7.15 Relief Valves—Determination of Required Capacity

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INTRODUCTION

Protection against overpressure is one of the most important design tasks in the chemical, petrochemical, oil, and gas industries. The various causes of overpressure fall into two broad categories: fire conditions and process conditions. The purpose of overpressure protection systems is to reduce or eliminate the potential for overpressure-initiated explosions and fires.

For the sizing, selection, and specification of pressure relief valves (PRVs), refer to the next section; for a discussion of rupture disks, see Section 7.17. In this section, the determination of the required relief capacity is discussed. The section begins with an explanation of the methods for relief capacity determination for fire protection. The second half of the section discusses some relief capacity determination techniques for other, nonfire process causes of overpressure conditions. This section is concluded by a listing of PRV-related terms and definitions, followed by a bibliography.

APPLICABLE CODES AND STANDARDS

Four major sets of codes and standards need to be considered when designing pressure relief systems. These have been prepared by the American Society of Mechanical Engineers (ASME), the American Petroleum Institute (API), the National Fire Protection Association, and the Occupational Safety and Health Administration (OSHA).

ASME Codes

The pressure relief requirements of both boilers and of pressure vessels are covered in the ASME Boiler and Pressure Vessel Code. Section I of this code describes the requirements for steam generators, fired boilers, and associated tanks, whereas Section VIII of this code covers the pressure relief requirements of unfired pressure vessels. The requirements of these two sections yield different results, and neither of the two sections covers the pressure relief requirements of storage vessels, which are designed for pressures under 15 PSIG.

Excerpts from ASME Code

UG-125(c)—All pressure vessels other than unfired steam boilers shall be protected by pressure-relieving devices that shall prevent the pressure from rising more than 10% or 3 psi, whichever is greater, above the maximum allowable working pressure except as permitted in (1) and (2). (See UG-134 for pressure settings.)

1. When multiple pressure-relieving devices are provided and set in accordance with UG-134(a), they shall prevent the pressure from rising more than 16% or 4 psi, whichever is greater, above the maximum allowable working pressure.

2. Where an additional hazard can be created by exposure of a pressure vessel to fire or other unexpected sources of external heat, supplemental pressure-relieving devices shall be installed to protect against excessive pressure. Such supplemental pressure-relieving devices shall be capable of preventing the pressure from rising more than 21% above the maximum allowable working pressure. The same pressure-relieving devices may be used to satisfy the capacity requirements of (c) or (c)(1) and this paragraph provided the pressure setting requirements of UG-134(a) are met.

3. Pressure relief devices, intended primarily for protection against exposure of a pressure vessel to fire or other unexpected sources of external heat installed on vessels having no permanent supply connection and used for storage at ambient temperatures of nonrefrigerated liquefied compressed gasses, are excluded from the requirements of (c)(1) and (c)(2), provided:

*B. P. Gupta and W. Y. Wong should also be credited for work on this section.
(a) the relief devices are capable of preventing the pressure from rising more than 20% above the maximum allowable working pressure of the vessels;
(b) the set pressure of these devices shall not exceed the maximum allowable working pressure of the vessels;
(c) the vessels have sufficient ullage to avoid a liquid full condition;
(d) the maximum allowable working pressure of the vessels on which these devices are installed is greater than the vapor pressure of the stored liquefied compressed gas at the maximum anticipated temperature that the gas will reach under atmospheric conditions; and
(e) pressure relief valves used to satisfy these provisions also comply with the requirements of UG-129(a)(5), UG-131(c)(2), and UG-134(e)(2).

**UG-126(b)**—Pilot-operated pressure relief valves may be used, provided that the pilot is self-actuated and the main valve will open automatically at not over the set pressure and will discharge its full rated capacity if some essential part of the pilot should fail.

**UG-126(c)**—The spring in a pressure relief valve in service for pressures up to and including 250 psi [17.2 bars] shall not be reset for any pressure more than 10% above or 10% below that for which the valve is marked. For higher pressures, the spring shall not be reset for any pressure more than 5% above or 5% below that for which the safety or relief valve is marked.

**UG-126(d)**—The set pressure tolerances, plus or minus, of pressure relief valves shall not exceed 2 psi for pressures up to and including 70 psi [4.8 bars] and 3% for pressures above 70 psi [4.8 bars].

**UG-131(d)(1)**—A capacity certification test is required on a set of three valves for each combination of size, design, and pressure setting. The stamped capacity rating for each combination of design, size, and test pressure shall not exceed 90% of the average capacity of the three valves tested. The capacity for each set of three valves shall fall within a range of ±5% of the average capacity. Failure to meet this requirement shall be cause to refuse certification of that particular safety valve design.

**UG-133(a)**—As permitted in (b), the aggregate capacity of the pressure-relieving devices connected to any vessel or system of vessels for the release of a liquid, air, steam, or other vapor shall be sufficient to carry off the maximum quantity that can be generated or supplied to the attached equipment without permitting a rise in pressure within the vessel of more than 16% above the maximum allowable working pressure when the pressure-relieving devices are blowing.

**UG-133(b)**—Protective devices as permitted in UG-125(c)(2), as protection against excessive pressure caused by exposure to fire or other sources of external heat, shall have a relieving capacity sufficient to prevent the pressure from rising more than 21% above the maximum allowable working pressure of the vessel when all pressure-relieving devices are blowing.

**UG-134(d)(1)**—The set pressure tolerance for pressure relief valves shall not exceed ±2 psi for pressures up to and including 70 psi and 3% for pressures above 70 psi [4.8 bars], except as covered in (d)(2).

**UG-134(d)(2)**—The set pressure tolerance of pressure relief valves which comply with UG-125(c)(3) shall be within −0%, +10%.

### API Standards and Recommended Practices

In general, oil refineries tend to base their pressure relief system designs on the API standards and recommended practices (RPs). The most widely used API documents are as follows:

- API Recommended Practice 520, Sizing, Selection, and Installation of Pressure-Relieving Devices in Refineries, 7th ed., January 2000
- API Recommended Practice 521, Guide for Pressure-Relieving and Depressuring Systems
- API Standard 2000, Venting Atmospheric and Low-Pressure Storage Tanks (Nonrefrigerated and Refrigerated), 2000 ed.

The API 2000 standard is also widely used in other industries beyond refineries to set the pressure relief requirements for storage vessels, which are designed for pressures under 15 PSIG. Some of the other API standards and recommended practices that are relevant to PRV system design include the following:

- API Standard 526, Flanged Steel Pressure Relief Valves
- API Standard 527, Seat Tightness of Pressure
- API Recommended Practice 550, Manual on Installation of Refinery Instruments and Control Systems
- API PR 576, Inspection of Pressure-Relieving Devices

### NFPA Codes

For determining the required relieving capacity from tanks and storage vessels, when exposed to external fire, both the API and the NFPA codes can be used. The most often used NFPA codes are the following:

- NFPA 30, Flammable and Combustible Liquids
- NFPA 58, Liquefied Petroleum Gases, Storage and Handling
OSHA Codes

The OSHA codes that relate to the design of pressure safety systems are the following:

- OSHA 1910.106, Flammable and Combustible Liquids
- OSHA 1910.110, Liquefied Petroleum Gases
- OSHA 1910.119, Process Safety Management

CAUSES OF OVERPRESSURE

Overpressure can be caused by fire and by nonfire process causes. In the second category, there can be many potential causes. These will be discussed after the treatment of fire protection that follows in the next paragraph. The potential nonfire causes of overpressure include the following:

1. Utility failures, which can be the failure of electric power, instrument air, steam, coolant, or fuel
2. Thermal expansion
3. Blocked outlets
4. Valve or process control failure
5. Equipment failure
6. Runaway chemical reaction
7. Human error

It should be emphasized that part of the goal of a safe plant design is the goal of minimizing the opportunities for human error.

Substituting for Pressure Relief Devices

In general it is not recommended to accept fail-safe instruments or the actions of automatic control loops as substitutes for PRVs. This is because the reliability of control systems has not advanced to the point where they are completely reliable. Their reliability has increased substantially by the invention of high integrity protective systems (HIPSSs), emergency power supplies (EPSs), uninterruptible power supplies (UPSs), triple redundancy, and “two out of three” voting systems. Yet, to date, there is no code or regulation that accepts automatic process control as a substitute for the installation of PRVs.

Similarly, the various safety oriented administrative procedures cannot be used as substitutes for PRVs. This is because human error can never be fully eliminated, and no matter what the administrative procedure says, (according to Murphy’s Law) if it is possible to forget to drain a pipeline of its toxic or hazardous content, it will happen. One exception involves the use of car seals open (CSO) and car seals locked (CSL) valves, which API RP 520 and 521 accept as means of guaranteeing that equipment will not be blocked in.

In the overpressure analysis of a plant, the design engineer does not need to consider the possibility of the simultaneous occurrence of more than one cause of overpressure. In other words, if, for example, a chemical reactor PRV has been sized to handle the largest of overpressure causes from among fire, run-away chemical reaction, loss of utilities, etc., that is sufficient. It is not necessary to consider their simultaneous occurrence and size the PRV for the sum of two or more of these causes.

FIRE PROTECTION

The ASME Unfired Pressure Vessel Code requires that pressure vessels covered by the code be adequately relieved. External fire is a potential overpressure source; therefore, for fire conditions, the code requires that relief devices be sized such that, at maximum relieving conditions, the vessel pressure does not exceed the vessel design pressure by more than 20%. This is referred to as 20% accumulation.

For vessels with adequate liquid inventory, the required relief capacity under fire conditions is a function of tank area exposed to fire, of the heat flux per unit area of tank surface, and of the latent heat of the process fluid. These three factors will be separately discussed below. The first to be discussed is the determination of the applicable heat flux.

Gas-Filled Tanks

If the vessel does not have an adequate liquid inventory, stress rupture can occur from overheated spots long before the internal pressure in the tank would reach the setting of the PRV. Therefore, gas-filled tanks and vessels with low liquid inventory require different approaches for protection against overpressure, and design engineers should consider API RP 521 for determining the PRV size required when the tank is exposed to fire and some or most of its inner surface is not wetted.

In most cases, PRVs sized in accordance with API RP 520 cannot give overpressure protection to gas-filled tanks. Therefore, when the installation of hydrogen or other flammable gas-filled vessels is being designed, the following options should also be considered:

1. Bury the tank under ground and cover it with earth.
2. Move the vessel away from the process area or surround it by a dike or a firewall.
3. Elevate the vessel over the fire height (API, 25 ft, NFPA, 30 ft above grade).
4. Use a water deluge system or install fireproof insulation.
5. Provide automatic vapor depressurization.
6. Provide automatic fire monitoring and automatic fire fighting capability.

Heat Absorption Across Unwetted Surfaces The effective discharge area of a relief valve required to protect a vessel that is exposed to external fire and has unwetted surface area can be determined by Equations 7.15(1) and 7.15(2).

\[ A = \frac{(F')}{(P_{0})} \]  

7.15(1)
where

\[ A = \text{the effective discharge area of the PRV valve, in}^2 \]
\[ A' = \text{the surface area of the vessel, which is exposed to fire, ft}^2 \]
\[ P_u = \text{the upstream relieving pressure, which is the sum of the atmospheric, the set pressure, and the over-pressure, } \text{PSIA} \]

The environmental factor \( F' \) is calculated from Equation 7.15(2) as follows:

\[ F' = (0.1406/CK_d)(T_u - T_1)^{1.25}/T_1^{0.6506} \quad 7.15(2) \]

where

\[ C = \text{a constant that depends on the specific heat ratio of the particular gas. For the specific heat ratio } (k) \text{ of a number of gases, refer to Table 7.15a, and for a curve relating this ratio to coefficient } C, \text{ refer to Figure 7.15b.} \]
\[ K_d = \text{the coefficient of discharge of the PRV, which, for preliminary sizing purposes, can be assumed to be 0.975} \]
\[ T_u = \text{the expected wall temperature of the tank, which, for carbon steel plate materials, can be assumed to be 1,100}^\circ\text{F} \]
\[ T_1 = \text{the gas temperature in } ^\circ\text{R at the upstream relieving pressure } (P_u). \text{ It is calculated by Equation 7.15(3) as follows:} \]
\[ T_1 = P_uT_u/P_a \quad 7.15(3) \]

where

\[ P_a = \text{the normal operating gas pressure, PSIA} \]
\[ T_u = \text{the normal operating gas temperature, } ^\circ\text{R} \]

Low Liquid Inventory Tanks

The definition of what is “adequate” in terms of liquid inventory is a function of the time required to evaporate that inventory during a fire vs. the response time of the fire fighters at the plant. Once the liquid is gone, the vessel becomes a gas-filled tank.

The minimum time is 10 to 15 min. This time period has to take into account the location of the fire-fighting equipment and the quality of the automatic fire monitoring instrumentation in the plant. A liquid inventory is usually considered “adequate” if it will last for at least 15 min during an external fire. If it does not, the fire protection rules for gas-filled tanks should be used.

Heat Flux Across Wetted Surfaces

When a vessel is exposed to external fire, the amount of heat absorption will depend on the following:

1. The wetted surface areas of the vessel and the connected associated piping
2. The amount and quality of the insulation provided on the tank and piping surfaces
3. The quality and availability of the fire-fighting equipment in the plant
4. The method applied to drain the flammable materials away from the tank

To determine the required relief capacity of a tank that is exposed to external fire, it is necessary to determine the heat flux. This is the rate at which heat is transferred into the vessel or other process equipment. A number of heat flux determination methods can be considered.

The simplest technique assumes that the heat flux is fixed and does not depend on the type and size of the vessel involved. Under such an assumption, the heat flux is taken to be a constant rate of 20,000 BTU/hr/ft\(^2\) (63 kW/m\(^2\)). Other approaches relate the magnitude of the heat flux to the size of the vessel, reasoning that the larger the tank, the less likely it is that it will be completely immersed in flames.

API RP 521 provides one commonly used method for determining heat flux under fire conditions. This bulletin gives two recommendations for calculating the heat flux in BTU per hour per square foot of total wetted surface of a vessel that is exposed to fire. The two formulas are given in Table 7.15c, one for tanks with adequate drainage away from the tank, and the other for tanks without adequate drainage. A graphic representation of the formula for the adequate drainage condition is shown in Figure 7.15d.

Total Heat Absorption

API Recommendation API RP 520, seventh edition (January 2000), presents two widely used equations for determining the total heat absorption of wetted surface areas under fire conditions. Equation 7.15(4) is applicable if the means for both prompt fire-fighting capability and adequate drainage of flammable materials away from the tank are provided (ground with over 1% slope); Equation 7.15(5) is applicable if they are not.

\[ Q = 21,000F(A)^{0.82} \quad 7.15(4) \]
\[ Q = 34,500F(A)^{0.82} \quad 7.15(5) \]

where

\[ Q = \text{total heat absorption of wetted surface area exposed to fire, BTU/hr} \]
\[ F = \text{environmental factor, a constant having a value of 1.0 or less} \]
\[ A = \text{the total wetted surface area of the tank, ft}^2 \]

The reader should consult the API Recommended Practice 520 for additional details.

NFPA Recommendations Another standard that is commonly used in the determination of heat flux under fire conditions is in the recommendations of NFPA Bulletin No. 30, Flammable
and Combustible Liquids. The National Fire Protection Association is an organization of insurance companies and regulatory organizations. Their recommendations are likely to meet the requirements of most insurance companies, as they are generally more conservative than the corresponding API recommendations.

Table 7.15e lists the equations recommended by NFPA for the determination of total heat absorption and for calculating the equivalent air flow for tanks exposed to external fire.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Molecular Weight</th>
<th>Specific Heat Ratio at 60°F and One Atmosphere</th>
<th>Critical Flow Pressure Ratio at 60°F and One Atmosphere</th>
<th>Specific Gravity at 60°F and One Atmosphere</th>
<th>Critical Constants</th>
<th>Condensation Temperature One Atmosphere (°F)</th>
<th>Flammability Limits (volume percent in air mixture)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>16.04</td>
<td>1.31</td>
<td>0.54</td>
<td>0.554</td>
<td>673</td>
<td>−116</td>
<td>−259</td>
<td>5.0–15.0</td>
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<td>Ethane</td>
<td>30.07</td>
<td>1.19</td>
<td>0.57</td>
<td>1.058</td>
<td>718</td>
<td>90</td>
<td>−128</td>
<td>2.9–13.8</td>
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<td>Ethylene</td>
<td>28.03</td>
<td>1.24</td>
<td>0.57</td>
<td>0.969</td>
<td>742</td>
<td>50</td>
<td>−155</td>
<td>2.7–34.8</td>
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<td>Propane</td>
<td>44.09</td>
<td>1.13</td>
<td>0.58</td>
<td>1.522</td>
<td>617</td>
<td>206</td>
<td>−44</td>
<td>2.1–9.5</td>
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<td>Propylene</td>
<td>47.08</td>
<td>1.15</td>
<td>0.58</td>
<td>1.453</td>
<td>667</td>
<td>197</td>
<td>−54</td>
<td>2.8–10.8</td>
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<tr>
<td>Isobutane</td>
<td>58.12</td>
<td>1.18</td>
<td>0.59</td>
<td>2.007</td>
<td>529</td>
<td>273</td>
<td>11</td>
<td>1.8–8.4</td>
</tr>
<tr>
<td>n-Butane</td>
<td>58.12</td>
<td>1.19</td>
<td>0.59</td>
<td>2.007</td>
<td>551</td>
<td>304</td>
<td>31</td>
<td>1.9–8.4</td>
</tr>
<tr>
<td>I-Butene</td>
<td>56.10</td>
<td>1.11</td>
<td>0.59</td>
<td>1.937</td>
<td>543</td>
<td>276</td>
<td>21</td>
<td>1.4–9.3</td>
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<tr>
<td>Isopentane</td>
<td>72.15</td>
<td>1.08</td>
<td>0.59</td>
<td>2.491</td>
<td>483</td>
<td>360</td>
<td>82</td>
<td>1.4–8.3</td>
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<tr>
<td>n-Pentane</td>
<td>72.15</td>
<td>1.08</td>
<td>0.59</td>
<td>2.491</td>
<td>490</td>
<td>386</td>
<td>97</td>
<td>1.4–7.8</td>
</tr>
<tr>
<td>I-Pentene</td>
<td>70.13</td>
<td>1.08</td>
<td>0.59</td>
<td>2.421</td>
<td>586</td>
<td>377</td>
<td>86</td>
<td>1.4–8.7</td>
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<td>n-Hexane</td>
<td>86.18</td>
<td>1.06</td>
<td>0.59</td>
<td>2.973</td>
<td>437</td>
<td>454</td>
<td>156</td>
<td>1.2–7.7</td>
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<tr>
<td>Benzene</td>
<td>78.11</td>
<td>1.12</td>
<td>0.58</td>
<td>2.697</td>
<td>714</td>
<td>552</td>
<td>176</td>
<td>1.3–7.9</td>
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<td>n-Heptane</td>
<td>100.20</td>
<td>1.05</td>
<td>0.60</td>
<td>3.459</td>
<td>397</td>
<td>513</td>
<td>209</td>
<td>1.0–7.0</td>
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<tr>
<td>Toluene</td>
<td>92.13</td>
<td>1.09</td>
<td>0.59</td>
<td>3.181</td>
<td>590</td>
<td>604</td>
<td>231</td>
<td>1.2–7.1</td>
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<td>n-Octane</td>
<td>114.22</td>
<td>1.05</td>
<td>0.60</td>
<td>3.944</td>
<td>362</td>
<td>564</td>
<td>258</td>
<td>0.96–</td>
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<td>n-Nonane</td>
<td>128.23</td>
<td>1.04</td>
<td>0.60</td>
<td>4.428</td>
<td>552</td>
<td>610</td>
<td>303</td>
<td>0.87–2.9</td>
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<td>n-Decane</td>
<td>142.28</td>
<td>1.03</td>
<td>0.60</td>
<td>4.912</td>
<td>304</td>
<td>632</td>
<td>345</td>
<td>0.78–2.6</td>
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<td>Air</td>
<td>29.96</td>
<td>1.40</td>
<td>0.53</td>
<td>1.000</td>
<td>547</td>
<td>−221</td>
<td>−313</td>
<td>2, 3</td>
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<td>Ammonia</td>
<td>17.03</td>
<td>1.30</td>
<td>0.53</td>
<td>0.588</td>
<td>1636</td>
<td>270</td>
<td>−28</td>
<td>15.5–27.0</td>
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<td>Carbon dioxide</td>
<td>44.01</td>
<td>1.29</td>
<td>0.55</td>
<td>1.519</td>
<td>1071</td>
<td>88</td>
<td>−109</td>
<td>2, 3</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>2.02</td>
<td>1.41</td>
<td>0.52</td>
<td>0.0696</td>
<td>188</td>
<td>−400</td>
<td>−423</td>
<td>4.0–74.2</td>
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<tr>
<td>Hydrogen sulfide</td>
<td>34.08</td>
<td>1.32</td>
<td>0.53</td>
<td>1.176</td>
<td>1306</td>
<td>213</td>
<td>−77</td>
<td>4.3–45.5</td>
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<td>Sulfur dioxide</td>
<td>64.04</td>
<td>1.27</td>
<td>0.55</td>
<td>2.212</td>
<td>1143</td>
<td>316</td>
<td>14</td>
<td>2, 3</td>
</tr>
<tr>
<td>Steam</td>
<td>18.01</td>
<td>1.33</td>
<td>0.54</td>
<td>0.622</td>
<td>3206</td>
<td>706</td>
<td>212</td>
<td>2, 3</td>
</tr>
</tbody>
</table>

*Estimated.

References:

Low-Pressure Tanks For above-ground tanks and storage vessels designed to operate from atmospheric pressure to 14 PSIG (104 kPa) and used for the storage of flammable liquids, still another method of determining heat flux under fire conditions is available. This recommendation is based on the American Petroleum Institute and is presented in their bulletin API-RP-2000. This method is also referred to in the National Fire Codes of the National Fire Protection Association, for informational purposes only.
Table 7.16f gives the NFPA-30 heat flux calculation equations as a function of tank design pressure and wetted area. The NFPA recommended values of the environmental factor F are listed in Table 7.15j. For low-pressure tanks with design pressures under 1 PSIG and having wetted surface areas exceeding 2800 ft$^2$ (260 m$^2$), they have concluded that complete fire coverage is unlikely, and the maximum total heat input has been limited to 14,090,000 BTU/hr (4,128,370 W/hr). This heat input corresponds to a free air vent rate of 742,000 SCFH.

For a comparison between API RP 521 based heat flux recommendation for adequately drained regular tanks and NFPA’s heat flux information for low pressure tanks, refer to Figure 7.15d.

**Free Air Calculation** This procedure relates the required relieving rate, expressed as cubic feet of free air per hour, to the wetted area. Relieving rates for low-pressure tanks are tabulated as shown in Table 7.15g. The data in this table are based on the physical properties of hexane and utilize the API recommendations for heat flux due to fire conditions. The total emergency relief capacity for any specific liquid may be calculated from Table 7.15g by the use of the following formula:

\[
\text{Design cubic feet of free air per hour} = \frac{V1337}{\sqrt{\lambda M_w}}
\]

**FIG. 7.16b**
The relationship between the specific heat ratio (k) of gases and coefficient C. (Courtesy of the American Petroleum Institute from API Recommended Practice 520, Sizing, Selection, and Installation of Pressure-relieving Devices in Refineries, Part I – Sizing and Selection, 7th ed., January 2000.)

Table 7.16f gives the NFPA-30 heat flux calculation equations as a function of tank design pressure and wetted area. The NFPA recommended values of the environmental factor F are listed in Table 7.15j. For low-pressure tanks with design pressures under 1 PSIG and having wetted surface areas exceeding 2800 ft$^2$ (260 m$^2$), they have concluded that complete fire coverage is unlikely, and the maximum total heat input has been limited to 14,090,000 BTU/hr (4,128,370 W/hr). This heat input corresponds to a free air vent rate of 742,000 SCFH.

For a comparison between API RP 521 based heat flux recommendation for adequately drained regular tanks and NFPA’s heat flux information for low pressure tanks, refer to Figure 7.15d.

**FIG. 7.15d**
Heat flux estimates under fire conditions as a function of wetted area recommended by API and NFPA. The solid line is based on API RP 521 and can be used for regular tanks, which are provided with adequate drainage under fire conditions. The dotted line describes NFPA information for low-pressure tanks only. For tanks having over 2800 ft$^2$ in wetted area and with design pressures of 1 PSIG or less, NFPA suggests the fixed maximum heat input of 14,090,000 BTU/hr (3,553,000 kcal/hr).
where $V$ = cubic feet of free air per hour, SCFH, listed in Table 7.15f

$\lambda$ = latent heat of vaporization of the specific liquid in units of BTU per pound

$M_w$ = molecular weight of the specific liquid

For calculation convenience, a table of physical property constants presented in the National Fire Codes of the National Fire Protection Association is reproduced as Table 7.15h.

This calculation, based on Equation 7.15(6), has the potential for oversizing relief valves on vessels in crude oil and other multicomponent liquid applications where the components have a wide range of boiling points. Latent heat of vaporization depends on the specific liquid, and, for multicomponent liquids such as crude oil, it cannot be tabulated.

In the case of crude oil, the heat input is initially absorbed by the oil and steel (minor part) as the temperature of the vessel and oil rises. Initially, the specific heat of the oil absorbs the heat, and only a small portion of the heat input is utilized as latent heat generating vapor, which must be relieved. With constant heat input, the amount of vapor generated varies with the temperature of the oil in the vessel. Process calculations must be made to determine the true (maximum) rate of vapor evolution, taking into consideration the actual process fluid. This calculation must consider the worst-case situation when a particular vessel can be used to store different liquids.

### Wetted Tank Area (A)

The factors that need to be considered in calculating the wetted area include the following:

1. The design basis, which can be API or NFPA
2. The tank shape, which can be horizontal, vertical, or spherical
3. The ground area of the fire zone
4. The effective fire height

While relief capacity determination is not directly impacted by it, the effect of fire on nonwetted surfaces can also cause structural failure from the steel softening at elevated temperatures. Thermal insulation or fire-resistant coatings,
<table>
<thead>
<tr>
<th>Chemical</th>
<th>$\lambda \sqrt{M_w}$</th>
<th>Molecular Weight ($M_w$)</th>
<th>Heat of Vaporization, BTU per lbm at Boiling Point ($\lambda$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetaldehyde</td>
<td>1673</td>
<td>44.05</td>
<td>252</td>
</tr>
<tr>
<td>Acetic acid</td>
<td>1350</td>
<td>60.05</td>
<td>174</td>
</tr>
<tr>
<td>Acetic anhydride</td>
<td>1792</td>
<td>102.09</td>
<td>177</td>
</tr>
<tr>
<td>Acetone</td>
<td>1708</td>
<td>58.05</td>
<td>224</td>
</tr>
<tr>
<td>Acetonitrile</td>
<td>2000</td>
<td>41.05</td>
<td>312</td>
</tr>
<tr>
<td>Acrylonitrile</td>
<td>1930</td>
<td>53.05</td>
<td>265</td>
</tr>
<tr>
<td>$n$-Amyl alcohol</td>
<td>2025</td>
<td>88.15</td>
<td>216</td>
</tr>
<tr>
<td>$iso$-Amyl alcohol</td>
<td>1990</td>
<td>88.15</td>
<td>212</td>
</tr>
<tr>
<td>Aniline</td>
<td>1795</td>
<td>93012</td>
<td>186</td>
</tr>
<tr>
<td>Benzene</td>
<td>1439</td>
<td>78.11</td>
<td>169</td>
</tr>
<tr>
<td>$n$-Butyl acetate</td>
<td>1432</td>
<td>116.16</td>
<td>133</td>
</tr>
<tr>
<td>$n$-Butyl alcohol</td>
<td>2185</td>
<td>74.12</td>
<td>254</td>
</tr>
<tr>
<td>$iso$-Butyl alcohol</td>
<td>2135</td>
<td>74.12</td>
<td>248</td>
</tr>
<tr>
<td>Carbon disulfide</td>
<td>1310</td>
<td>76.13</td>
<td>150</td>
</tr>
<tr>
<td>Chlorobenzene</td>
<td>1422</td>
<td>112.56</td>
<td>134</td>
</tr>
<tr>
<td>Cyclohexane</td>
<td>1414</td>
<td>84.16</td>
<td>154</td>
</tr>
<tr>
<td>Cyclohexanol</td>
<td>1953</td>
<td>100.16</td>
<td>195</td>
</tr>
<tr>
<td>Cyclohexanone</td>
<td>1625</td>
<td>98.14</td>
<td>164</td>
</tr>
<tr>
<td>$o$-Dischlorobenzene</td>
<td>1455</td>
<td>147.01</td>
<td>120</td>
</tr>
<tr>
<td>$cis$-Dechloroethylene</td>
<td>1350</td>
<td>96.95</td>
<td>137</td>
</tr>
<tr>
<td>Diethyl amine</td>
<td>1403</td>
<td>73.14</td>
<td>164</td>
</tr>
<tr>
<td>Dimethyl acetamide</td>
<td>1997</td>
<td>87.12</td>
<td>214</td>
</tr>
<tr>
<td>Dimethyl amine</td>
<td>1676</td>
<td>45.08</td>
<td>250</td>
</tr>
<tr>
<td>Dimethyl formamide</td>
<td>2120</td>
<td>73.09</td>
<td>248</td>
</tr>
<tr>
<td>Dioxane (diethylene ether)</td>
<td>1665</td>
<td>88.10</td>
<td>177</td>
</tr>
<tr>
<td>Ethyl acetate</td>
<td>1477</td>
<td>88.10</td>
<td>157</td>
</tr>
<tr>
<td>Ethyl alcohol</td>
<td>2500</td>
<td>46.07</td>
<td>368</td>
</tr>
<tr>
<td>Ethyl chloride</td>
<td>1340</td>
<td>64.52</td>
<td>167</td>
</tr>
<tr>
<td>Ethyl dichloride</td>
<td>1363</td>
<td>98.97</td>
<td>137</td>
</tr>
<tr>
<td>Ethyl ether</td>
<td>1310</td>
<td>74.12</td>
<td>152</td>
</tr>
<tr>
<td>Furan</td>
<td>1362</td>
<td>68.07</td>
<td>165</td>
</tr>
<tr>
<td>Furfural</td>
<td>1962</td>
<td>96.08</td>
<td>200</td>
</tr>
<tr>
<td>Gasoline</td>
<td>1370–1470</td>
<td>96.0</td>
<td>140–150</td>
</tr>
<tr>
<td>$n$-Heptane</td>
<td>1383</td>
<td>100.20</td>
<td>138</td>
</tr>
<tr>
<td>$n$-Hexane</td>
<td>1337</td>
<td>86.17</td>
<td>144</td>
</tr>
<tr>
<td>Hydrogen cyanide</td>
<td>2290</td>
<td>27.03</td>
<td>430</td>
</tr>
<tr>
<td>Methyl alcohol</td>
<td>2680</td>
<td>32.04</td>
<td>474</td>
</tr>
<tr>
<td>Methyl ethyl ketone</td>
<td>1623</td>
<td>72.10</td>
<td>191</td>
</tr>
<tr>
<td>Methyl methacrylate</td>
<td>1432</td>
<td>100.14</td>
<td>143</td>
</tr>
<tr>
<td>$n$-Octane</td>
<td>1412</td>
<td>114.22</td>
<td>132</td>
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<tr>
<td>$n$-Pentane</td>
<td>1300</td>
<td>72.15</td>
<td>153</td>
</tr>
<tr>
<td>$n$-Propyl acetate</td>
<td>1468</td>
<td>102.13</td>
<td>145</td>
</tr>
<tr>
<td>$n$-Propyl alcohol</td>
<td>2295</td>
<td>60.09</td>
<td>296</td>
</tr>
</tbody>
</table>
TABLE 7.15h Continued
Relief Capacity Determination: Table of Constants*

<table>
<thead>
<tr>
<th>Chemical</th>
<th>$\lambda \sqrt{M_w}$</th>
<th>Molecular Weight $(M_w)$</th>
<th>Heat of Vaporization, BTU per lbm at Boiling Point $(\lambda)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>iso-Propyl alcohol</td>
<td>2225</td>
<td>60.09</td>
<td>287</td>
</tr>
<tr>
<td>Tetrahydrofuran</td>
<td>1428</td>
<td>72.10</td>
<td>168</td>
</tr>
<tr>
<td>Toluene</td>
<td>1500</td>
<td>92.13</td>
<td>156</td>
</tr>
<tr>
<td>Vinyl acetate</td>
<td>1532</td>
<td>86.09</td>
<td>165</td>
</tr>
<tr>
<td>O-Xylene</td>
<td>1538</td>
<td>106.16</td>
<td>149</td>
</tr>
</tbody>
</table>

*One BTU/lb = 0.5556 kcal/kg

if not dislodged by the fire, can reduce the probability of vessel failure caused by steel softening.

API or NFPA As will be noted from the discussions in the paragraphs that follow, there are some differences between the recommendations of NFPA and API. For this reason, it is suggested that design engineers decide which set of recommendations are to be followed in designing the particular plant before considering the shapes of tanks or the expected fire height.

NFPA 58, Liquefied Petroleum Gases, Storage and Handling, requires the design engineer to calculate the wetted area on the basis of a 30-ft fire height above ground, whereas API RP 520 and 521 require us to consider only a 25-ft fire height above the source of flame.

Tank Shape NFPA RP 521 recommends that, when a tank is exposed to external fire, its wetted area is to be calculated on the basis of a percentage of total exposed area of the vessel. This percentage is 55% for a sphere or spheroid, 75% of total exposed area of a horizontal tank, and the first 30 ft (9 m) above grade of a vertical tank.

API recommendations for calculations of wetted area are similar to NFPA's, except that, for a sphere or spheroid, the total exposed surface up to the maximum horizontal diameter or to a height of 25 ft (7.5 m) is used, whichever is greater. In case of distillation towers, normally, only the heights of liquid layers on the trays are considered in determining the wetted area.

Fire Zone When determining the wetted surface area that is exposed to an external fire, it is necessary to define the ground area of the fire, called the fire zone. According to API RP 521, the probable maximum ground area that a fire incident is likely to cover is 2,500 to 5,000 ft$^2$. For engineering design purposes, this area corresponds to that of a circle having a diameter of 55 to 80 ft.

When a PRV protects several vessels, the design engineers should be conservative and select, from the various possible fire zones, the fire zone (circle of 80 ft in diameter) that would include the largest total wetted surface area protected by that PRV. When several vessels share a single PRV for overpressure protection, no regular block valves are to be installed between them. The use of CSO valves is allowed.

Fire Height If NFPA 58, Liquefied Petroleum Gases, Storage and Handling, is selected as the basis of the design, the design engineer must calculate the wetted area on the basis of a 30-ft fire height above ground.

If API RP 520 and 521 are used as the design basis for the plant, the design engineer must consider only a 25-ft fire height and measure that height, not necessarily from ground, but from above the source of flame. In other words, the API code requires the design engineer to also consider the possibility that a pool of flammable materials might accumulate at any elevation (other than ground) and catch fire.

In some cases, the NFPA and API recommendations can give substantially different results. To illustrate, take the example of a vertical tank with its bottom tangent line at 20 ft above ground and containing a 10 ft level of liquid so that the liquid surface is 30 ft above grade level. Let us also assume that, in this case, flammable materials can accumulate only at grade level and, therefore, the “source of flame” is at that level. In this case, the calculated wetted surface area using API will be half as much as if it were determined using the NFPA recommendations.

Vertical Tanks If the liquid level is above the bottom tangent line in a vertical vessel that is provided with an elliptical head, Equation 7.15(7) can be used to calculate its wetted surface $(A_w)$ in square feet.

$$A_w = 1.089D^2 + \pi D[h - (SE-FH)]$$  \hspace{1cm} 7.15(7)

where

- $A_w$ = the wetted surface area in ft$^2$
- $D$ = the diameter of the vertical tank in feet
- $h$ = the actual liquid level in the tank in feet
- $SE$ = the above grade liquid surface elevation in the tank in feet
- $FH$ = the fire height in feet (25 for API, 30 for NFPA)

If $(h - (SE-FH))$ is zero or negative, the vessel is above the effective fire height, so the fire case is not relevant.
**Horizontal Tanks**  
Equation 7.15(8) can be used if one desires to calculate the wetted surface area of a horizontal tank provided with ellipsoidal heads.

\[ A_w = (2.178D^2 + \pi DL)(S/\pi D) \quad 7.15(8) \]

where  
\( A_w \) = the wetted surface area in ft\(^2\)  
\( D \) = the diameter of the horizontal tank in feet  
\( L \) = the length of the cylindrical portion of the horizontal tank in feet  
\( S \) = calculated by either Equation 7.15(9) or 7.15(10), depending on which is applicable.

If the liquid level is below the centerline of the horizontal tank, Equation 7.15(9) is to be used. If the level is above, Equation 7.15(10) is applicable.

\[ S = D \cos^{-1}[(D - 2[h - (SE - FH)])/D] \quad 7.15(9) \]

\[ S = D\{\pi - \cos^{-1}[(2[h - (SE - FH)] - D)/D]\} \quad 7.15(10) \]

where  
\( D \) = the diameter of the horizontal tank in feet  
\( h \) = the actual liquid level in the tank in feet  
\( SE \) = the above grade liquid surface elevation in the tank in feet  
\( FH \) = the fire height in feet (25 for API, 30 for NFPA)

If \( h - (SE - FH) \) is zero or negative, the vessel is above the effective fire height, so the fire case is not relevant.

**Environmental Factors**

If certain conditions are met, the value of the environmental factor (F) can be less than 1.0. These reduced values of F are listed in Table 7.15i and can be applied to the API recommended heat flux calculation in Equation 7.15(4) to reduce the required relieving capacity of the PRV. Another set of environmental factors is listed in Table 7.15j. These factors appear in the NFPA National Fire Codes.

These environmental factors are suggested values only, and whenever the conditions are not exactly as described in Tables 7.15i or 7.15j, the reader must exercise sound engineering judgment when applying them.

**API’s Environmental Factors**  
As noted in Table 7.15i, API allows for more factors than does NFPA. A factor of 0.03 is used for earth-covered storage above grade, and a factor of 0.0 is used for underground storage. In addition, credit is given for the thickness and/or conductance of the insulation used. On the other hand, it should be noted that API does not allow credit for water application facilities on bare metal surfaces. Because of uncertainties in the reliability of effective water spray application systems, they feel that no reduction in environmental factors should be allowed.

To take insulation into account when determining heat flux, the insulation should be of the type that will not be damaged or removed by fire or firewater streams, exposing the bare metal surface to the fire. The means of fastening the insulation should be such that it will not fall because of the fusion of the banding material under fire conditions.

**API and NFPA Environmental Factors**  
Table 7.15i lists the environmental factors recommended by API, and Table 7.15j lists the NFPA ones. They both relate to the type of fireproof insulation and its thickness as used on the tank. As can be seen from Table 7.15i, API gives an estimate of environmental factors on the basis of insulation thickness; NFPA does not.

From the perspective of NFPA, for a tank insulation to qualify as “fireproof,” it must function effectively while subjected to fire temperatures of 1000 to 2000°F for a period of 20 to 60 min. NFPA also requires that the insulation not be dislodged when impacted by firewater—it is to be held in place by stainless steel banding or jacketing. Table 7.15j also shows that NFPA gives credit both for having fireproof insulation and for drainage away from the tank.

The main difference between API and NFPA is that API does not allow credit for water deluge systems, but NFPA does. API’s position is that the NFPA rules are too complicated and that the sprinkler systems are not sufficiently reliable. They

---

**Table 7.15i**

API Recommended Environmental Factors (F) for Tank Installations

<table>
<thead>
<tr>
<th>Type of Installation</th>
<th>Factor (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Bare vessel</td>
<td>1.0</td>
</tr>
<tr>
<td>2. Insulated vessels (listed below are three conductance values expressed in units of BTU/hr/ft(^2)/°F)</td>
<td></td>
</tr>
<tr>
<td>Conductance of 4.0 (API – 1 insulation)</td>
<td>0.3</td>
</tr>
<tr>
<td>Conductance of 2.0 (API – 2 insulation)</td>
<td>0.15</td>
</tr>
<tr>
<td>Conductance of 1.0 (API – 4 insulation)</td>
<td>0.075</td>
</tr>
<tr>
<td>3. Water application facilities provided on bare vessels</td>
<td>1.0</td>
</tr>
<tr>
<td>4. Depressurizing and emptying facilities provided</td>
<td>1.0</td>
</tr>
<tr>
<td>5. Underground storage</td>
<td>0.0</td>
</tr>
<tr>
<td>6. Earth-covered storage above grade</td>
<td>0.03</td>
</tr>
</tbody>
</table>

---

**Table 7.15j**

NFPA Recommended Environmental Factors (F)

<table>
<thead>
<tr>
<th>Installation</th>
<th>Factor (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage in accordance with NFPA No. 30 (≥1% slope) for tanks with over 200 ft(^2) (18 m(^2)) of exposed wetted area</td>
<td>0.5</td>
</tr>
<tr>
<td>Approved water spray (water deluge system) in place</td>
<td>0.3</td>
</tr>
<tr>
<td>Approved fireproof insulation installed</td>
<td>0.3</td>
</tr>
<tr>
<td>Approved water spray (water deluge system), drainage, and approved (fireproof) insulation</td>
<td>0.15</td>
</tr>
</tbody>
</table>
argue that the sprinklers are not regularly tested; they can freeze in northern regions and are often the first systems to be destroyed when a fire breaks out, because they are fragile.

**Calculating the Relieving Capacity**

The steps required to determine the relief capacity under fire conditions are as follows:

1. Establish wetted surface area \( A_w \) of the tank, considering its size, shape, and location within the fire zone.
2. Based on the selected code (API, NFPA, other) and on the type of thermal insulation, water spray, and other installation featured, select the applicable environmental factor \( F \).
3. Based on the wetted surface area \( A_w \) and based on the selected code (API, NFPA, other), determine the equation to be used to calculate the total heat absorption due to fire. (The equation to be used can be 7.15(4), 7.15(5), or one of the equations in Tables 7.15e and 7.15g.)
4. Calculate the relief capacity required \( W \) by Equation 7.15(11) as follows:

\[
W = \frac{Q}{\lambda}
\]

where

\( W \) = the required relief capacity in pounds per hour (lb/hr)

\( Q \) = the total heat absorbed by the tank, calculated by Equation 7.15(4), 7.15(5), or by one of the equations in Tables 7.15e and 7.15g

\( \lambda \) = the latent heat of vaporization at relieving conditions of the liquid in the tank to be protected by the PRV that is being sized. (For calculation convenience, a table of physical property constants presented in the National Fire Codes of the National Fire Protection Association is reproduced in Table 7.15h.)

**Latent Heat of Vaporization**  When sizing PRVs to protect tanks that contain multicomponent hydrocarbon liquids, there is no accurate way to determine the latent heat of vaporization. The actual process during a fire condition is one in which the lighter hydrocarbon components will vaporize first, and the heavier components will follow. Because the latent heat of vaporization varies with not only the composition of the boiling liquid but also with the relieving temperature and pressure, only approximations can be made.

Computer simulation software, if available, is the preferred method of obtaining the latent heat for sizing the PRV that is to protect a multicomponent hydrocarbon storage vessel. These simulations are usually based on the assumption that anywhere from 70 to 95% of the hydrocarbons are still in the liquid state in the vessel when the latent heat is calculated.

When computer simulation is not available, the design engineer can refer to API RP 521, in which the vapor pressure and heat of vaporization of pure, single-component paraffin hydrocarbons are given in Figure A1. Using the relieving pressure and the average molecular weight of the multicomponent hydrocarbon liquid, one can use this chart to estimate the latent heat of vaporization of the mixture at relieving conditions.

**Protecting Liquid-Full Tanks**

When a liquid-full vessel is exposed to external fire, the relieving process will be initiated by the thermal expansion of the liquid. This will be followed by a period during which both liquid and vapor are simultaneously relieved. This continues until enough vapor space is created for vapor-liquid disengagement in the vessel, which usually starts when 1 or 2 ft of vapor space is cleared.

The PRV for such a liquid-full tank is sized for this last, all-vapor relieving phase, because the relieving area requirement of thermal expansion is small, and the time period of two-phase relieving is short. When a liquid-filled tank is connected to another vessel with a vapor space in it, the control and check valves in the connecting piping should be carefully evaluated. As to the selection of the set pressure of the PRV, it is recommended to base it on the design pressure of the tank’s bottom minus the hydrostatic head of the liquid column.

**Fluids at the Critical Point**  If the latent heat of a hydrocarbon mixture is approaching zero, and the sensible heat dominates its behavior, it is said to be at or near the critical point. If, under the relieving conditions, the liquid in a pressure vessel is above the critical point, it should be handled as a gas. If the process fluids under the relieving conditions are below the critical region, and there is no accurate latent heat value available, API RP 520 allows the use of an approximate latent heat of 50 BTU/lb.

Once the design heat flux is determined, calculations are made to determine the rate of thermal expansion of the vessel contents. To calculate this properly, the gas specific heat and the gas compressibility factor must be known. It is inadequate to assume the vapor to be an ideal gas, because, just above the critical point, the compressibility factor of the vapor changes very rapidly. The maximum required valve capacity is often determined not at the critical point but at some point above it where the change in vapor compressibility is less drastic.

It should be noted that, under these conditions, the metal wall of the vessel will rapidly approach the flame temperature and will fail prematurely, because it is not being cooled by the latent heat of vaporization of the boiling liquid contents of the tank. Under these conditions, it is advisable to protect the metal surface of the tank with a cooling water spray to prevent premature failure.

**NONFIRE PROTECTION OVERPRESSURE**

The possible nonfire causes of overpressure can be utility failures, thermal expansion, blocked outlets, valve or process control failure, equipment failure, runaway chemical reac-
When a liquid filled system is blocked in and heated, the resulting expansion can cause very high pressures. The heat source of thermal expansion can be a heater, heat exchanger, or heat tracing, or it can be solar or other radiant heat or external fire.

Thermal-expansion PRVs should be installed if a section of the process can be blocked in during maintenance or shut-down. If the plant uses strictly enforced and checked procedures to drain all liquid filled vessels during shutdown, the need for thermal-expansion PRVs is reduced, but human error can never be fully eliminated. Therefore, if the blocked-in section contains toxic or environmentally hazardous materials, the installation of thermal-expansion PRVs is recommended.

On the other hand, no metal seated block valve can provide 100% bubble-tight closure. Therefore, if the blocked-in pipe section is of small diameter and less than 100 ft in length, the required thermal expansion relieving capacity is less than the leakage of the block valve, so a thermal relief valve is not required.

In addition, thermal-expansion PRVs are not required on pipelines that cannot be blocked in or that cannot be heated by any heat source other than the ambient and are normally operating at a temperature exceeding the ambient. Thermal expansion relief valves also are not required if the blocked-in pipe or equipment is not liquid full but has a vapor pocket.

When thermal-expansion PRVs are required, and the trapped in liquid is toxic, corrosive, volatile, or flammable, the PRV must discharge into a closed receiver. Environmentally safe liquids such as water can be discharged directly into a sewer.

Set Pressure and Sizing  

The set pressure of a thermal-expansion PRV must be high enough that the valve will open only as a result of thermal expansion. In selecting the set pressure, the design engineers should carefully evaluate the backpressure that might be acting on the valve; if it is variable, the selected PRV should be provided with balanced bellows.

If the protected volume is small, sizing calculations need not be performed, and it is sufficient to install a 1/2 x 3/4-in. or 3/8 x 1-in. nominal thermal relief valve. When large vessels or long, large-diameter pipelines are to be protected against thermal expansion, the required relief capacity in GPM (without vaporization) can be calculated using Equation 7.15(12).

\[
GPM = \frac{BQ}{500(SpG)(Cp)}
\]

where

- \( B \) = the cubical expansion coefficient per °F for the liquid at the expected temperature (typical values are 0.0001 for water, 0.0004 for hydrocarbons <34.9°API gravity, 0.0005 for 35 to 50.9, 0.0006 for 51 to 63.9, 0.0007 for 64 to 78.9, 0.0008 for 79 to 88.9, and so on)
- \( Q \) = the thermal expansion relief rate required in GPM
- \( SpG \) = the specific gravity of the process fluid referred to water at 60°F = 1.0
- \( Cp \) = the specific heat of the trapped in liquid on the cold side in BTU/°F
- \( GPM \) = the total heat transfer rate in BTU/hr

Blocked Outlet Conditions

Whenever an inlet stream pressure can exceed the maximum allowable working pressure of the receiving tank or other equipment, overpressure protection is needed in case of outlet blockage. The blocking of the outlet line can be caused by instrument air or power failure, by control valve malfunction, or by inadvertent valve operation.

The set pressure of the PRV should be selected to correspond to the design pressure at the bottom of the tank minus the hydrostatic head above it. The discharge piping of the PRV should have no pockets. It is advisable to install bleeding valves at the lowest points to eliminate liquid accumulation. When liquid discharges to a flare header, the sizing of the flare header should take the total volume of the discharged liquid into consideration.

Sizing the PRV

PRVs must always be installed on the outlets of compressors and of positive displacement pumps. These PRVs should be sized for the rated capacity of the compressor or pump. On other sources, a PRV is required only if the source pressure can be higher than the maximum allowable working pressure of the protected equipment or tank. A PRV is not required if the outlet cannot be blocked. When CSO valves are used, the system is assumed to be not blocked.

The required sizing capacity for blocked-outlet PRVs is not always the normal flow rate of the blocked line. 1 When the liquid outlet is blocked, the PRV has to relieve the liquid accumulation, which might fluctuate. At high levels in the protected tank and with two-phase input, the vapor-liquid separation can become impossible, and the PRV can also be relieving a two-phase flow.

Therefore, when the vessel has a large liquid inventory, it is important to provide the tank with a void space corresponding to 10 to 15 min of inlet flow. This way, after a blockage, the operator will have some time to prevent the level from further increasing. An even safer approach is to provide a high-level alarm when the remaining residence time above the liquid level drops to, say, 20 min, and in addition, install a high-high level alarm when it drops to 15.

Process Equipment Considerations

In the following paragraphs, some unit-operation related advice will be given on how to protect such equipment as low-pressure tanks, heat exchangers, pumps and compressors.
Low-Pressure Storage Tanks

In designing the “breathing” of atmospheric storage tanks, there are two considerations. One is the need to vent the displaced air when liquid is being pumped into the vessel, and the other is the need to admit air into the tank when liquid is being pumped out of the vessel. This “breathing” is needed to (a) prevent over-pressure while pumping liquid in and (b) collapsing the vessel as a result of vacuum when liquid is being pumped out and the corresponding volume is not replaced with air.

Quoting once again the API Guide for Tank Venting, RP-2000, the following recommendations apply:

- Inbreathing—8 scfh (0.226 m³/hr) air for each gpm (3.78 lpm) of maximum emptying rate
- Outbreathing—8.5 scfh (0.24 m³/hr) air for each gpm (3.78 lpm) of maximum filling rate for fluids with a flashpoint of 100°F (37.8°C) or higher, and 17 scfh (0.48 m³/hr) air for each gpm (3.78 lpm) of maximum fill rate for fluids with a flashpoint below 100°F (37.8°C)

Thermal Venting Capacity

In addition to pumping, provision must be made to accommodate the thermal venting requirements of the vessel. This is defined as the expansion or contraction of the vapors in the tank resulting from changes in the tank’s ambient temperature. For example, at the beginning of a rainstorm, the vapors in the tank would cool and contract. Under such conditions, to avoid creating a vacuum in the atmospheric tank, additional air must be admitted into the vapor space of the tank.

The API recommendations are based on an in-breathing capacity of 2 ft³ of air per hour per square foot (0.61 m³/hr/m²) of total shell and roof area for very large tanks (a capacity of more than 20,000 barrels or 3180 m³). For tanks with a capacity of less than 20,000 barrels (3180 m³), an in-breathing requirement of 1 ft³ of air per hour (0.028 m³/hr) for each barrel (0.158 m³) of tank capacity is recommended. This capacity is based on a rate of change of vapor space temperature of 100°F (37.8°C) per hour. This maximum rate of temperature change is assumed to occur during such events as a sudden cold rain.

It is assumed that the tank roof and shell temperatures cannot rise as rapidly as they can drop under any conditions. It is further assumed that, for liquids with a flashpoint of 100°F (37.8°C) or above, the thermal out-breathing requirement has been assumed to be 60% of the in-breathing capacity requirement.

For materials with a flashpoint below 100°F (37.8°C), the thermal out-breathing requirement has been assumed to be equal to the in-breathing requirement. This allows for vaporization of the liquid and for the fact that the specific gravity of the vapors in tanks containing volatile hydrocarbons is greater than air. The thermal venting capacity requirements as recommended by API were given in Table 7.15g.

The total in-breathing and out-breathing requirements of a tank should always be calculated as the sum of the thermal venting capacity requirements and the requirements to compensate for in or out pumping rates.

Heat Exchangers

Heat exchangers are a class of process equipment requiring special relief considerations because of the potential need for protection against thermal expansion, external fire, blocked outlets, and tube rupture cases.

Blocked-In Exchangers

Heat exchangers frequently have valves located on both their inlet and outlet piping. When these valves are all closed, the exchanger is “blocked in.” If the cold side of the heat exchanger can be blocked in, relief devices are installed to provide protection against thermal expansion of liquids in the exchanger. This is always done for the cold side of an exchanger, where the liquid can be heated by the hot fluid on the other side or can be heated by ambient temperature while sitting with the inlet and outlet valves closed.

No relief device is necessary for the protection of either side of an exchanger that cannot be blocked in. In such installations, it is assumed that the relief of the unit is taken care of by the relief device on the related tank or equipment.

Liquid Refrigerants

In the case of liquid refrigerants, a relief device should always be provided for the protection of the refrigerant side if that side can be blocked in and if the vapor pressure of the refrigerant, when its temperature rises to that of the hot side, exceeds the design pressure of the exchanger. This is also done whenever the vapor pressure of the material flowing at 100°F (37.8°C) is greater than the design pressure of the exchanger. This recommendation is somewhat site specific and is based on an assumed (maximum) ambient temperature of 100°F (37.8°C); this temperature may lower for some geographical areas.

Gas-Fired Tubular Heaters

Direct gas-fired tubular heaters are always protected by relief valves on their tube side. The valve is normally sized for the design heat transfer rating of the heater and must initially handle a fluid rate corresponding to the rate of thermal expansion in the tubes when they are blocked in.

When designing fired heaters, there should be no block valve on its outlet. This is because PRVs for high-temperature services exceeding 550°F are not available with dependable seat and seal materials.

Tube Rupture

Consideration should be given to relief protection of low-pressure equipment in the event that an
exchanger tube ruptures because of corrosion, vibration, or thermal shock. ASME Code, Section VIII, Division 1, Paragraph UG-133(d) require such protection.

This consideration is particularly critical when the low-pressure side design pressure is less than the operating pressure on the high-pressure side. In terms of high- and low-pressure side design pressures, PRV protection against tube rupture is recommended if the design pressure of the low-pressure side is less than 77% of the high-pressure side design pressure.

Reference 2 provides some advice on the sizing of PRVs to protect against overpressure caused by tube rupture. The PRV, which is to protect the exchanger, should be located directly on the exchanger or very close to it.

**Pumps and Compressors**

Reciprocating compressors should be protected against over-pressure on the discharge side in case the discharge piping can be blocked. In the case of positive displacement pumps, a relief device is required to relieve the pumped liquid when the discharge line is blocked in. This relief device is sometimes provided as an integral part of the pump.

The routing of the discharge from the PRVs should be carefully evaluated. In many cases, directing the relieved fluid back to the pump or compressor suction may result in dangerous overheating of the fluid because of the work input by the pump or compressor. This may result in unit overheating, fluid vaporization, seal failure, and so on.

**Sizing** In sizing the PRV, the type of pumping equipment must be taken into consideration. In the case of rotary pumps with a fairly uniform instantaneous flow rate, the PRV is sized for the rated pump capacity.

In the case of reciprocating pumps, consideration must be given to the fact that the rated flow rate is the average of the total stroke of the piston. It is suggested that, for a single-piston pump, four times the average flow rate be used as the basis for relief sizing. With a duplex or triplex pump, there is some flow averaging, and the engineer must exercise safe judgment.

In general, the PRV should be sized for the maximum capacity that the pump or compressor can generate. Therefore, the design engineer should always consider the maximum impeller size and 105% of the normal speed of the compressor or pump in selecting the sizing capacity.

**Set Pressure** The design pressure of the weakest part of the system downstream should determine the pressure setting of the relief device used. This may be the design pressure of the pump casing, the design pressure of some valve or equipment in the line, or another appropriate specification. Normally, a set pressure is selected to be below this limit but high enough that the PRV will not open under normal operating conditions.

In the case of turbine pumps, relief devices are generally provided to protect the pump, the associated piping, and the equipment that may be blocked in. In the case of centrifugal-type pumps, it is uncommon that the maximum pump shutoff pressure would exceed the maximum allowable working pressure (MAWP) of any system components, but the design engineer still must fully evaluate the overpressure possibilities.

**Distillation Towers**

Several conditions and combinations of conditions can result in the overpressure of distillation columns. These can include the failure of power, instrument air, reflux, cooling water, control system, and control valves. Other causes can include abnormal heat input, tube rupture, blocked outlets, and thermal expansion.

In evaluating the above conditions, one must always ask, “When this failure occurs, will the feed, the steam flow to the reboiler, the cooling water flow, etc. continue, or will it stop?” The answers to such questions will help determine if secondary effects such as overhead condenser flooding also need to be considered in the safety analysis.

In all distillation towers, there is a normal heat input at the column reboiler. The vapors generated are normally condensed in an overhead condenser. In the event of the failure of cooling water or cooling medium to the overhead condenser (or a failure of the fan drive unit on air-cooled condensers), a dangerous overpressure situation may develop because of the continued generation of vapors in the reboiler. A relief device must be added to relieve the vapors thus generated, and this PRV is generally rated for the normal heat input of the reboiler.

Overpressure can also develop when the source of heat is continuous and the overhead vapor line from the column is accidentally blocked. In this case, a relief device must relieve the vapors as they are generated by the column reboiler.

Reflux failure to a column where reflux acts as a coolant may also cause an overpressure condition. Similarly, loss of feed may result in an overpressure condition, especially if the reboiler continues to operate when the feed has stopped.

**Pipe Headers**

The design engineer must always consider that automatic control systems do fail and can accidentally subject some equipment to pressures exceeding their design pressures. Such an overpressure condition can occur because of the failure of steam pressure reducing stations. To illustrate this, assume a case in which high-pressure steam (150 PSIG, or 1035 kPa) is reduced to a lower pressure (30 PSIG, or 207 kPa). Should this control station fail as a result of the control valve sticking open, all equipment connected to the low-pressure steam header could be subjected to high pressure. In such case, a relief device is normally placed on the low-
pressure header near the pressure-reducing control valve and
is rated for the maximum capacity of that control valve.

As another example, liquid from a high-pressure source
may be admitted to a vessel that is operating under either
level or flow control. Should the control valve fail, the equip-
ment downstream of the control valve may be subjected to
pressures in excess of its design pressure. Here again, relief
devices capable of handling the maximum flow through the
control valves involved need to be provided.

**Bypass Valves** When considering overpressure conditions
caused by control valve failure, it is also prudent to evaluate
the impact of bypass valves around control valves that can
be open or partially open. Unless the bypass valves are sealed
closed, there can be situations where the bypass valves are
intentionally used to obtain additional capacity.

Alternatively, performing maintenance or testing on the
control valve while the process is in operation could result
in a situation in which the bypass valve is open and the
control valve fails open. In considering these possibilities, a
conservative approach is to size the relief capacity on the
basis of the combined Cv of the control valve and the bypass
valve.

However, this oversizing can cause problems such as
causing chatter in the relief valve. This dilemma must be
resolved based on the individual circumstances for each
installation, including an assessment of operating and main-
tenance practices. The capacity of the process piping should
also be examined, because the piping may actually be the
limiting factor if a combined Cv approach is used in sizing
the relief valve.

**Chemical Reactors**

Protecting chemical reactors from overpressure is probably
the most complex task in process safety design. It is that
complicated because of the possibility of runaway reactions,
and because the speed of response of some conventional
PRVs might not be fast enough to match them. As a result,
special (explosive actuated) PRV designs may be needed.

What makes chemical reactors unique among the unit
operations in a processing plant is that “runaway” exothermic
reactions can occur in them. An example of such a case is a
polymerization reactor in which cooling water or agitator
failure can cause a runaway reaction. The sizing problems
fall into two categories.

The first problem is that it is difficult and sometimes
impossible to determine the actual rate of heat evolution
during a runaway reaction, because data are often not avail-
able for such a condition at high relief temperatures. The
second problem is that the PRV does not usually relieve a
pure vapor stream but a mixture of liquids, gases, and solids.

When sizing such a relief valve, one approach first rec-
ommends the determination of the rate of heat evolution and
the conversion of this heat to equivalent vapor generation.

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**TABLE 7.15k**

<table>
<thead>
<tr>
<th>Nominal Reactor Volume, gal (l)</th>
<th>Relief Valve</th>
<th>Orifice Area, in.$^2$ (mm.$^2$)</th>
<th>in.$^3$/gal (mm.$^2$/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 (3780)</td>
<td>2L3</td>
<td>1.287 (830)</td>
<td>0.0013 (0.2218)</td>
</tr>
<tr>
<td>2500 (9450)</td>
<td>3L4</td>
<td>2.85 (1,838)</td>
<td>0.0012 (0.2048)</td>
</tr>
<tr>
<td>3750 (14,175)</td>
<td>4P6</td>
<td>6.38 (4,115)</td>
<td>0.0017 (0.2901)</td>
</tr>
<tr>
<td>5200 (19,656)</td>
<td>4P6</td>
<td>6.38 (4,115)</td>
<td>0.0012 (0.2048)</td>
</tr>
</tbody>
</table>

When this vapor volume is determined, the PRV is sized
under the assumption that the relief device will vent this
calculated volume as 100% liquid. This approach appears
to be safe and conservative. In these cases, the relief devices
sometimes are sized based on past practice. Table 7.15k presents
typical relief sizes for PVC reactors as an example.

In cases where relief requirements cannot be quantita-
tively determined, the design engineer should be careful to
use simplifying assumptions that will lead to conservative
results.

**Discharging the PRVs**

The selected discharge system should be a function of the
process fluid handled. The following types of discharges are
allowable to be sent to open collection systems or to the
atmosphere:

1. Vapors that are lighter than air and are not toxic, flam-

mable, or hazardous to humans or the environment can
be discharged.
2. Water or nontoxic, nonflammable liquids from waste
heat boilers and thermal relief systems can be dis-
charged into open collection systems before further
treatment and discharge into the sewer.
3. Local regulations also allow some specific gases/
vapors to be discharged to the atmosphere in certain
limited volumes.

**Discharging to Closed Locations**

The PRV discharge must be sent to a closed location in the
following cases:

1. The discharged vapor is toxic, corrosive, or flammable
and/or will condense at atmospheric conditions.
2. The discharged vapor is heavier than air or is flamma-
ble, toxic, or hazardous either to humans or the envi-
ronment.
3. The discharged fluid is liquid or partially liquid and
is toxic, flammable, corrosive, high temperature, or
otherwise hazardous to humans or the environment.
4. The discharged amount/volume would exceed local
regulations.
When the PRVs are discharged into a closed system, they are sent through a manifold and blowdown drum to a flare system. The blowdown drum separates the liquids from the vapors. The vapors are then sent to the flare system while the liquids are pumped to the treatment and disposal system. In a processing plant, there can be flare header systems for different pressures or for different types of process materials, such as, for example, a separate \( H_2S \) flare header or other system.

**CONCLUSIONS**

Overpressure analysis is more art than science. The design engineer must always exercise care and sound judgment when determining the sizing basis for relief capacity determination. There are so many combinations of installations and circumstances that it is beyond our scope here to do much more than present some generalized advice and a fairly long list of further reading material in the bibliography.

In many cases, it is necessary to calculate relief capacity requirements based on a combination of several considerations, such as fire, cooling water failure, runway reactions, etc., and determine which will require the largest relief device. There can also be installations where the relief capacity requirements based on fire and those based on some other consideration should be additive, because both conditions are likely to exist simultaneously.

Concurrently, the engineer must be aware that oversizing of relief valves can also present problems such as chattering, which creates a dilemma in relief valve sizing and selection. Computer simulations can be very valuable in specific cases, such as when the relieving conditions are near critical. On the other hand, one should always remember that software packages are only as good as the programmer who has prepared them and are applicable only under the same conditions and for the same equipment configuration for which they have been prepared.

**TERMINOLOGY AND NOMENCLATURE**

**Accumulation.** This is the pressure increase over the maximum allowable working pressure of a tank or vessel during discharge through the pressure relief valve. It is given as a percentage of the maximum allowable working pressure or in pressure units (e.g., bars or pounds per square inch).

**Backpressure.** Pressure on the discharge side of a pressure relief valve. This pressure is the sum of the superimposed and the built-up backpressures. The superimposed backpressure is the pressure that exists in the discharge piping of the relief valve when the valve is closed.

**Balanced safety relief valve.** A safety relief valve with the bonnet vented to atmosphere. The effect of backpressure on the performance characteristics of the valve (set pressure, blowdown, and capacity) is much less than on the conventional valve. The balanced safety relief valve is made in three designs: (1) with a balancing piston, (2) with a balancing bellows, and (3) with a balancing bellows and an auxiliary balancing piston.

**Blowdown (blowback).** The difference between the set pressure and the reseating (closing) pressure of a pressure relief valve, expressed in percent of the set pressure or in bars or pounds per square inch.

**Built-up backpressure.** Variable backpressure that develops as a result of flow through the pressure relief valve after it opens. This is an increase in pressure in the relief valve’s outlet line caused by the pressure drop through the discharge headers.

**Chatter.** Rapid, abnormal, reciprocating variations in lift during which the disc contacts the seat.

**Cold differential test pressure (CDTP).** The pressure at which the PRV is adjusted to open during testing. The CDTP setting includes the corrections required to consider the expected service temperature and backpressure.

**Constant backpressure.** Backpressure that does not change under any condition of operation, regardless of whether the pressure relief valve is closed or open.

**Closing pressure (reseat pressure).** The pressure, measured at the valve inlet, at which the valve closes, flow is substantially shut off, and there is no measurable lift.

**Conventional safety relief valve.** A safety relief valve with the bonnet vented either to atmosphere or internally to the discharge side of the valve. The performance characteristics (set pressure, blowdown, and capacity) are directly affected by changes of the backpressure on the valve.

**Design pressure.** This pressure is equal to or less than the maximum allowable working pressure. It is used to define the upper limit of the normal operating pressure range.

**Effective coefficient of discharge.** This is a coefficient used to calculate the minimum required discharge area of the PRV.

**Flutter.** Rapid, abnormal, reciprocating variations in lift during which the disc does not contact the seat.

**Lift.** The rise of the disc in a pressure relief valve.

**Maximum allowable operating pressure (MAOP).** The maximum pressure expected during normal operation.

**Maximum allowable working pressure (MAWP).** This is the maximum pressure allowed for continuous operation. As defined in the construction codes (ASME B31.3) for unfired pressure vessels, it equals the design pressure for the same design temperature. The maximum allowable working pressure depends on the type of material, its thickness, and the service conditions set as the basis for design. The vessel...
may not be operated above this pressure or its equivalent at any metal temperature other than that used in its design; consequently, for that metal temperature, it is the highest pressure at which the primary pressure relief valve can be set to open.

Operating pressure. The operating pressure of a vessel is the pressure, in pounds per square inch gauge, to which the vessel is usually subjected in service. A processing vessel is usually designed for a maximum allowable working pressure, in pounds per square inch gauge, that will provide a suitable margin above the operating pressure to prevent any undesirable operation of the relief device. It is suggested that this margin be approximately 10% or 25 PSI (173 kPa), whichever is greater. Such margin will be adequate to prevent the undesirable opening and operation of the pressure relief valve caused by minor fluctuations in the operating pressure.

Operating pressure margin. The margin between the maximum operating pressure and the set pressure of the PRV.

Operating pressure ratio. The ratio of the maximum operating pressure to the set pressure of the PRV.

Overpressure. This is the pressure increase over the set pressure of the primary relief device. When the set pressure is the same as the maximum allowable operating pressure (MAOP), the accumulation is the same as the overpressure. Pressure increase over the set pressure of the primary relieving device is overpressure. Note: from this definition, it will be observed that, when the set pressure of the first (primary) safety or relief valve is less than the maximum allowable working pressure of the vessel, the overpressure may be greater than 10% of set pressure.

Pressure-relieving device. The broadest category in the area of pressure relief devices, it includes rupture discs and pressure relief valves of both the simple spring-loaded type and certain pilot-operated types.

Pressure relief valve (PRV). A generic term that might refer to relief valves, safety valves, and pilot-operated valves. The purpose of a PRV is to automatically open and relieve the excess system pressure by sending the process gases or fluids to a safe location when its pressure setting is reached.

Rated relieving capacity. This is the maximum relieving capacity of the PRV. This rating is normally provided on the nameplate of the PRV. The rated relieving capacity of the PRV exceeds the required relieving capacity and is the basis for sizing the vent header system.

Relief valve. An automatic pressure-relieving device actuated by the static pressure upstream of the valve, which opens in proportion to the increase in pressure over the operating pressure. It is used primarily for liquid service.

Relieving pressure (opening pressure plus overpressure). The pressure, measured at the valve inlet, at which the relieving capacity is determined.

Reopening pressure. The opening pressure when the pressure is raised as soon as practicable after the valve has reseated or closed from a previous discharge.

Safety relief valve. An automatic pressure-actuated relieving device suitable for use as either a safety or relief valve.

Safety valve. An automatic pressure-relieving device actuated by the static pressure upstream of the valve and characterized by rapid and full opening or pop action. It is used for steam, gas, or vapor service.

Seal-off pressure. The pressure, measured at the valve inlet after closing, at which no further liquid, steam, or gas is detected at the downstream side of the seat.

Set pressure (opening pressure). The pressure at which the relief valve is set to open. It is the pressure measured at the valve inlet of the PRV at which there is a measurable lift or at which discharge becomes continuous as determined by seeing, feeling, or hearing. In the pop-type safety valve, it is the pressure at which the valve moves more in the opening direction as compared to corresponding movements at higher or lower pressures. A safety valve or a safety relief valve is not considered to be open when it is simmering at a pressure just below the popping point, even though the simmering may be audible.

Simmer (warn). The condition just prior to opening at which a spring-loaded relief valve is at the point of having zero or negative forces holding the valve closed. Under these conditions, as soon as the valve disc attempts to rise, the spring constant develops enough force to close the valve again.

Start-to-leak pressure. The pressure at the valve inlet at which the relieved fluid is first detected on the downstream side of the seat before normal relieving action takes place.

Superimposed backpressure. Variable backpressure that is present in the discharge header before the pressure relief valve starts to open. It can be constant or variable, depending on the status of the other PRVs in the system.

Variable backpressure. Backpressure that varies as a result of changes in operation of one or more pressure relief valves connected to a common discharge header.

References
