Safety distance for pressure-resistance tests of cylindrical pressure vessels in the industrial field

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Abstract
The number of pressure vessel bursts (PVBs) has reduced since the 1990s due to the introduction of many rules and regulations. However, accidents frequently occur during pressure resistance tests (pneumatics) and there are scant safety guidelines for examining pressure vessels. Thus, this study proposes a safe distance to prevent accidents during a test, based on the explosion energy and vessel shape. First, the maximum explosion energy was computed using Brode's equation and the distance and overpressure were nondimensionalized via Sachs' scaling. Next, the overpressure ratio of the spherical tank ($o_{\text{sphere}}$) was calculated based on the overpressure ratio of the cylindrical tank ($o_{\text{cylinder}}$), considering the length to diameter ratio of the cylindrical vessel. Finally, the function of the safety distance was obtained. The result was validated by comparing it with data from the catastrophic failure that occurred at D. D. Williamson & Co. Inc. in 2003. This study could help establish safety guidelines and the prevention of PVB damage.

KEYWORDS
explosion, pneumatic pressure test, pressure vessel, pressure vessel burst, pressure-resistant test, safety distance

1 INTRODUCTION
A pressure vessel burst (PVB) is a type of explosion whereby a pressure vessel ruptures due to compressed gas.1 Hence, a PVB can occur in any chemical field where reactors, tanks, or vessels are used.2,3 Meanwhile, PVBs are often confused with vapor cloud explosions (VCEs) and boiling–liquid expanding vapor explosions (BLEVEs); however, VCEs concern the explosion of flammable or reactive materials whereas PVBs can occur just with inert gases such as Nitrogen and Helium. In addition, PVBs are different from BLEVEs in that phase change is not necessary.

PVBs occurred very frequently before the 1990s; however, once standards were established by the American Society of Mechanical Engineers (ASME), the accident frequency drastically decreased.1 Although the number of accidents has decreased, PVBs still occur...
According to Dubal and Kadam, the causes of pressure vessel explosions—including not only PVBs but also VCEs and BLEVEs—are improper design, misapplication, wrong operation, and—predominantly, that is, over 60%—fallacious maintenance; these result in casualties and property losses. Damage is caused mostly by blast pressure and fragments in the PVBs and the thermal effect is negligible. According to the Center for Chemical Process Safety (CCPS), approximately 20%–50% of the explosion energy is used for debris; steel vessels require only 1–10 kJ for rupture. Almost all of the remaining energy is allocated to the blast wave. A key example of PVBs was observed at D. D. Williamson & Co. Inc. (DDW) in April 2003. Due to overheating, the vessel was subject to elevated pressure but there was no pressure-releasing equipment. Thus, the vessel exploded, killing one operator and requiring approximately 1500 people to relocate to a shelter-in-place. In addition, according to the KOSHA data, the accident ratio of the pressure vessel occupies a large portion of the explosion or rupture (Figure 1). These patterns are irregular over time; however, it can be concluded that the risk surrounding pressure vessels is constant.

Many countries have enacted laws to prevent PVBs. In the United States, standards have been established by the American Petroleum Institute (API), National Institute of Science and Technology (NIST), and so on. These standards have different design specifications for pressure vessels, which are normally two-five times the maximum allowable working pressure (MAWP). In South Korea, the Ministry of Employment and Labor (MOEL) has established rules and regulations. In particular, the Korea Occupational Safety and Health Agency (KOSHA), a MOEL-affiliated organization, ensures that the rules and regulations are obeyed. For example, to quantify the accident risk of explosion or dispersion, KOSHA published technical instructions for pressure vessels. In addition, before operating pressure vessels or pipes, they should be tested by KOSHA. However, no safety instructions for the operator or supervisor are provided, only a test pressure or testing material.

Meanwhile, studies on PVBs have been conducted on the calculation of explosion energy, overpressure, or fragment and the effect of the ground or vessel shape on PVBs, and so on. Many equations have been developed to predict explosion energy: constant volume energy addition, constant pressure energy addition, isentropic expansion, isothermal expansion, Aslanov’s definition, and thermodynamic availability. Among these, the first, third, and sixth methods provide realistic explosion energy, and the first equation, devised by Brode, outputs the maximum explosion energy, which enables conservative prediction.

Equations, computational fluid dynamics (CFD), and curves were introduced to compute overpressure. Among these, the trinitrotoluene (TNT) equivalence method, TNO multienergy method (TNO MEM), and Baker–Streblow–Tang method (BST) are most commonly employed for calculating the overpressure or power of explosion, according to Baker et al. In addition, these three methods have been applied in Phast, which is the most popular simulator for evaluating quantitative risk developed by DNV GL. In the TNT equivalent method, the mass of a combustible chemical is substituted by an equivalent weight of TNT; this method is easy to apply but apt to overpredict PVB overpressure at short distances and underpredict it at long distances. However, TNO MEM and BST are more appropriate for gas explosions than the TNT method. In addition, because these two methods reflect the types of flame expansion, fuel reactivity, and obstacle density, various cases can be considered. However, because users choose the mentioned values subjectively, a lack of objectivity is inevitable. Furthermore, TNO MEM usually underestimates the effect, except for a very short distance. The BST curve is used for normal explosions and the Baker–Tang (BT) curve is only used for PVBs.

A PVB brings about not only air blasts but also fragments. Because damage from fragments varies according to geography, features of the vessel (structure and materials), and so on, it is difficult to theorize the effect of scattering fragments. Thus, only prediction methods for fragment velocity or the range of flying debris have been researched. Baker et al. found that the explosion energy should be doubled when a pressure vessel is located on the ground because of surface reflection. In addition, the PVB of a nonspherical tank has been studied.

![Figure 1](image_url) Loss of lives by explosion or rupture in Korea.
Clancey described the impact of PVBs on structures and humans. A loud noise is possible at 0.04 psig and glass breaks at 0.15 psig. Minor structural damage starts at 0.4 psig and uninhabitable destruction occurs at 1.0 psig. Houses can be almost completely destroyed in the range of 5–7 psig. Moreover, according to Kinney and Graham, people can knockdown by 1 psig. Over 5 psig, the eardrum is ruptured. This study focuses on the impact of 1.0 psig (6.9 kPa-gauge), which is also chosen as a standard value in KOSHA code P-31-2011. This overpressure is important because its expected damage is partial demolition of houses and makes them inhabitable. Thus, the distance at which 1 psig is reached is considered the safety distance.

However, there have been studies on the safety distance or separation distance. Sklavounos and Rigas suggested the safety distance of a fuel gas pipeline by simulating the specific worst scenario. The safety distance for preventing the domino effect has only been researched for VCEs and BLEVEs with respect to spherical vessels.

Although prevention methods for PVBs have been devised and studies on PVBs have progressed, it is difficult to intuitively understand the effect of a PVB, necessitating

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**TABLE 1** Overpressure ratio ($r_o$) converted from Geng et al.

| Overpressure ratio | Distance $R$ |
|--------------------|--------------|
|                    | 0.3 | 0.6 | 1.0 | 1.3 | 1.6 | 2.0 |
| Pressure ratio ($p_1/p_0$) |     |     |     |     |     |     |
| 10                 | 0.99 | 1.37 | 1.36 | 1.13 | 1.11 | 1.09 |
| 20                 | 1.07 | 1.40 | 1.23 | 1.07 | 1.05 | 1.05 |
| 50                 | 1.28 | 1.32 | 1.17 | 1.04 | 1.03 | 1.03 |
| 100                | 1.28 | 1.28 | 1.13 | 1.03 | 1.01 | 1.01 |

When $L/D = 2$

| Pressure ratio ($p_1/p_0$) | 10 | 20 | 50 | 100 |
|---------------------------|----|----|----|-----|
| 1.20                      | 1.60 | 1.51 | 1.40 | 1.39 |
| 1.44                      | 1.60 | 1.36 | 1.27 | 1.24 |
| 1.07                      | 1.55 | 1.45 | 1.21 | 1.17 |
| 1.23                      | 1.57 | 1.45 | 1.17 | 1.09 |

When $L/D = 5$

| Pressure ratio ($p_1/p_0$) | 10 | 20 | 50 | 100 |
|---------------------------|----|----|----|-----|
| 0.70                      | 1.00 | 1.33 | 1.75 | 1.63 |
| 0.78                      | 1.18 | 1.48 | 1.60 | 1.47 |
| 0.93                      | 1.33 | 1.62 | 1.35 | 1.30 |
| 1.07                      | 1.50 | 1.57 | 1.28 | 1.20 |

When $L/D = 10$

| Pressure ratio ($p_1/p_0$) | 10 | 20 | 50 | 100 |
|---------------------------|----|----|----|-----|
| 0.70                      | 1.00 | 1.33 | 1.75 | 1.63 |
| 0.78                      | 1.18 | 1.48 | 1.60 | 1.47 |
| 0.93                      | 1.33 | 1.62 | 1.35 | 1.30 |
| 1.07                      | 1.50 | 1.57 | 1.28 | 1.20 |

**TABLE 2** Adjustable factor ($r_o$) according to $L/D$

| $L/D$ | 2   | 5   | 10  |
|-------|-----|-----|-----|
| $r_o$ | 1.4 | 1.6 | 1.8 |
appropriate planning of safety measures. Specifically, on the pressure resistance test before starting to use a pressure vessel, rules and regulations are needed to protect workers and other equipment from the PVB. Thus, this study focuses on presenting an equation to determine the safety distance for supervisors, using the cylindrical vessel shape, volume, and overpressure as variables. Section 2 explains the methodology. The results are presented in Section 3 and Section 4 validates the results against past accident data. It is expected that this

| TABLE 3  | Safety distance calculated by Fortran. |
|-----------|----------------------------------------|
| **Vol. \( V_1, \text{m}^3 \)**   | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| **Safety distance (m)**             | 5 | 11 | 14 | 16 | 18 | 19 | 21 | 22 | 23 | 24 | 24 |
|                                          | 10 | 17 | 21 | 24 | 27 | 29 | 30 | 32 | 34 | 35 | 36 |
|                                          | 20 | 23 | 29 | 33 | 37 | 40 | 42 | 44 | 46 | 48 | 50 |
|                                          | 40 | 31 | 39 | 44 | 49 | 53 | 56 | 59 | 62 | 64 | 66 |
|                                          | 70 | 38 | 48 | 55 | 61 | 65 | 69 | 73 | 76 | 79 | 82 |
|                                          | 100 | 44 | 55 | 63 | 69 | 75 | 79 | 83 | 87 | 91 | 94 |
|                                          | 140 | 49 | 62 | 71 | 78 | 84 | 90 | 94 | 99 | 103 | 106 |
|                                          | 200 | 56 | 71 | 81 | 89 | 96 | 102 | 108 | 112 | 117 | 121 |
|                                          | 300 | 65 | 82 | 94 | 103 | 111 | 118 | 124 | 130 | 135 | 140 |

when \( L/D = 2 \)

| Pressure \( p_1, \text{bar} \) | 5 | 11 | 14 | 16 | 18 | 19 | 21 | 22 | 23 | 24 | 24 |
|---------------------------------|---|----|----|----|----|----|----|----|----|----|----|
| 10 | 17 | 21 | 24 | 27 | 29 | 30 | 32 | 34 | 35 | 36 |
| 20 | 23 | 29 | 33 | 37 | 40 | 42 | 44 | 46 | 48 | 50 |
| 40 | 31 | 39 | 44 | 49 | 53 | 56 | 59 | 62 | 64 | 66 |
| 70 | 38 | 48 | 55 | 61 | 65 | 69 | 73 | 76 | 79 | 82 |
| 100 | 44 | 55 | 63 | 69 | 75 | 79 | 83 | 87 | 91 | 94 |
| 140 | 49 | 62 | 71 | 78 | 84 | 90 | 94 | 99 | 103 | 106 |
| 200 | 56 | 71 | 81 | 89 | 96 | 102 | 108 | 112 | 117 | 121 |
| 300 | 65 | 82 | 94 | 103 | 111 | 118 | 124 | 130 | 135 | 140 |

when \( L/D = 5 \)

| Pressure \( p_1, \text{bar} \) | 5 | 13 | 16 | 18 | 20 | 22 | 23 | 24 | 25 | 26 | 27 |
|---------------------------------|---|----|----|----|----|----|----|----|----|----|----|
| 10 | 19 | 24 | 27 | 30 | 32 | 34 | 36 | 37 | 39 | 40 |
| 20 | 26 | 32 | 37 | 41 | 44 | 47 | 49 | 52 | 54 | 56 |
| 40 | 34 | 43 | 49 | 54 | 59 | 62 | 66 | 69 | 71 | 74 |
| 70 | 42 | 54 | 61 | 67 | 73 | 77 | 81 | 85 | 88 | 91 |
| 100 | 48 | 61 | 70 | 77 | 83 | 88 | 93 | 97 | 101 | 104 |
| 140 | 55 | 69 | 79 | 87 | 94 | 100 | 105 | 110 | 114 | 118 |
| 200 | 62 | 79 | 90 | 99 | 107 | 113 | 119 | 125 | 130 | 135 |
| 300 | 72 | 91 | 104 | 115 | 124 | 131 | 138 | 144 | 150 | 156 |

when \( L/D = 10 \)

| Pressure \( p_1, \text{bar} \) | 5 | 14 | 18 | 20 | 22 | 24 | 25 | 27 | 28 | 29 | 30 |
|---------------------------------|---|----|----|----|----|----|----|----|----|----|----|
| 10 | 21 | 26 | 30 | 33 | 35 | 37 | 39 | 41 | 43 | 44 |
| 20 | 28 | 36 | 41 | 45 | 48 | 51 | 54 | 57 | 59 | 61 |
| 40 | 38 | 47 | 54 | 60 | 64 | 68 | 72 | 75 | 78 | 81 |
| 70 | 47 | 59 | 67 | 74 | 80 | 85 | 89 | 93 | 97 | 100 |
| 100 | 53 | 67 | 77 | 85 | 91 | 97 | 102 | 107 | 111 | 115 |
| 140 | 60 | 76 | 87 | 96 | 103 | 109 | 115 | 120 | 125 | 130 |
| 200 | 69 | 86 | 99 | 109 | 117 | 125 | 131 | 137 | 143 | 148 |
| 300 | 79 | 100 | 114 | 126 | 136 | 144 | 152 | 159 | 165 | 171 |

| TABLE 4  | Coefficient for the safety distance calculation. |
|-----------|-----------------------------------------------|
| \( L/D = 2 \) | \( L/D = 5 \) | \( L/D = 10 \) |
| \( f_{00} \) | 5.035 | 5.636 | 6.232 |
| \( f_{10} \) | \( 3.976 \times 10^{-1} \) | \( 4.415 \times 10^{-1} \) | \( 4.844 \times 10^{-1} \) |
| \( f_{01} \) | 7.641 | 8.494 | 9.331 |
| \( f_{20} \) | \( -7.961 \times 10^{-4} \) | \( -8.844 \times 10^{-4} \) | \( -9.713 \times 10^{-4} \) |
| \( f_{11} \) | \( 1.724 \times 10^{-2} \) | \( 1.913 \times 10^{-2} \) | \( 2.096 \times 10^{-2} \) |
| \( f_{02} \) | \( -4.171 \times 10^{-1} \) | \( -4.635 \times 10^{-1} \) | \( -5.088 \times 10^{-1} \) |
study will help to reduce damage from PVBs by suggesting an appropriate safety distance.

2 | METHODOLOGY

The methodology shown in Figure 2 is used to obtain the safety distance for a PVB. Although the theory is valid for any shape of cylindrical pressure vessels, the function of the safety distance is, in this study, confined to cylindrical pressure vessels with a length-to-diameter ratio (L/D) of 2, 5, and 10. It is assumed that these vessels are located immediately above the ground; thus, the explosion energy is doubled by surface reflection. In addition, it is assumed that $V_1$ ranges from 1 to 10 m$^3$ and $p_1$ ranges from 5 to 300 bar.

In the first step, the explosion energy is calculated using Brode’s definition, which gives the maximum energy value. The equation is as follows:

$$E_{ex,Br} = \frac{(p_1 - p_0) \cdot V_1}{\gamma_1 - 1}.$$  

As this study assumes that a cylindrical pressure vessel is located right above the ground, the energy should be multiplied by $2^{1.25}$; thus, the total explosion energy, $E_{ex}$ equals $2 \cdot E_{ex,Br}$. Sachs’ scaling was introduced for nondimensionalization. The dimensionless distance and overpressure are computed according to the following equations:

$$\bar{R} = \frac{R \cdot P_0^{1/3}}{E^{1/3}},$$

**FIGURE 5** Three-dimensional curve of safety distance.
Using Sachs’ scaling, overpressure is quasi-analytically estimated as a function of energy and distance, as shown in the BT curve (Figure 3). In Step 2, an adjustable factor \( r_o \) should be defined before applying the BT curve; this is the maximum overpressure ratio when \( L/D \) is fixed. Geng found that the overpressure ratio of a cylindrical pressure vessel changes according to \( L/D \), as shown in Figure 4. The graph is transformed to Table 1, which demonstrates that the overpressure ratio and its location \( \bar{R} \) are different. Although this overpressure ratio is also affected by the distance and pressure ratio, for conservative guidelines, the maximum value is chosen, as presented in Table 2.

As the BT curve is based on the explosion of a spherical pressure vessel, the overpressure ratio of the cylindrical tank should be modified using the following equation:

\[
op_{\text{cylinder}} = r_o \times \op_{\text{sphere}}
\]

Because \( \op_{\text{cylinder}} \) is a value for the cylinder, the calculated \( \op_{\text{sphere}} \) is used to read \( \bar{R} \) from the BT curve. For example, when \( L/D = 2 \) \( (r_o = 1.4) \), \( \op_{\text{sphere}} \) is 0.714 psig (0.0486 atm) to satisfy \( \op_{\text{cylinder}} = 1 \) psig (0.068 atm); based on Figure 3, 0.0486 atm corresponds to \( \bar{R} = 4 \).

In the final step, \( R \) is attained via Sachs’ scaling, which indicates the safety distance. This reverse process of reading \( \bar{R} \) is performed using Fortran coding.

### 3 | RESULT

The results are presented in Table 3. Using Fortran coding, the safety distance is presented by the independent variables \( V_1 (m^3) \) and \( p_1 \) (bar). As \( L/D \) increases, the safety distance also increases.

![Damage contours of D. D. Williamson & Co. Inc.’s pressure vessel burst.](image)
For generalization, the data were fitted to a three-dimensional (3D) curve using the MATLAB curve fitting tool. The function is shown below and the coefficients are presented in Table 4.

\[
f(p_1, V_1) = f_{00} + f_{10} p_1 + f_{01} V_1 + f_{20} p_1^2 + f_{11} p_1 V_1 + f_{02} V_1^2.
\]

Using the coefficients, 3D curves (Figure 5) were obtained. As the adjusted-\(R^2\) of this function is 0.9868, the equation is considered reliable.

## 4 | VALIDATION

The result was compared with a catastrophic failure that occurred at DDW. DDW has produced caramel coloring for food products, such as coke, sauces, and seasonings. The explosion occurred in feed tank 2 and the conditions of the accident are listed in Table 5. According to the US Chemical Safety and Hazard Investigation Board (CSB), the worst-case scenario occurs when the pressure in feed tank 2 reaches 130 psi. Thus, the safety distance of this scenario was calculated and then compared with the actual damage.

The accident results are shown in Figure 6, based on the actual layout. The contours indicate where the designated overpressure has been reached. When the devised function is applied, the safety distance is 31.6 m. At this distance, the pipes are broken, followed by gas leakage, and the concrete wall of the spray collapses; this is comparable to the criteria of Clancey and Kinney and Graham, who stated that partial demolition of houses under an overpressure of 1 psi. In addition, when the function of the safety distance expands to the \(O_{\text{cylinder}} = 2.5\) psi line (15 m) and the \(O_{\text{cylinder}} = 7\) psi line (6 m), the accident result and the criteria show a united tendency, as described in Figure 6.

## 5 | CONCLUSION

Although many studies and laws for PVBs have been introduced, PVBs still occur frequently and cause loss of lives and property, especially during pressure resistance tests. This study devises a function for calculating the safety distance for the test of a cylindrical pressure vessel based on the vessel capacity \((V_1)\), \(L/D\) ratio, and internal pressure before burst \((p_1)\). The distance at which the overpressure reaches 1 psi is chosen owing to Korean rules and regulations.

The safety distances from this methodology can be a bit more conservative compared to using only Brode’s equation due to the adjustable factors for the \(L/D\) ratios. In the future, more \(L/D\) ratios need to be investigated and CFD approaches might help for more accurate results. This study contributes to the industrial field in that this equation can be easily used to improve safety when pressure vessels are tested. Furthermore, this could help establish safety laws. The target pressure can be expanded to other ranges or other vessel shapes. In addition, this methodology can be used to prevent the domino effect.

## NOMENCLATURE

\(E_{\text{ex}}\) explosion energy  
\(E_{\text{ex,Br}}\) explosion energy defined by Brode  
\(O_{\text{cylinder}}\) overpressure ratio of cylinder  
\(O_{\text{sphere}}\) overpressure ratio of sphere  
\(P\) overpressure of PVB from spherical vessel  
\(P_{	ext{so}}\) peak side-on overpressure  
\(R\) standoff distance  
\(r_0\) adjustable factor  
\(\bar{R}\) dimensionless standoff distance  
\(V_1\) volume occupied by gas in vessel  
\(\gamma_1\) specific heat ratio of the gas in vessel

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