THEORY

BLEVE BLAST

DATE: December 2023

This document describes the theory of the BLEVE blast model. The model predicts the blast parameters of peak overpressure and positive phase impulse resulting from the burst of pressurised vessels filled with gas, 2-phase or superheated liquid.

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ABSTRACT

This document describes the theory of the BLEVE blast model to be implemented into PHAST/SAFETI 6.4 to satisfy the requirement that the current BLEVE consequence model be extended to incorporate overpressure effects from the storage of flammable and non-flammable materials. The model predicts the blast parameters of peak overpressure and positive phase impulse resulting from the burst of pressurised vessels filled with gas, vapour, liquid above the normal boiling point or a mixture of vapour and liquid.

The model is based on the integrated methodology recommended in the CCPS guidelines for evaluating the characteristics of vapour cloud explosions, flash fires and BLEVEs. A BLEVE results from the explosively rapid vaporisation and corresponding release of energy of a liquid, flammable or otherwise, upon its sudden release from containment under greater-than-atmospheric pressure at a temperature above its atmospheric boiling point. The most important blast parameters for predicting structural damage from a vessel burst at a particular position (i.e., target) are the peak overpressure and impulse for the duration of positive overpressure of the first shock wave. The first step in estimating these blast parameters is to determine the energy involved in the explosion. This can be initially estimated from the difference in internal energies between the failure and post-expansion states of the fluid. In addition, the calculation of explosion energy depends on the proximity of the vessel to the ground (free air or grounded/near ground bursts), and whether the escaping fluid is observed or assumed to behave ideally or non-ideally. For non-ideal fluids, the expansion process is assumed to follow an isentropic thermodynamic trajectory. Once the explosion energy is calculated, the peak overpressure and positive impulse at the target can be estimated using data derived for spherical vessels in air. These data relate these blast parameters to explosion energy, distance from the explosion source and the speed of sound. Algorithms for overpressure calculations for ideal as against non-ideal behaving fluids differ depending on the proximity of the target to the explosion source. Finally, with the aid of suitable adjustment factors, the effect of vessel geometry (cylindrical/spherical) and elevation (free air/grounded explosions), on the calculated blast parameters, is modelled.

Results generally show that, for a fixed mass of fluid, prior to its loss of containment, the farther its physical state is from the liquid state, the higher the overpressure and impulse developed at a fixed distance. Furthermore, for a fixed mass of fluid, the higher the combined values of explosion energy and failure pressure or temperature, the higher the overpressure and/or impulse developed at distances near field (i.e., at a scaled distance: $R \leq 2$) of the explosion.

Table of contents

Table of figures

1 INTRODUCTION

The Safeti and Phast 6.4 project requires that the current BLEVE consequence model be extended to incorporate blast effects from storage of flammable and non-flammable materials. A literature review of various BLEVE models has been conducted by H.M.W Witlox[1] and it has been decided to implement the method of treatment of BLEVE blast described by the CCPS[2]. This document is therefore largely based on the CCPS[2] guidelines.

The term "BLEVE" is an acronym for boiling liquid expanding vapour explosion and may be defined as any sudden loss of containment of a liquid above its normal boiling point at the moment of vessel failure. Failure may result from the development of cracks which are mainly caused by impact on the vessel, corrosion, internal overheating and construction defects. A common cause of failure leading to BLEVE is due to fire engulfment of a vessel containing liquid under pressure. As the liquid heats up, the vapour pressure rises which may actuate the safety valve causing the liquid level in the vessel to fall as vapour is released. Because the heat capacity of vapour is lower than liquid, the portion of the vessel walls in contact with the vapour increases in temperature as heat is transferred from the fire while that in contact with the liquid remains relatively cool. This may result in non-uniform expansion and sufficient loss of strength of the vessel walls to rupture.

The BLEVE event can give rise to a blast wave, fragment projection and if a flammable fluid is involved, either a fireball, flash fire or vapour cloud explosion. This document is only concerned with the blast effects arising from either a BLEVE or a gas-filled pressurised vessel burst. The BLAST effect of a BLEVE results from the rapid flashing of liquid and the expansion of vapour in the vessel's head space when the pressure drops suddenly to atmospheric pressure. The process starts with an expansion from the initial volume which causes a shock wave travelling faster than the speed of sound. The fluid expands spherically and does not mix at first with the surrounding air resulting in a bubble-like interface with the surrounding air. The fluid's momentum causes the bulk fluid to expand to a pressure below atmospheric pressure resulting in a rarefaction wave following the initial shock. After the interface has reached its maximum diameter, the pressure differential causes an inwardly moving wave which reflects at the origin to produce a second, smaller shock. The system will continue to oscillate, producing ever smaller shocks until it comes to rest. The most important blast parameters for predicting structural damage at a particular position are the peak overpressure of the first or main shock and the impulse for the duration of positive pressure of the main shock.

This document describes the mechanism of a BLEVE and then gives an integrated method to estimate blast parameters to describe an explosion from a BLEVE or a gas-filled pressurised vessel burst. The first step in estimating the blast parameters is to determine the energy involved in the explosion. The energy is then employed in estimating the peak overpressure and positive phase impulse using the method developed by Baker et al [3].

2 MATHEMATICAL MODEL

2.1 Mechanism of a BLEVE blast

The most commonly accepted theory of BLEVE blast is the superheat limit theory of Reid[4,5] . When a liquid is heated to its boiling point, the liquid starts to form vapour bubbles at interfaces with solids such as vessel walls or, in the bulk fluid, at impurities, crystals or ions. When there is a shortage of nucleation sites in the bulk liquid, the temperature of the liquid can be raised above the saturated vapour temperature without transition to vapour and the liquid becomes superheated. There is a limit at a given pressure above which the liquid cannot be superheated where vapour develops spontaneously in the bulk liquid known as the superheat limit. Therefore if a liquid under pressure is stored at a temperature above the superheat limit for atmospheric pressure and the vessel subsequently ruptures, microscopic vapour bubbles form in the bulk fluid and a large fraction of vapour can flash off within milliseconds.

There are a number of correlations which estimate the superheat limit temperature for atmospheric pressure depending on the equation of state. Reid[6] used the Redlich-Kwong equation of state to obtain:

$$T_{sl} = 0.895 T_c \tag{1}$$

Where:

T_{sl} = superheat limit temperature at atmospheric pressure (K)

T_c = critical temperature (K)

Reid's theory is a good explanation of the strong blast waves that can be generated in a BLEVE. However, strong blasts can also be caused by rapid vaporization, following vessel failure, of pressurised liquids stored below the superheat limit temperature but above their boiling point at atmospheric pressure. For this reason the CCPS[2] recommends a conservative assumption for an integrated BLEVE blast method. In this method, explosive boiling is assumed to occur following failure of vessels containing liquids stored at temperatures above their normal boiling point.

2.2 Explosion Energy

Of all the blast parameters, the explosion energy has the most influence on the peak overpressure and positive phase impulse and hence the destructive potential of a blast. Thermodynamic approaches to estimating explosion energy have been overwhelmingly favoured by investigators due to their ease of use. In a thermodynamic approach the state of the material before the explosion is compared to the state of the material after the explosion and the difference in internal energies between the two states gives the explosion energy. The calculation methods presented in the CCPS[2] guidelines follow different paths for ideal gas[i] and non-ideal gas filled vessels.

2.2.1 Ideal Gas

The CCPS[2] guidelines recommend using Brode's[7] definition of explosion energy for failure of a vessel containing an ideal gas. Brode proposed that the explosion energy is that energy required to raise the pressure of a gas at constant volume from atmospheric pressure to the failure pressure. The internal energy for an ideal gas is given by:

$$U = \frac{PV}{\gamma - 1} \tag{2}$$

Where:

U = internal energy (J)
P = absolute pressure (Pa)
V = volume (m^3)
γ = ratio of constant pressure, C_p, and constant volume, C_v, specific heat capacities (-)

For an ideal gas C_p, C_v and therefore γ are independent of pressure so the explosion energy predicted by Brode, $E_{EX,Br}$ is:

$$E_{EX,Br} = \frac{(P_1 - P_0)V_1}{\gamma_1 - 1} \tag{3}$$

Where:

P_1 = absolute pressure at failure state (Pa)
P_0 = absolute pressure of ambient air (Pa)
γ_1 = ratio of specific heats of stored gas at failure state (-)
V_1 = volume occupied by stored gas (m^3)

2.2.2 Non-ideal Fluid

The approach in section 2.2.1 is not suitable for vessels filled with superheated liquids or vapour that cannot be described by ideal behaviour. A more appropriate method recommended by the CCPS[2] is to calculate the difference in the internal energy between the initial and final states assuming isentropic expansion. Although experiments indicate that the blast

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[i] The fluid's compressibility is employed as a suitable judge of the degree of its ideality. Significant deviations from the value of 1 for the fluid compressibility indicate non-ideality. The accepted range for ideal gas behaviour is taken as $0.97 \leqslant$ Fluid Compressibility (Z) $\leqslant 1.03$

wave from the expanding vapour is separate from that of the flashing liquid, the CCPS[2] conservatively suggests assuming blast waves from each phase are combined. An equation of state can be used to estimate the specific enthalpy and the specific volume at the state of interest which then enables calculation of internal energy.

By definition:

$$h = u + Pv \tag{4}$$

Where:

h = specific enthalpy (J/kg)
u = specific internal energy (J/kg)
P = absolute pressure (Pa)
v = specific volume (m^3)

The above equation can be expanded to include the case of a two-phase mixture of saturated liquid and saturated vapour and we can therefore obtain an expression for the internal energy of the initial state (denoted by subscript 1) of the fluid prior to vessel failure:

$$u_1 = x_{L,1}h_{L,1} + (1-x_{L,1})h_{G,1} - x_{L,1}P_1v_{L,1} - (1-x_{L,1})P_1v_{G,1} \tag{5}$$

Where:

$h_{L,1}$ = specific enthalpy of the saturated liquid in the initial state (J/kg)
$h_{G,1}$ = specific enthalpy of the saturated vapour in the initial state (J/kg)
$x_{L,1}$ = mass fraction of liquid in the initial state
$v_{L,1}$ = specific volume of the saturated liquid in the initial state (m^3/kg)
$v_{G,1}$ = specific volume of the saturated vapour in the initial state (m^3/kg)

A similar expression can be derived for the final state (denoted by subscript 2), based on the isentropic expansion of each fluid phase existing at failure conditions, taking into account that the final pressure, P_2, is equal to the ambient pressure, P_0:

$$\begin{aligned} u_2 = {} & x_{L1}\left(x_{L,2}^{L1}h_{L,2}^{L1} + (1-x_{L,2}^{L1})h_{G,2}^{L1} - x_{L,2}^{L1}P_0v_{L,2}^{L1} - (1-x_{L,2}^{L1})P_0v_{G,2}^{L1}\right) + \\ & (1-x_{L1})\left(x_{L,2}^{G1}h_{L,2}^{G1} + (1-x_{L,2}^{G1})h_{G,2}^{G1} - x_{L,2}^{G1}P_0v_{L,2}^{G1} - (1-x_{L,2}^{G1})P_0v_{G,2}^{G1}\right) \end{aligned} \tag{6}$$

The superscripts *L1* and *G1* in equation (6) refer to fluid properties calculated from the isentropic expansion of fluid fractions in the liquid (*L1*) and gaseous (*G1*) state at failure conditions. The subscripts G and L refer to fluid properties in the vapour and liquid states respectively.

In order to calculate u_2, the liquid fractions $x_{L,2}^{G1}$, and $x_{L,2}^{L1}$, and the final temperatures corresponding to each liquid fraction (i.e., T_2^{G1} and T_2^{L1}) need to be solved for to describe the state and hence enable calculation of $h_{L,2}^{G1}(T_2^{G1}, P_0)$, $h_{G,2}^{G1}(T_2^{G1}, P_0)$, $v_{L,2}^{G1}(T_2^{G1}, P_0)$, $v_{G,2}^{G1}(T_2^{G1}, P_0)$, $h_{L,2}^{L1}(T_2^{L1}, P_0)$, $h_{G,2}^{L1}(T_2^{L1}, P_0)$, $v_{L,2}^{L1}(T_2^{L1}, P_0)$, $v_{G,2}^{L1}(T_2^{L1}, P_0)$ from an equation of state. A method of solution for $x_{L,2}^{L1}$ and T_2^{L1} or $x_{L,2}^{G1}$ and T_2^{G1} assuming isentropic expansion is described in the DISC theory documentation[8]. According to the CCPS[2] a crude estimate of the internal energy of a mixture can be made by summing the internal energies of the individual components. It is not possible to do this with the current property modelling because mixtures are assumed to be equivalent pseudo-components and thus the internal energy is calculated from other pseudo-component properties which in turn are calculated by mixing rules.

The expansion energy can then be given by[ii]:

$$E_{EX} = M(u_1 - u_2) \tag{7}$$

Where:

E_{EX} = Explosion energy (J)
M = mass of fluid (kg)

2.2.3 Isentropic to Brode energy adjustment

Pierorazio & Syed[9] highlighted the need to convert the calculated explosion energy for bursting pressure vessels of real fluids to Brode energy to use the blast curves published in CCPS[2], but no method is recommended for the conversion in the paper. If using the non-ideal fluid method in Phast/Safeti, this option is available to convert the isentropic energy to Brode energy[10]. This increases the energy and provides further conservatism on the assumption that the CCPS blast curves are based on Brode energy. Otherwise the modelling will be the same as with the CCPS second edition model. The conversion is given below assuming the ratio of specific heats is 1.4;

$$E_{Adjusted} = E_{EX}\,\frac{\dfrac{P_1}{P_0} - 1}{\dfrac{P_1}{P_0} - \left[\dfrac{P_1}{P_0}\right]^{\frac{1}{\gamma_1}}} \tag{8}$$

2.3 Blast Parameters of Free Air Bursts from Spherical Vessels

The CCPS[12] book recommends the blast curve method for the prediction of the blast parameters for vessel bursts. Tang, Cao and Baker[11] published a complete set of blast curves based on a systematic one-dimensional (spherical) numerical study. The study ignored the effects of energy dissipation into the fragments of the vessel as kinetic energy. The pressure vessel blast curves are for spherical, free air pressure vessel bursts and do not include ground reflection.

The Tang, Cao and Baker[11] curves were developed with a numerical simulation that reduced overpressure losses associated with artificial viscosity in prior models (see CCPS[2]). As a result far field predictions are somewhat higher. The Tang, Cao and Baker[11] curves also have the advantage of simplifying calculations by developing curves for specific burst pressures, eliminating the need for iterative solution of the shock tube equation.

The blast curves relate scaled distance, $\overline{R}$ to scaled overpressure, $\overline{P}_S$ and scaled impulse, $\overline{I}$:

$$\overline{R} = r\left[\frac{P_0}{E_{EX}}\right]^{1/3} \tag{9}$$

Where:

r = distance from the explosion source (m)

$$\overline{I} = \frac{i_s a_0}{{P_0}^{2/3} {E_{EX}}^{1/3}} \tag{10}$$

[ii] When thermodynamic graphs are used the CCPS[2] mentions to follow the constant entropy line from the state at the failure pressure to the state at atmospheric pressure to get the final specific enthalpy and internal volume from which the final internal energy can be calculated. However when thermodynamic tables are used, the CCPS[2] calculates a separate final state for the expansion of the saturated liquid from that for the expansion of the saturated vapour and sums the explosion energy from each expansion. This is the method implemented above.

Where:

a_0 = speed of sound in ambient air (m/s)

i_s = positive phase side on impulse (Pa.s)

$$\overline{P_s} = \frac{p_s}{P_0} - 1 \qquad (11)$$

Where:

p_s = peak side on absolute pressure (Pa)

Error! Reference source not found. Figure 1 shows the scaled overpressure versus scaled distance data for pressure vessel bursts arrived at by CCPS[12] in graphical form in the range $10^{-2} \leq \overline{R} \leq 10^{0}$. It also includes a single curve for the high explosive, Pentolite, demonstrating that the pressure vessel overpressure data appears to coalesce with the high explosive overpressure data in the far field. This result compares well with work done by Adamczyk[13] who noted the equivalence in the far field of pressure vessel bursts with high explosives for high bursting pressure ratios and temperature ratios. Figure 3 shows the scaled overpressure versus scaled distance data for Pentolite only on the broader scale $10^{-2} \leq \overline{R} \leq 10^{3}$[iii], and it is the curve used for scaled distances in the range of $10 \leq \overline{R} \leq 10^{3}$.

Figure 2 shows the scaled impulse versus scaled distance data for pressure vessel bursts arrived at by CCPS[12] in the range $10^{-2} \leq \overline{R} \leq 10^{0}$.

2.4 Blast Parameters of Grounded and Cylindrical Vessel Bursts

- Elevated spherical vessels

When an explosion takes place close to the ground, the shock wave will be reflected by the earth. The constructive interference from the reflected wave increases the strength of the first. The CCPS[12] recommend, based on results of Baker et al [3] for high explosives, that the energy of a ground burst explosion be multiplied by 2 and that the blast parameters $\overline{P}_s$ and $\overline{I}$, for spherical vessel bursts, be multiplied by the factors given respectively in Figure 4 and Figure 5 at the given scaled distance. The correction factors are a function of both the scaled distance and the ratio of vessel elevation to vessel radius. The vessel elevation is measured from the centre of the spherical vessel to the ground level.

- Grounded cylinder vessels

When a blast occurs from a non-spherical vessel, the resulting blast wave will also be non-spherical thus increasing complicity to numerical calculations and experiments which need to be made in two or three dimensions. The blast wave of a cylindrical vessel will be weaker along its axis as opposed to normal to its axis. Since strong shock waves travel faster than weaker shock waves it is logical that the shock wave approaches spherical in the far field. The CCPS[12] recommends the blast parameters, $\overline{P}_s$ and $\overline{I}$, to be predicted using the methods given above for spherical vessels with correction factors as given in Figure 6 and Figure 7 to correct for the influence of shape where cylindrical vessel bursts are modelled. The correction factors are dependent on both the scaled distance and the ratio of length to diameter of the cylindrical vessel. According to CCPS[12] correction factors can be applied to both vertical and horizontal cylinders placed directly on the ground. However, the blast wave from a cylindrical vessel is weakest along its axis. Thus the blast field is asymmetrical for a vessel placed horizontally. The correction factors given by CCPS[12] is for the direction normal to the vessel axis but it is sued for all directions, so this will provide conservative predictions.

- Elevated cylindrical vessels

[iii]

Correction factors are multiplied where both corrections, for elevation and for vessel shape, are required. The vessel elevation for the case of cylindrical vessels is measured from the bottom of the vessel and not from the centre of the sphere as is the case of spherical vessels.

3 VALIDATION AND ACCURACY

The BLEVE-blast model can be employed in determining:

- Overpressure at a given distance, OR
- Distance at a given overpressure

The determination of distance at a given overpressure requires an iterative solution. This involves calculating overpressures from guessed distances until a distance that matches the given overpressure is obtained. Algorithms that describe the solution procedure for the two problem statements mentioned above have been presented in BLBL_design.doc

Details of verification, validation, and sensitivity analysis of the BLEVE-blast model, using the algorithms described in BLBL_design.doc, are presented and discussed elsewhere (see BLBL_Testing.doc).

With respect to accuracy, the methods presented give upper estimates of blast parameters. The CCPS[2] states that the blast parameters from experimental vessel bursts vary widely even in well controlled conditions.

A major source of deviation can be found in estimates of explosion energy. It is uncertain whether the suggested calculation of explosion energy gives a good prediction and in addition the energy converted to the kinetic energy in not taken into account. According to the CCPS[2] this can produce an error in the explosion energy of up to 50% which translates to an overstatement of overpressure by 25%.

In practice, releases will not be spherical as it is assumed and ductile fractures may produce a highly directional shock wave. In the near field overpressure along the major axis may be as low as one quarter of those along the minor axis.

There is no relation for peak shock overpressure from a superheated liquid. In addition it is assumed that all superheated liquid can flash explosively, regardless of whether they are above their superheat limit temperature for atmospheric pressure or not. Furthermore the blast energies of the evaporating liquid and the expanding vapour are taken together while in practice they may produce separate blasts.

The CCPS[2] states that in practice explosion energy in an actual blast may only be estimated in this method within an order of magnitude and overpressures might well be as low as one-fifth of those predicted. Furthermore, there is need to crosscheck the value of predicted overpressures simulated by this method as it may exceed the maximum possible overpressure attainable following a vessel burst (i.e., $P_1 – P_0$). If this occurs, the CCPS[2] recommends that the calculated overpressure be replaced with ($P_1 – P_0$).

4 FUTURE DEVELOPMENTS

The following improvements to the current model may be considered for future implementation

Fragments

The energy translated into kinetic energy of fragments and ejected liquid is not subtracted from the blast energy which translates into an over prediction of overpressure. It may be possible to develop an adjusted relation for explosion energy for this effect.

APPENDICES

Appendix A *Assumptions for curve reading for the computational model*

Assumptions are necessary in order to compute values of scaled overpressure, and scaled impulse at a given scaled distance using the curves of Baker et al [3] (section **2.3**).

All curves have been plotted using selected points, extracted from Figure 1 to Figure 4 , and reproduced on a log-log scaled axis (see Extracted-Bleve-Blast-Data.xls). Each curve was subsequently fitted to a sixth order polynomial. Details of the procedure employed in extracting data from the figures mentioned above, and obtaining the coefficients of the polynomial curve fits employed in the model are presented in BLBL_design.doc.

When using Figure 1, the CCPS guidelines recommend using the curve on which the pair of values $\overline{R}_0$ and $\overline{P}_{S0}$ lie or else drawing a parallel curve to the nearest curve. If point ($\overline{R}_0$, $\overline{P}_{S0}$) lies between two curves, the approach taken in the model is to interpolate using the ratio of distance between the point ($\overline{R}_0$, $\overline{P}_{S0}$) and the lowermost of the two curves, and the distance between the two curves. If ($\overline{R}_0$, $\overline{P}_{S0}$) lies above the top most curve (curve 1), it is assumed unreasonable that the overpressure should be greater than that for the high explosive, Pentolite, and therefore curve 1 (Pentolite is used). However, if ($\overline{R}_0$, $\overline{P}_{S0}$) lies below the Pentolite curve but is not enclosed by any of the vessel burst curves for which data is available at $\overline{R}_0$, then the nearest curve to ($\overline{R}_0$, $\overline{P}_{S0}$) is determined, and a curve parallel to the nearest curve which passes through ($\overline{R}_0$, $\overline{P}_{S0}$) is drawn. For the latter case, the newly drawn parallel curve is employed in subsequent overpressure and distance calculations. Curves 1-6 are assumed to have a lower bound, approximated from Figure 1 of 10-1.82. This means that curves 2 and 6 are extrapolated back to this point which will fall in line with the CCPS recommendation of drawing parallel curves to the nearest curve for which data is available. Curves 3-8 in Figure 1 are assumed by the model to merge with the high explosive, Pentolite curve (curve 1). Curves 8 – 11 are assumed to have lower bounds, approximated from Figure 1 as given in Table 1.

Table 1 Lower bounds for curves 8, 9, 10 and 11

I	**Lower** $\overline{R}$
8	0.042
9	0.1
10	0.224
11	0.289

FIGURES

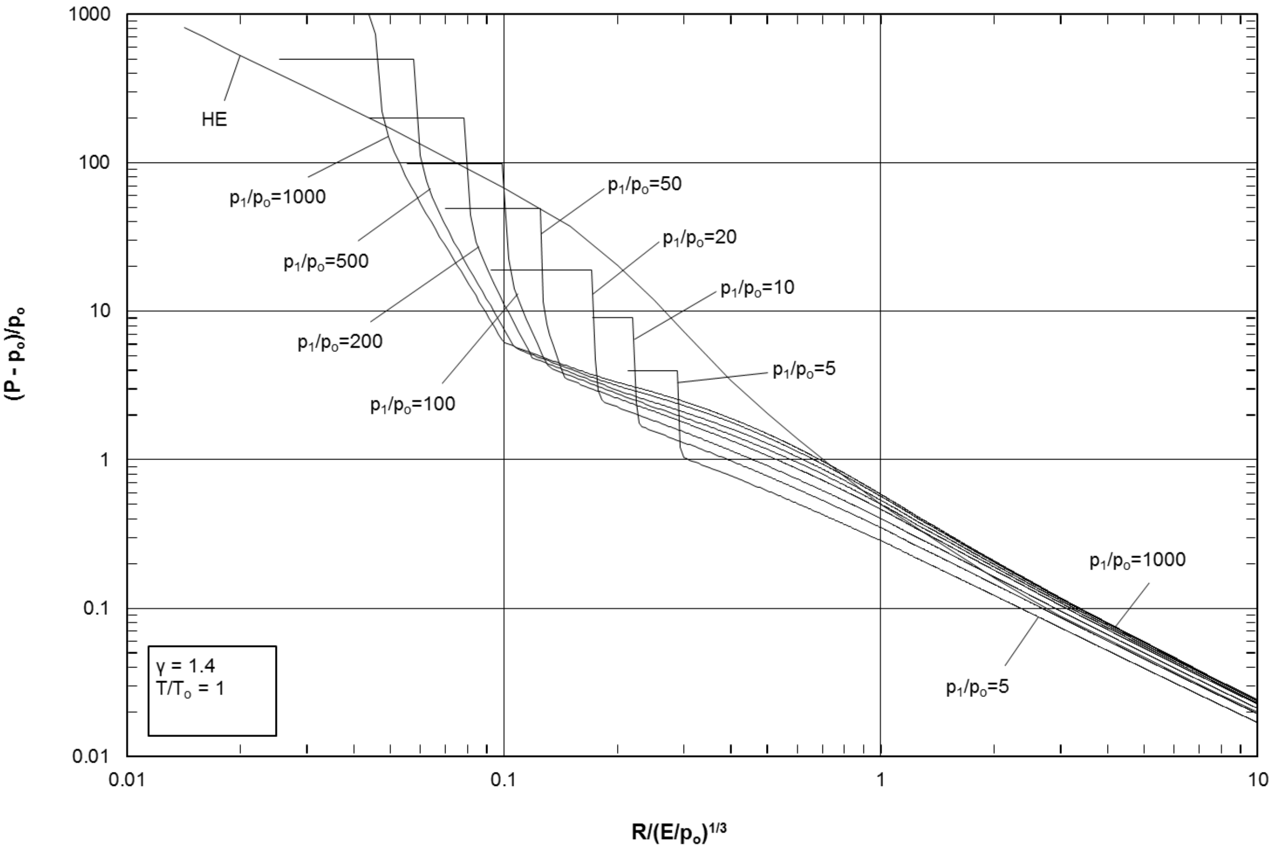

Figure 1 Scaled Overpressure vs. Scaled Distance (CCPS^2 guidelines)

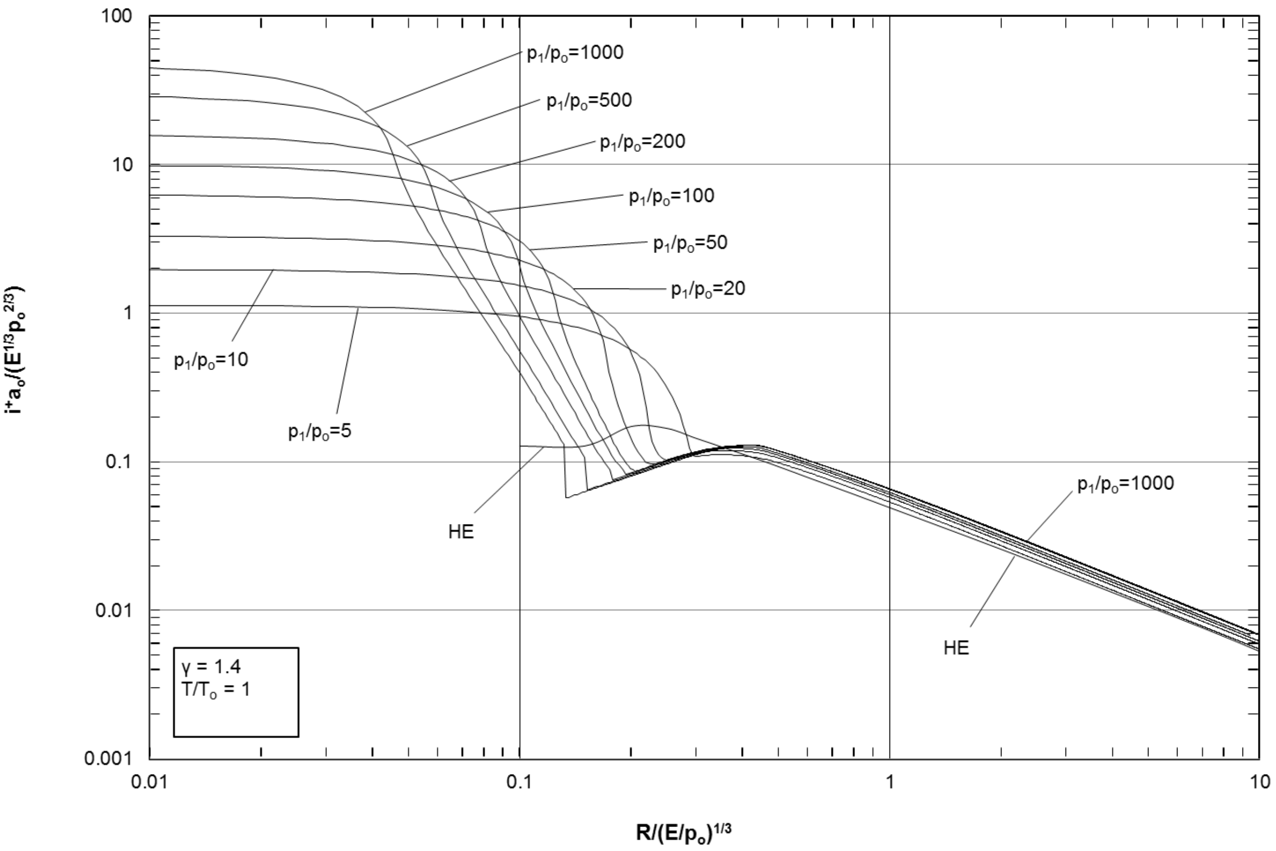

Figure 2 Scaled Impulse vs. Scaled Distance for gas vessel bursts (CCPS[2] guidelines)

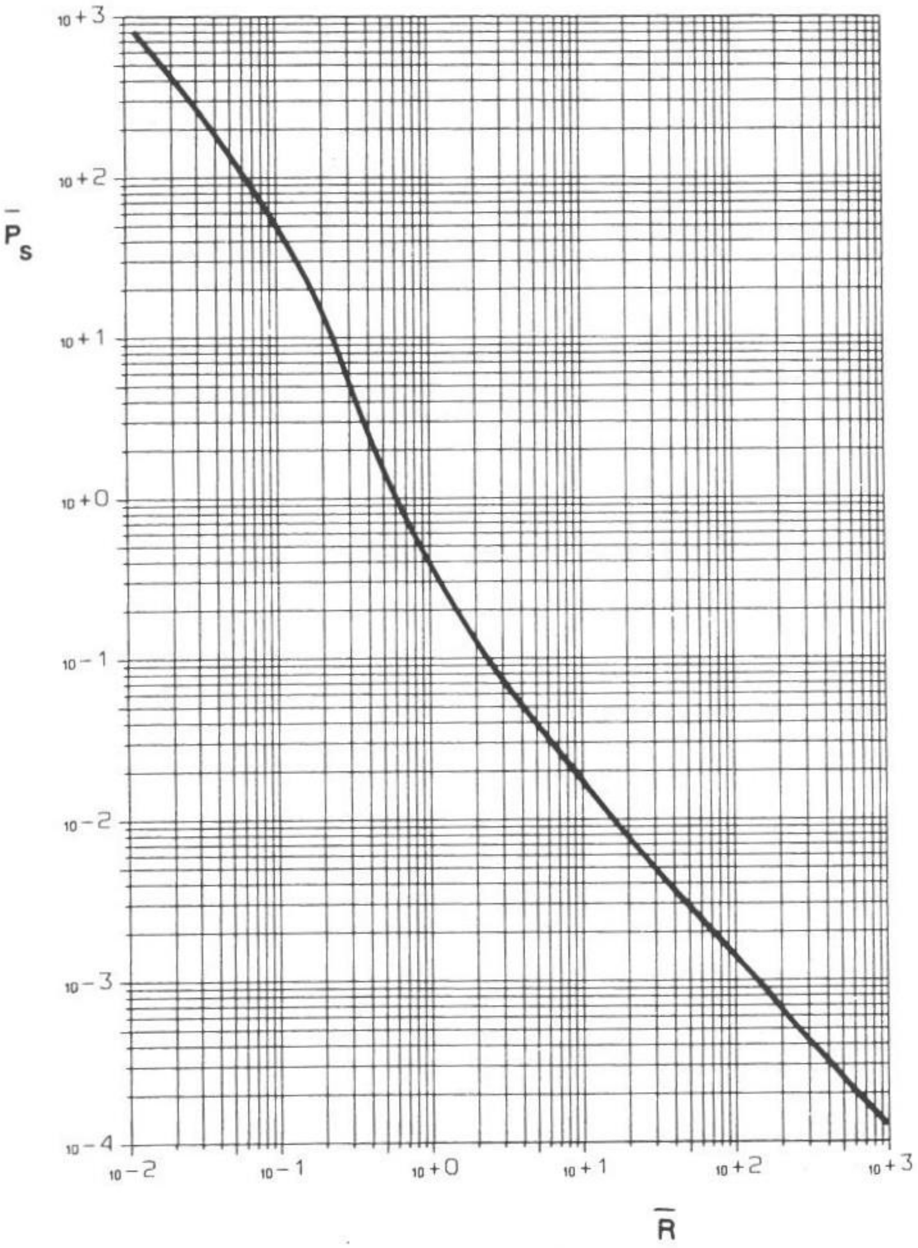

Figure 3. Scaled Overpressure vs. Scaled Distance for Pentolite (Baker et al 3)

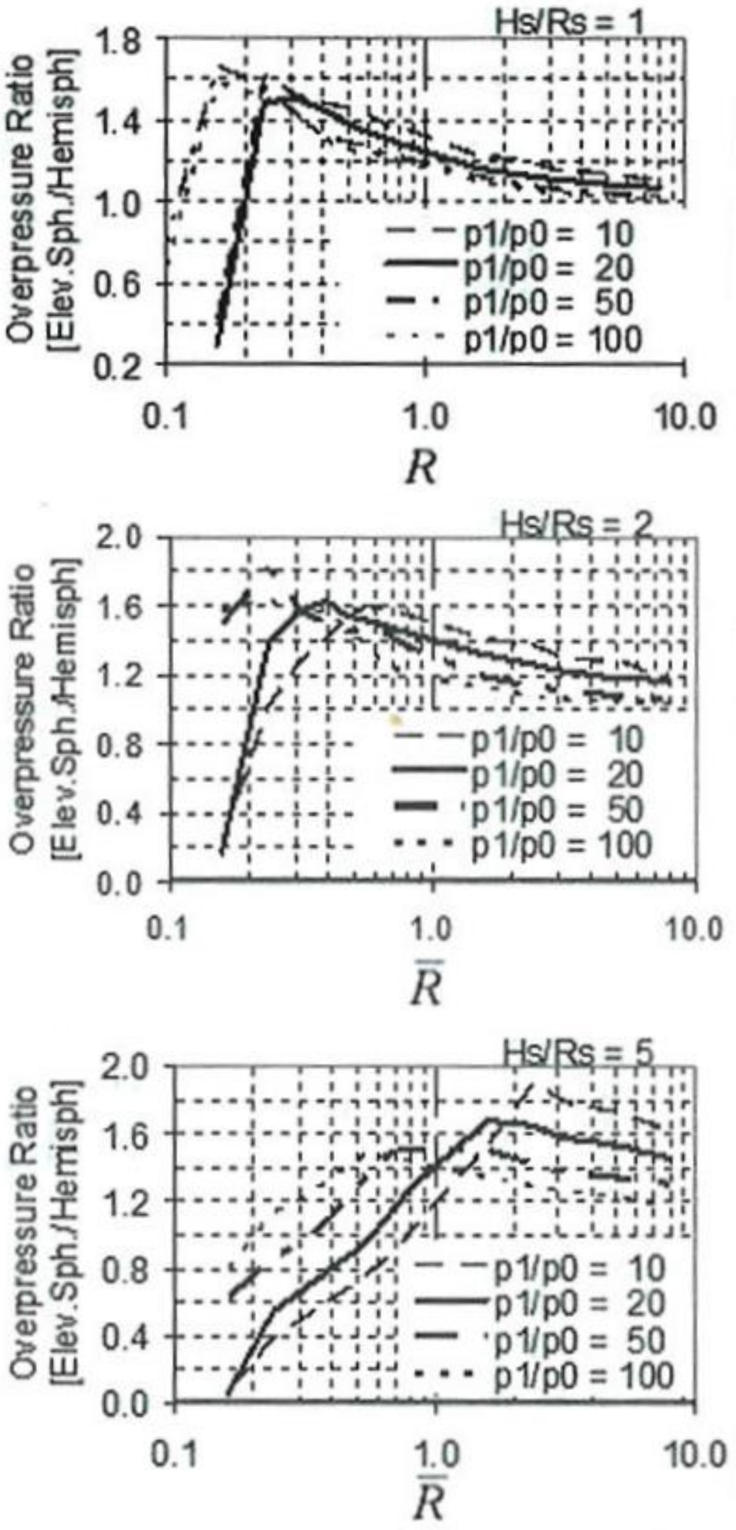

Figure 4. **Correction factors for overpressure vs scaled distance for spherical vessels at different height to radius ratios (Hs/Rs)**

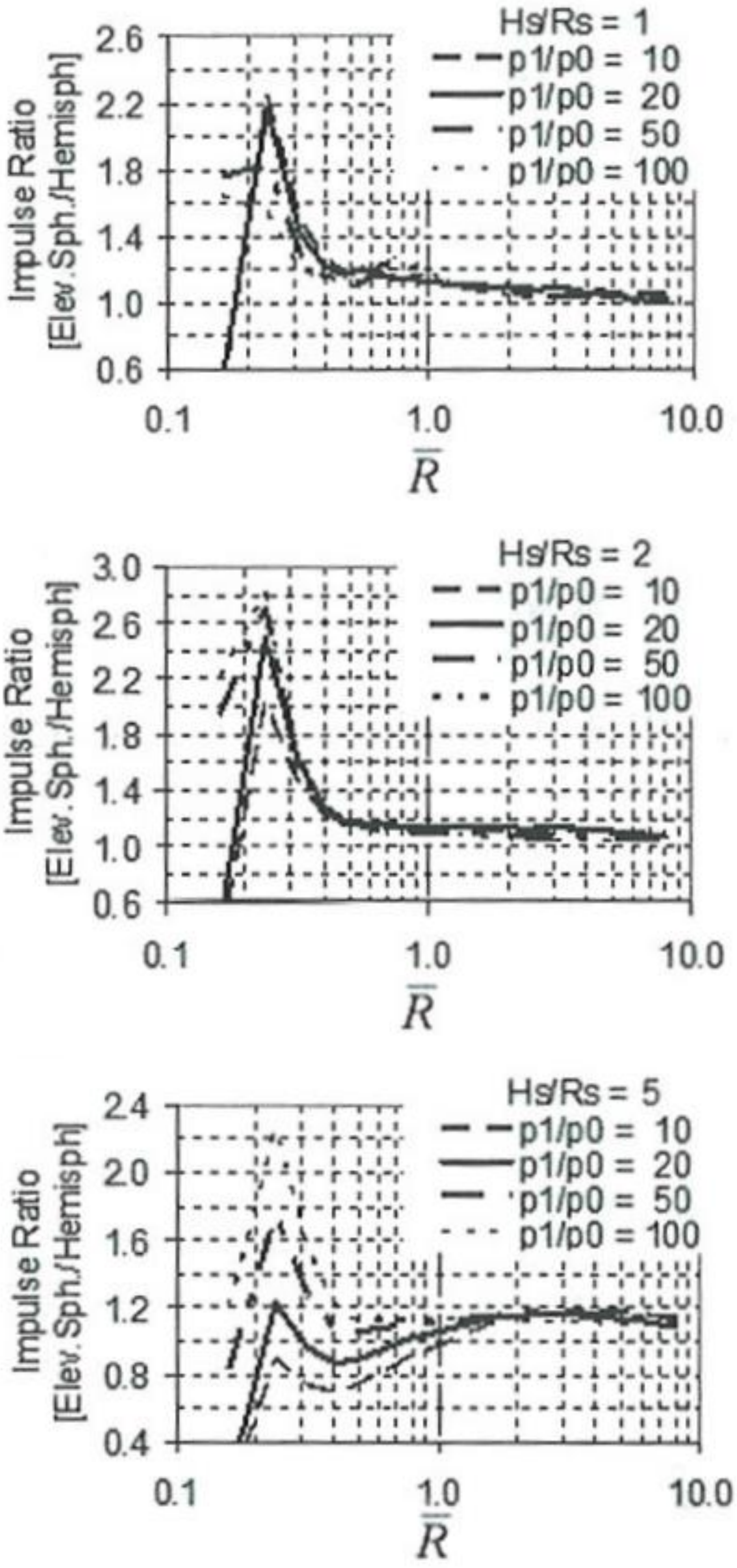

Figure 5. **Correction factors for impulses vs scaled distance for spherical vessels at different height to radius ratios (Hs/Rs)**

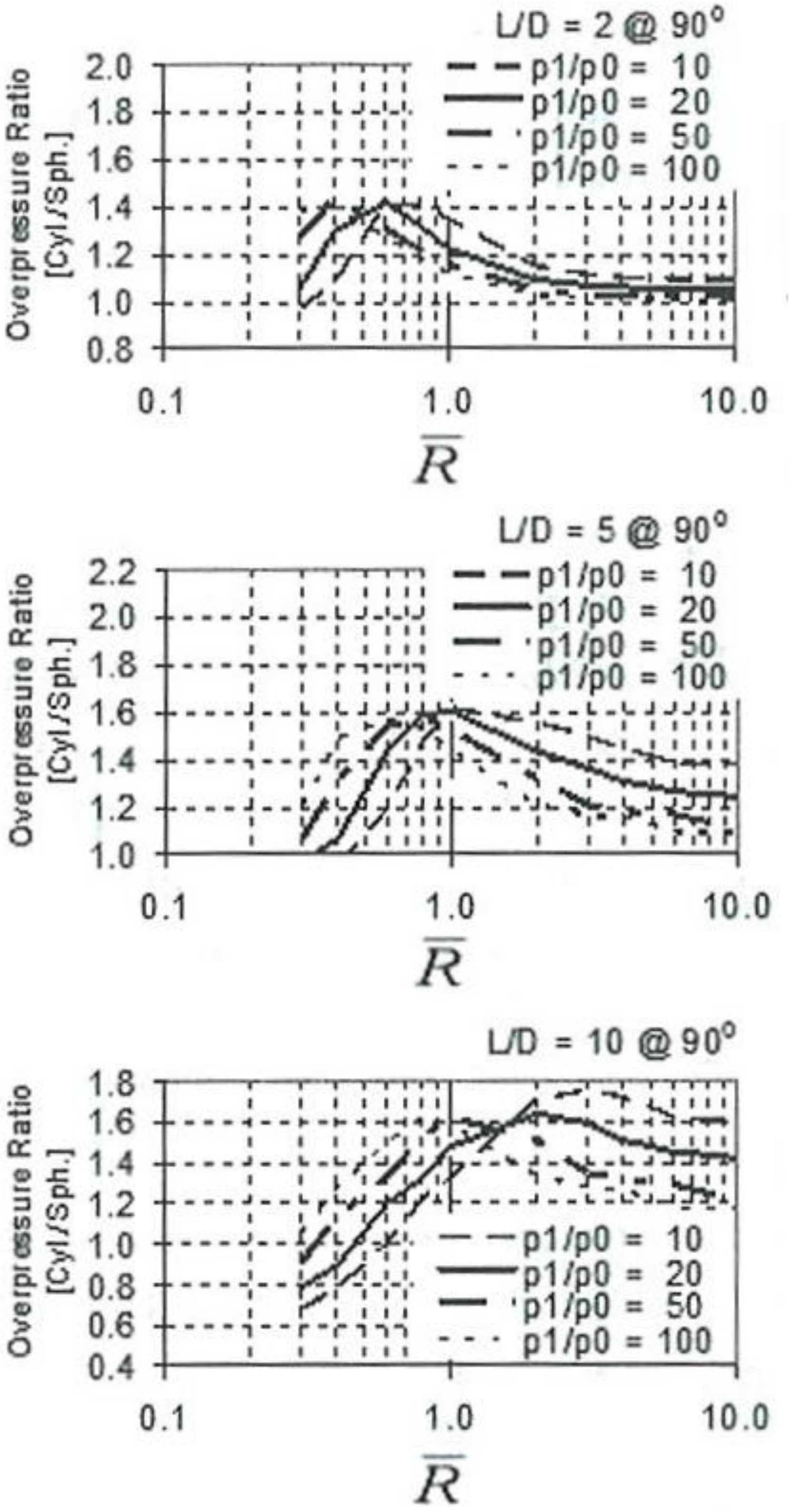

Figure 6. **Correction factors for overpressures vs scaled distance for cylindrical vessels at different length to diameter ratios (L/D)**

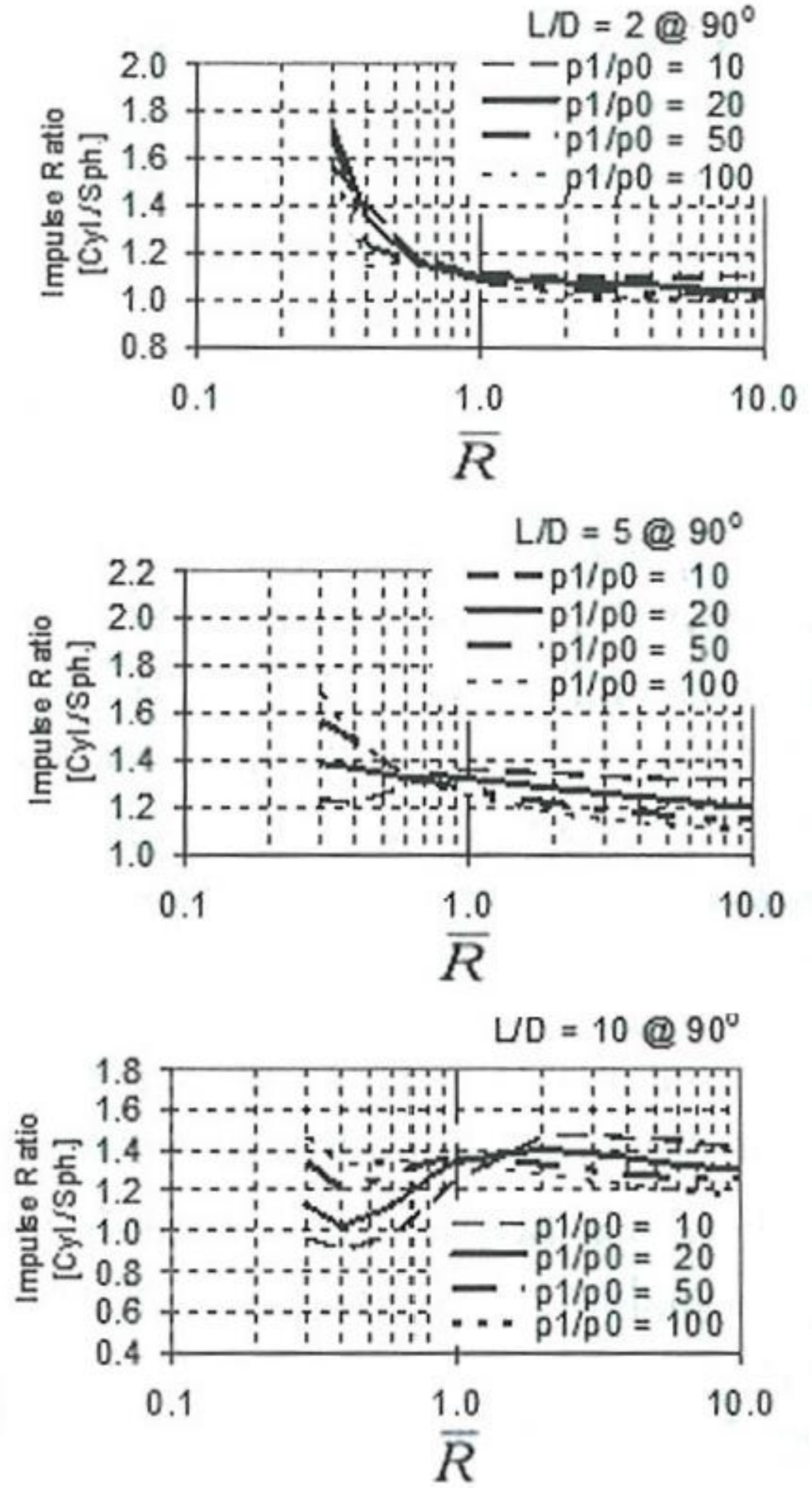

Figure 7. **Correction factors for impulses vs scaled distance for cylindrical vessels at different length to diameter ratios (L/D)**

NOMENCLATURE

T_{sl}	superheat limit temperature at atmospheric pressure (K)
T_c	critical temperature (K)
U	internal energy (J)
P	absolute pressure (Pa)
P_0	absolute pressure of ambient air (Pa)
V	volume (m^3)
γ	ratio of constant pressure, C_p , and constant volume, C_v , specific heat capacities (-)
h	specific enthalpy (J/kg)
h_L	specific enthalpy of the saturated liquid (J/kg)
h_G	specific enthalpy of the saturated vapour (J/kg)
u	specific internal energy (J/kg)
v	specific volume (m^3)
v_L	specific volume of the saturated liquid (m^3/kg)
v_G	specific volume of the saturated vapour (m^3/kg)
x_L	mass fraction of liquid (-)
T	temperature (K)
E_{EX}	Explosion energy (J)
$E_{EX,Br}$	Brode's Explosion energy (J)
M	mass of fluid (kg)
$\overline{R}$	blast scaled distance (-)
$\overline{P}_S$	blast scaled overpressure (-)
$\overline{I}$	blast scaled impulse (-)
r	distance from the explosion source (m)
r_0	distance from the explosion source of the shock wave immediately after failure (m)
$\overline{R}_0$	blast scaled distance of the shock wave immediately after failure (-)
$\overline{P}_{S0}$	blast scaled overpressure immediately after failure (-)

a_0	speed of sound in ambient air (m/s)
i_s	positive phase side on impulse (Pa.s)

Subscripts

1	denotes fluid at the initial state of failure
2	denotes fluid at the final state after expansion to atmospheric pressure.

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