Clarification of Pressurization Scenarios in PSV Sizing

Protecting an enclosure by pressure relief device (PRD) involves the following steps:
- Deciding on requirement of PRD from technical and legal view point
- Choosing the location of PRD on the enclosure, which is generally on the top the enclosure and vertically upward
- Deciding on PRD type and the required arrangement: if it should be pressure safety valve (PSV) or rupture disc(RD), or other less popular PRD's. Moreover, it must be determined whether or not a single PRD is enough or if there is a need to have multiple of them in parallel or series configuration
- Determining the PRD set pressure
- Estimating the governing release rate, which is the maximum flow rate of fluid through PRD during a pressurizing event.
- Specifying orifice size of PSV (or holder size of RD) by plugging in appropriate formula for the governing release rate
- Checking other criteria to make sure all the requirements are met

The design process is not a straightforward process and might need a few iterations of the steps listed above in order to optimize the PRD system.

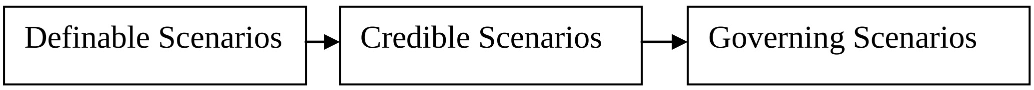
The subject of this article is estimating the release rate. Estimating the release rate of a PRD has includes these three steps:

- Defining pressurizing scenarios

- Specifying credible scenarios

- Quantifying the release in different scenarios and finding the governing scenario

The block diagram below (Fig. 1) displays this process.

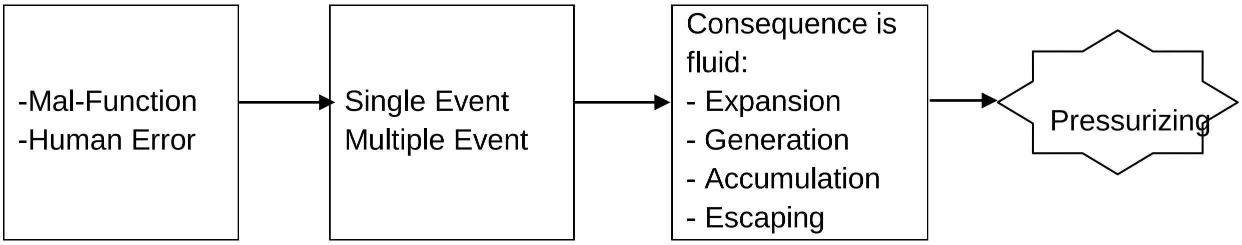


After preparing a list of "definable scenarios" the next step is to short list them to credible or valid scenarios. Then, after calculating release rate in each scenario, the governing scenario can be specified.

1. Defining Pressurizing Scenarios

The first stage is to define a "Pressurizing scenario".

A block diagram of a Pressurizing Scenario is shown in Figure 2:



Box 1: Root Cause

A Pressurizing Scenario starts with the malfunction of equipment/ Instrument/ valve etc. or a human error.

Sometimes, a human error causes a hardware malfunction and then a pressurizing scenario will result.

These are the principal reasons of a pressurizing event. Although it is not always important to know these root reasons, identifying them may help the designer to decide if the scenario is credible or non-credible- likely or unlikely. In some cases, it also helps the designer to estimate and calculate more accurately the release rate.

Box 2: Event

The result of malfunction or human error is a bad event. An event is a peril which causes pressurizing. Some of the pressurizing events listed below are considered unfavorable.

- A check valve jammed in open position (check valve malfunction), and the event is happening in a direction which is not intended (reverse flow).
- A control valve failed in wide open position (control valve malfunction) and flow in higher flow rate happens and even may lead to “sweep” of gas stream while the pipe was intended to be in liquid service.
- A long piece of outdoor pipe isolated by two manual valves and left un- drained (human error), and then the sun radiation increases the temperature of the trapped liquid inside of the pipe.
- A fire happened (because of equipment malfunction or human error) and the temperature of equipment content rises (and a phase change may occur, too).
- The cooling water of a reactor was discontinued because of a cooling tower failure and side reactions initiated which created gas phase products (run away reactions).

The next step is to investigate if a single event or multiple events happen because of one root cause or not. Multiple-events could be followed by a fault in systems in which they are distributed through a network. The famous causes of multiple events are:

- Instrument air Failure
- Power failure
- Cooling media failure (e.g. Cooling Water, Cooling Glycol, cryogenic network)

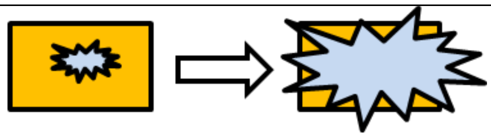
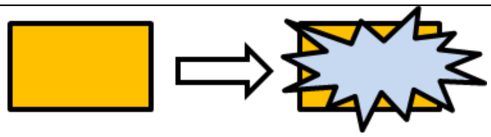
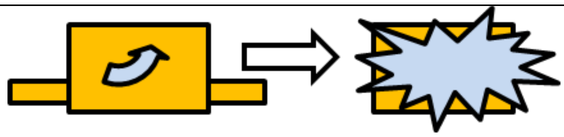
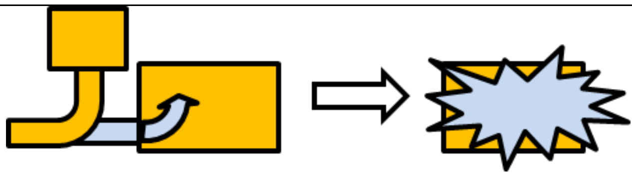
Although each of the above utility network failures can be sub-classified as regional failure and plant wide failure, usually power grid failure can happen in one those sub classes.
It is a good practice to evaluate pressurizing scenarios caused by multiple events "after" doing single event scenarios. This should be done one-by-one on each protected system.

For each to-be-protected system the effects of each single event out of multiple events needs to be evaluated separately. Then, their interactions should be evaluated. The events can interact with each other in synergistic, antagonistic, or additive forms. Additive or synergistic effect of events should be taken with due diligence as they increase the severity of over pressure.

An antagonistic event is an event which delineates the other event on increasing pressure, not always taken into consideration for conservativeness purposes.

There are some multiple events which don't have combined effect on "one" protected system and instead trigger many single events in different protecting systems simultaneously. In such cases, the multiple events only affect the sizing of disposal system (e.g. flare network) and not the sizing of each single PSV.

Box 3: Consequence
The next step is to identify if the event is a pressuring event or not by investigating its consequences. This can be done by analyzing the pressurizing scenarios against one of the four classes below. Pressurizing occurs when a fluid expands, when a fluid is produced, and when a fluid is accumulated in a system or when a fluid escapes to an unsuitable system.

Expansion	
Generation	
Accumulation	
Escaping	

1. Fluid Expansion: The volume of the fluid inside of a system increases beyond the capacity of the system. Fluid expansion could be liquid hydraulic

expansion (if the full content of the enclosure is liquid and stays liquid during the event) or gas expansion (if the content of the enclosure is gas or vapor) or phase change from liquid to gas phase and then liquid and/or vapor expansion.

Although the consequence of gas expansion is likely pressurization, it can only be mitigated by installing PSV’s on enclosure.

One example of this consequence is liquid thermal expansion, which is the case of trapped liquid outdoor and under the sun ray or trapped liquid inside of heat exchanger as the cold side. In the first case, the liquid expands due to solar radiation, while in the second case, the expansion is caused by heating fluid in the Heater. “Fire Case” is the name of other event which causes fluid expansion: liquid, gas, or phase change. The other example is some accidental mixings. In some cases an accidental mixing can lead to heat evolving (exothermic mixing or reaction) and this heat can expand the fluid and pressurize the system.

2. Fluid Generation: In this event, the fluid is generated or a fluid “destroying” system fails. Fluid generation could be result of a run-away reaction or just lack of gas/vapor suppression which can be deemed as “fluid production”. One example is failure of a condenser which can increase the pressure of the system because of the unintended presence of vapor in the downstream equipment. In distillation/fractionation towers, loss of reflux system on top or side of tower deprived the tower from a vapor dampening system and tower pressure increases. In a gas-liquid adsorbing tower, the loss of liquid adsorbent causes non-absorbed gas to pressurize the system.
3. Normal flow Fluid Accumulation: In this case, fluid is flowing in a normal route, however for some reason, all flow (or a portion of that flow) will accumulate in the system and create midterm or long term high pressure. For example, fluid accumulation is an obvious consequence of mal operations like overfilling a container with a liquid. The other example is introducing a stream with high content of non-condensable gases to heat transfer equipment with no means to remove them. The accumulation of non-condensable gases pressurizes the system.
4. Accidental flow Fluid Escaping: is transferring a fluid from a higher capacity system to a lower capacity system in a non-normal situation. This action is, in other words, short circuiting the flow. The capacity here can be defined as pressure or volume of the destination system. For example, the control valve fail can pressurize the downstream system and/or overfilling it. The gas blow-by case (or vapor break-through) are special cases of control valve fail open. In this case, a high pressure gas or vapor accidentally comes from an upstream high pressure system through a pipe (which is a liquid pipe in normal operation) and reaches the low pressure, downstream container.

   Tube–rupture (or tube splitting) in shell and tube heat exchanger is another example that falls in this category. If the high pressure fluid is in the tube side (which is a popular case) and low pressure fluid in shell side there is a low chance of(but still not negligible) to have a tube leakage(mostly in tube sheet in the form of leakage) and high pressure fluid “escapes” from high pressure tube to low pressure weak shell. When this happens, the shell side needs to be protected.

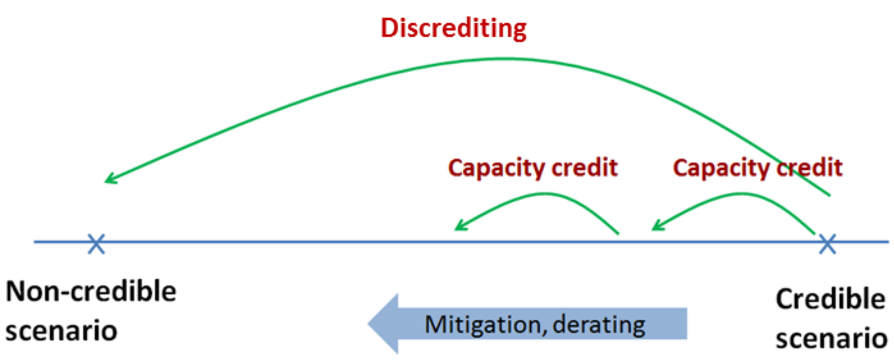
Not all the pressurizing scenarios can be clearly placed in each the above categories.

2. Specifying credible scenarios

This step includes going from Definable to Credible Scenario.
The question here is where or not a defined pressurizing scenario is justified for placing a PSD. From a purely technical view- and assuming a hypothetical situation which there is no regulatory bodies involved- placing a PSD is justified if all of the following requirements are met:

- Requirement 1: There is at least one valid over-pressurizing scenario for a container with trapped fluid (or not-sufficient alternate relieving route).
- Requirement 2: This over-pressurizing scenario will increase the pressure of the vessel beyond MAWP (Maximum Allowable Working pressure) during the life of the container.
- Requirement 3: This pressurizing scenario does not void the integrity of the vessel prematurely before PSD action.
- Requirement 4: The risk of explosion (without PSD) is higher than what is tolerable.

Requirement 1: To find out if there is at least one valid scenario, all the scenarios need to be evaluated and confirmed that they cannot be discredited. To discredit a defined scenario, different actions could be taken to discredit it. Sometimes a technique cannot discredit a scenario but can decrease the release rate of PSD. This capacity credit also helps to decrease the cost of PSD.



There are many techniques to discredit a scenario and some are ranked below based on their effectiveness level:

1. Choosing to use an inherently safe system
2. Application of “double Jeopardy concept”
3. Scenario-specific discrediting tools
4. Implementing specific procedure

The important item in discrediting a scenario is to make sure the discrediting factor is always available and there is no chance of loosing it because of another human error or system failure or system aging. Based on this principal rule, it is not a good idea to discredit a scenario based on implementing a “procedure” even if it is very firm and/or already implemented. For example, if a discrediting factor is an alternate available release route, the question needs to be answered about whether or not it can be assured that the line can be closed by a manual valve (by a careless operator) or control valve failed close(even if the control valve is fail open cases) or even due to plugging caused by fouling/precipitation.

Changing the system to an inherently safe system might have a large impact in project cost and/or schedule. It is difficult to conduct change during the detail engineering stage of project, when PSD sizings are usually performed. One example is discrediting the tube rupture scenario by replacing the shell & Tube heat exchanger with another type of heat exchanger. Although the other types of heat exchangers might have another scenario similar to tube rupture, which needs to be considered again.

The double jeopardy concept in PSV context means: No two or more independent malfunctions or human errors which happen simultaneously to create a pressurizing event can be based for PSV sizing. It is important to consider that the concept is not that two independent malfunctions/human errors can NOT happen; it is, “It won’t be considered as the basis for PSV sizing”.
“Independent malfunctions/human errors” are ones which don’t have any mechanical, electrical or even procedural link between them.

Scenario-specific discrediting tools are the discrediting tools which are available for each specific scenario. For example, for the fire pool scenario, discrediting the scenario by proving no combustible content is not correct; as long as there are some combustible material even in neighborhood of the system, fire pool could be a valid case. However, the release rate can be decrease if the container is insulated and the insulation (including insulation bands) is fire resistant. This concept named a valid derating tool. If the designer can prove there is no sustaining floor around the tank (e.g. the tank is on perforated platform), he might be able to discredit the scenario. Over-rating tools can be viewed as parameters or conditions which can be evaluated by the client to be considered for the purpose of scenario evaluation and release rate calculation more than the requirements by code and/or standards. Theses over-rating tools most likely change the type or size of PSD to more expensive ones. In fire pool scenario the flame height is considered xx ft for release rate calculation per standards; however, a more cautious client can ask to use a taller flame like 75ft or 100ft for the calculation.
The below table summarizes these features of few famous scenarios.

	Invalid Derating/discrediting	Valid Derating	Valid Discrediting	Over-Rating Tools
Fire Pool	Not combustible content of container	Fire resistance insulation, firefighting system, deluge system	No combustible around, no sustaining surface	75-100 ft wetted height
CV (Control valve)Fail Open & Gas blow-by	Mechanical stops on CV, fail open Valve	RO(restrictive Orifice) upstream of CV(some companies accept this as long as RO is welded to the flange), 2 CV with separate control loop	--	Bypass valve open
Shell and Tube Heat Exchanger: Tube rupture	2/3 rule	--	Same pressure in tube-side and shell-side, 10/13 rule, changing HX type	--
Thermal expansion	procedure in place for operators to drain pipes as soon as possible	Pipe wall expansion	Indoor system, smart heat tracing used, no trapped liquid, cooling stream in trapped liquid in heat exchanger	--

Requirement 2: The second issue is if the pressurizing scenario increases the pressure to beyond the Maximum Allowable Working pressure (MAWP) of the protecting system or not. If the answer is no, there is no need to place a PSD. MAWP is a value provided by the manufacturer of the system. This number should definitely be equal to or larger than the design pressure of the system which is specified by the design engineer. As MAWP is not always available during the design stage of project, it could be acceptable to use design pressure (which is smaller number) for this purpose.

For example, in a tube-rupture case, if the design pressure of tube side is equal to that of shell side, it is obvious that no pressurizing happens as a consequence of tube rupture, and therefore the scenario is not valid.
If the case planned to be discredited based on “enough MAWP pressure”, monitoring systems should be checked to ensure that they are in place to make certain that there is no wall thickness loss as a result of corrosion/erosion- and consequently the decrease in design pressure. Finding an assuring answer to the above issue is not easy.

The other issue of this discrediting tool is uncertainty of estimation of maximum attainable pressure in a pressurizing scenario. It could be due to the complex nature of the scenario or lack of ability of accurate estimation of event duration.
If the undesired event is short, it is possible the system cannot reach steady-state and the maximum pressure of the system cannot be estimated without complicated models. However, if the undesired event can be considered long-term, the system can reach to steady-state conditions and it may be easier to estimate maximum attainable pressure.
In such cases that the estimation of pressure rise caused by a pressuring scenario involves uncertainty or needs bunch of assumptions which cannot be confirmed easily, it is safer to assure that the pressurizing scenario definitely increases the pressure beyond the MAWP.
One famous case is fire. This scenario can be considered as long-term event, however due to its uncertain nature, the estimation of "maximum attainable pressure" might not be easily doable. In such case, the designer doesn't bother himself to estimate the maximum attainable pressure and he assumes the pressure exceeds MAWP.
An example of a case which the estimation of maximum attained pressure during the pressurizing event is easy is the blocked outlet of a centrifugal pump. In this scenario the maximum attained pressure can easily be read from the pump curve of the pump where it shows the dead head pressure of the pump. Some companies take more conservative approaches and check the dead head pressure of the centrifugal pump with the largest impeller and the largest electromotor which can be coupled.

Another example is the thermal expansion of trapped liquid scenario. To estimate maximum attainable pressure, the absorbed heat then the expansion of liquid and also expansion of the pipe wall needs to be calculated. One uncertainty is found in the heat absorbed, if the system is located outdoors and heat is provided by solar radiation. Some companies use the solar radiation from meteorological data. One simplification is ignoring expansion of pipe wall because it has relaxing effect. However, some companies don't calculate the maximum attainable pressure at all and size and place PSV if the scenario exists.

Requirement 3: The PSV should function to protect the system. Thus, it should pop up before the system explosion. The validity of the integrity of protected system until PSD opening is a debatable issue. An exaggerated case is the question regarding necessity of placing PSD on a "paper" tank for the fire case or not. The answer for this question could be clear; however, it is not easy to answer similar question when the tank is wooden or fiberglass. Some companies decide to not go further in this issue and to just accept that this requirement is valid.

Requirement 4: Generally, no one evaluates this requirement and usually companies assume (as a conservative approach) the risk of accident because of the lack of PSD is definitely not tolerable.

3. Quantifying the release rate

This step basically is going from Credible to Governing Scenario.
In this step, the calculation should be done to find the biggest release rate which specifies a governing scenario.
To gain a good result, a suitable calculation methodology needs to be chosen.
The nature of PSV popping up is a dynamic nature. However because of complexity of dynamic simulations usually the release rate calculation is done with steady state assumption. Therefore, the designer needs to have a good understanding of system behavior change during the PSV opening to take a realistic snap shot of the worst case to be used in his steady-state calculation.

The other aspect of safety related calculation is the way we deal with uncertainty and inaccuracy in calculation methods.

In these cases, if there are inaccuracies is one calculation methodology, it is better to use a more conservative approach but with less inaccuracies. This approach is preferred because a PSV is considered as the last line of defense against the pressurization. Typically, this approach is acceptable unless the more conservative approach lead to big PSV's. In these circumstances, one could question if the approach is "acceptable; more conservative" or "unacceptable; overly conservative".
There are some calculation methodologies which need properties of the fluid or flow which cannot be estimated accurately. If this is the case, the calculation methodology needs to be avoided unless it gives a conservative number within the acceptable range.

For example, for gas blow-by case a simplistic, more conservative approach is assuming the system is only an orifice which is the control/ solve wide open orifice.

However, in some cases this approach leads to a big release rate. This is the case especially when the pressure difference between high pressure and low pressure system in huge. If this happens, a less conservative (more realistic) could be taken which is adiabatic compressible flow in pipe with wide open control valve.

Yet, the reason that the compressible flow is not taken from the beginning is uncertainty in compressible flow calculation in comparison to only orifice with compressible flow.

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