Waves of Safety - Evaluating Overpressure Risks from Gases in Ductile Equipment

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1. Introduction

Risk assessment is a fundamental task for process and plant safety experts, commonly referred to as PPS Practitioners at Bayer. This procedure involves systematically evaluating potential hazards to ensure the safety and integrity of operations. Utilizing a risk matrix, practitioners together with a team classify during Hazard and Operability Studies (HAZOPs) the likelihood of various possible initiating events - such as the malfunction of the Basic Process Control System (BPCS) - and assess the severity of the resulting consequences.

These assessments play a crucial role in evaluating the reliability requirements for the necessary safety measures. By establishing robust safety concepts, practitioners aim to protect not only human lives but also the environment.

This article focuses on the methodologies employed in risk assessment, particularly regarding hazards associated with gas over-pressurization of equipment made from ductile materials. We will highlight the significance of accurate classification and the implications of these evaluations for reliability requirements of safety measures. By fostering a comprehensive understanding of risk assessment in the context of overpressurized equipment with gases, we aim to significantly reduce efforts for detailed analysis and the costs associated with safety oversights, while promoting the careful application of simplified methods, when appropriate, within the chemical and pharmaceutical industry.

1.1 Methodologies for Severity Classification

The classification of severity levels during HAZOPs is typically based on guiding principles outlined in company policies, procedures, and knowledge documents, supplemented by the individual judgments of practitioners and the HAZOP team members. In complex scenarios, severity assessments will be supplemented by modelling the physical consequences. The severity of harmful and toxic material releases or thermal radiation from fires is typically estimated using simplified methods or consequence modelling. However, modeling the consequences of physical explosions is complex, resource-intensive, and necessitates multiple boundary conditions and assumptions. To enhance this process, we developed a method that effectively correlates equipment design data with the resulting severity classifications. These classifications are based on calculations of gas-generated pressure waves for diverse ductile equipment configurations with underlying conservative assumptions. Based on the results a user-friendly table was developed that enables practitioners to more easily determine the appropriate and comparable severity level for different design and deviation scenarios, ultimately improving safety practices in risk assessment.

1.2 Severity Levels and Classification of Safety Measures According to Bayer Methodology

The severity of consequences is categorized into five levels according to the Bayer risk matrix, ranging from negligible (S5) to very high (S0). In our methodology, we focus on four levels (S1-S4) that are most relevant to overpressure scenarios caused by gas-containing equipment under excessive pressure. For clarity and ease of reference throughout this article, these levels are presented in the table 1 below. Additionally, examples of safety measures classifications are presented in the table 2 below.

Table 1: Severity levels based on Bayer internal methodology

|  |  |
| --- | --- |
| Severity Level | Consequences resulting from the release of energy (specifically, the pressure wave) |
| **S1**  **S2**  **S3**  **S4** | Severe injuries leading to fatalities from the release of energy with life-threatening effects inside the site fence, and severe injuries with irreversible health effects outside the main site fence.  Severe injuries with irreversible health effects to a limited number of personnel, where fatalities are unlikely but cannot be entirely ruled out, due to the release of energy.  Moderate injuries with short-term health effects, preventing return to work the following day.  Minor injuries requiring first aid or simple medical treatment, allowing for return to work without a lost workday. |

Table 2: Examples of safety measures classification based on Bayer internal methodology for failure frequency: one initiating event per 1 to 10 years

|  |  |  |
| --- | --- | --- |
| Severity Level | Max. Achievable  Measure Class | Examples |
| **S1**  **S2**  **S3**  **S4** | **VH** (Very high reliability)  **H** (High reliability)  **I** (Increased reliability)  **N** (Normal reliability) | Safety Instrumented Systems in SIL3, certified Pressure Relief Valves  Safety Instrumented Systems in SIL2, orifice plates  Safety Instrumented Systems in SIL1, non-certified Pressure Relief Valves  Measures in a BPCS with no additional safety related requirements |

2. Technical Background and Development

The concept behind our methodology is not new; it is rooted in the German legislation known as the German Ordinance on Industrial Safety and Health (Betriebssicherheitsverordnung, BetrSichV) and in the European Pressure Equipment Directive, which categorize equipment based on design pressure and volume. These regulations identify four categories of equipment based on the product of design pressure (PS in barg) and volume (V in liters). Category I includes small vessels, such as portable gas cylinders and air compressors. Category II encompasses medium-sized boilers, while Category III covers large-scale steam boilers. Finally, Category IV is designated for large industrial pressure vessels like reactors. The requirements for risk assessment, safety measures, and testing vary by category, with lower requirements for the lower categories and the highest for Category IV. Through this framework, the German regulatory authority helps ensure the health and safety of employees working with such equipment.

Based on the fundamental principles of the aforementioned method, we have formulated an equation to correlate the severity with the energy potential of an overpressurized vessel:

|  |  |
| --- | --- |
|  | (1) |

Applying this equation for design conditions the resulting Severity Level is deemed acceptable, as all design parameters remain within specified limits. According to the Pressure Equipment Directive (PED), any exceedance of design parameters is not permitted, necessitating the implementation of appropriate safety measures. For the sake of simplicity of this method, we did not consider the design temperature of the equipment, assuming it will remain within design limits under all circumstances which is a boundary condition for the application of the tool.

2.1 Boundary Conditions for Applying and Developing the Method

Generally, this method is applicable to all pressure equipment (with a design pressure of 0.5 barg or higher, as the Pressure Equipment Directive (PED) defines 0.5 barg as the threshold for pressure equipment). For equipment with a design pressure below 0.5 barg, severity rankings of S1 or S2 due to pressure waves from rupture can reasonably be excluded.

This method was developed for pressure equipment containing gas phases and introduces a severity classification based on pressure waves generated by overpressurization of those gas phases. Additionally, this classification is applicable only to equipment constructed from ductile materials; its use for equipment made from brittle materials is not allowed. Even in the case of cryogenic media, the construction material must be designed for operational conditions; otherwise, it shall be classified similarly to brittle materials.

Furthermore, these severity ratings are generally intended for outdoor locations or in larger rooms. In smaller spaces or in congested areas, it is possible that pressure waves may be compounded as the initial pressure wave is reflected or that other consequences may arise not directly from the pressure wave, but from debris, such as damaged walls or equipment in the room.

2.2 PS x V Table with Corresponding Severity Levels

Assuming that the energy content of a pressurized vessel can be estimated using Equation 1, which involves multiplying the design pressure by the vessel's volume, we conducted numerous calculations for various ductile vessel volumes and design pressures. For these calculations, we employed a conservative default bursting pressure factor of 5, as historical data indicates that pressure vessels typically fail catastrophically at pressures ranging from 2 to 5 times their design pressure. For example, API 581 assumes an empirical overpressure factor of 4 times the design pressure for vessels designed according to API standards.

The energy of the physical explosion was calculated using the thermodynamic availability method, as described in various sources, primarily D. A. Crowl's work and the CCPS Guidelines. Generally, thermodynamic availability represents the maximum mechanical energy extractable from a compressed gas as it reversibly moves into equilibrium with the environment when released. For simplicity, the following assumptions were made:

* The entire available mechanical energy of the compressed air is used to produce the pressure wave.
* The system involves only inert compressed gases, such as air.
* The vessel is spherical.
* The ambient and content temperatures were assumed to be 20°C.

The following Figure 1 illustrates the results of one example calculation for four vessel volumes all having a design pressure of 6 barg. The Y-axis represents the magnitude of the pressure wave overpressure as a function of distance from the center of the bursting vessel.

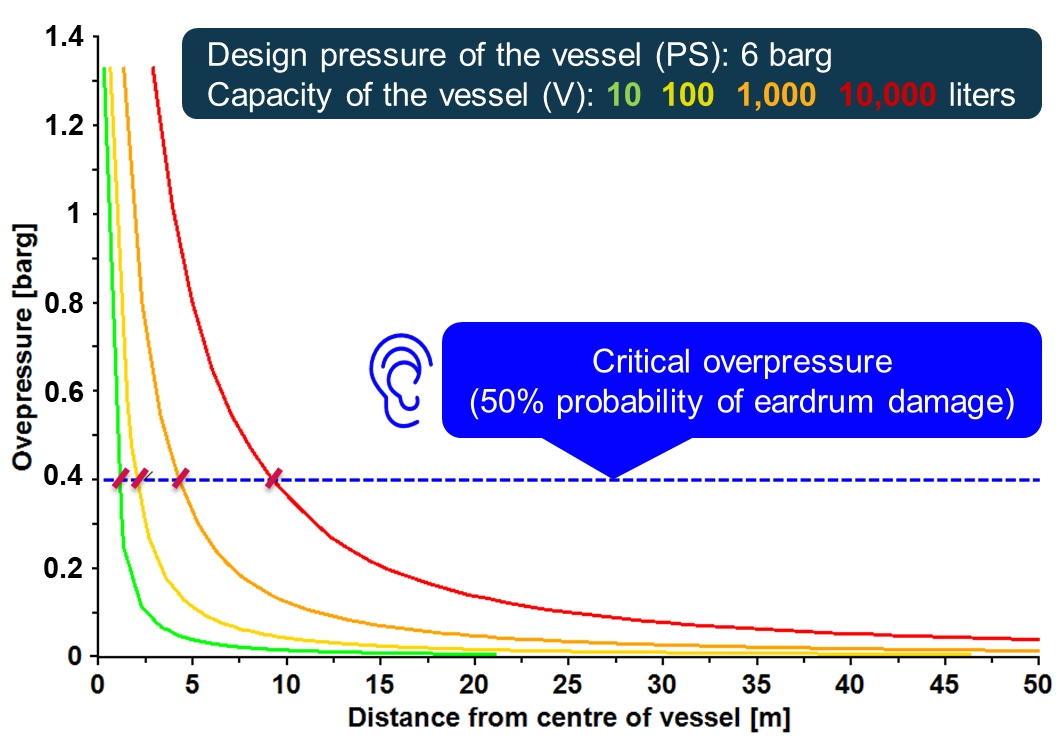


Figure 1. Overpressure history from pressure waves generated by bursting ductile equipment under various design conditions and capacities.

We established a convention based on various vessel configurations to identify critical overpressure distances associated with significant injury risks, such as a 50% probability of eardrum rupture. After analyzing various vessel configurations, we adopted a convention indicating that severity levels S1 to S4 are expected if our defined threshold is exceeded at specific distances from the vessel. This approach enabled us to correlate the energy content of the vessel with different degrees of severity, a relationship confirmed by extensive calculations. Consequently, this led to the development of our new severity table based on PS × V boundaries.

Table 3: PS x V Table - Examples of severity levels based on pressure wave by pressuring of ductile equipment with gas phases (without consideration of physical effects/ consequences)

|  |  |  |  |
| --- | --- | --- | --- |
| Severity  Level | Design Pressure x Volume  Column 1 – **Base Case**  (> 3 x PS) | Design Pressure x Volume  Column 2  (maximum 3 x PS) | Design Pressure x Volume  Column 3  (< 2 x PS) |
| S1  S2  S3 | 6,000 < PS x V  600 < PS x V < 6,000  200 < PS x V < 600 | 18,000 < PS x V  1,000 < PS x V < 18,000  400 < PS x V < 1,000 | 30,000 < PS x V  2,000 < PS x V < 30,000  600 < PS x V < 2,000 |
| S4 | PS x V < 200 | PS x V < 400 | PS x V < 600 |

Typically, Column 1 in Table 3 (Base Case) is used to identify the severity of bursting of a pressurized equipment, where the maximum achievable deviation pressure can exceed 3 times the equipment design pressure. But according to the boundary conditions, the conservative calculation is based on rupture at 5 times the design pressure. In cases where the maximum achievable pressure (even in the event of deviations) is intrinsically limited according to high mechanical integrity design principles (HMI) or protected by VH preventative measures to values lower than three times the design pressure, Column 2 can be applied. Additionally, there may be situations where the design pressure can be exceeded, but the pressure source cannot reach twice the original design pressure. In such cases, Column 3 can be utilized, as the pressure wave calculations were based upon rupture at 2 times design pressure.

3. Specific cases and applications

3.1 Standard applications - case studies

The assessment of failure scenarios is a collaborative effort undertaken by the HAZOP team, which comprises both PPS Practitioner and plant operational personnel. As highlighted under section 1, this evaluation is based on internal company policies, procedures, knowledge documents, and the individual experiences of the team.

The internal regulation for Process and Plant Safety describes each severity level in general (see table 1 in section 1.2) and provides examples for the overpressure scenarios that support in classifying the associated risk levels.

Before the PS x V method was developed, the scenario of overpressurizing a “ductile” equipment due to vapor pressure/gaseous pressure (excluding other effects such as toxicity) was assessed in many cases using the following criteria:

* with volume greater than 10 l: S1 (for high risk),
* with volume lower than 10 l: S2 (for significant risk).

This estimation neglects the correlation between the equipment's design pressure and volume, as well as the impact of the pressure wave's magnitude. Therefore, the new PS x V method based on calculations of these factors is closer to the reality, which was confirmed by statistical / empirical data of accidents. Furthermore, this method describes 4 categories of severities, in contradiction to the old method where only 2 severity levels could be applied.

In the following sections, examples of the application of the new method are presented. In these cases, the maximum allowable pressure is equal to the design pressure. In the first example (figure 2), a stainless-steel liquid vessel with a volume of 140 liters and a design pressure of 3 barg is considered.

Ein Bild, das Maschine, Bautechnik, Industrie, Pfeife Flöte Rohr enthält.

Automatisch generierte Beschreibung

Figure 2: Stainless-Steel Liquid Vessel pressurized with compressed air in failure scenario.

This vessel is emptied using compressed air. The failure scenario involves pressurizing the closed vessel with compressed air up to the maximum achievable protected pressure of 7 barg. This scenario was previously classified as S1. The table below shows how the severity level changes according to the new approach. The calculation is performed for the entire gas volume as the worst case.

Table 4: Estimation of severity for the Liquid Vessel acc. PS x V Table (Example 1)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Volume (V) | Design  Pressure (PS) | Max.  Pressure (Pmax) | PS x V | Pmax / PS | Severity Level acc. to Table 3. Column 2 (maximum 3 x PS) |
| 140 | 3 | 7 | 420 | 2.3 times | 400 < PS x V < 1,000 => **S3** |

Using this method, the severity level could be reduced by two orders of magnitude and now equates to level S3. This can reduce the cost of installing additional pressure safety measures with higher quality, such as a VH rated certified pressure relief valve, with all the required calculations/ documentation and life-cycle management.

The second example (figure 3) is a stainless-steel distillation column, which is also a pressure equipment. The total volume of the column, including the vapor line and condenser, is 2,250 liters, representing the amount of stored energy. The design pressure of the column is 5 barg.

Ein Bild, das Industrie, Pfeife Flöte Rohr, Bautechnik, Zylinder enthält.

Automatisch generierte Beschreibung

Figure 3: Stainless-Steel Distillation Column pressurized with compressed air in failure scenario.

In this column, steam with a maximum pressure of 6 barg is used for solvent removal. The malfunction scenario where steam is applied to the column with the vent line and outlet line closed. In this case the previous risk was also assessed with severity level S1. The new validation is presented below. The calculation is based on the total system volume as the worst case.

Table 5: Estimation of severity for the Distillation Column acc. PS x V Table (Example 2)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Volume (V) | Design  Pressure (PS) | Max.  Pressure (Pmax) | PS x V | Pmax / PS | Severity Level acc. to Table 3. Column 3 (< 2 x PS) |
| 2,250 | 5 | 6 | 11,250 | 1.2 times | 2,000 < PS x V < 30,000 => **S2** |

In this situation, a detailed calculation and the use of Column 3 enabled the severity level to be reduced by one level. This also had positive impact on the planned safety measures. The planned upgrade PCT installation for the SIL3 pressure interlock was no longer necessary, as the existing SIL2 high pressure interlock was sufficient.

The third example (figure 4) is a stainless-steel filter with a strainer. The function of this filter is to retain deposits, foreign material and fibers. Compared to the examples above, this filter contains both liquid and gas. The total volume of the filter and the directly connected pipes is 300 liters, while the remaining gas volume is 60 liters. The design pressure of the system is 4 barg.

Ein Bild, das Stahl, Maschine, Pfeife Flöte Rohr, Rad enthält.

Automatisch generierte Beschreibung

Figure 4: Stainless-steel filter with a strainer pressurized with pumps in failure scenario.

The filter is pressurized by two centrifugal pumps connected in series. When the valve on the pressure side of the filter behind the second pump is closed, a maximum pressure of 15.5 barg is generated by both pumps. The overpressure scenario of this system due to the displaced gas volume of the pump was previously rated as S1. However, the new method gives a different result. The following calculation is applied to the existing gas phase only.

Table 6: Estimation of severity for the filter with a strainer acc. PS x V Table (Example 3)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Volume (V) | Design  Pressure (PS) | Max.  Pressure (Pmax) | PS x V | Pmax / PS | Severity Level acc. to Table 3. Column 1 (> 3 x PS)  Base Case |
| 60 | 4 | 15.5 | 240 | 3.9 times | 200 < PS x V < 600 => **S3** |

As in the first case, the severity level is now reduced by two levels with this method and is now equal to S3. In this example, no further safety measures were required as the existing pressure switch-off in SIL 1 was adequate.

3.2 Specific cases – derated pressure

There may be situations where equipment is manufactured to a specific design pressure, but due to process conditions or additional requirements for registering and maintaining equipment as pressure vessels, it is assigned a Maximum Allowable Working Pressure (MAWP) that is lower than the original design pressure. In such cases, the original design pressure cannot be used for the PS x V calculation. Instead, a 'theoretical' design pressure should be determined based on a conservative approach, which assesses the potential severity of equipment failure at the maximum achievable pressure.

Example:

A vessel has a volume of 10,000 liters and a design pressure of 6 barg. In this example, the maximum achievable pressure in the process is 5 barg (limited by VH measure or HMI). The derated pressure (referred to as “Fertiggemeldeter Druck” or MAWP) is set at 0.5 barg. While exceeding the original design pressure is not possible, the MAWP can be exceeded.

In this case we need to determine a new ‘theoretical’ design pressure.

For determining the product "PS x V" a “theoretical” design pressure is calculated by the following formula:

|  |  |
| --- | --- |
|  | (2) |

Factor 2 is to be used in all cases, to then determine the potential severity using column 3 in Table 3.

The Severity Level can be estimated according to the following equation and Table 3 and results in a classification of S2:

|  |  |
| --- | --- |
|  | (3) |

Essentially using a max. achievable pressure divided by two, then applying factor 2 means that we determine a severity based on stored energy at the max. protected pressure.

In the upcoming chapters, the practical implementation of this method will be presented for two different equipment types.

A common case in chemical companies where the Maximum Allowable Working Pressure (MAWP) is lower than the design pressure are storage tanks. These are often operated with pressure of equal to or below 0.5 barg, although they are intended for a higher design pressure. The following example (figure 5) refers to a stainless-steel tank with a maximum allowable working pressure of 0.5 barg and a design pressure of 6 barg. The volume of the tank equals 32,000 liters. In this example, the maximum achievable pressure in the process is 5 barg (limited by VH measure or HMI).

Ein Bild, das Industrie, Zylinder, Pfeife Flöte Rohr, Speichertank enthält.

Automatisch generierte Beschreibung

Figure 5: Stainless-Steel Storage Tank pressurized with pump in failure scenario.

Table 7: Estimation of severity for the tank acc. PS x V Table (Example 1)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Volume (V) | Design  Pressure  (PS) | Derated Pressure  (MAWP) | Max. Pressure  (Pmax) | New Theoretical  Design Pressure  (new PS = Pmax / 2) | new  PS x V | Severity Level acc. to Table 3. Column 3 |
| 32,000 | 6 | 0.5 | 5 | 2.5 | 80,000 | 30,000 < PS x V => **S1** |

The result of this calculation shows that the severity level has not changed. This confirms that, as in this case, a non-pressure equipment designed for pressure above 0.5 barg can initially rupture at higher pressures due to its design, which can be life-threatening.

For comparison, a stainless-steel exhaust gas scrubber (figure 6) with a significantly smaller volume of 1,000 liters is considered below. The maximum allowed pressure of this scrubber is 0.5 barg, while the design pressure is 6 barg.

Ein Bild, das Maschine, Industrie, Pfeife Flöte Rohr, Bautechnik enthält.

Automatisch generierte Beschreibung

Figure 6: Stainless-Steel Exhaust Gas Scrubber pressurized with nitrogen in failure scenario.

The exhaust gas scrubber is purged with nitrogen, maintaining a protected pressure of 3 barg, In this example, the maximum achievable pressure in the process is 3 barg (limited by VH measure or HMI). With the vent path closed, the apparatus may become overpressurized. This scenario had previously been assessed as S1. The following calculation enables a validation of the severity level using the new method.

Table 8: Estimation of severity for the Exhaust Gas Scrubber acc. PS x V Table (Example 2)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Volume (V) | Design  Pressure  (PS) | Derated Pressure  (MAWP) | Max. Pressure (Pmax) | New Theoretical  Design Pressure  (new PS = Pmax / 2) | new  PS x V | Severity Level acc. to  Table 3. Column 3 |
| 1,000 | 6 | 0.5 | 3 | 1.5 | 1,500 | 600 < PS x V < 2,000 => **S3** |

In this case, the severity of mechanical damage to the apparatus is reduced from S1 to S3. The assessment avoided an upgrade of the interlock to SIL3.

4. Conclusions

In this article, we introduced a user-friendly table that enables PPS Practitioners to easily determine the appropriate severity level for various overpressure scenarios resulting in physical explosions. This innovation not only enhances safety practices in risk assessments but also aims to achieve better harmonization of severity level determination and safety concepts throughout Bayer.

By fostering a comprehensive understanding of risk assessment in the context of overpressurized equipment with gases, we aim to significantly reduce the efforts of HAZOP teams and promote the application of simplified methods within the chemical and pharmaceutical industry. This approach ensures a more consistent and accurate evaluation of risks, leading to improved safety outcomes and optimized resource allocation.

The successful application of this method has been confirmed through examples from Bayer plants, demonstrating the practical benefits and effectiveness of this approach. These case studies validate the advantages of the new methodology, including enhanced efficiency, reduced costs, and improved safety harmonization across the organization.

However, this method does not consider additional consequences that may need to be addressed, such as the release of harmful, toxic, or flammable substances. In such cases, the physical impact of the resulting pressure wave may be significantly less than that associated with the properties of the substances involved. Additionally, this table is not applicable for internal explosions or decomposition/deflagration scenarios. In these situations, the potential generation of debris cannot be excluded, which may result in an underestimation of the overall severity of consequences.

It should be emphasized that local regulation, which may be more stringent, need always be considered and whichever have the higher requirements must be applied.

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