Selection and Sizing of Pressure Relief Valves

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Outline/Scope/Introduction

Course Outline

1. Codes and Standards
2. Equation Nomenclature
3. Selection and Sizing
4. Summary
5. Additional Resources
6. Glossary* (see note on page 2)
7. References

Scope

There are numerous types of pressure-relieving devices and systems, both re-closing and non-re-closing (rupture discs). This course contains technical information limited to pressure relief valves. The primary purpose of a pressure relief valve is the protection of life and property by venting fluid from over-pressurized equipment. Information contained in this course applies to the overpressurization protection of pressure vessels, lines, and systems.

The basic formulae and capacity correction factors contained in this course have been, for the most part, empirically developed over time within the valve industry. The material presented reflects current and generally accepted engineering practice. Formulations in this course are consistent with the requirements of ASME Section VIII, Division 1, and API Recommended Practice 520.

Introduction

The function of a ***pressure relief valve*** is to protect pressure vessels, piping systems, and other equipment from pressures exceeding their ***design pressure*** by more than a fixed, predetermined amount. The permissible amount of ***accumulation*** is covered by various codes and is a function of the type of equipment and the conditions causing the accumulation.

*

> **NOTE:**
> For ease of learning, the student is encouraged to print the glossary near the end of the course and while studying, refer to the definitions of bold italicized ***words*** or ***phrases*** when they are first encountered.

It is not the purpose of a pressure relief valve to control or regulate the pressure in the vessel or system that the valve protects, and it does not take the place of a control or regulating valve.

The aim of safety systems in processing plants is to prevent damage to equipment, avoid injury to personnel and to eliminate any risks of compromising the welfare of the community at large and the environment. Proper sizing, selection, manufacture, assembly, test, installation, and maintenance of a pressure relief valve are critical to obtaining maximum protection.

Types, Design, and Construction

A pressure relief valve must be capable of operating at all times, especially during a period of power failure; therefore, the sole source of power for the pressure relief valve is the process fluid.

The pressure relief valve must open at a predetermined ***set pressure***, flow a ***rated capacity*** at a specified ***overpressure***, and ***close*** when the system pressure has returned to a safe level. Pressure relief valves must be designed with materials compatible with many process fluids from simple air and water to the most corrosive media. They must also be designed to operate in a consistently smooth manner on a variety of fluids and fluid phases. These design parameters lead to the wide array ray of pressure relief valve products available in the market today.

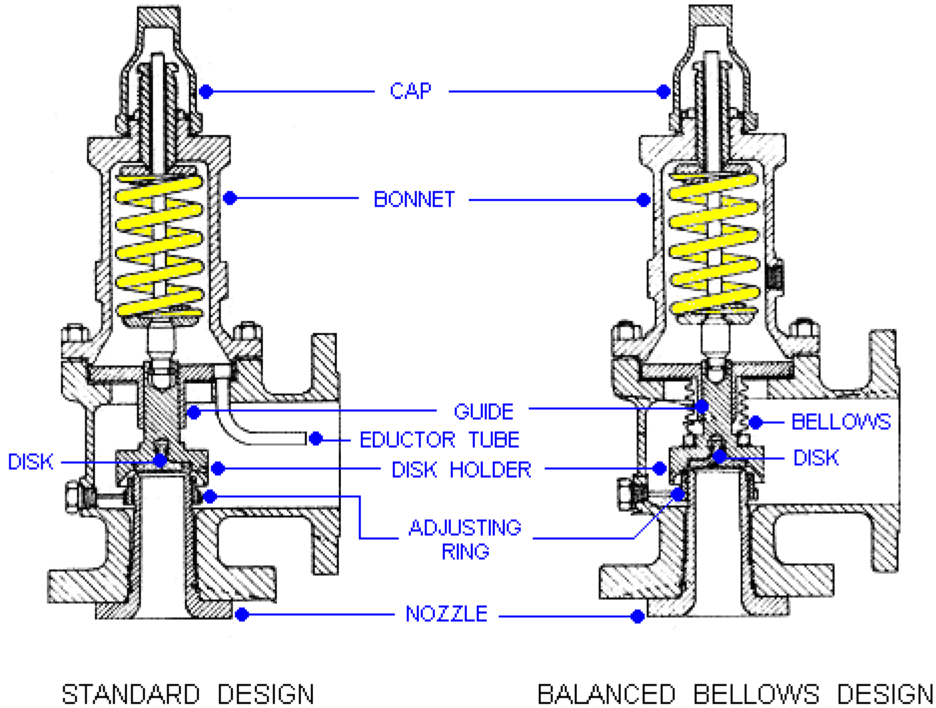


FIGURE 1 – TWO TYPES OF RELIEF VALVES

The standard design ***safety relief valve*** is spring-loaded with an adjusting ring for obtaining the proper ***blowdown*** and is available with many optional accessories and design features. Refer to Figure 1 for cross-sectional views of typical valves. The bellows and balanced bellows design isolate the process fluid from the bonnet, the spring, the stem, and the stem bushing with a bellows element. Jacketed valve bodies are available for applications requiring steam or heat transfer mediums to maintain viscosity or prevent freezing. ***Pilot-operated valves*** are available with the set pressure and blowdown control located in a separate control pilot. This type of valve uses the line pressure through the control pilot to the piston in the main relief valve and thereby maintains a high degree of tightness, especially as the set pressure is being approached. Another feature of the pilot-operated valve is that it will permit a blowdown as low as 2 percent. The disadvantage of this type of valve is its vulnerability to contamination from foreign matter in the fluid stream.

Codes and Standards

Introduction

Since pressure relief valves are safety devices, there are many Codes and Standards in place to control their design and application. The purpose of this section of the course is to familiarize the student with and provide a brief introduction to some of the Codes and Standards which govern the design and use of pressure relief valves. While this course scope is limited to ASME Section VIII, Division 1, the other Sections of the Code that have specific pressure relief valve requirements are listed below. The portions of the Code that are within the scope of this course are indicated in red:

List of Code Sections Pertaining to Pressure Relief Valves

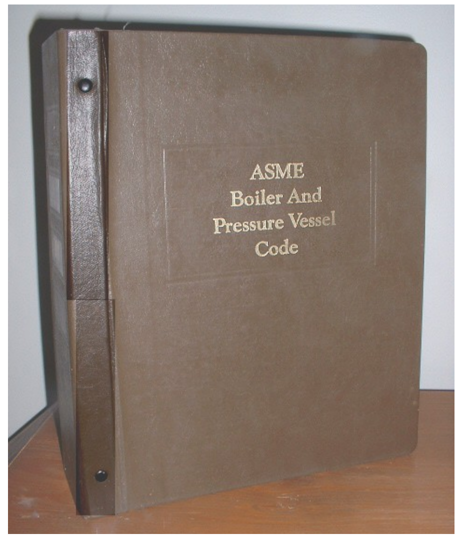
Section I	Power Boilers
Section III, Division 1	Nuclear Power Plant Components
Section IV	Heating Boilers
Section VI	Recommended Rules for the Care and Operation of Heating Boilers
Section VII	Recommended Rules for the Care of Power Boilers
Section VIII, Division 1	Pressure Vessels
Appendix 11	Capacity Conversions for Safety Valves
Appendix M	Installation and Operation
Section VIII, Division 2	Pressure Vessels - Alternative Rules
B31.3, Chapter II, Part 3	Power Piping - Safety and Relief Valves
B31.3, Chapter II, Part 6	Power Piping - Pressure Relief Piping

ASME specifically states in Section VIII, Division 1, paragraph UG-125 (a):

> "All pressure vessels within the scope of this division, irrespective of size or pressure, shall be provided with pressure relief devices in accordance with the requirements of UG-125 through UG-137."

Reference is made to the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1. The information in this course is NOT to be used for the application of overpressurization protection to power boilers and nuclear power plant components that are addressed in the Code in Section I and Section III respectively. The student should understand that the standards listed here are not all-inclusive and that there exist specific standards for the storage of chlorine, ammonia, compressed gas cylinders, and the operation of refrigeration units, among probable others.

A Brief History of the ASME Code



Many states began to enact rules and regulations regarding the construction of steam boilers and pressure vessels following several catastrophic accidents that occurred at the turn of the twentieth century that resulted in a large loss of life. By 1911 it was apparent to manufacturers and users of boilers and pressure vessels that the lack of uniformity in these regulations between states made it difficult to construct vessels for interstate commerce. A group of these interested parties appealed to the Council of the American Society of Mechanical Engineers to assist in the formulation of standard specifications for steam boilers and pressure vessels. (The American Society of Mechanical Engineers was organized in 1880 as an educational and technical society of Mechanical Engineers.) After years of development and public comment the first edition of the code, *ASME Rules of Construction of Stationary Boilers and for Allowable Working Pressures,* was published in 1914 and formally adopted in the spring of 1915. From this simple beginning, the code has now evolved into the present eleven section document, with multiple subdivisions, parts, subsections, and mandatory and non-mandatory appendices.

The ASME Code Symbol Stamp and the letters "UV" on a pressure relief valve indicate that the valve has been manufactured in accordance with a controlled quality assurance program and that the relieving capacity has been certified by a designated agency, such as the National Board of Boiler and Pressure Vessel Inspectors. The Code stamp shown is copyright The American Society of Mechanical Engineers.

The Universal Acceptance of the ASME Code

The ASME Boiler and Pressure Vessel Code enjoys widespread acceptance and is by adoption, to varying degrees, a legal document in all national and many international jurisdictions. The student should consult with local regulatory authorities, *e.g.* state agencies, to determine any specialized jurisdictional requirements for pressure relief valves that may be applicable.

Equation Nomenclature

Unless otherwise noted, all symbols used in this course are defined as follows:

A = Valve effective orifice area, in^2.

C = Flow constant determined by the ratio of specific heats (k), see Table 2 on page 20 (use $C = 315$ if k is unknown).

G = Specific gravity referred to water = 1.0 at 70° F

K = Coefficient of discharge obtainable from valve manufacturer ($K = 0.975$ for many nozzle-type valves)

K_b = Correction factor due to back pressure. This is valve specific; refer to the manufacturer's literature.

K_n = Correction factor for saturated steam at set pressures > 1,500 psia, see Equation 6

K_p = Correction factor for relieving capacity verses. lift for relief valves in liquid service, see Equations 1 and 2

K_{sh} = Correction factor due to the degree of superheat in steam ($K_{sh} = 1.0$ for saturated steam)

K_v = Correction factor for viscosity, see Equations 8 & 9 (use $K_v = 1.0$ for all but highly viscous liquids)

K_w = Correction factor due to back pressure for use with balanced bellows valves

M = Molecular weight

N_{Re} = Reynolds number

P_1 = Upstream pressure, psia (set pressure + overpressure + atmospheric pressure). (Sometimes referred to as actual relieving pressure)

ΔP = Differential pressure (set pressure minus back pressure, psig)

Q = Flow, gpm

T = Inlet vapor temperature, °R (°F + 460)

W = Flow, lb/hr

Z = Compressibility factor (use $Z = 1$ for ideal gas)

μ = Liquid dynamic (absolute) viscosity, centipoise

Selection and Sizing

Introduction

Pressure relief valves must be selected by those who have complete knowledge of the pressure relieving requirements of the system to be protected and the environmental conditions particular to that installation. Too often pressure relief valve sizes are determined by merely matching the size of an existing available vessel nozzle or the size of an existing pipeline connection.

Correct and comprehensive pressure relief valve sizing is a complex multi-step process that should follow the following stepwise approach:

1. Each piece of equipment in a process should be evaluated for potential overpressurization scenarios.

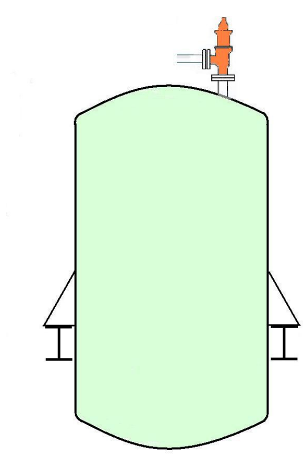
2. An appropriate design basis must be established for each vessel. Choosing a design basis requires assessing alternative scenarios to find the credible worst-case scenario.

3. The design basis is then used to calculate the required pressure relief valve size. If possible, the sizing calculations should use the most current methodologies incorporating such considerations as two-phase flow and exothermic reaction heat sources.

This course addresses pressure relief valves as individual components. Therefore, detailed design aspects of ancillary piping systems are not covered. Ancillary components are clearly noted in the course. These design issues can be addressed by piping analysis using standard accepted engineering principles; these are not within the scope of this course. Where relief device inlet and outlet piping are subject to important guidance by the ASME Code, it is so noted.

NOTE:
A detailed example of analysis and selection methods of relief valve discharge pipe size based on pressure drop for two-phase flow can be found in PDHcenter.com course number M270, *Selecting the Optimum Pipes Size*.

To properly select and size a pressure relief valve, the following information should be ascertained for each vessel or group of vessels which may be isolated by control or other valves. The data required to properly perform pressure relief valve sizing calculations are quite extensive.

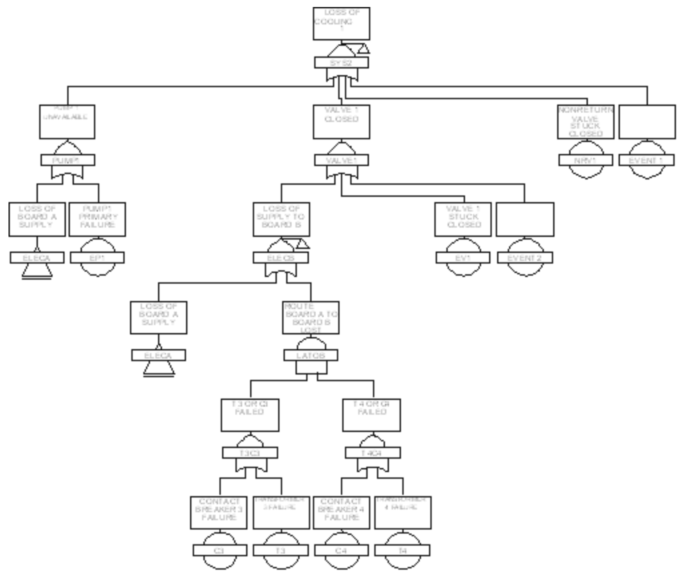


1. The equipment dimensions and physical properties must be assembled. Modeling heat flow across the equipment surface requires knowledge of the vessel material's heat capacity, thermal conductivity, and density (if vessel mass is determined indirectly from vessel dimensions and wall thickness).
2. The vessel geometry – vertical or horizontal cylinder, spherical, etc. – is a necessary parameter for calculating the wetted surface area, where the vessel contents contact vessel walls.
3. The properties of the vessel contents must be quantified. This includes density, heat capacity, viscosity, and thermal conductivity. Values of each parameter are required for both liquid and vapor phases. Boiling points, vapor pressure, and volumetric thermal expansion coefficient values also are

required. Ideally, the properties will be expressed as functions of temperature, pressure, and compositions of the fluid.

Determination of the Worst-Case, Controlling Scenario

The most difficult aspect of the design and sizing of pressure relief valves is ascertaining the controlling cause of overpressurization. This is sometimes referred to as the worst-case scenario. Overpressurization of equipment may result from several causes or a combination of causes. Each cause must be investigated for its magnitude and the probability of its occurrence with other events. The objective is to document which particular design basis is the correct choice. The question that is begged: which scenario is the credible worst case? Among the techniques available to solve this problem is fault-tree analysis. A fault tree is a graphical representation of the logical connections between basic events (such as a pipe rupture or the failure of a pump or valve) and resulting events (such as an explosion, the liberation of toxic chemicals, or over-pressurization in a process tank). A complete treatment of fault-tree theory and analysis is beyond the scope of this course.

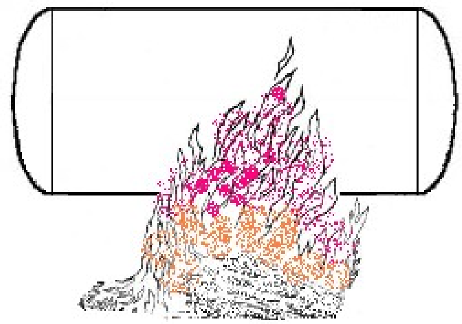


Common Potential Overpressurization Scenarios

The usual causes of overpressurization and ways of translating their effects into pressure relief valve requirements are given in the following summarization. In most cases, the controlling overpressurization will be that resulting from an external fire.

COMMON POTENTIAL OVERPRESSURIZATION SCENARIOS

1. External fire;
2. Blocked outlets
   a. Blocked liquid outlet;
   b. Blocked vapor outlet;
3. Utility failures, including:
   a. General power failure;
   b. Partial power failure;
   c. Loss of instrument air;
   d. Loss of cooling water;
   e. Loss of steam;
   f. Loss of fuel gas or fuel oil.
4. Loss of cooling duty, caused by:
   a. Loss of quenching medium;
   b. Air-cooled exchanger failure;
   c. Loss of cold feed;
   d. Loss of top or intermediate reflux.
5. Thermal expansion;
6. Abnormal heat input;
7. Abnormal vapor input;
8. Loss of absorbent flow;
9. Entrance of volatile material;
10. Accumulation of non-condensables;
11. Valve malfunction, such as;
    a. Check valve malfunction;
    b. Inadvertent valve operation (open/close/bypass);
    c. Control valve failure fully open;
    d. Control valve failure fully closed.
12. Process control failure;
13. Mechanical equipment failure;
14. Exchanger tube rupture;
15. Upstream pressure relief;
16. Runaway chemical reaction;
17. Human error.



Pressure relief valves must have sufficient capacity when fully opened to limit the maximum pressure within the vessel to 110% of the ***maximum allowable working pressure*** (MAWP). This incremental pressure increase is called the pressure accumulation. However, if the overpressurization is caused by fire or other external heat, the accumulation must not exceed 21% of the MAWP. Section VIII does not outline a detailed method to determine the required relieving capacity in the case of external fire. Appendix M-14 of the Code recommends that the methods outlined in API Recommended Practice 520 (Reference 3) be employed. The student is directed to Reference 7 for an excellent treatment, including examples, of the methodology of Reference 3.

Selecting the Set Point Pressure

Process equipment should be designed for pressures sufficiently higher than the actual working pressure to allow for pressure fluctuations and normal ***operating pressure*** peaks. So that that process equipment is not damaged or ruptured by pressures in excess of the design pressure, pressure relief valves are installed to protect the equipment. The design pressure of a pressure vessel is the value obtained after adding a margin to the most severe pressure expected during the normal operation at a coincident temperature. Depending on the situation, this margin might typically be the maximum of 25 psig or 10%.

The setpoint of a pressure relief valve is typically determined by the MAWP. The setpoint of the relief device should be set at or below this point. When the pressure relief valve to be used has a set pressure below 30 psig, the ASME Code specifies a maximum allowable overpressure of 3 psi.

Pressure relief valves must start to open at or below the maximum allowable working pressure of the equipment. When multiple pressure relief valves are used in parallel, one valve shall be set at or below the MAWP and the remaining valve(s) may be set up to 5% over the MAWP. When sizing for multiple valve applications, the total required relief area is calculated on an overpressure of 16% or 4 psi, whichever is greater.

POINT OF CLARIFICATION

Much confusion often prevails because there are so many possible pressure values that simultaneously exist for a given process and pressure relief valve application. It may help to view these values graphically. Look at the illustration below. The pressures are arranged in ascending value from bottom to top.

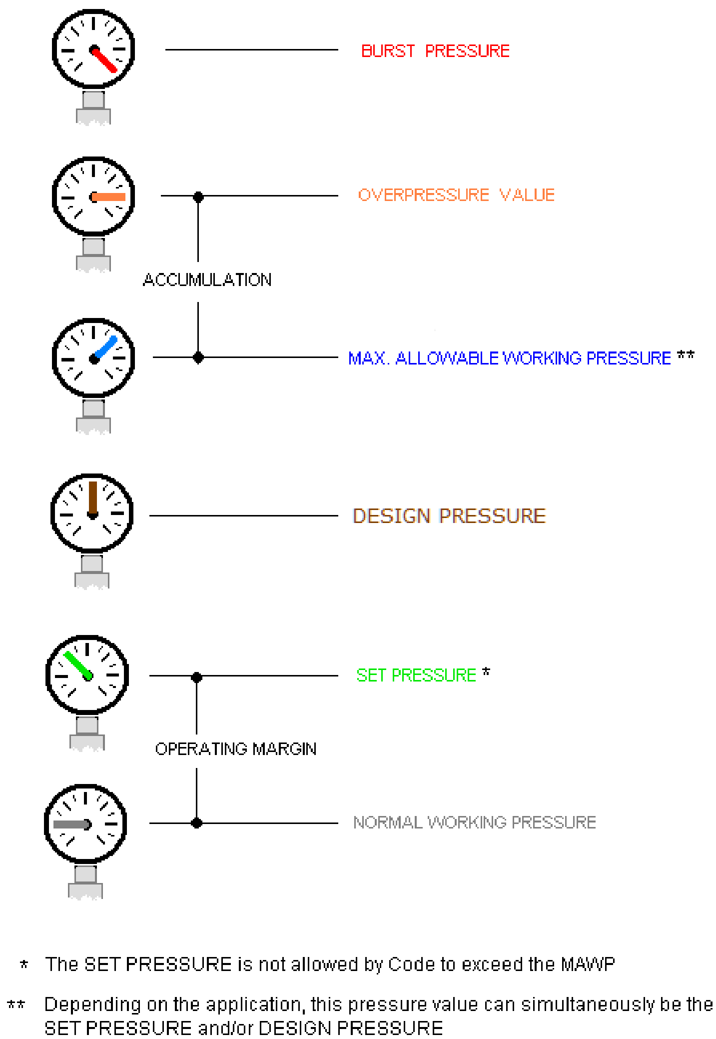


FIGURE 2 – HIERARCHY OF PRESSURE VALUES

Back Pressure Considerations

Back pressure in the downstream piping affects the standard type of pressure relief valve. Variable ***built-up back pressure*** should not be permitted to exceed 10% of the valve set pressure. This variable back-pressure exerts its force on the topside of the disc holder over an area approximately equal to the seating area. This force plus the force of the valve spring, when greater than the kinetic force of the discharge flow will cause the valve to close. The valve then pops open as the static pressure increases, only to close again. As this cycle is repeated, severe ***chattering*** may result, with consequent damage to the valve.

IMPORTANT CONSIDERATION

Static pressure in the relief valve discharge line must be taken into consideration when determining the set pressure. If a constant static back-pressure is greater than atmospheric, the set pressure of the pressure relief valve should be equal to the process theoretical set pressure minus the static pressure in the discharge piping.

Conventional pressure relief valves are used when the back pressure is less than 10%. When it is known that the ***superimposed back pressure*** will be constant, a conventional valve may be used. If the back pressure percentage is between 10 to 40, a balanced bellow safety valve is used. Pilot operated pressure relief valves are normally used when the back pressure is more than 40% of the set pressure or the operating pressure is close to the pressure relief valve set pressure.

If back pressure on valves in gas and vapor service exceeds the critical flow pressure value of,

$$P_1\left[\frac{2}{k+1}\right]^{k/(k-1)}$$

the flow correction factor K_b must be applied. If the back pressure is less than the critical flow pressure, no correction factor is generally required.

Impact of Overpressure in Liquid Service

The back pressure correction factor K_b just cited should not be confused with the correction factor K_p that accounts for the variation in relieving capacity of relief valves in liquid service that occurs with the change in the amount of overpressure. Typical values of K_p range from 0.3 for an overpressure of 0%, 1.0 for 25%, and up to 1.1 for an overpressure of 50%. A regression analysis by Whitesides on a typical manufacturer's performance data produced the following correlation equations for K_p:

For % overpressure < 25,

$$K_p = -0.0014(\%\ \text{overpressure})^2 + 0.073(\%\ \text{overpressure}) + 0.016 \qquad [1]$$

For % overpressure 25 → 50,

$$K_p = 0.00335(\%\ \text{overpressure}) + 0.918 \qquad [2]$$

Finding the Effective Orifice Area

Once the pressure and rate of relief have been established for a particular vessel or pipeline, the required size of the pressure relief valve orifice, or the ***effective area***, can be determined. Sizing formulae in this course can be used to calculate the required effective area of a pressure relief valve that will flow the required volume of system fluid at anticipated relieving conditions. The appropriate valve size and style may then be selected having an ***actual discharge area*** equal to or greater than the calculated required effective area. The industry has standardized on valve orifice sizes and has identified them with letters from D through T having areas of 0.110 in^2 through 26.0 in^2, respectively. The standard nozzle orifice designations and their corresponding ***discharge areas*** are given in Table 1.

NOZZLE ORIFICE AREAS	
Size Designation	Orifice Area, in^2
D	0.110
E	0.196
F	0.307
G	0.503
H	0.785
J	1.280
K	1.840
L	2.850
M	3.600
N	4.340
P	6.380
Q	11.050
R	16.000
T	26.000

TABLE 1 – STANDARD NOZZLE ORIFICE DATA

There are several alternative methods to arrive at the proper size. If the process fluid application is steam, air, or water and the pressure relief valve discharges to the atmosphere, manufacturer's literature can be consulted. These publications contain capacity tables for the manufacturer's various valves for the fluids just mentioned at listed set pressures plus several overpressure values. Given the large number of tables usually presented, caution must be exercised to use the proper table. With careful consideration, the tables' usefulness can be expanded by making the proper adjustments via correction factors for specific heat ratio, temperature, molecular weight, specific gravity, inlet and outlet piping frictional pressure losses, and fluid viscosity. This extrapolation of the standard tables is not recommended by this writer.

EXAMPLE 1 Steam Application

Given:

Fluid:	Saturated steam
Required Capacity:	40,000 lb/hr
Set Pressure:	140 psig
Overpressure:	10% (or 14 psig)
Back Pressure:	Atmospheric
Inlet relieving Temperature:	Saturation temperature
Molecular Weight:	18

Find: XYZ Valve Company's standard orifice for this application.

Solution: Refer to Figure 3 on page 17 and find that a "P" orifice is required, which will have a capacity of 53,820 lb/hr.

Most major pressure relief valve manufacturers also offer sizing software. While not an endorsement, two such products are *SizeMaster™ Mark IV* by Farris Engineering and *PRV²SIZE* by Emerson Automation Solutions. Pressure relief valve sizing software is unlimited in its capability to accept wide variability in fluid properties and is therefore extremely versatile.

When standard tables are not applicable or software is not available, the Engineer is relegated to a manual calculation to determine size. The required orifice size (effective area) may be calculated with the following formulas:

Vapor or gases,

$$A = \frac{W\sqrt{TZ}}{C\,K\,P_1\,K_b\sqrt{M}} \qquad [3]$$

Steam,

$$A = \frac{W}{51.5\,P_1\,K\,K_n\,K_{sh}} \qquad [4]$$

(orifice area formulas are continued on page 18)

FIGURE 3 – TYPICAL CAPACITY TABLE FROM THE XYZ RELIEF VALVE COMPANY

Capacity in Pounds per Hour of Saturated Steam at Set Pressure Plus 10% Overpressure

Set Press (psig)	ORIFICE DESIGNATION													
	D	E	F	G	H	J	K	L	M	N	P	Q	R	T
10	141	252	395	646	1009	165	10	3666	4626	5577	8198	14200	20550	33410
20	202	360	563	923	1440	2362	3373	5235	6606	7964	11710	20280	29350	47710
30	262	467	732	1200	1872	3069	4384	6804	8586	10350	15220	26350	38200	62010
40	323	575	901	1476	2304	3777	5395	8374	10570	12740	18730	32430	47000	76310
50	383	683	1070	1753	2736	4485	6405	9943	12550	15120	22230	38510	55800	90610
60	444	791	1939	9030	3167	5193	7416	11510	14530	17510	25740	44590	64550	104900
70	504	899	1408	2306	3599	5901	8427	13080	16510	19900	29250	50660	73400	119200
80	565	1005	1576	2583	4031	6609	9438	14650	18490	22290	32760	56740	82100	133500
90	625	1115	1745	2860	4463	7317	10450	16220	20470	24670	36270	69890	90900	147800
100	686	1220	1914	3136	4894	8024	11460	17790	22450	27060	39780	68900	99700	162110
120	807	1440	2252	2690	5758	9440	13480	20930	26410	318300	46800	81050	117000	190710
140	998	1655	2590	4943	6621	10860	15550	24070	30370	36610	53290	93210	135000	
160	1050	1870	2927	4796	7485	12270	17530	27200	34330	41380	60830	105400	152500	
180	1170	2085	3265	5349	8348	136900	19550	30340	38290	46160	67850	117500	170000	
200	1290	2300	36030	5903	9212	15100	21570	33480	42250	50930	74870	129700	188000	
220	1410	2515	3940	6456	10080	16520	23590	36620	46210	55700	81890	141800	205500	
240	1535	2730	4278	7009	10940	17930	25610	39760	50170	60480	88910	154000	223000	
260	1655	2945	4616	7563	11800	19350	27630	49890	54130	65250	95920	166100	240500	
280	1775	3160	4953	8116	12670	20770	29660	46030	58090	70030	102900	178300	258000	
300	1895	3380	5291	8669	13530	22180	31680	49170	62050	74800	110000	190400	276000	
320	2015	3595	5629	9223	14390	23600	33700	52310	66010	79570	117000	202600		
340	2140	3810	5967	9776	15260	25010	35720	55450	69970	84350	124000	214800		
360	2260	4025	6304	10330	16120	26430	37740	58590	73930	89120	131000	226900		
380	2380	4240	6642	10880	16980	27840	39770	61720	77890	93900	138000	239100		
400	2500	4455	6980	1440	17850	29260	41790	64860	81850	98670	145100	251200		
420	2620	4670	7317	11990	18710	30680	43810	68000	85810	103400	152100	263400		
440	2745	4885	7655	12400	19570	32090	45830	71140	89770	108200	159100	275500		
460	2865	5105	7993	13100	20440	33510	47850	74280	93730	113000	166100	287700		
480	2985	5320	8330	13650	21300	34920	49870	77420	97690	117800	173100	299800		
500	3105	5535	8668	14200	22160	36340	51900	80550	101600	122500	180100	312000		
550	3410	6075	9512	15590	24390	39880	56950	88400	111500	1345000	197700	343400		
600	3710	6610	103600	169700	26480	43490	62000	96250	121400	146400	215200	372800		
650	4015	7150	11200	18350	28640	46960	67060	104100	131300	158300	232800			
700	4315	7690	12050	19740	30800	50500	72110	111900	141200	170300	250300			
750	4620	8230	128900	21120	32960	54030	77170	119800	151100	182200	267900			

Liquids,

$$A = \frac{Q\sqrt{G}}{27.2\, K_p\, K_w\, K_v \sqrt{\Delta P}} \qquad [5]$$

Manufacturer's customized versions of Equation 5 should be used when available. These typically modify the equation presented to reflect actual coefficients of discharge (K_d) based on required ASME capacity certification testing. In some cases, the variable K_p may be absent. The gas and vapor formula presented as Equation 3 is based on perfect gas laws. Many real gases and vapors, however, deviate from a perfect gas. The compressibility factor Z is used to compensate for the deviations of real gases from the ideal gas. In the event the compressibility factor for a gas or vapor cannot be determined, a conservative value of $Z = 1$ is commonly used. Values of Z based on temperature and pressure considerations are available in the open literature.

The standard equations listed above may not fully take into consideration the effect of back pressure on the valve capacity. As previously stated, the capacity of pressure relief valves of conventional design will be markedly reduced if the back pressure is greater than 10% of the set pressure. For example, a back pressure of 15% of the set pressure may reduce the capacity as much as 40%. The capacities of bellows valves with balanced discs are not affected by back pressure until it reaches 40 to 50% of the set pressure.

Equation 4 is based on the empirical Napier formula for steam flow. Correction factors are included to account for the effects of superheat, back pressure and sub-critical flow. An additional correction factor K_n is required by ASME when relieving pressure (P_1) is above 1,500 psia:

$$K_n = \frac{0.1906 P_1 - 1000}{0.2292 P_1 - 1061} \qquad [6]$$

EXAMPLE 2 Manual Calculation Verification of Example 1 Steam Application

Given: Same conditions and fluid properties as Example 1

Find: The correct standard orifice size to meet the given requirements.

Solution:

① Because the steam is saturated and the set pressure < 1,500 psia, K_{sh} = 1.0 and K_n = 1.0

② Calculate an orifice effective area using Equation 4:

$$A = \frac{W}{51.5\, P_1\, K\, K_n\, K_{sh}} = \frac{40{,}000}{(51.5)(140+14+14.7)(0.975)(1.0)(1.0)} = 4.72 \text{ in}^2$$

③ From Table 1 on page 15 find the smallest standard orifice designation that has an area equal to or greater than A.

④ Select a "P" orifice with an actual area equal to 6.38 in^2.

EXAMPLE 3 Gas/Vapor Application (see Table 2 on page 20)

Given:

Fluid:	Saturated ammonia vapor (NH_3)
Required Capacity:	15,000 lb/hr
Set Pressure:	325 psig (constant back pressure of 15 psig deducted)
Overpressure:	10%
Back Pressure:	15 psig (constant)
Inlet relieving Temperature:	NH_3 saturation temperature @ P_1 (138°F)
Molecular Weight:	17

Find: The correct standard orifice size to meet the given requirements.

Solution:

① Determine from Table 2 (page 20) that NH_3 has a specific heat ratio of k = 1.31 and a nozzle constant of C = 347.

TABLE 2 - RELIEF VAVLE CONSTANTS FOR COMMON GASES AND VAPORS		
GAS OR VAPOR	$k = c_p / c_v$	Nozzle constant (***C***)
Air	1.40	356
Ammonia	1.31	347
Benzene	1.12	329
Carbon Dioxide	1.29	346
Carbon Monoxide	1.40	356
Chlorine	1.36	352
Hexane	1.06	322
Hydrogen	1.41	357
Hydrogen Chloride	1.41	357
Hydrogen Sulfide	1.32	349
Methane	1.31	348
Monatomic Gases (A, He, Ne)	1.67	378
Natural Gas	1.27	344
Nitric Oxide	1.40	356
Nitrogen	1.40	356
Oxygen	1.40	356
Propane	1.13	330
Steam	1.32	349
Sulfur Dioxide	1.29	346
Toluene	1.09	326

EXAMPLE 3 Gas/Vapor Application (continued from page 19)

② Find the actual relieving pressure P_1 to be:

$$\begin{aligned} P_1 &= \text{set pressure} + \text{overpressure} + \text{atmospheric pressure} \\ &= 325 + 32.5 + 14.7 \\ &= 372.2 \text{ psia} \end{aligned}$$

③ Calculate the critical flow pressure as,

$$P_1\left(\frac{2}{k+1}\right)^{k/(k-1)} = 372.2\left(\frac{2}{1.31+1}\right)^{1.31/(1.31-1)} = 202 \text{ psia}$$

Because the back pressure (≈ 30 psia) is less than the critical flow pressure, assume K_b = 1.0

④ Assume that NH_3 is an ideal gas, $\therefore Z = 1.0$

⑤ Since a coefficient of discharge is not given, assume $K = 0.975$

⑥ Calculate an orifice effective area using Equation 3:

$$A = \frac{W\sqrt{TZ}}{CK\,P_1K_b\sqrt{M}} = \frac{15{,}000\sqrt{(138+460)(1.0)}}{(347)(0.975)(325+32.5+14.7)(1.0)\sqrt{17}} = 0.707 \text{ in}^2$$

⑦ From Table 1 on page 15 find the smallest standard orifice designation that is equal to or greater than A.

⑧ Select an "H" orifice with an actual area equal to 0.785 in^2.

Inlet and Outlet Piping Considerations

While the detailed design or stress analysis of the inlet and outlet piping of pressure relief valves is not within the scope of this course, some important considerations are worth mentioning:

Satisfactory operation of a pressure relief valve requires that it be mounted vertically, preferably on a nozzle at the top of a vessel or on a tee connection on top of a pipeline. The minimum inlet piping size should be equal in size to the pressure relief valve; the length should be minimized to reduce pressure drop and bending moments resulting from the reaction thrust developed from the discharging fluid. A rule of thumb is to design the inlet piping such that the total pressure drop in the inlet piping does not exceed 3% of the valve set pressure. When a single pressure relief valve is installed to protect several vessels, the connecting piping between these vessels should be adequate in size to keep the pressure drop within these limits.

The type of discharge piping selected will depend largely on the hazardous nature of the service and on the value of the fluid that might be lost through a discharge event. For air or non-hazardous gas service, the discharge piping is normally directed vertically and extended such that it does not present a safety concern. Discharge elbows fitted with drain lines are normally used on steam and

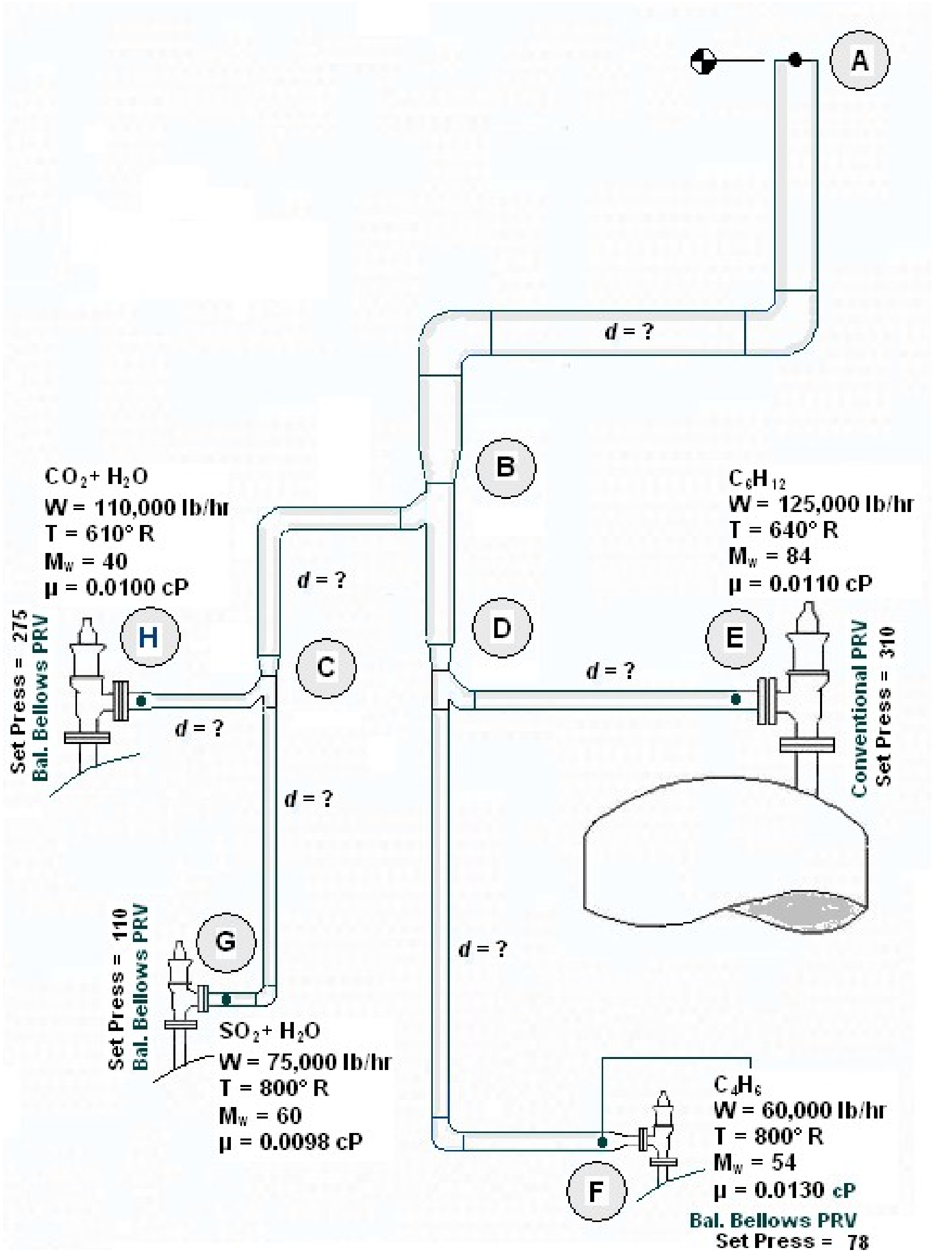


FIGURE 4 – TYPICAL RELIEF PIPING MANIFOLD

(Source: Fig.14a, page 63, PDHcenter.com course number M270)

vapor services. The vapor discharge from these elbows is directed into a larger diameter riser pipe that is independently supported. The discharge piping should be extended vertically downward to a suitable drain for non-hazardous liquid service. A closed discharge piping system is required for hazardous services, or services involving expensive chemicals. Collection systems for these categories of fluids may consist of a considerable quantity of piping with numerous pressure relief valves discharging into a common manifold (see Figure 4). The pressure drop through this type of piping system must be calculated accurately, taking into consideration the fact that simultaneous discharge events may occur (see PDHcenter.com course number M270).

The classical methods for pressure drop determination can be employed for both inlet and outlet piping arrangements. Values for the density, velocity, and viscosity of the discharging fluid should be based on the average pressure and temperature of the respective pipe component. The formation of hydrates, polymerization, and fluid solidification in pressure relief valve piping might be an additional concern. A rule of thumb is to design the discharge piping such that the total pressure drop in the outlet piping does not exceed 10% of the valve set pressure.

Supports for pressure relief valve piping should be designed to minimize the transference of pipe loads to the valve body. Allowance shall be made for piping expansion in cases of high-temperature service; valve displacement due to thermal expansion may cause valve leakage or faulty operation. The internal pressure, dead loads, thermal expansions, reaction thrust and the resulting dynamic forces, and resulting bending stresses due to discharging fluid will be exerted on the pressure relief valve inlet and outlet bends and elbows.

Additional considerations are:

1. Design discharge piping with clean-outs to preclude internal obstructions;
2. Test the piping hydrostatically to 150% of the maximum anticipated pressure of the discharge system;
3. Provide covers or caps to prevent the intrusion and accumulation of rain or the entrance of birds or rodents;
4. Design piping to be self-draining.

Viscous Fluid Considerations

The procedure to follow to correct for a viscous fluid, *i.e.* a fluid whose viscosity is greater than 150 centipoise (cP), is to:

1. Determine an initial trial required pressure relief valve orifice size (effective area) discounting any effects for viscosity. This is done by using the standard liquid sizing formula and setting the viscosity correction factor $K_v = 1.0$. Select the standard orifice size letter designation that has an actual area equal to or greater than this effective area.

2. Use the actual area of the viscous trial size orifice selected in Step 1 to calculate a Reynolds number (N_{Re}) using the following formula:

$$N_{\text{Re}} = \frac{2800\, G\, Q}{\mu\, A} \qquad [7]$$

3. Use the Reynolds number calculated in Step 2 to calculate a viscosity correction factor K_v from the following equations:

For $N_{\text{Re}} < 200$,

$$K_v = 0.27 \ln N_{\text{Re}} - 0.65 \qquad [8]$$

For N_{Re} $200 \rightarrow 10{,}000$

$$K_v = -0.00777\left(\ln N_{\text{Re}}\right)^2 + 0.165 \ln N_{\text{Re}} + 0.128 \qquad [9]$$

4. Determine a corrected required effective area of the pressure relief valve orifice using the standard liquid sizing formula and the value of K_v determined in Step 3.
5. Compare the corrected effective area determined in Step 4 with the chosen actual orifice area in Step 1. If the corrected effective area is less than the actual trial area assumed in Step 1, then the initial viscous trial size assumed in Step 1 is acceptable. Repeat this iterative process until an acceptable size is found.

EXAMPLE 4 Viscous Liquid Application

Given:

Fluid:	No. 6 Fuel Oil
Required Capacity:	1,200 gal/min
Set Pressure:	150 psig
Overpressure:	10%
Back Pressure:	Atmospheric
Inlet relieving Temperature:	60° F
Dynamic Viscosity:	850 cP
Specific Gravity:	0.993

Find: The correct standard orifice size to meet the given requirements.

Solution:

① Since the overpressure is < 25%, determine the correction factor K_p from Equation 1:

$$K_p = -\,0.0014\left(\%\text{ overpressure}\right)^2 + 0.073\left(\%\text{ overpressure}\right) + 0.016$$
$$K_p = -\,0.0014\left(10\right)^2 + 0.073\left(10\right) + 0.016$$
$$K_p = 0.61$$

② Select an initial orifice size by setting $K_v = 1.0$ and using Equation 5. Since the back pressure = 0 then $K_w = 1.0$:

$$A = \frac{Q\sqrt{G}}{27.2\;K_p\;K_w\;K_v\sqrt{\Delta P}} = \frac{1{,}200\sqrt{0.993}}{(27.2)(0.61)(1.0)(1.0)\sqrt{150-0}} = 5.89\text{ in}^2$$

③ From Table 1 on page 15 it can be seen that an orifice size designation "P" with an actual area of 6.38 in^2 must be used.

④ Using the trial "P" orifice area, calculate the Reynolds number using Equation 7:

$$N_{\text{Re}} = \frac{2800\,G\,Q}{\mu\,A} = \frac{(2800)(0.993)(1200)}{(850)(6.38)} = 615$$

⑤ Since $N_{\text{Re}} > 200$, use Equation 9 and compute a viscosity correction factor K_v:

$$K_v = -\,0.00777\left(\ln N_{\text{Re}}\right)^2 + 0.165\ln N_{\text{Re}} + 0.128$$
$$K_v = -\,0.00777\left(6.422\right)^2 + 0.165\left(6.422\right) + 0.128$$
$$K_v = 0.87$$

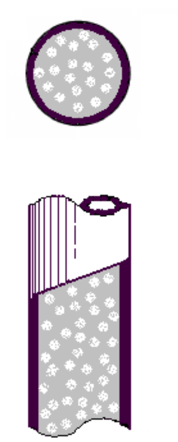
⑥ Compute a corrected orifice effective area based on the now known value of K_v:

$$A = \frac{Q\sqrt{G}}{27.2\;K_p\;K_w\;K_v\sqrt{\Delta P}} = \frac{1{,}200\sqrt{0.993}}{(27.2)(0.61)(1.0)(0.87)\sqrt{150-0}} = 6.76\text{ in}^2$$

⑦ Since the corrected orifice effective area (6.76 in^2) is greater than the selected trial orifice area (6.38 in^2), the "P" orifice is unacceptable. Select the next larger size orifice (Q) with an area of 11.05 in^2 for this viscous application.

Two-Phase Flow Ramifications

In recent years, methodologies originally used to determine pressure relief valve orifice areas have come under increasing scrutiny. Research into current design codes and practices for pressure relief valves has shown that the commonly applied calculations methods may underestimate relief capacity. Newer more theoretically sound models are now being developed. Because flashing-liquid (two-phase) flow is so commonplace in the chemical process industries, this subject is at the forefront of the developmental effort.



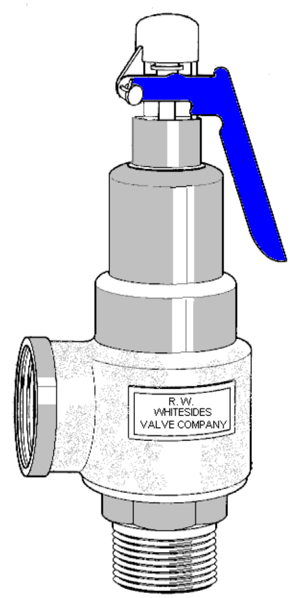
The flow occurring in a pressure relief valve is complex. To select an appropriate model, several factors such as flow patterns, phase distribution, flow conditions, and fluid properties must be considered concerning the nature of the fluid. There are a wide variety of theoretical models which apply to two-phase flow. Each model has limitations and while a particular model may work well under certain conditions, it may not be applicable in others. In some special processes, it has even been determined that some two-phase flow is in fact three phase, *i.e.* solid, liquid and gas, flow.

Because two-phase flow generally has a decreased flow capacity compared to single-phase flow, greater relief orifice area often is required for two-phase flow. Sizing technology that is no longer considered adequate or appropriate can be problematic. Oversizing can be as detrimental as under sizing. Oversizing a pressure relief valve with two-phase flow can have dangerous consequences. Excessive fluid flashing on the downstream side of an oversized pressure relief valve can cause back pressure buildup to the point that the relief device function is impaired. The result could be a catastrophic vessel failure.

Recent research conducted by AIChE's Design Institute for Emergency Relief Systems (DIERS) has indicated that the API method of sizing pressure relief valves for two-phase flow leads to undersized valves in comparison with homogenous equilibrium models (HEM) under certain conditions. The HEM treats the flashing two-phase flow mixture much like a classical compressible gas while undergoing an adiabatic expansion with thermodynamic equilibrium in both phases. The HEM yields conservative estimates of the flow capacity in a pressure relief valve.

Summary

The adequacy of any safety relief system is subject to certain conditions that are the principal basis for the design. Determination of the correct required relieving capacity is often the most obtuse step in the design process. For this reason, knowledge of sophisticated failure probability and evaluation techniques such as fault-tree analysis is important in making correct decisions regarding process upset severity. While the tired and true methods for pressure relief valve sizing are probably adequate, and generally produce conservative results, increased knowledge in the field of two-phase hydraulics, highlighted by test work and information published by groups such as AIChE's DIERS, should be considered in any design of a pressure relief system.



Pressure relief valves should be designed to passively protect against a predetermined set of "worst-case" conditions and should be installed to react to these conditions regardless of daily operational activities.

For each piece of equipment requiring overpressurization protection, a credible worst-case scenario should be defined. For a given vessel, several plausible scenarios may exist – from external fire to various operating contingencies, such as overfill or vessel swell conditions. System overpressurization is assumed to be caused by the controlling scenario. Most controlling scenarios are loaded with conservative assumptions that are never achieved in actual operating conditions. It is the controlling scenario relieving rate that dictates the pressure relief valve size. If sized correctly, the pressure relief valve should have enough discharge capacity to prevent the pressure in the pressure vessel rising 10% above its maximum allowable working pressure.

In addition to liquids, the scope of this course has been limited to all vapor flow. It is applicable when it is known that only vapor will be present or when the liquid portion is assumed to completely flash. Where mixed flow is present, and the total mass quantity (flow rate) is known, an all vapor model should yield conservative results. It may be prudent to be conservative given the uncertainly of two-phase prediction models.

Additional Resources

The student should read/review Reference 2 paragraphs UG-125 through UG-137 when designing pressure relief systems and selecting and sizing pressure relief valves.

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202-682-8000
Website: www.api.org

Glossary

This section contains common and standard definitions related to pressure relief valves. It is in accordance with generally accepted terminology.

accumulation – a pressure increase over the maximum allowable working pressure (MAWP) of the equipment being protected, during discharge through the pressure relief valve, usually expressed as a percentage of MAWP. Compare with ***overpressure***.

actual discharge area – the net area of a selected orifice which dictates the pressure relief valve relieving capacity.

back pressure – the static pressure existing at the outlet of a pressure relief valve due to pressure in the discharge system.

balanced safety relief valve – a pressure relief valve which incorporates means of minimizing the effect of back pressure on the operational characteristics (opening pressure, closing pressure, and relieving capacity).

blowdown – the difference between actual lifting pressure of a pressure relief valve and actual reseating pressure expressed as a percentage of set pressure.

blowdown pressure – the value of decreasing inlet static pressure at which no further discharge is detected at the outlet of a pressure relief valve after the valve has been subjected to a pressure equal to or above the lifting pressure.

built-up back pressure – pressure existing at the outlet of a pressure relief valve caused by the flow through that particular valve into a discharge system.

***chatter* –** the abnormal rapid reciprocating motion of the movable parts of a pressure relief valve in which the disc contacts the seat.

***closing pressure* –** the value of decreasing inlet static pressure at which the valve disc reestablishes contact with the seat or at which lift become zero.

***coefficient of discharge* –** the ratio of the measured relieving capacity to the theoretical relieving capacity.

***constant back pressure* –** a superimposed back pressure which is constant with time.

***conventional safety relief valve* –** a pressure relief valve which has its spring housing vented to the discharge side of the valve. The operational characteristics (opening pressure, closing pressure, and relieving capacity) are directly affected by changes in the back pressure on the valve.

***design pressure* –** the value selected for the design of equipment for the most severe condition of coincident pressure and temperature expected in normal operation, with provision for a suitable margin above these operating conditions to allow for operation of the pressure relief valve. The design pressure usually becomes the maximum allowable working pressure.

***discharge area* –** *see actual discharge area.*

***effective discharge area* –** a computed area of flow through a pressure relief valve, contrasted to actual discharge area. For use in recognized flow formulas to determine the required capacity of a pressure relief valve.

***flow capacity* –** *see rated relieving capacity.*

***flow-rating pressure* –** the inlet static pressure at which the relieving capacity of a pressure relief valve is measured.

***inlet size* –** the nominal pipe size of the inlet of a pressure relief valve, unless otherwise designated.

***lift* –** the actual travel of the disc away from the closed position when a valve is relieving.

***maximum allowable working pressure* –** (1) the pressure determined by employing the allowable stress values of the materials used in the construction of the equipment. It is the least value of allowable pressure value found for any part of a piece of equipment for a given temperature. The equipment may not be operated above this pressure and consequently, it is the highest pressure at which the primary pressure relief valve is set to open. (2) the maximum gauge pressure permissible at the top of a pressure vessel in its normal operating position at the designated coincident temperature specified for that pressure.

nozzle constant, nozzle coefficient - a variable (C) in the standard gas and vapor sizing formula which is dependent on the specific heat ratio of the fluid. See equation 3 and Table 2.

operating pressure **–** the service pressure to which a piece of equipment is usually subjected.

orifice area **–** *see actual discharge area*

outlet size **–** the nominal pipe size of the outlet of a pressure relief valve, unless otherwise designated.

overpressure **–** a pressure increase over the set pressure of a pressure relief valve, usually expressed a percentage of set pressure. Compare with ***accumulation***.

pilot-operated pressure relief valve **–** a pressure relief valve in which the major relieving device is combined with and is controlled by a self-actuated pressure relief valve.

pressure relief valve **–** a generic term for a re-closing spring-loaded pressure relief device which is designed to open to relieve excess pressure until normal conditions have been restored.

rated relieving capacity **–** that portion of the measured relieving capacity permitted by the applicable code of regulation to be used as a basis for the application of a pressure relief valve.

relief valve **–** a pressure relief valve actuated by inlet static pressure and having a gradual lift generally proportional to the increase in pressure over opening pressure. It is primarily used for liquid service.

relieving pressure **–** set pressure plus overpressure.

safety valve **–** a pressure relief valve actuated by inlet static pressure and characterized by rapid opening or pop action. It is normally used for steam and air service.

safety relief valve **–** a pressure relief valve characterized by rapid opening or pop action, or by opening in proportion to the increase in pressure over the opening pressure, depending on the application. It may be used in either liquid or compressible fluid applications based on configuration.

set pressure **–** the value of increasing inlet static pressure at which a pressure relief valve begins to open.

superimposed back pressure **–** the static pressure existing at the outlet of a pressure relief valve at the time the valve is required to operate. It is the result of pressure in the discharge system from other sources.

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