

Size Depressurization and Relief Devices for Pressurized Segments Exposed to Fire

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Piping and equipment must withstand fires without rupturing. This can be accomplished by properly designing relief and depressurization systems and using passive fire protection, when needed.

This article presents the minimum requirements for performing proper depressurization and fire-relief calculations together with a procedure for sizing depressurization and relief systems for pressurized systems exposed to fire. An engineering approach for modeling geometrically complex process segments is detailed. This approach excludes the necessity of describing the total segment geometry in detail. A fire model is described with its required input parameters. The parameters will vary for different fire characteristics.

Minimum requirements for calculations

Several simulation tools are available for sizing depressurization orifices and relief valves. Most lack the necessary physical modeling required. The list below summarizes the minimum requirements for the design of depressurization and relief devices for pressurized systems exposed to fire:

- rigorous thermodynamics (multicomponent fluid model and use of equation of state)
- fire modeling (emissivities, absorptivity, temperature, convection, initial flux, duration and size)
- segment (vessel, pipe) material properties, *i.e.*, tensile (rupture) strength, heat capacity, conductivity — all are temperature-dependent

- heat-transfer coefficients (boiling, radiation, convection and conduction)
- mass transfer between the fluid phases (boiling and condensation)
- fluid flow, *i.e.*, flow-regime calculations (laminar or turbulent) that are input into heat-transfer and pressure-drop calculations
- modeling of the process-segment geometry (system volume, system outer and inner wall areas, weight, wall thickness, liquid and gas volumes)
- insulation (thickness and conductivity)
- stress or strain, depending upon the rupture criteria used, to which all pipes and equipment are exposed.

The fire

Modeling of fires for engineering purposes requires simplifications compared to the more thorough turbulent-combustion models used in computational fluid dynamics (CFD). Nonetheless, large-scale tests (3) have verified that an engineering approach to fire modeling gives wall- and fluid-temperature profiles that are close to measured ones when choosing the appropriate input parameters for Eq. 1.

Before proceeding with the fire model, some terminology needs to be defined:

A *global fire* is a large fire that engulfs the entire or a significant part of the process segment. A *local fire* exposes a small (local) area of the process segment to the fire peak heat-flux. A *jet fire* is an ignited release of pressurized, flammable fluids. A *pool fire*

This article is extracted from the Norsk Hydro Best Practice on Depressurization and Fire Relief Design. This Best Practice is a major basis for the international guide, "Guidelines for the Design and Protection of Pressure Systems to Withstand Severe Fires" (1) (to be issued shortly) and the Norwegian guide, "Guidelines for Protection of Pressurized Systems Exposed to Fire" (2).

is the combustion of flammable or combustible fluids spilled and retained on a surface. The *ventilation- and fuel-controlled fires* are related to the stoichiometric ratio of air-to-fuel (Figure 1).

Figure 1 is general for both a jet and a pool fire; the difference being a higher flux for the jet fire. For a pool fire, the API fire (4) is illustrated as the lower, dashed line to the right. Note that in the equation API RP 521 uses, increasing the area reduces the flux. The dashed lines represent the average heat flux. However, when studying the total volume of a fire, any point on the continuous curve will be found. A ventilation-controlled fire is to the left of the peak heat-flux in Figure 1 at a stoichiometry of < 1. The fuel-controlled fire is to the right, *i.e.*, the stoichiometry is > 1.

The fire equation

The heat flux absorbed by a segment from a fire, $q_{absorbed}$ (kW/m²), can be modeled as:

$$q_{absorbed} = \kappa(\alpha_{segment} \epsilon_{fire} T_{fire}^4 - \epsilon_{segment} T_{segment}^4) + h \times (T_{gas} - T_{segment}) \tag{1}$$

The absorbed heat flux will be reduced with increasing segment temperature, and a steady-state segment temperature will be reached when the heat influx from the fire equals the heat outflux from the segment.

The view factor, which is not included in Eq. 1, is a scaling factor for the radiative terms. The view factor is ≤ 1.0. It equals 1.0 when the segments that absorb radiation “see” nothing but an optical, thick flame. Calculation of view factors is difficult and a conservative assumption involves use of a view factor of 1.0, which results in Eq. 1.

The incident heat flux is calculated by setting $\alpha_{segment} = 1.0$ and disregarding the segment emissivity term. The “initial incident heat flux” from a fire is calculated by setting $\alpha_{segment} = 1.0$ and $T_{segment}$ equal to the normal operating temperature (of the cold segment).

Input to the fire equation

The different terms in the fire equation are combined to achieve the required initial heat fluxes. Tables 1, 2 and 3 suggest values to be used. The segment absorptivity and emissivity in Eq. 1 are normally equal and depend upon the nature of the surface. Typical values are 0.7–0.9. A value of about 0.8 is typical for oxidized surfaces. The value will change as more

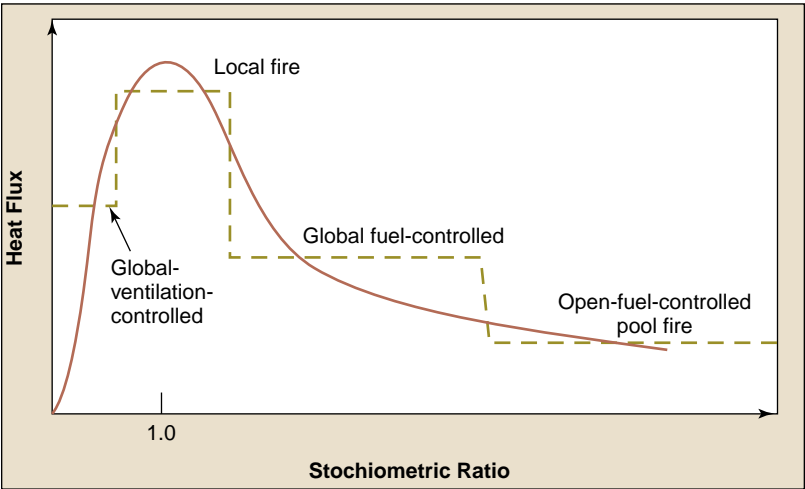


Figure 1. The heat flux from a fire and its relation to the stoichiometric ratio.

and more soot attaches to the surface. For more on absorptivity and emissivity, see Ref. 5.

By combining the suggested highest or lowest typical values into the fire equation, the heat fluxes toward a cold segment are found (Table 4 (6)). Typical heat fluxes measured in large-scale jet fire and pool-fire tests are within the maximum and minimum values in Table 4. Norsok (7) recommends using the initial incident heat fluxes as specified in Table 5.

Sizing procedures

The fire-relief and depressurization calculations determine:

- size of the relief valves and depressurization orifices
- requirements for passive fire protection (PFP)
- size of the pipes downstream from the relief and depressurization valves (if any)

Table 1. Typical flame emissivities for global and local fires.		
Type of Fire	Global Fire ϵ_{fire}	Local Fire ϵ_{fire}
Ventilation-controlled pool fire	0.6–0.75	0.7–0.9
Fuel-controlled pool fire	0.6–0.75	0.7–0.8
Jet fire	0.5–0.75	0.6–0.75

Table 2. Typical temperatures and convective heat-transfer coefficients for a global fire.			
Type of Fire	$T_{fire}, ^\circ\text{C}$	$T_{gas}, ^\circ\text{C}$	$h, \text{W/m}^2\cdot\text{K}$
Ventilation-controlled pool fire	1,000–1,050	850–950	15–30
Fuel-controlled pool fire	950–1,000	800–900	15–30
Jet fire	1,000–1,150	950–1,050	50–125

Table 3. Typical temperatures and convective heat-transfer coefficients for a local fire.			
Type of Fire	$T_{fire}, ^\circ\text{C}$	$T_{gas}, ^\circ\text{C}$	$h, \text{W/m}^2\cdot\text{K}$
Ventilation-controlled pool fire	1,050–1,125	Equal to T_{fire}	20–30
Fuel-controlled pool fire	1,000–1,050	Equal to T_{fire}	20–30
Jet fire	1,000–1,150	Equal to T_{fire}	100–150

Table 4. Minimum and maximum heat fluxes calculated by Eq. 1 for the suggested values of the input parameters toward a cold segment.

Type of Fire	Maximum Incident Flux, kW/m ²	Minimum Incident Flux, kW/m ²	Maximum Absorbed Flux, kW/m ²	Minimum Absorbed Flux, kW/m ²
Global jet fire	326	121	306	98
Local jet fire	367	187	347	160
Global fuel-controlled pool fire	138	88	127	65
Local fuel-controlled pool fire	187	124	171	92
Global ventilation-controlled pool fire	158	101	145	75
Local ventilation-controlled pool fire	228	142	208	105

- optimum location of the system's sectionalization valves

- minimum design temperature for the flare system (if any) and for the pressurized segment.

The minimum design temperature may influence the materials selection of the system under evaluation. The design usually begins by considering carbon steel or stainless steel as the material of construction. However, temperature calculations may result in the need to use a different grade of steel, for example, replacing a normal carbon steel with one suited for low temperatures.

Depressurization-orifice-sizing procedure

Prior to running depressurization calculations, the following must be established:

- the fire scenarios (jet fire, pool fire, local fire, global fire, etc.); define the initial heat flux, the duration and the size (extent) of the fire(s)
- the criteria for unacceptable rupture, which are usually one or more of the rupture pressures, the released flammable/toxic fluid at rupture, and the time to rupture
- the time from the start of a fire until depressurization is initiated
- the physical properties — ultimate tensile strength (UTS), heat capacity and thermal conductivity — at elevated temperatures (up to 800–1,000°C) for the materials of construction used in the depressurization segments
- the depressurization segment geometry (system volume, wall area, weight, etc.).

Once the above data are assembled, follow the iterative procedure in Figure 2. The goal of this depressurization design is to limit the use of passive fire protection (PFP) by depressurizing as fast as possible, while remaining within the discharge capacity of the flare system. PFP should be avoided due to the risk of the consequences of undetected corrosion under insulation, and the additional installation and maintenance costs incurred by PFP systems.

When designing a new plant, it is not recommended to consider using the entire flare-system capacity in the cal-

Table 5. Initial incident heat fluxes against "cold" segment (7).

Type of Fire	Global Fire (Average load)	Local Fire (Maximum point load)
Pool fire, enclosed area, ventilation-controlled	130 kW/m ²	200 kW/m ²
Pool fire (crude), open or enclosed area, fuel-controlled	100 kW/m ²	150 kW/m ²
Jet fire	250 kW/m ²	

culations. This is to allow for future tie-ins and expected project growth. However, by increasing the design capacity of flare system, less PFP will usually be required.

Although a local fire has a higher heat flux than a global fire, the global fire normally exposes the pressurized segment to the largest flux of heat energy, due to the larger area encompassed by a global fire. Hence, the global-fire parameters determine the rupture pressure. On the other hand, the local fire has the highest heat flux, so its parameters determine the rupture temperature of the process segment.

Valves and flanges are not accounted for in the procedure. Also, it does not consider the mitigating effects of active fire protection (such as a deluge). The sizing criteria are set to avoid an unacceptable rupture that could escalate the fire.

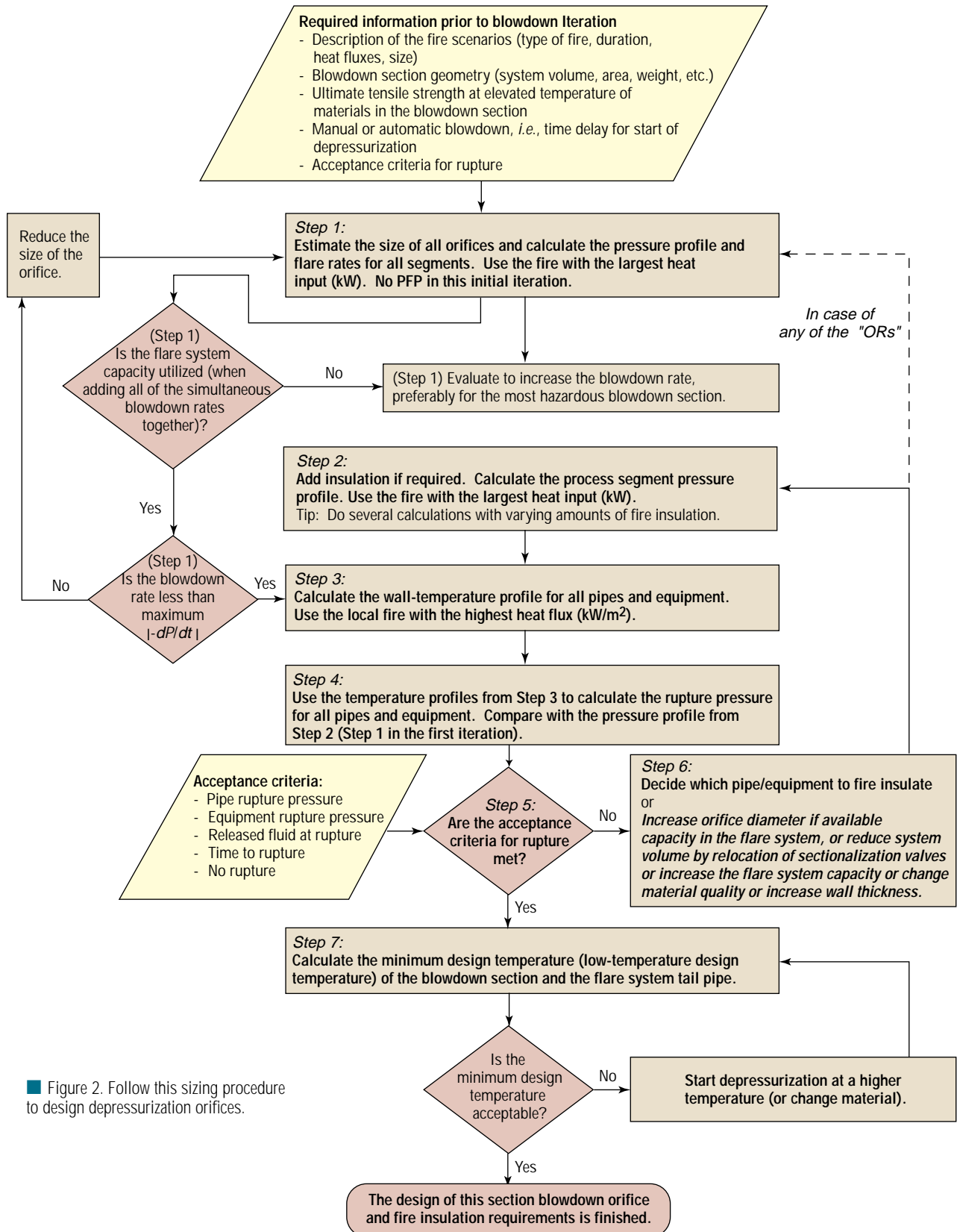
Step 1: Perform an initial estimate of the size of all de-

Nomenclature

h	= convection heat-transfer coefficient of air/flame in contact with segment, W/m ² K
q_{absorbed}	= absorbed heat flux from the fire, W/m ²
T_{fire}	= flame temperature, K
T_{gas}	= temperature of air/flame in contact with segment, K
T_{segment}	= segment temperature (time-dependent), K

Greek letters:

α_{segment}	= segment absorptivity, dimensionless
ϵ_{fire}	= flame emissivity, dimensionless
$\epsilon_{\text{segment}}$	= segment emissivity, dimensionless
κ	= Stefan-Boltzmann constant = 5.67×10^{-8} W/m ² ·K ⁴
σ_{axial}	= longitudinal stress, MPa
σ_{hoop}	= hoop stress, MPa
$\sigma_{\text{Von Mises}}$	= equivalent stress (Von Mises), MPa



■ Figure 2. Follow this sizing procedure to design depressurization orifices.

pressurization orifices, using the capacity of the flare system in the calculations. A recommended first estimate is an orifice diameter that takes the pressure below the “unacceptable” rupture pressure within the typical time to rupture. The initial pressure should be the highest normal operating pressure or an equalization pressure (settle-out pressure) for a compression segment. A global fire should be used. The typical time-to-rupture can be set at that interval it takes to reach a 600–800°C wall-temperature, depending upon the wall thickness. A value of 5–10 min is typical for a dry wall exposed to a medium-heat-flux jet-fire, with no depressurization.

One way of improving the safety of the plant is increase the rate of depressurization, as the hazardous aspects of the segment increase. The total blowdown rate can be kept unchanged by increasing the depressurization times of the less hazardous segments. A segment containing large amounts of light liquids (*e.g.*, condensate or liquefied petroleum gas (LPG)), those that will result in boiling-liquid expanding-vapor explosions (BLEVEs) are regarded as a particularly hazardous section. In any case, there may be limitations on maximum pressure gradients for items such as compressors or gaskets.

Step 2: Add insulation, if required, and simulate the pressure profile during depressurization when exposing the segment to the global fire. For the first iteration only, omit this step and go to Step 3. A global fire will add heat to the fire-exposed area without PFP. The initial pressure in this calculation should be equal to the highest normal operating or settle-out pressure. Credit for insulation should be given only for PFP. Piping and equipment with insulation used for purposes other than for PFP should be regarded as uninsulated.

Unrealistic backpressure in the flare system may result in a too-rapid simulated depressurization. The orifice backpressure should be based on the time-dependent simultaneous depressurization rates.

If a depressurization segment is 100% fire-insulated, then the integrity of the insulation and supports usually determines the maximum allowable depressurization time, which is typically 30–60 min. Account for the integrity of the insulation by extending the depressurization time for a 100% fire-insulated section. The reduced depressurization rate for this section is used to allow for the increase of the rate from a most-hazardous depressurization-section. A reduced depressurization rate may increase the fire duration, if a leak in this section is the source of the fire.

Step 3: Simulate the temperature profile for all piping and equipment in the depressurization segment when exposed to the local peak-heat flux. A jet fire is normally used in these calculations, but the local load for a pool fire should be used if the segment will not be exposed to a jet fire. “All piping” means all pipes with different diameters, pressure classes and/or material qualities. The temperature profile for one particular pipe usually is rather insensitive to pressure changes

within a segment, *i.e.*, the temperature profiles from the first iteration can be kept throughout the whole iteration procedure. A final update of the temperature profiles must be performed prior to the last iteration.

Step 4: Calculate whether or not rupture occurs. Determine the stress or strain that all pipes and equipment are exposed to for the temperatures and pressures seen during the depressurization (Calculated in Steps 1 or 2, and Step 3) and determine whether the segment will rupture.

Two failure (rupture) criteria are often used: the maximum stress or maximum strain (% elongation). The maximum stress criterion is usually the UTS. Rupture strain is a matter of definition. Strain calculations require finite-element modeling of the system, which is usually not performed during this step-wise method. Such calculations should be performed for verification purposes during the final design.

The suggested approach is to calculate the stress from the internal pressure and add extra stress (margins) when calculating the longitudinal stress. The stresses of importance for a pipe are the hoop stress caused by internal pressure, and the longitudinal stress. The longitudinal stress is the sum of axial stresses due to pressure; the weight of the pipe, valves, fittings, branch pipes, etc; stress due to reaction forces exerted on the pipe by pressure; and stress due to thermal elongation of the pipe. The equivalent stress (von Mises) is the stress to be compared with the temperature-dependent UTS to determine whether rupture occurs. The hoop stress, σ_{hoop} , is equal to:

$$\sigma_{hoop} = \frac{\text{Pressure} \times \text{Outer dia.}}{2 \times \text{Wall thickness}} \quad (2)$$

The longitudinal stress, σ_{long} , is given by:

$$\sigma_{long} = 1/2\sigma_{hoop} + x \quad (3)$$

The equivalent stress is given by:

$$\sigma_{Von_Mises} = \sqrt{\sigma_{hoop}^2 + \sigma_{axial}^2 - \sigma_{hoop} \times \sigma_{axial}} \quad (4)$$

The term x in Eq. 3 represents all stress except for that set up by the pressure. A piping engineer should be consulted when determining the value of x .

It is recommended that the UTS be reduced by 20% or more, depending on the reliability of the UTS data. The 20% is a safety margin. Reduce the wall thickness by accounting for the mill tolerance. It must be assumed that the lower mill tolerance is delivered. Reduce the strength by including the weld factor. Again, a piping engineer should be consulted.

Step 5: Check the rupture pressure against the acceptance criteria. If all piping and equipment in the de-

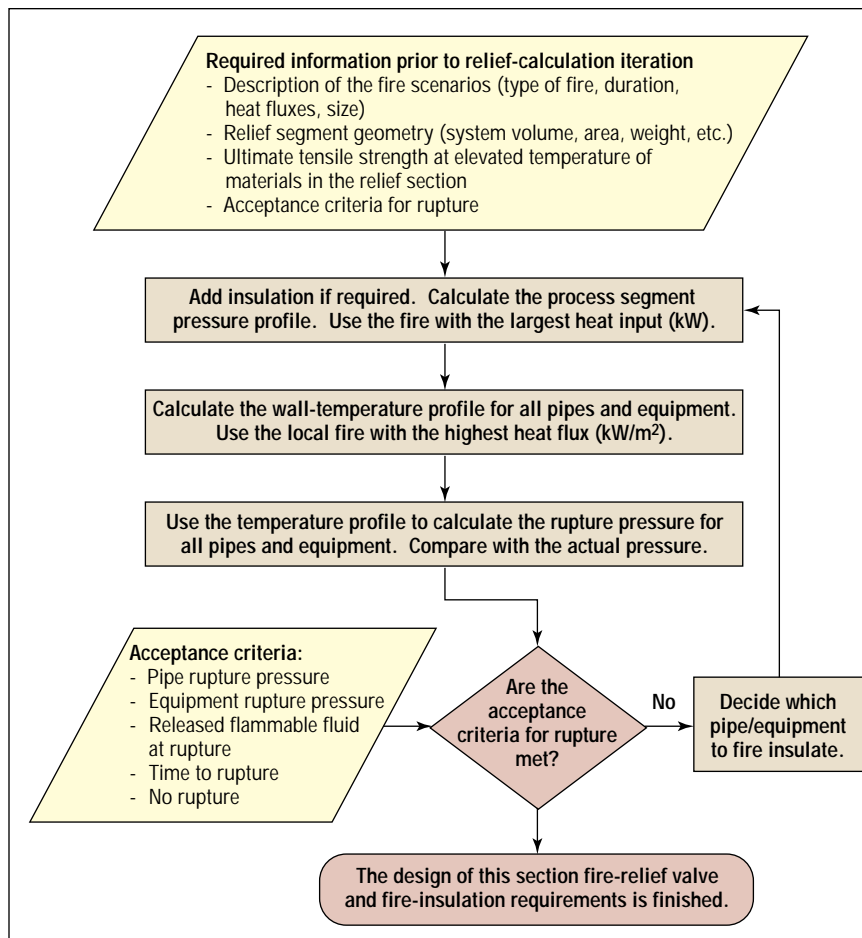


Figure 3. Sizing procedure for fire-relief valves is similar to that for orifices.

pressurization segment meet the acceptance criteria, then the fire insulation is completed. Go to Step 7 for low-temperature calculation, otherwise go to Step 6 and add in insulation. Alternatively, go back to Step 1 and increase the size of the orifice or increase the flare system capacity.

Step 6: Decide which piping/equipment to fire-insulate. If any run of piping or piece of equipment does not meet the acceptance criteria, then add PFP to one or more of these components. It is recommended to add PFP to the corrosion-resistant pipe with the largest diameter. But, if there are pipes that are already insulated for reasons other than PFP, these should be fire-insulated first.

The reasons for choosing the pipe with the largest diameter are it is the most critical with respect to reaction forces and pressure waves when it ruptures, and it will require the largest amount of insulation per length. Large pipes are also cheaper to paint and insulate (per unit area) than smaller ones. The reason for insulating the corrosion-resistant pipes first is to avoid insulation on metals that corrode more easily. When partially insulating pipes, it is preferable to add the covering on an area where the possibility of a fire is largest and where inspection of the insulation and pipe can be performed easily.

Step 7: Calculate the design low-temperature limitation of the depressurization segment (this is known as the minimum design-temperature calculation) and in

the flare-system tail-pipe. This depressurization calculation should be performed without fire input to the section. All planned types of insulation (not only fire insulation) should be taken into account. The initial temperature should be the minimum ambient temperature or minimum operating temperature, whichever is lower. The initial pressure is calculated from a cooldown of the system down to the start temperature, prior to depressurization. The cooldown calculation should be performed using the trip pressure from the highest shutdown pressure. The minimum temperature in the flare tail-pipe should be calculated with the depressurization segment as the only source to the flare system.

Other considerations

Some key ones to note are:

- The loss of bolt pre-tensioning due to bolt elongation as a result of increasing temperature is important when studying flange failure. The piping engineer should be consulted on this. Flanges are recommended to be fire-insulated.

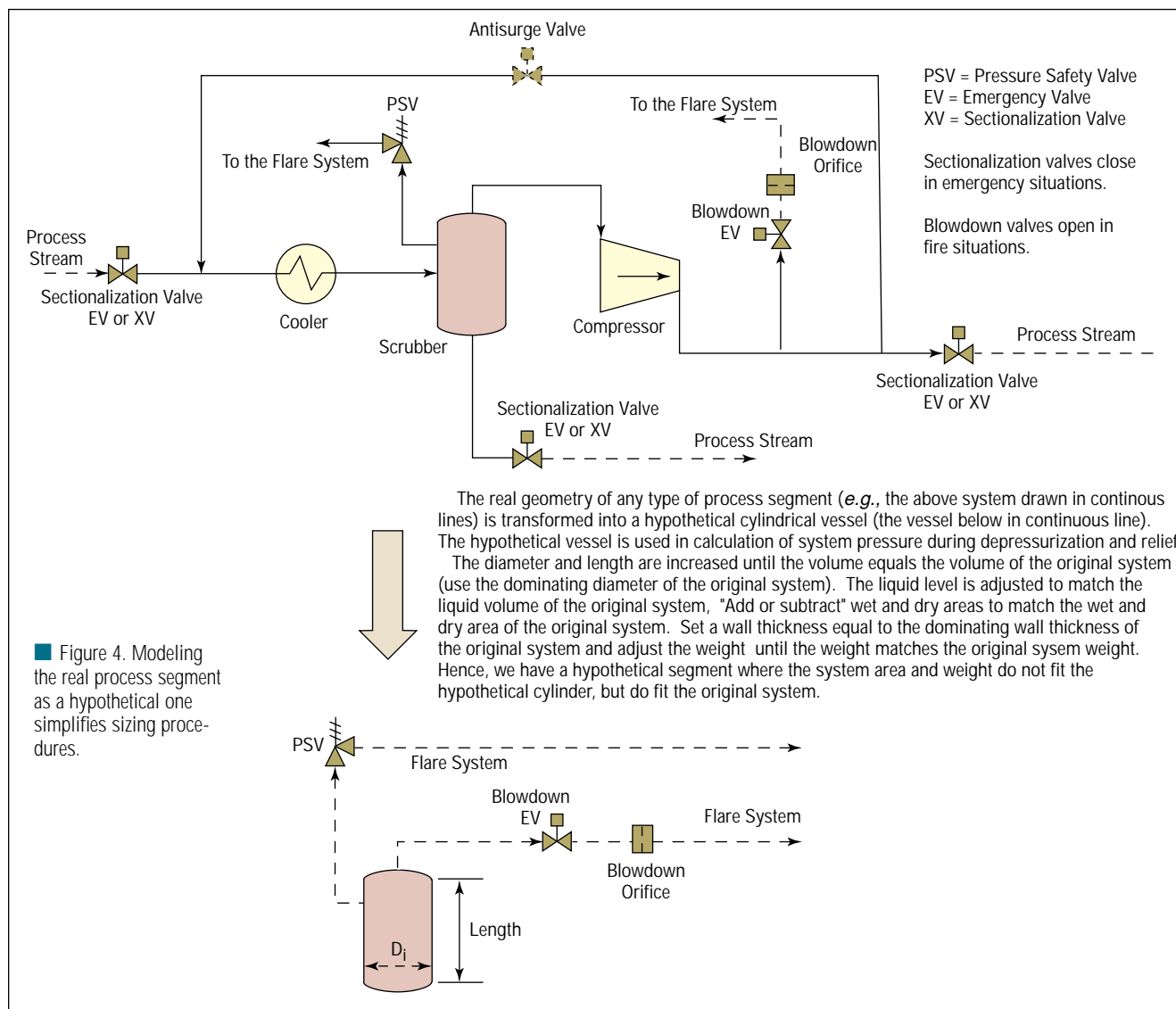
- Lines in the flare system having

no flow during a fire depressurization (e.g., downstream pressure-control and pressure-relief valves) are usually fire-insulated because: they are thin-walled and can heat up rapidly; the depressurization gas flowing in the flare system does not cool these pipes; and the flare system will be pressurized to a value near its design pressure, at the same time that the pipe temperature is high.

Fire-relief-valve sizing procedure

Sizing of the fire-relief valves (Figure 3) should be performed with the same minimum requirement as specified at the beginning of the article. Also, the procedure closely follows that for sizing depressurization orifices, with the exception, of course, that the pressure will increase until the relief valve opens. The size of the relief valve should be such that the minimum relief-rate equals the liquid boil-off and gas-expansion rates. This avoids a pressure increase above the set pressure of the relief valve.

A fire-relief valve will usually not protect a pressurized system against rupture if the gas-filled part of the system is exposed to fire. The fire-relief valve will normally protect against rupture if the flame is exposed to the wetted wall only when the boiling liquid on the inside keeps the wall temperature at a reasonably low value. For multicomponent mixtures, the temperature



■ Figure 4. Modeling the real process segment as a hypothetical one simplifies sizing procedures.

will increase as the lighter components evaporate, and the wall will eventually reach the rupture temperature, even if it is liquid-filled.

Modeling process segments

Here, we present an approach to modeling complex depressurization and relief segments. The method models the complete complex geometry by creating one hypothetical segment that represents the total system volume and heat-transfer areas, and several sub-segments that represent the "real" geometries of the segment.

The hypothetical segment is used for calculation of the system pressure during depressurization or relief. The sub-segments are used for calculation of the temperature response of each piece of piping and equipment within a process segment. The sub-segments are modeled with the same geometric information that is required for a wall-temperature-response calculation — namely, the sub-segment wall thickness, segment or pipe diameter and inside fluid.

Hypothetical segment used for system pressure

The hypothetical segment is modeled with the real system volume, system outer-area, with and without PFP, system inside-area in contact with the gas, system inside-area in contact with the liquid, and system weight (of piping and equipment).

The hypothetical segment is modeled as a cylinder. This shape is specified with a diameter equal to the most-dominating (volume) diameter of any item of piping or equipment in the original segment. The associated wall thickness for this diameter should be used. The length of the cylinder is set such that its volume equals the volume of the original segment. The liquid level is adjusted to obtain the actual liquid volume. The hypothetical cylinder now represents the correct system volume. However, the outer area of this cylinder must be corrected to the real-system outer area by subtracting or adding gas and liquid area to the segment. Therefore, heat transfer with the surroundings (fire, ambient air) will be modeled over the real

area. The system outside and inside areas may be different for a high-pressure system (typically, 100–150 bar), with large amount of small-diameter piping (usually, 3 in. and below), and should similarly be corrected to the real system inside area. This effect is largest for pipes with a corrosion allowance, that is, those made of carbon steel, generally. The dominating (by weight) metal quality should be specified.

Unique geometry used for wall-temperature calculations. The temperature response of a pipe or piece of equipment exposed to fire depends upon the metal wall thickness, metal properties (e.g., heat capacity and conductivity) and the thermal mass of the inside fluid. Each combination of these must be calculated individually to determine the possible different wall-temperature responses of the system.

The exact inside and outside diameters (I.D.s and O.D.s) should be used. The I.D. will determine the thermal mass of the inside fluid. The O.D. will enable calculation of the fire-exposed area. Any length can be used, since the sub-segment volume and mass are proportional to the length. The actual thickness, minus a corrosion allowance, should be used. The actual thickness is the nominal wall thickness, minus the allowable tolerance of the pipe thickness (the mill tolerance). The corrosion allowance should be accounted for after reduction by the mill tolerance. Typical values of the mill tolerance are 1.5–3 mm for carbon steel, with the larger value being

more common. The mill tolerance is specified on the pipe data sheet. When this tolerance is not specified by the pipe supplier, consult a piping engineer.

The correct metal or alloy composition must be used to obtain the correct material properties (i.e., heat capacity, conductivity and the UTS). If the UTS is not available at elevated temperatures, a preliminary tensile curve can be made based on the UTS at 20°C; this is usually available. When the strength at an elevated temperature is known for a material that is close in physical properties (the same family of materials, such as two different carbon steels), then the percentage difference in the UTS at 20°C is kept at all temperatures. That is, the new tensile strength curve should have the same shape as the known curve. When the tensile strength at elevated temperatures is not known for a material in the same family, then the percentage difference between the UTS and yield at 20°C is reduced linearly between 20 and 1,000°C. The UTS should be released by at least 30% (not 20%) in such an approximation. When the UTS is equal to the yield strength in the above calculation, then the UTS should be set equal to the yield strength at higher temperatures.

Concluding remarks

We believe that the calculation of longitudinal stress represents the major challenge when performing depressurization and fire relief design. Modeling of time-dependent fire characteristics (the extent and heat flux) also represents a challenge, since the plant layout is usually unknown during the design stage. Yield and UTS data at temperatures above 400–500°C often do not exist for the materials used in the system. ♦

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Acknowledgment

We would like to thank Erik Odgaard, Jan A. Pappas and Geir Johansen (Norsk Hydro, safety and piping discipline) for their helpful discussions.

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