and Reynolds number. Repeat this procedure until the solution converges on a Reynolds number.

Liquid sizing example

A detailed study has determined the required relief flow through a conventional spring-operated relief valve on a process vessel to be 300 gpm of water. Assume a set pressure of 100 psig, a maximum overpressure of 10%, a temperature of 70°F, and no backpressure.

With a set pressure of 100 psig and an overpressure of 10% of the set pressure, or 10 psig, the upstream relieving pressure, P_1 , is 110 psig.

For a conventional relief valve, no backpressure correction is necessary ($K_w = 1.0$). The volumetric discharge rate, Q , through the relief valve is given as 300 gpm. The discharge coefficient, K_d , is not specified; for a preliminary estimate, assume $K_d = 0.65$.

The Reynolds number through the relief valve is not known. However, at a volumetric discharge rate of 300 gpm,

the Reynolds number is almost certainly above 16,000. Thus, assume $K_v = 1.0$. The liquid is water at 70°F, so $G = (\rho/\rho_{ref}) = 1.0$.

From Eq. 4:

$$A = \left[\frac{\text{in.}^2 (\text{psi})^{1/2}}{38.0 \text{ gpm}} \right] \frac{300 \text{ gpm}}{(0.65)(1.0)(1.0)} \sqrt{\frac{1.0}{110 \text{ psig} - 0 \text{ psig}}} = 1.16 \text{ in.}^2$$

Thus, the minimum required relief orifice area would be 1.16 in.² in this example.

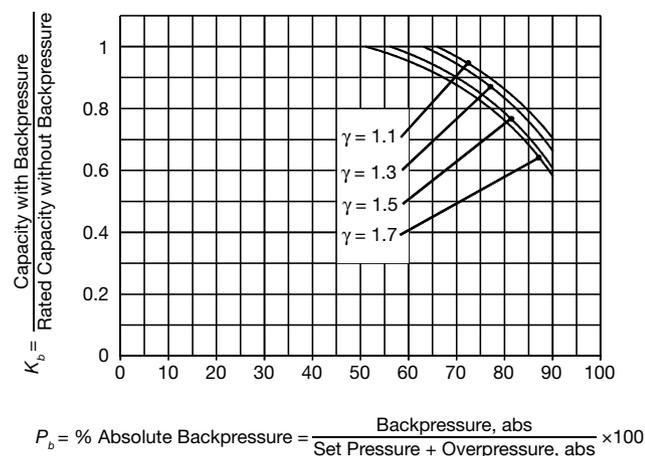
Sizing for gas service

For conventional spring-operated relief devices in gas or vapor service, choked flow through the relief orifice is assumed. Choked flow through an orifice is represented by the following equation (2):

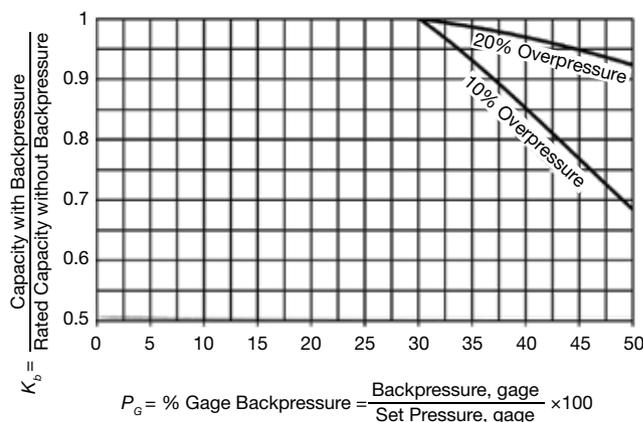
$$W = K_d A P_1 \sqrt{\frac{\gamma \times g_c M}{R_g T} \left(\frac{2}{\gamma + 1} \right)^{(\gamma+1)/(\gamma-1)}} \quad (5)$$

where W is the mass flowrate (mass/time); K_d is the discharge coefficient (unitless); P_1 is the upstream relieving pressure for vapor service (absolute pressure); γ is the heat capacity ratio of the gas or vapor (unitless); M is the molecular weight of the gas (mass/mol); R_g is the ideal gas constant (pressure-volume/mol-deg.); and T is the absolute temperature (deg.).

To simplify the calculation, the term C , which is a function of only the heat capacity ratio, is defined as:



▲ **Figure 7.** Use this plot to determine the backpressure correction factor, K_b , for conventional spring-operated relief devices in vapor service. It is drawn using the equation and constants in Table 2 and data from Ref. 3.



▲ **Figure 8.** Use this plot to determine the backpressure correction factor, K_b , for balanced-bellows relief devices in vapor service. It is drawn using the equation and constants in Table 3 and data from Ref. 3.

$$C = \sqrt{\frac{\gamma \times g_c}{R_g} \left(\frac{2}{\gamma + 1} \right)^{(\gamma+1)(\gamma-1)}} \quad (6)$$

Equation 5 is modified by adding a compressibility factor, z , to account for nonideal gas behavior, and the backpressure correction, K_b , to account for backpressure. With these adjustments, Eq. 5 can be solved for the relief area:

$$A = \frac{W}{CK_d P_1 K_b} \sqrt{\frac{T \times z}{M}} \quad (7)$$

K_d and K_b are normally provided by the valve manufacturer. For preliminary sizing purposes, a discharge coefficient, K_d , of 0.975 is used. The backpressure correction factor, K_b , is determined by Figure 7 or 8, depending on whether the relief device is a conventional spring-operated device or a balanced-bellows valve. Data for Figure 7 were derived from the equation in Table 2 and data for Figure 8 were derived from the equation in Table 3.

For Figure 8, K_b is a function of the ratio of the backpressure and the set pressure. For Figure 7, K_b is a function of the ratio of the backpressure and the maximum allowable relieving pressure, P_{max} , which is determined from the allowable accumulation:

$$\begin{aligned} P_{max} &= 1.1 \times P_{MAWP} \text{ for unfired pressure vessels} \\ P_{max} &= 1.21 \times P_{MAWP} \text{ for vessels exposed to fire} \\ P_{max} &= 1.33 \times P_{MAWP} \text{ for piping} \end{aligned} \quad (8)$$

Table 2. These factors can be used to compute the backpressure correction factor for conventional spring-operated relief devices in vapor service. Figure 7 was constructed based on this equation.

| $K_b = a + bP_b^3$ | | | |
|--------------------|--------|--------|--------------------------|
| □ | Range | a | b |
| 1.1 | 66–90% | 1.3026 | -1.137×10^{-6} |
| 1.3 | 63–90% | 1.294 | -1.1703×10^{-6} |
| 1.5 | 56–90% | 1.203 | -1.143×10^{-6} |
| 1.7 | 51–90% | 1.148 | -1.109×10^{-6} |

Table 3. For balanced-bellows relief devices in vapor service, this equation can be used to compute the backpressure correction factor, and was used to construct Figure 8.

| $K_b = 1/(a + bG^3)$ | | | |
|----------------------|--------|------------------------|--------|
| Overpressure | a | b | Range |
| 10% | 0.8707 | 4.724×10^{-6} | 30–50% |
| 20% | 0.9760 | 8.360×10^{-7} | 30–50% |

where both P_{MAWP} and P_{max} are in gage pressure units. To use Figure 7, the backpressure and P_{max} must be converted to absolute pressure units with an equation such as:

$$P_1 = P_{max} + 14.7 \quad (9)$$

where P_{max} is in psig and P_1 is in psia.

Gas sizing example

A spring-operated relief device must be sized for a pressure vessel containing an ideal hydrocarbon vapor. The controlling scenario has a mass discharge rate, W , of 50.0 kg/s. Assume a vessel P_{MAWP} of 8 barg, no superimposed backpressure, a built-up backpressure equal to 10% of set pressure, and a process temperature of 473 K. A review of normal operating pressures concludes that a set pressure, P_s , of 7 barg will be used. The vapor has a molecular weight of 100, a heat capacity ratio of 1.3, and is ideal so $z = 1.0$.

This is an unfired pressure vessel, so from Eq. 8, the maximum allowable relieving pressure in gage units is:

$$P_{max} = (1.1)(8 \text{ barg}) = 8.8 \text{ barg}$$

The absolute maximum pressure is then $P_1 = 8.8 + 1.013 = 9.813 \text{ bara} = 9.81 \times 10^5 \text{ N/m}^2$. The backpressure is 10% of the set pressure = $(0.10)(7 \text{ barg}) = 0.7 \text{ barg}$. To use Figure 8 to find the backpressure correction, K_b , the percent absolute backpressure is needed:

$$\begin{aligned} \text{Backpressure, abs\%} &= \frac{\text{Backpressure, abs}}{(\text{Set Pressure} + \text{Overpressure}), \text{ abs}} \\ &= \frac{0.7 \text{ bara} + 1.013 \text{ bara}}{9.813 \text{ bara}} = 0.175 \text{ or } 17.5\% \end{aligned}$$

From Figure 7, at 17.5% absolute backpressure, $K_b = 1.0$. With $z = 1.0$, $\gamma = 1.3$, $T = 473 \text{ K}$, and $M = 100 \text{ kg/kg-mol}$, from Eq. 6:

$$\begin{aligned} C &= \sqrt{1.3 \left(\frac{1 \text{ kg m/s}^2 \text{ N}}{8314 \text{ N-m/kg-mol K}} \right) \left(\frac{2}{1.3 + 1} \right)^{\frac{2.3}{0.3}}} \\ &= 7.32 \times 10^{-3} \frac{(\text{kg kg-mol K})^{1/2}}{\text{s N}} \end{aligned}$$

Assuming a discharge coefficient of $K_d = 0.975$, the minimum required area is determined from Eq. 7:

$$\begin{aligned} A &= \frac{50 \text{ kg/s}}{7.32 \times 10^{-3} \frac{(\text{kg kg-mol K})^{1/2}}{\text{s N}} (0.975) (9.81 \times 10^5 \text{ N/m}^2)} \\ &\times \sqrt{\frac{(473 \text{ K})(1.0)}{100 \text{ kg/kg-mol}}} = 1.53 \times 10^{-2} \text{ m}^2 \end{aligned}$$

Back to Basics

and from the area, the equivalent orifice diameter of the relief device is determined by:

$$d = \sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4(1.53 \times 10^{-2} \text{ m}^2)}{3.14}} = 0.140 \text{ m} = 14.0 \text{ cm}$$

This scenario requires a relatively large orifice size of 14.0 cm because the relief valve must handle a large volumetric discharge rate.

Wrapping it up

Relief devices are safety systems that you hope are never activated. However, if they do activate, they must be designed and sized properly to ensure that they work every time.

CEP

Nomenclature

| | |
|--------------|--|
| A | = equivalent orifice area (area) |
| C | = simplification term defined by Eq. 6 |
| G | = specific gravity of the liquid at the flowing temperature referenced to water at 70°F (unitless) |
| g_c | = gravitational constant (length-mass/force-time ²) |
| K_b | = adjustment factor for backpressure in vapor/gas service (unitless) |
| K_d | = discharge coefficient (unitless) |
| K_v | = adjustment factor for viscosity in liquid service (unitless) |
| K_w | = adjustment factor for backpressure in liquid service (unitless) |
| M | = molecular weight (mass/mol) |
| P_1 | = upstream relieving pressure (gauge pressure) in Eq. 4 and (absolute pressure) in Eq. 7 |
| P_2 | = total backpressure (gauge pressure) |
| P_G | = percent gage backpressure (unitless) |
| P_{max} | = maximum overpressure for vapor service (gauge pressure) |
| P_{MAWP} | = maximum allowable working pressure, MAWP (gauge pressure) |
| P_s | = set pressure (gauge pressure) |
| ΔP | = pressure drop across the orifice (force/area) |
| Q | = volumetric discharge rate (volume/time) |
| R_g | = ideal gas constant (pressure-volume/mol-deg.) |
| T | = absolute temperature (deg.) |
| u | = average discharge velocity of the fluid through the relief orifice (distance/time) |
| W | = mass flow rate (mass/time) |
| z | = compressibility factor for nonideal gases (unitless) |
| γ | = heat capacity ratio of the gas or vapor (unitless) |
| ρ | = density of the fluid (mass/volume) |
| ρ_{ref} | = reference density (mass/volume) |

DANIEL A. CROWL is the Herbert H. Dow Professor for Chemical Process Safety at Michigan Technological Univ. (Houghton, MI; Phone: (906) 487-3221; Email: crowl@mtu.edu). He has been involved with process safety education and research since 1985. He is the author or editor of several books on process safety, has produced many modules and student certificate programs for the Safety and Chemical Engineering Education (SChE) program, and is a past editor of AIChE's quarterly journal *Process Safety Progress*. He worked for two years as a process control engineer for St. Regis Paper Co., and then spent 16 years teaching at Wayne State Univ. in Detroit before joining Michigan Tech in 1993. His research is in flammability and reactivity, and he consults with industry in these areas. He is a member of the AIChE SChE Committee, the 11a Committee on Loss Prevention, the Chem-E-Car Rules Committee, and the ASTM E27 Committee on the Hazard Potential of Chemicals. He is a Fellow of AIChE, the Center for Chemical Process Safety (CCPS), the ACS Div. of Chemical Health and Safety, and the National Speleological Society. He has received numerous awards, including most recently the Merit Award from the Mary Kay O'Connor Process Safety Center at Texas A&M Univ. He received a BS in fuel science from the Pennsylvania State Univ. and an MS and PhD in chemical engineering from the Univ. of Illinois.

SCOTT A. TIPLER is the Overpressure Protection Expertise Area Leader for The Dow Chemical Co. (Midland, MI; Phone: (989) 638-6634; Email: SATipler@Dow.com). He has been employed by Dow Chemical in a variety of manufacturing and engineering roles since 1985. He has over 20 years of overpressure protection design experience and assumed his current role in 2007. He received a BS in chemical engineering from the Michigan Technological Univ.

LITERATURE CITED

1. **Kelly, B. D.**, "What Pressure Relief Really Means," *Chem. Eng. Progress*, **106** (9), pp. 25–30 (Sept. 2010).
2. **Crowl, D. A., and J. F. Louvar**, "Relief Sizing," Chapter 10 in "Chemical Process Safety: Fundamentals with Applications," 3rd ed., Prentice Hall, Englewood Cliffs, NJ, pp. 459–503 (May 2012).
3. **American Petroleum Institute**, "Recommended Practice for the Sizing, Selection, and Installation of Pressure-Relieving Systems in Refineries," API RP 520, Part 1, 8th ed., API, Washington, DC (2008).
4. **Fisher, H. G., et al.**, "Emergency Relief System Design Using DIERS Technology," American Institute of Chemical Engineers, New York, NY (1992).
5. **Anderson Greenwood and Crosby**, Technical Service Manual, www.andersongreenwood.com/literature.asp (Aug. 2013).
6. **American Society of Mechanical Engineers**, "Boiler and Pressure Vessel Code," Section VIII, "Rules for Construction of Pressure Vessels," ASME, New York, NY (2013).

ADDITIONAL RESOURCES

- American Institute of Chemical Engineers**, "Guidelines for Pressure Relief and Effluent Handling Systems," Center for Chemical Process Safety (CCPS), New York, NY (1998).
- Hellemans, M.**, "The Safety Relief Valve Handbook," Elsevier, Oxford, U.K. (2009).
- Malek, M.**, "Pressure Relief Devices," Mc-Graw-Hill, New York, NY (2005).