

Pressure Relief Valves Design – A Short Tutorial

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Pressure vessels are equipped with a relief device for the purposes of mechanical protection against over pressure scenarios. Typically, once the design parameters of the vessel are determined based on the process conditions, the relief valve [RV] parameters such as set pressure [SP], overpressure, accumulation, vessel's MAWP based on material selection and plate thickness and the hydrostatic head is worked out.

The following article demonstrates how the above parameters are determined based on ASME/API standards for pressure vessels operating under internal pressure.

General Notes

The various definitions of pressure terminologies for the pressure vessel is described as follows,

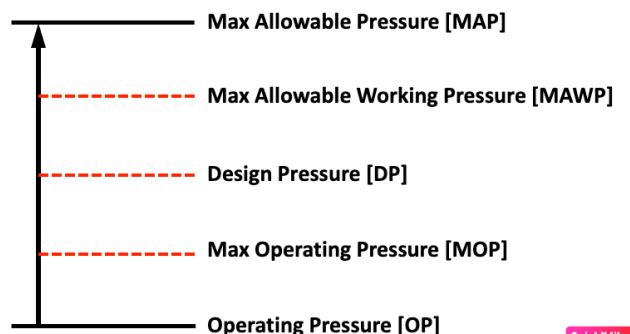


Fig 1. Vessel Pressure Terminology

1. Going by ASME Sec VIII Div 1 [Ref 1], the definition of Design pressure [DP] and Maximum Allowable Working pressure [MAWP] is defined as,

Design Pressure - The pressure used in the design of a vessel component together with the coincident design metal temperature, for the purpose of determining the minimum permissible thickness of physical characteristics of the different zones of the vessel. When applicable, static head shall be added to the design pressure to determine

the thickness of any specific zone of the vessel.

Maximum Allowable Working Pressure [MAWP]

- The maximum gauge pressure permissible at the top of a completed vessel in its normal operating position at the designated coincident temperature for that pressure. This pressure is the least of the values for the internal or external pressure to be determined by the rules of this Division for any of the pressure boundary parts, including the static head thereon, using nominal thicknesses exclusive of allowances for corrosion and considering the effects of any combination of loadings listed in UG-22 that are likely to occur at the designated coincident temperature. It is the basis for the pressure setting of the pressure relieving devices protecting the vessel. The design pressure may be used in all cases in which calculations are not made to determine the value of the maximum allowable working pressure.

2. The Maximum Operating Pressure [MOP] is taken as the highest gauge pressure which provides operational flexibility and is typically set at 105% of the operating pressure [OP] or a minimum of 1 barg higher than the vessel's OP.
3. Design pressure [DP] is typically taken to be 110% of the Maximum operating pressure [MOP], but can vary from project to project depending on local regulations. However non-pressure loads [such as motors, piping, insulation, instrumentation, etc], are to be excluded as per ASME Sec VIII UG-22. Since the vessel experiences higher pressure at the bottom due to the static head contributed by the liquid, the static head is

to be included in the vessel's wall thickness estimation as per ASME Sec VIII UG-27. Design pressure [DP] is only to be used to determine the minimum vessel thickness required.

4. MAWP needs to include both the static head contributed by the liquid and non-pressure loads, but excluding the corrosion allowance [CA]. MAWP may be assumed to be the same as DP when calculations are NOT made to determine the MAWP.
5. To estimate the Maximum allowable pressure [MAP], the corrosion allowance is to be added to the selected wall thickness. MAP is the highest permissible pressure based on the vessel's weakest parts for a new and cold condition.
6. As per ASME Sec VIII UG-99(b), vessels designed for internal pressure shall be subjected to hydrotesting such that at each point in the vessel, the hydrotest pressure must be atleast equal to 130% of MAWP multiplied by the lowest stress ratio [LSR].

The terminology associated with pressure safety relief valve can be inferred from API Recommended Practice 520 as,

1. Set Pressure [SP] - The inlet gauge pressure at which the pressure relief device [PRD] is set to open under service conditions.
2. Accumulation - The pressure increase over the MAWP of the vessel, expressed in pressure units or as a percentage of MAWP or design pressure. Maximum allowable accumulations are established by applicable codes for emergency operating and fire contingencies.
3. Overpressure - The pressure increase over the SP of the relieving device. Overpressure is expressed in pressure units or as a percentage of set pressure. Overpressure is the same as accumulation only when the

relieving device is set to open at the MAWP of the vessel.

4. Relieving Pressure - The inlet pressure and temperature on a PRD during an overpressure condition. The relieving pressure is equal to the valve set pressure plus the overpressure. The temperature of the flowing fluid at relieving conditions may be higher or lower than the operating temperature.

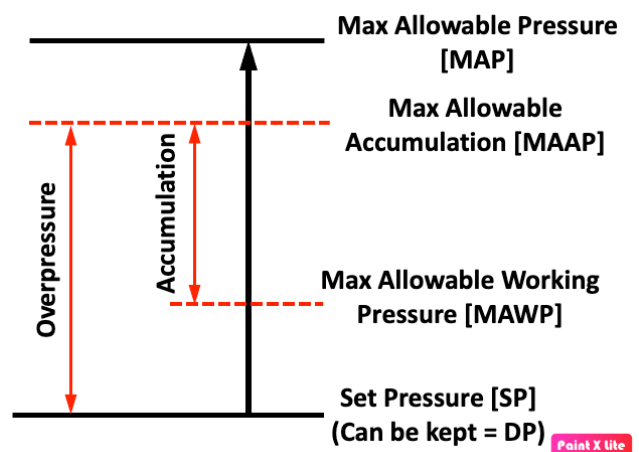


Fig 2. PRD Pressure Terminology

5. As per API 520, Part 1 [Ref 2], in accordance with the requirements of the ASME Code, accumulated pressure shall be limited to 110% of the MAWP in vessels that are protected by a single pressure-relief device sized for operating (non-fire) contingencies. The set pressure of the device shall not exceed MAWP. Accordingly, the allowable accumulation is 3 psi when the MAWP is between 15 psig and 30 psig in accordance with the ASME Code.
6. For multiple RVs, the accumulated pressure shall be limited to 116% of the MAWP in vessels that are protected by multiple pressure relief devices sized for operating (non-fire) contingencies. The set pressure of the first device shall not exceed the MAWP. The set pressure of the additional device or devices shall not exceed 105 % of the MAWP. Accordingly, the allowable

accumulation is 4 psi when the MAWP is between 15 psig and 30 psig.

7. For fire case, the accumulated pressure shall be limited to 121% of the MAWP in vessels that are protected by pressure-relief devices [PRDs] sized for fire contingencies. This applies to single, multiple, and supplemental device installations.
8. Single or multiple devices sized for fire case may also be utilized for relieving requirements attributed to operating (non-fire) contingencies, provided that the constraint of 110% and 116% (of MAWP) accumulated pressure for the non-fire contingencies is observed.
9. A multiple device installation requires the combined capacity of two or more devices to alleviate overpressure. The set pressure of the first device shall not exceed the MAWP. The set pressure of the last device to open shall not exceed 105% of MAWP.
10. A supplemental device installation provides relieving capacity for an additional hazard created by exposure to fire or other unexpected sources of external heat. The set pressure of a supplemental device for fire shall not exceed 110% of the MAWP.
11. As per ASME Sec VIII Div 1, for vessels under internal pressure, the shell wall thickness t is estimated as,

$$t = \frac{(P \times R)}{(S \times E) - (0.6 \times P)} \quad (1)$$

Where,

t = Wall thickness excluding CA [in]

P = MAWP [psig]

R = Inside radius before addition of CA [in]

S = Maximum Allowable Stress [psi]

E = Joint Efficiency [-]

12. Re-arranging, MAWP is calculated as,

$$P = \frac{(S \times E \times t)}{R + (0.6 \times t)} \quad (2)$$

Table 1. SP and Accumulation for PRDs [Ref 2]

Contingency	Single Device Installations		Multiple Device Installations	
	Max SP [%]	Max Accumulated Pressure [%]	Max SP [%]	Max Accumulated Pressure [%]
Non Fire Case				
First Relief Device	100	110	100	116
Additional Device(s)	-	-	105	116
Fire Case				
First Relief Device	100	121	100	121
Additional Device(s)	-	-	105	121
Supplemental Device	-	-	110	121

Case Study

A vertically oriented pressure vessel of 60 inches diameter operates at an MOP of 100 psig and MOT of 120°F. The ambient temperature and barometric pressure is taken as 100°F and 14.7 psia. The max liquid level in the vessel is 50 ft. The DP criteria to determine the vessel's DP, DT, MAWP, is shown below,

Table 2. Design Pressure Criteria [Ref 3]

Design Pressure [DP] Criteria		
MOP Range [psig]		DP Margin [% / psi]
0	50	15 psi
51	250	10%
251	500	10%
501	1000	50 psi
1001	above	5%

The design temperature margin is taken as 77°F [25°C]. The vessel's liquid content has a density of 850 kg/m³. The vessel's material of construction [MOC] is as follows,

Table 3. Vessel's Shell Details

Parameter	Value
Vessel Head Type	2:1 Ellipsoidal
Plate Material	SA-516 Gr 70
Allow Stress $[S]$ at DT [psi]	20,015
Allow Stress $[S_a]$ at Ambient [psi]	20,015
Joint Efficiency [-]	0.85
Shell Radius [in]	30
Corrosion Allowance [CA] [in]	0.125

Methodology

Based on the data provided, the design pressure from Table 2 is,

$$\text{Design Pressure } [DP] = 1.1 \times 100 = 110 \text{ psig} \quad (3)$$

$$\text{Design Temperature } [DT] = 120 + 77 = 197^\circ\text{F} \quad (4)$$

Taking, RV Set Pressure [SP] = DP = 110 psig, the liquid head is estimated as,

$$\text{Head } [H] = \frac{(50 \times 0.3048) \times 850 \times 9.812 \times 14.7}{10^5} = 18.7 \text{ psi} \quad (5)$$

The shell pressure [P] is then estimated as,

$$P = DP + H = 110 + 18.7 = 128.7 \quad (6)$$

The minimum shell thickness [$t_{\min}$] estimated as per ASME Sec VIII Div 1 is,

$$t_{\min} = \frac{128.7 \times 30}{(20,015 \times 0.85) - (0.6 \times 128.7)} = 0.228 \text{ in} \quad (7)$$

Taking one size higher, the selected plate wall thickness or nominal thickness without CA, is 0.2362 inches [Ref 4]. For the nominal thickness, the maximum allowable working pressure [MAWP] is,

$$MAWP = \frac{20,015 \times 0.85 \times 0.236}{30 + (0.6 \times 0.236)} = 133 \text{ psig} \quad (8)$$

Taking a corrosion allowance of 0.125 in, the nominal thickness is,

$$t_{\text{nom}} = 0.2362 + 0.125 = 0.3612 \text{ in} \quad (9)$$

Taking the nominal thickness, the maximum allowable pressure [MAP] is,

$$MAP = \frac{20,015 \times 0.85 \times 0.3612}{30 + (0.6 \times 0.3612)} = 203 \text{ psig} \quad (10)$$

To estimate the hydrostatic head [ASME Sec VIII, UG-99(b)], the LSR value is estimated as,

$$LSR = \frac{S_a}{S} = \frac{20,015}{20,015} = 1 \quad (11)$$

$$P_{\text{Hydro}} = 1.3 \times MAWP \times LSR \quad (12)$$

$$P_{\text{Hydro}} = 1.3 \times 133 \times 1 = 173 \text{ psig} \quad (13)$$

With the MAWP calculated, the relief valve [RV] pressure settings can be estimated. For this case study, the RV's maximum allowable accumulation pressure [MAAP], allowable over pressure and relieving pressure [P_1] is

performed for single and multiple RV installations and for fire and non-fire cases.

A. For Single RV – Non Fire Case

$$MAAP = 1.1 \times 133 = 146.6 \text{ psig} \quad (14)$$

$$\text{Allowable Overpressure} = MAAP - SP \quad (15)$$

$$\text{Overpressure} = 146.6 - 110 = 36.6 \text{ psi} \quad (16)$$

$$\text{Relieving Pressure } [P_1] = MAAP + P_{\text{baro}} \quad (17)$$

$$P_1 = 146.6 + 14.7 = 161.3 \text{ psia} \quad (18)$$

B. For Single RV – Fire Case

$$MAAP = 1.21 \times 133 = 161.3 \text{ psig} \quad (19)$$

$$\text{Overpressure} = 161.3 - 110 = 51.3 \text{ psi} \quad (20)$$

$$P_1 = 161.3 + 14.7 = 176 \text{ psia} \quad (21)$$

C. For Multiple RV – Non Fire Case

First Relief Valve [RV]

$$MAAP = 1.16 \times 133 = 154.6 \text{ psig} \quad (22)$$

$$\text{Overpressure} = 154.6 - 110 = 44.6 \text{ psi} \quad (23)$$

$$P_1 = 154.6 + 14.7 = 169.3 \text{ psia} \quad (24)$$

Additional Relief Valve [RV]

$$SP = 1.05 \times 133 = 140 \text{ psig} \quad (25)$$

$$MAAP = 1.16 \times 140 = 154.6 \text{ psig} \quad (26)$$

$$\text{Overpressure} = 154.6 - 140 = 14.7 \text{ psi} \quad (27)$$

$$P_1 = 154.6 + 14.7 = 169.3 \text{ psia} \quad (28)$$

D. For Multiple RV – Fire Case

The first RV max set pressure [SP] follows the same as single RV fire case [SP = 100% of MAWP].

The additional RV max set pressure [SP] follows the same as multiple RV fire case [SP = 105% of MAWP].

For the supplemental valve,

$$SP = 1.1 \times 133 = 140 \text{ psig} \quad (29)$$

$$MAAP = 1.21 \times 133 = 161.3 \text{ psig} \quad (30)$$

$$\text{Overpressure} = 161.3 - 140 = 14.7 \text{ psi} \quad (31)$$

$$P_1 = 161.3 + 14.7 = 176 \text{ psia} \quad (32)$$

References & Further Reading

1. *Rules for Construction of Pressure Vessels*, ASME Sec VIII Div 1, 2019 Ed.
2. *Sizing, Selection, and Installation of Pressure Relieving Devices, Part 1 - Sizing and Selection*, API 520, 9th Edition, July 2014
3. *Surface Production Operations – Design of Oil Handling Systems and Facilities*, Ken Arnold, Maurice Stewart, 3rd Ed.
4. <https://www.csecplates.com/sa-516-gr-70-plate-stockists-suppliers.html>

Appendix A

Relief Valve [RV] Design		
Parameter	Value	Unit
Equipment Number	V-100	-
Barometric Pressure	14.7	psia
Ambient Temperature	100	°F
Max Operating Pressure [MOP]	100	psig
Max Operating Temperature [MOT]	120	°F
Design Temperature [DT] Margin	77	°F
Relief Valve [RV] parameters		
Design Pressure [DP]	110	psig
Design Temperature [DT]	197	°F
RV Set Pressure [SP] = DP	110	psig
MAWP [ASME Sec VIII Div 1]	133	psig
Hydrotest Pressure [ASME UG-99]	173	psig
Single RV Installation		
Non Fire Case		
Maximum Accumulated Pressure [MAAP]	146.6	psig
Allowable Overpressure	36.6	psi
Relieving Pressure [P ₁]	161.3	psia
Fire Case		
Maximum Accumulated Pressure [MAAP]	161.3	psig
Allowable Overpressure	51.3	psi
Relieving Pressure [P ₁]	176.0	psia
Multiple RV Installation		
Non Fire Case		
Maximum Accumulated Pressure [MAAP] - First RV	154.6	psig
Allowable Overpressure - First RV	44.6	psi
Relieving Pressure [P ₁] - First RV	169.3	psia
Additional RV Set Pressure [SP] [105% of MAWP]	140.0	psig
Maximum Accumulated Pressure [MAAP] - Additional RV	154.6	psig
Allowable Overpressure - Additional RV	14.7	psi
Relieving Pressure [P ₁] - Additional RV	169.3	psia
Fire Case		
Maximum Accumulated Pressure [MAAP] - First RV	161.3	psig
Allowable Overpressure - First RV	51.3	psi
Relieving Pressure [P ₁] - First RV	176.0	psia
Additional RV Set Pressure [SP] [105% of MAWP]	140.0	psig
Maximum Accumulated Pressure [MAAP] - Additional RV	161.3	psig
Allowable Overpressure - Additional RV	21.3	psi
Relieving Pressure [P ₁] - Additional RV	176.0	psia
Supplemental RV Set Pressure [SP] [110% of MAWP]	146.6	psig
Maximum Accumulated Pressure [MAAP] - Supplemental RV	161.3	psig
Allowable Overpressure - Supplemental RV	14.7	psi
Relieving Pressure [P ₁] - Supplemental RV	176.0	psia

Liquid Level [ft] 2

Head Type 2:1 Ellipsoidal

Radius [R]

Max Liq Level [ft] 50

Liquid Level [ft] 60

Design Pressure [DP] Criteria			
MOP Range [psig]	DP Margin [% / psi]	DP	
0	50	15	
51	250	10%	110
251	500	10%	
501	1000	50	
1001	above	5%	

Contingency	Single Device Installations		Multiple Device Installations	
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Additional Device(s)	-	-	105	116
Fire Case				
First Relief Device	100	121	100	121
Additional Device(s)	-	-	105	121
Supplemental Device	-	-	110	121

Shell Details		
Plate Material	SA-516 Gr 70	-
Allowable Stress [S] at Design Temperature	20,015	psi
Allowable Stress [S _a] at Ambient Temperature	20,015	psi
Lowest Stress Ratio [LSR] [ASME Sec VIII UG-99(b)]	1	-
Shell Pressure [P = DP + H]	128.7	psig
Joint Efficiency [E]	0.85	-
Shell Radius [R]	30	in
Shell Min. Thickness [t] @ [DP+H]	0.228	in
Plate Thickness Chosen [Nominal thickness w/o CA]	0.236	in
Shell Max Allowable Working Pressure [MAWP]	133	psig
Corrosion Allowance [CA]	0.125	in
Nominal Thickness [with CA] [t _t CA]	0.3612	in
Shell Max Allowable Pressure [MAP]	203	psig
Hydrotest Pressure [UG-99] [1.3 x MAWP x LSR]	173	psig

Vessel Hydrostatic Head		
Vessel Liquid Level [L]	50	ft
Vessel Liquid Density [ρ]	850	kg/m ³
Liquid Static head [H]	18.7	psi