2.2.3. Physical Explosion

2.2.3.1. BACKGROUND

Purpose
When a vessel containing a pressurized gas ruptures, the resulting stored energy is released. This energy can produce a shock wave and accelerate vessel fragments. If the contents are flammable it is possible that ignition of the released gas could result in additional consequence effects. Figure 2.46 illustrates possible scenarios that could result. This subsection illustrates calculation tools for both shock wave and projectile effects from this type of explosion.

Philosophy
A physical explosion relates to the catastrophic rupture of a pressurized gas filled vessel. Rupture could occur for the following reasons:

1. Failure of pressure regulating and pressure relief equipment (physical overpressurization)
2. Reduction in vessel thickness due to
   a. corrosion
   b. erosion
   c. chemical attack
3. Reduction in vessel strength due to
   a. overheating
   b. material defects with subsequent development of fracture
   c. chemical attack, e.g., stress corrosion cracking, pitting, embrittlement
   d. fatigue induced weakening of the vessel
4. Internal runaway reaction.
5. Any other incident which results in loss of process containment.

Failure can occur at or near the operating pressure of the vessel (items 2 and 3 above), or at elevated pressure (items 1 and 4 above).

When the contents of the vessel are released both a shock wave and projectiles may result. The effects are more similar to a detonation than a vapor cloud explosion (VCE). The extent of a shock wave depends on the phase of the vessel contents originally present. Table 2.22 describes the various scenarios.

There is a maximum amount of energy in a bursting vessel that can be released. This energy is allocated to the following:

- vessel stretch and tearing
- kinetic energy of fragments
- energy in shock wave
- “waste” energy (heating of surrounding air)

The relative distribution of these energy terms will change over the course of the explosion. Exactly what proportion of available energy will actually go into the production of shock waves is difficult to determine. Saville (1977) in the UK High Pressure Safety Code suggests that 80% of the available system energy becomes shock wave energy for brittle type failure. For the ejection of a major vessel section, 40% of the
available system energy becomes shock wave energy. For both cases, the remainder of the energy goes to fragment kinetic energy.

In general, physical explosions from catastrophic vessel rupture will produce directional explosions. This occurs because failure usually occurs from crack propagation starting at one location. If the failure were brittle, resulting in a large number of fragments, the explosion would be less directional. However, the treatment of shock waves from this type of failure usually does not consider directionality.

2.2.3.2. DESCRIPTION

Description of Technique

Several methods relate directly to calculation of a TNT equivalent energy and use of shock wave correlations as in Figure 2.48 and Table 2.17. There are various expressions that can be developed for calculating the energy released when a gas initially having a volume, $V$, expands in response to a decrease in pressure from a pressure, $P_1$, to atmospheric pressure, $P_0$. The simplest expression is due to Brode (1959). This expression determines the energy required to raise the pressure of the gas at constant volume from atmospheric pressure, $P_0$, to the initial, or burst, pressure, $P_1$,

$$E = \frac{(P_1 - P_0)V}{\gamma - 1}$$

(2.2.11)

where $E$ is the explosion energy (energy), $V$ is the volume of the vessel (volume), and $\gamma$ is the heat capacity ratio for the expanding gas (unitless).

If it is assumed that expansion occurs isothermally and that the ideal gas law applies, the following equation can be derived (Brown, 1985):

$$W = \left(1.39 \times 10^{-6} \ \frac{\text{lb} - \text{mole}}{\text{ft}^3} \frac{\text{lb} - \text{TNT}}{\text{BTU}}\right) V \left(\frac{P_1}{P_0}\right) R_g T_0 \ln\left(\frac{P_1}{P_2}\right)$$

(2.2.12)

where

- $W$ is the energy (lb TNT)
- $V$ is the volume of the compressed gas (ft$^3$)
- $P_1$ is the initial pressure of the compressed gas (psia)
- $P_2$ is the final pressure of expanded gas (psia)
- $P_0$ is the standard pressure (14.7 psia)

### Table 2.22. Characteristics of Various Types of Physical Explosions

<table>
<thead>
<tr>
<th>Type</th>
<th>Shock Wave Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas-filled vessel</td>
<td>Expansion of gas</td>
</tr>
<tr>
<td>Liquid-filled vessel</td>
<td>Expansion of gas from vapor space volume; liquid contents unchanged and runs out.</td>
</tr>
<tr>
<td>Liquid temperature &lt; Liquid boiling point</td>
<td>Expansion of gas from vapor space volume coupled with flash evaporation of liquid.</td>
</tr>
</tbody>
</table>
is the standard temperature (492°F)

Rg is the gas constant (1.987 Btu/lb-mole-F)

1.39 \times 10^{-6} is a conversion factor (this factor assumes that 2000 BTU = 1 lb TNT)

Another approach (Crowl, 1992) is to apply the concept of available energy. Available energy represents the maximum mechanical energy that can be extracted from a material as it moves into equilibrium with the environment. Crowl (1992) showed that for a nonreactive material initially at a pressure \( P \) and temperature \( T \), expanding into an ambient pressure of \( P_E \), then the maximum mechanical energy, \( E \), derivable from this material is given by

\[
E = R_g T \left[ \ln \left( \frac{P}{P_E} \right) - \left( 1 - \frac{P_E}{P} \right) \right]
\]  

(2.2.13)

Note that the first term within the brackets is equivalent to the isothermal energy of expansion. The second term within the parenthesis represents the loss of energy as a result of the second law of thermodynamics. The result predicted by Eq. (2.2.13) is smaller than the result predicted assuming an isothermal expansion, but greater than the result assuming an adiabatic expansion.

The calculated equivalent amount of TNT energy can now be used to estimate shock wave effects. The analogy of the explosion of a container of pressurized gas to a condensed phase point source explosion of TNT is not appropriate in the near field since the vessel is not a point source. Prugh (1988) suggests a correction method using a virtual distance from an explosion center based on work by Baker et al. (1983) and Petes (1971). This method is described below.

When an idealized sphere bursts, the air shock has its maximum overpressure right at the contact surface between the gas sphere and the air. Since, initially, the flow is strictly one-dimensional, a shock tube relationship between the bursting pressure ratio and shock pressure can be used to calculate the pressure in the air shock. The blast pressure, \( P_b \), at the surface of an exploding pressure vessel is thus estimated from the following expression (Baker et al., 1983; Prugh, 1988):

\[
P_b = P_s \left( 1 - \frac{3.5(y - 1)(P_s - 1)}{\sqrt{y T/M} (1 + 5.9 P_s)} \right)^{-2y/(y-1)}
\]  

(2.2.14)

where

- \( P_s \) is the pressure at the surface of the vessel (bar abs)
- \( P_b \) is the burst pressure of the vessel (bar abs)
- \( y \) is the heat capacity ratio of the expanding gas (\( C_p/C_v \))
- \( T \) is the absolute temperature of the expanding gas (K)
- \( M \) is the molecular weight of the expanding gas (mass/mole)

The above equation assumes that expansion will occur into air at atmospheric pressure at a temperature of 25°C. A trial and error solution is required since the equation is not explicit for \( P_s \).

Equation (2.2.14) also assumes that the explosion energy is distributed uniformly across the vessel. In reality this is rarely the case.
The procedure of Prugh (1988) for determining the overpressure at a distance from a bursting vessel is as follows:

1. Determine the energy of explosion using Eq. (2.2.12).
2. Determine the blast pressure at the surface of the vessel, \( P_s \), using Eq. (2.2.14). This is a trial and error solution.
3. The scaled distance, \( Z \), for the explosion is obtained from Figure 2.48, or the equations in Table 2.17. Most pressure vessels are at or near ground level.
4. A value for the distance, \( R \), from the explosion center is calculated using Eq. (2.2.7) where the equivalent energy of TNT, \( W \), has been calculated from Eq. (2.2.1).
5. The distance from the center of the pressurized gas container to its surface is subtracted from the distance, \( R \), to produce a virtual "distance" to be added to distances for shock wave evaluations.
6. The overpressure at any distance is determined by adding the virtual distance to the actual distance, and then using this distance to determine \( Z \), the scaled distance. Figure 2.48 or Table 2.17 is used to determine the resulting overpressure.

AIChE/CCPS (1994) describe a number of techniques for estimating overpressure for a rupture of a gas filled container. These methods are derived mostly from the work of Baker et al. (1983) based on small scale experimental studies.

The first method is called the "basic method" (AIChE/CCPS, 1994). The procedure for this method is

1. Collect data. This includes:
   - the vessel's internal absolute pressure, \( P_1 \)
   - the ambient pressure, \( P_0 \)
   - the vessel's volume of gas filled space, \( V \)
   - the heat capacity ratio of the expanding gas, \( \gamma \)
   - the distance from the center of the vessel to the "target," \( r \)
   - the shape of the vessel: spherical or cylindrical
2. Calculate the energy of explosion, \( E \), using the Brode equation, Eq. (2.2.11). The result must be multiplied by 2 to account for a surface explosion.
3. Determine the scaled distance, \( \bar{R} \), from the target using
   \[
   \bar{R} = r \left( \frac{P_0}{E} \right)^{1/3}
   \] (2.2.15)
4. Check the scaled distance. If \( \bar{R} < 2 \) then this procedure is not applicable and the refined method described later must be applied.
5. Determine the scaled overpressure, \( \bar{P}_o \), and scaled impulse, \( \bar{i}_s \), using Figures 2.58 and 2.59, respectively.
6. Adjust \( \bar{P}_o \) and \( \bar{i}_s \) for geometry effects using the multipliers shown in Tables 2.23 and 2.24.
7. Determine the final overpressure and impulse from the definitions of the scaled variables.
8. Check the final overpressure. In the near field, this approach might produce a pressure higher than the vessel pressure, which is physically impossible. If this occurs, take the vessel pressure as the calculated overpressure.
If $R < 2$, then the above procedure must be replaced by a more detailed approach (AIChE/CCPS, 1994). This approach replaces steps 4 and 5 above in the basic procedure with the following steps:

4a. Calculate the initial vessel radius. A hemispherical vessel on the ground is assumed for this calculation. From simple geometry for a sphere, the following equation for the initial vessel radius is obtained:

$$r_0 = \left( \frac{3V}{2\pi} \right)^{1/3} = 0.782V^{1/3} \quad (2.2.16)$$

where $r_0$ is the initial vessel radius (length) and $V$ is the vessel volume (length$^3$)
TABLE 2.23. Adjustment Factors for $\bar{P}$, and $\bar{i}$, for Cylindrical Vessels as a Function of $\bar{R}$ (Baker et al., 1975)

<table>
<thead>
<tr>
<th>$\bar{R}$</th>
<th>$\bar{P}$</th>
<th>$\bar{i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;0.3$</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>$\geq0.3 \leq1.6$</td>
<td>1.6</td>
<td>1.1</td>
</tr>
<tr>
<td>$&gt;1.6 \leq3.5$</td>
<td>1.6</td>
<td>1</td>
</tr>
<tr>
<td>$&gt;3.5$</td>
<td>1.4</td>
<td>1</td>
</tr>
</tbody>
</table>

TABLE 2.24. Adjustment Factors for $\bar{P}$, and $\bar{i}$, for Spherical Vessels as a Function of $\bar{R}$ (Baker et al., 1975)

<table>
<thead>
<tr>
<th>$\bar{R}$</th>
<th>$\bar{P}$</th>
<th>$\bar{i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;1$</td>
<td>2</td>
<td>1.6</td>
</tr>
<tr>
<td>$&gt;1$</td>
<td>1.1</td>
<td>1</td>
</tr>
</tbody>
</table>

Scaled variable definitions:

$$\bar{R} = r \left( \frac{P_0}{E} \right)^{1/3}, \quad \bar{P} = \frac{P}{P_0} - 1, \quad \bar{i} = \frac{i_i a_0}{a_0 R_0^{2/3} E^{1/3}}$$

4b. Determine the initial starting distance, $\bar{R}_0$, for the overpressure curve,

$$\bar{R}_0 = r_0 \left( \frac{P_0}{E} \right)^{1/3}$$ (2.2.17)

4c. Calculate the initial peak pressure, $P_0$, using Eq. (2.2.14). A trial and error solution is required.

4d. Locate the starting point on the overpressure curves of Figure 2.60 using $\bar{R}_0$ and $P_0$. The closest curve shown on the figure, or an interpolated curve is appropriate here.

5. Determine $P_0$ at another $\bar{R}$ from Figure 2.60 using the curve (or interpolated curve) which goes through the starting point of step 4d.

Tang et al. (1996) present the results of a detailed numerical simulation procedure to model the effects of a bursting spherical vessel. They numerically solved the nonsteady, nonlinear, one-dimensional flow equations. This resulted in a more detailed figure to replace Figure 2.60.

AIChE/CCPS (1994) also provides a more detailed method to include the effects of explosively flashing liquids during a vessel rupture.

**Projectiles**

When a high explosive detonates, a large number of small fragments with high velocity and chunky shape result (AIChE/CCPS, 1994). In contrast, a BLEVE produces only a few fragments, varying in size (small to large), shape (chunky or disk shaped), and ini-
Scaled Distance, $R = r \left( \frac{P_0}{E} \right)^{1/3}$

**FIGURE 2.60.** Scaled overpressure curve for rupture of a gas-filled vessel for the more detailed method.

tial velocities. Fragments can travel long distances because large, half-vessel fragments can “rocket” and disk-shaped fragments can “frisbee.” Schulz-Forberg et al. (1984) describe an investigation of BLEVE-induced vessel fragmentation. Baum (1984) also discusses velocities of missiles from bursting vessels and pipes.

Baker et al. (1983), Brown (1985, 1986) and AIChE/CCPS (1994) provide formulas for prediction of projectile effects. They consider fracture of cylindrical and spherical vessels into 2, 10, and 100 fragments. Typically, for these types of events, only 2 or 3 fragments occur.

The first part of the calculation involves the estimation of an initial velocity. Once fragments are accelerated they will fly through the air until they impact another object or target on the ground. The second part of the calculation involves estimation of the distance a projectile could travel.

In general, according to Baker et al. (1983), the technique for predicting initial fragment velocities for spherical or cylindrical vessels bursting into equal fragments requires knowledge of the internal pressure ($P$), internal volume ($V_0$), mass of the container/fragment ($M_c$), ratio of the gas heat capacities ($\gamma$), and the absolute temperature of the gas at burst ($T_0$).

The results of a parameter study (Baker et al., 1983) were used to develop Figure 2.61, which is used to determine the initial fragment velocity, $u$. The scaled pressure in Figure 2.61 is given by

$$\bar{P} = \frac{(P - P_0)V}{M_c a_0^2}$$

(2.2.18)

where

- $\bar{P}$ is the scaled pressure (unitless)
- $P$ is the burst pressure of the vessel (force/area)
Scaled Pressure, $P = (P - P_0) V / (M_c a_0^2)$

FIGURE 2.61. Scaled fragment velocity versus scaled pressure (Baker et al., 1983).

$P_0$ is the ambient pressure of the surrounding gas (force/area)

$V$ is the volume of the vessel (length$^3$)

$M_c$ is the mass of the container (mass)

$a_0$ is the speed of sound of the initial gas in the vessel (length/time)

The speed of sound for an ideal gas is computed from

$$a_0 = \left(\frac{T y R_g}{M}\right)^{1/2} \quad (2.2.19)$$

where

$a_0$ is the speed of sound (length/time)

$T$ is the absolute temperature (temperature)

$\gamma$ is the heat capacity ratio of the gas in the vessel (unitless)

$R_g$ is the ideal gas constant (pressure - volume/mole deg)

$M$ is the molecular weight of the gas in the vessel (mass/mole)

The $y$-axis in Figure 2.61 is the dimensionless velocity given by

$$\frac{v_i}{K a_0} \quad (2.2.20)$$

where $v_i$ is the velocity of the fragment (length/time), $K$ is a correction factor for unequal mass fragments given by Figure 2.62, and $a_0$ is the speed of sound of the gas in the vessel (length/time).

Table 2.25 contains curve fit equations for the fragment velocity correlations presented in Figure 2.61. The data in Figure 2.62 are curve fit by the equation

$$K = 1.306 \times (\text{Fragment Mass Fraction}) + 0.308446 \quad (2.2.21)$$

The procedure for applying this approach is as follows:

1. Given: Number of fragments, $n$
   Total mass of vessel, $M_c$
   Mass fraction for each fragment
TABLE 2.25. Curve Fit Equations for the Fragment Velocity Data of Figure 2.61

\[
\ln \left( \frac{\nu_i}{K_0} \right) = a \ln \bar{P} + b
\]

<table>
<thead>
<tr>
<th>Number of fragments, ( n )</th>
<th>Spheres</th>
<th>Cylinders</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a )</td>
<td>( b )</td>
<td>( a )</td>
</tr>
<tr>
<td>2</td>
<td>0.622206</td>
<td>0.213936</td>
</tr>
<tr>
<td>10</td>
<td>0.598495</td>
<td>0.221165</td>
</tr>
<tr>
<td>100</td>
<td>0.603469</td>
<td>0.287515</td>
</tr>
</tbody>
</table>

Variables:
- \( \nu_i \) is the velocity of the fragment (length/time)
- \( K \) is the correction factor for unequal fragments
- \( a_0 \) is the speed of sound of the gas in the vessel (length/time)
- \( \bar{P} \) is defined by Eq. (2.2.18)

Internal burst pressure of vessel, \( P \)
Volume of vessel, \( V \)
Ambient pressure, \( P_0 \)
Absolute temperature of gas in vessel, \( T \)
Heat capacity ratio of gas in vessel, \( \gamma \)
Molecular weight of gas in vessel, \( M \)

2. Determine speed of sound of gas in vessel using Eq. (2.2.19).
3. Determine scaled pressure using Eq. (2.2.18).
4. Determine dimensionless velocity from Figure 2.61 or Table 2.25.
5. Determine unequal fragment correction from Figure 2.62 or Eq. (2.2.21).
6. Determine actual velocity for each fragment using Eq. (2.2.20).

An empirically derived formula developed by Moore (1967) provides a simplified method to determine the initial velocity, \( u \), of a fragment,

\[
u = 1.092 \left( \frac{EG}{M_c} \right)^{1/2} \tag{2.2.22}
\]

where for spherical vessels

\[
G = \left( 1 + \frac{3C}{5M_c} \right)^{-1} \tag{2.2.23}
\]

and for cylindrical vessels

\[
G = \left( 1 + \frac{C}{2M_c} \right)^{-1} \tag{2.2.24}
\]

where
- \( u \) is the initial fragment velocity (m/s)
- \( C \) is the total gas mass (kg)
- \( E \) is the energy (J)
- \( M_c \) is the mass of casing or vessel (kg)
Moore's equation was derived for fragments accelerated from high explosives packed in a casing. The equation predicts velocities higher than actual, especially for low pressures and few fragments.

For pressurized vessels, a simplified method to determine the initial velocity of a fragment is by the Moore (1967) equation,

$$u = 2.05 \sqrt[2]{\frac{PD^3}{W}}$$

where
- $u$ is the initial velocity of the fragment (ft/s)
- $P$ is the rupture pressure of the vessel (psig)
- $D$ is the fragment diameter (inches)
- $W$ is the weight of the fragment (lb)

The next step is to determine the distance the fragments will fly. From simple physics, it is well-known that an object will fly the greatest distance at a trajectory angle of 45°. The maximum distance is given by

$$r_{\text{max}} = \frac{u^2}{g}$$

where $r_{\text{max}}$ is the maximum horizontal distance (length), $u$ is the initial object velocity (length/time), and $g$ is the acceleration due to gravity (length/time$^2$).

Kinney and Graham (1985) suggest a very simple formula for estimating a safety distance from a bomb explosion

$$r = 120w^{1/3}$$

where $r$ is the distance (m) and $w$ is the mass of TNT (kg).

Baker et al. (1983) plotted the solutions to a set of differential equations, incorporating the effects of fluid-dynamic forces. The solutions are shown on Figure 2.63. The
results assume that the position of the fragment remains the same with respect to its trajectory, that is, that the fragment does not tumble. Figure 2.63 plots scaled maximum range, $R$, versus the scaled initial velocity, $\bar{u}$. These quantities are given by

$$
\bar{R} = \frac{\rho_0 C_D A_D r}{M_f}
$$

(2.2.28)

$$
\bar{u} = \frac{\rho_0 C_D A_D u^2}{M_f g}
$$

(2.2.29)

where
- $\bar{R}$ is the scaled maximal range (dimensionless)
- $\bar{u}$ is the scaled initial velocity (dimensionless)
- $r$ is the maximal range (length)
- $\rho_0$ is the density of the ambient atmosphere (mass/volume)
- $C_D$ is the drag coefficient, provided in Table 2.26 (unitless)
- $A_D$ is the exposed area in plane perpendicular to the trajectory (area)
- $g$ is the acceleration due to gravity (length/time$^2$)
- $M_f$ is the mass of the fragment (mass)

Figure 2.63 requires a specification of the lift-to-drag ratio,

$$
\frac{C_L A_L}{C_D A_D}
$$

(2.2.30)

where $C_L$ is the lift coefficient (unitless) and $A_L$ is the exposed area in the plane parallel to the trajectory (area).
For "chunky" fragments, which are normally expected, the lift coefficient is zero for these objects and the lift-to-drag ratio is thus zero. For thin plates, which have a large lift-to-drag ratio, the "frisbee" effect can occur, and the scaled range more than doubles the range calculated when lift forces are neglected. Refer to Baker et al. (1983, Appendix E, page 688) for a discussion and additional values for the lift coefficient, $C_l$. Table 2.26 contains drag coefficients for various shapes.

**TABLE 2.26. Drag Coefficients for Fragments (Baker et al., 1983)**

<table>
<thead>
<tr>
<th>Shape</th>
<th>Sketch</th>
<th>$C_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right circular cylinder (long rod), side on</td>
<td><img src="image" alt="Sketch of a right circular cylinder" /></td>
<td>1.20</td>
</tr>
<tr>
<td>Sphere</td>
<td><img src="image" alt="Sketch of a sphere" /></td>
<td>0.47</td>
</tr>
<tr>
<td>Rod, end on</td>
<td><img src="image" alt="Sketch of a rod, end on" /></td>
<td>0.82</td>
</tr>
<tr>
<td>Disk, face on</td>
<td><img src="image" alt="Sketch of a disk, face on" /></td>
<td>1.17</td>
</tr>
<tr>
<td>Cube, face on</td>
<td><img src="image" alt="Sketch of a cube, face on" /></td>
<td>1.05</td>
</tr>
<tr>
<td>Cube, edge on</td>
<td><img src="image" alt="Sketch of a cube, edge on" /></td>
<td>0.80</td>
</tr>
<tr>
<td>Long rectangular member, face on</td>
<td><img src="image" alt="Sketch of a long rectangular member, face on" /></td>
<td>2.05</td>
</tr>
<tr>
<td>Long rectangular member, edge on</td>
<td><img src="image" alt="Sketch of a long rectangular member, edge on" /></td>
<td>1.55</td>
</tr>
<tr>
<td>Narrow strip, face on</td>
<td><img src="image" alt="Sketch of a narrow strip, face on" /></td>
<td>1.98</td>
</tr>
</tbody>
</table>
The procedure for implementing this method is as follows:

1. Given: Fragment mass, $M_f$
   - Initial fragment velocity, $u$
   - Exposed area perpendicular to direction of movement, $A_D$
   - Density of the ambient air, $\rho_0$
   - Lift to drag ratio.
2. Determine drag coefficient from Table 2.26.
3. Determine scaled velocity from Eq. (2.2.29).
4. Determine scaled range from Figure 2.63.
5. Determine actual range from Eq. (2.2.28)

The dashed line on Figure 2.63 represents the maximum range computed using Eq. (2.2.26).

Brown (1985, 1986) provides other methods for fragment prediction. Additional references on projectiles include Sun et al. (1976), TNO (1979), and Tunkel (1983). TNO considers that the most likely failure point will be at an attachment to the vessel, so they consider nozzles, manholes, and valves as typical projectiles in their analysis.

Fragment distances and sizes are discussed further in Section 2.2.4 (BLEVE) and Section 2.3 (injuries and damage from projectiles).

Applications
In general, these types of failures result in risk to in-plant personnel. However, vessel fragments can be accelerated to significant distances. The Canvey Study (Health & Safety Executive, 1978) considered projectile damage effects on other process vessels.

Logic Diagram
A logic diagram for the modeling of projectile effects due to the explosion of pressure vessels is provided in Figure 2.64.

Theoretical Foundation
The technology of energy release from pressurized gas containers has been receiving attention for over a century beginning with catastrophic failures of boilers and other pressure vessels. Ultra high pressure systems has also generated interest.

Much experimental work has been done, primarily small scale with containers which burst into a large number of fragments, to relate the shock wave phenomena to the well developed TNT relationships.

Input Requirements and Availability
The technology requires data on container strength. Maximum bursting pressure of the container can be derived from specific information on the metallurgy and design. In accidental releases, pressure within a vessel at the time of failure is not always known. However, an estimate can usually be made (AIChE/CCPS, 1994). If failure is initiated by a rise in initial pressure in combination with a malfunctioning or inadequately designed pressure-relief device, the pressure at rupture will equal the vessel’s failure pressure, which is usually the maximum allowable working pressure (MAWP) times a safety factor. For initial calculations, a usual safety factor of four is applied for vessels
made of carbon steel, although higher values are possible. In general, the higher the failure pressure, the more severe the effect.

Output
The output from this analysis is overpressure and impulse versus distance for shock wave effects and the velocity and expected maximum range of projectiles which are generated by the burst vessel.

Simplified Approaches
The techniques presented are basically simplified approaches. It can be conservatively assumed that 100% of the stored energy is converted to a shock wave.

2.2.3.3. EXAMPLE PROBLEMS

Example 2.22: Energy of Explosion for a Compressed Gas. A 1-m³ vessel at 25°C ruptures at a vessel burst pressure of 500 bar abs. The vessel ruptures into ambient air at
a pressure of 1.01 bar and 25°C. Determine the energy of explosion and equivalent mass of TNT using the following methods:

a. Brode's equation for a constant volume expansion, Eq. (2.2.11).
b. Brown's equation for an isothermal expansion, Eq. (2.2.12)
c. Crowl's equation for thermodynamic availability, Eq. (2.2.13)

**Solution:**

(a) Substituting the known values into Eq. (2.2.11)

\[ E = \frac{(P - P_0)V}{\gamma - 1} \]

\[ E = \frac{(500 \text{ bar} - 1.01 \text{ bar})(10^5 \text{ Pa/bar})(1 \text{ m}^3)(\text{Nm}^{-2}/\text{Pa})}{1.4 - 1} \]

\[ E = 1.25 \times 10^8 \text{ Nm} = 125 \text{ MJ} \]

Since TNT has an explosion energy of 1120 cal/gm = 4.69 \times 10^6 J/kg

\[ \text{TNT equiv. mass} = \frac{1.25 \times 10^8 J}{4.69 \times 10^6 J/kg} = 26.6 \text{ kg TNT} \]

(b) For this case, 1 \text{ m}^3 = 35.3 \text{ ft}^3, T_0 = 536^\circ \text{R}. Substituting into Eq. (2.2.12)

\[ W = \left(1.39 \times 10^{-6} \frac{\text{lb-mole lb-TNT}}{\text{ft}^3 \text{BTU}}\right) V \left(\frac{P_1}{P_0}\right) R_G T_0 \ln \left(\frac{P_1}{P_2}\right) \]

\[ W = \left(1.39 \times 10^{-6} \frac{\text{lb-mole lb-TNT}}{\text{ft}^3 \text{BTU}}\right)(35.3 \text{ ft}^3)(500 \text{ bar}) \]

\[ \times \left(1987 \frac{\text{BTU}}{\text{lb-mole}^\circ \text{R}}\right)(536^\circ \text{R}) \ln \left(\frac{500 \text{ bar}}{1.01 \text{ bar}}\right) \]

\[ W = 160.7 \text{ lb of TNT} = 72.9 \text{ kg of TNT.} \]

Since TNT has an energy of 4.69 \times 10^6 J/kg, this represents 342 MJ of energy.

c. Substituting into Eq. (2.2.13),

\[ E = R_G T \left[ \ln \left(\frac{P}{P_E}\right) - \left(1 - \frac{P_E}{P}\right) \right] \]

\[ E = (8.314 \text{ J/mole K})(298 \text{ K}) \left[ \ln \left(\frac{500 \text{ bar}}{1.01 \text{ bar}}\right) - \left(1 - \frac{1.01 \text{ bar}}{500 \text{ bar}}\right) \right] \]

\[ E = 1.29 \times 10^4 \text{ J/mole} \]

The number of moles of gas in the vessel is determined from the ideal gas law. It is 20,246 gm-moles. The total energy of explosion is thus,

\[ E = (1.29 \times 10^4 \text{ J/mole})(20,246 \text{ moles}) = 261 \text{ MJ} \]

This is equivalent to 55.7 kg of TNT.
Example 2.22: Energy of Explosion for a Compressed Gas

Input Data:
- Vessel volume: 1 m$^3$
- Vessel pressure: 500 bar abs
- Final pressure of expanded gas: 1.01 bar abs
- Ambient pressure: 1.01 bar abs
- Heat capacity ratio of expanding gas: 1.4
- Temperature of gas: 298 K

Calculated Results:

- Brode's equation assuming constant volume expansion:
  - Energy of explosion: $1.25 \times 10^8$ Joules
  - TNT equivalent: 26.60 kg TNT
- Brown's equation assuming isothermal expansion:
  - TNT equivalent: 160.68 lb TNT
  - Energy of explosion: $3.42 \times 10^8$ Joules
- Growl's equation from thermodynamic availability:
  - Moles of gas in vessel: 20246.36 gm-moles
  - Energy of explosion: $2.61 \times 10^8$ Joules
  - TNT equivalent: 55.69 kg TNT

FIGURE 2.65. Spreadsheet output for Example 2.22: Energy of explosion for a compressed gas.

The calculation for all three parts of this example is readily implemented via spreadsheet. The output is shown in Figure 2.65.

The three methods do provide considerably different results.

Example 2.23: Prugh's Method for Overpressure from a ruptured sphere. A 6-ft$^3$ sphere containing high pressure air at 77°F ruptures at 8000 psia. Calculate the side-on overpressure at a distance of 60 ft from the rupture. Assume an ambient pressure of 1 atm and temperature of 77°F.

Additional data for air:
- Heat capacity ratio, $\gamma$: 1.4
- Molecular weight of air: 29

Solution: From Eq. (2.2.12)

$$W = \left(1.39 \times 10^{-6} \frac{\text{lb \cdot mole}}{\text{ft}^3 \text{BTU}}\right) V \left(\frac{P_1}{P_0}\right) R_T \ln\left(\frac{P_1}{P_2}\right)$$

For this particular case,
- $P_1 = 8000$ psia = 551 bar abs
- $P_2 = 14.7$ psia = 1.01 bar
- $P_0 = 14.7$ psia = 1.01 bar
- $V = 6 \text{ ft}^3 = 0.170 \text{ m}^3$
- $R = 1.987 \text{ BTU/lb-mol} \cdot \text{R}$
- $T_0 = 77^\circ\text{F} = 537^\circ\text{R} = 298 \text{ K}$
Substituting into the equation

\[
W = \left(1.39 \times 10^{-6} \frac{\text{lb - mole lb - TNT}}{\text{ft}^3 \text{ BTU}} \right) (6 \text{ ft}^3) \left(\frac{8000 \text{ psia}}{14.7 \text{ psia}} \right) \left(\frac{1.987 \text{ BTU}}{\text{lb - mol}^o \text{ R}} \right) \times (537^o \text{ R}) \ln \left(\frac{8000 \text{ psia}}{14.7 \text{ psia}} \right)
\]

\[W = 305 \text{ lb TNT} = 138 \text{ kg TNT}\]

The pressure at the surface of the vessel is calculated from Eq. (2.2.14)

\[
P_b = P_s \left[1 - \frac{3.5(\gamma - 1) (P_s - 1)}{(\gamma T/M)(1 + 5.9P_s)}\right]^{-\frac{2}{\gamma(y-1)}}
\]

where

- \(P_s\) is the pressure at surface of vessel, 1.01 bar abs
- \(P_b\) is the burst pressure of vessel, 551 bar abs
- \(\gamma = 1.4\)
- \(T = 298^o\text{K}\)
- \(M = 29 \text{ gm/gm-mole}\)

By a trial-and-error solution

\[P_s = 10.21 \text{ bar abs} = 148.1 \text{ psia}\]

Since the vessel is at grade, the blast wave will be hemispherical. The scaled pressure is

\[\frac{\bar{P}}{P_s} = \frac{P_0}{P_s} = \frac{148 \text{ psia}}{14.7 \text{ psia}} = 10.07\]

From Figure 2.48, and Eq. (2.2.7)

\[Z = 1.14 = R/W^{1/3}\]

Since \(W = 13.8 \text{ kg TNT}\) it follows that \(R = 2.74 \text{ m} = 8.99 \text{ ft}\).

The radius of the spherical container is

\[r = 0.782 V^{1/3} = 0.782 (6 \text{ ft}^3)^{1/3} = 1.4 \text{ ft}\]

The “virtual distance” to be added to distances for blast effects evaluations would be \(8.99 - 1.4 = 7.59 \text{ feet} (2.31 \text{ m})\). Therefore, the blast pressure at a distance of 60 ft (18.28 m) from the center of the sphere would be evaluated using a scaled distance of

\[Z = (18.28 \text{ m} + 2.31 \text{ m})/(12.7 \text{ kg TNT})^{1/3}\]

or

\[Z = 8.58\]

From Figure 2.48 this results in a final overpressure of 18.38 kPa or 2.67 psia. Without the virtual distance, the final overpressure is 3.18 psi.

The entire procedure is readily implemented via a spreadsheet, as shown in Figure 2.66. This implementation requires two trial-and-error procedures. The first is used to determine the pressure at the surface of the vessel and the second procedure is used to determine the final overpressure. The user must manually adjust the guessed value until the recomputed value is identical.
Example 2.23: Prugh's Method for Overpressure from a Ruptured Sphere

Input Data:
- Vessel burst pressure: 551.43 bar abs
- Distance from vessel center: 18.28 m
- Vessel volume: 0.17 m³
- Final pressure: 1.01325 bar abs
- Heat capacity ratio: 1.4
- Molecular weight of gas: 29
- Gas temperature: 298 K

Calculated Results:

<table>
<thead>
<tr>
<th>Calculated Result</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>English units equivalents of above data:</td>
<td></td>
</tr>
<tr>
<td>Vessel burst pressure:</td>
<td>8000.02 psia</td>
</tr>
<tr>
<td>Vessel volume:</td>
<td>6.00 ft³</td>
</tr>
<tr>
<td>Final pressure:</td>
<td>14.7 psia</td>
</tr>
<tr>
<td>Temperature:</td>
<td>536.4 R</td>
</tr>
<tr>
<td>Energy of Explosion from Brown's Equation:</td>
<td>30.49 lb TNT</td>
</tr>
<tr>
<td></td>
<td>13.83 kg TNT</td>
</tr>
</tbody>
</table>

Trial and error solution to determine surface pressure:

- Guessed Value: 10.21 bar abs
- Calculated Value: 10.20937 bar abs
- English Equivalent: 148.12 psia

Trial and error solution to determine virtual distance:

- TNT Mass: 13.83 kg
- Distance from blast: 2.738 m

Calculated Results:

<table>
<thead>
<tr>
<th>Calculated Result</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scaled distance, z:</td>
<td>1.1407 m/kg**(1/3)</td>
</tr>
<tr>
<td>Overpressure Calculation: (only valid for z &gt; 0.0674 and z &lt; 40)</td>
<td></td>
</tr>
<tr>
<td>a+b*log(z):</td>
<td>-0.13717</td>
</tr>
<tr>
<td>Overpressure:</td>
<td>1021.44 kPa</td>
</tr>
<tr>
<td></td>
<td>148.1886 psia</td>
</tr>
<tr>
<td>Radius of vessel:</td>
<td>0.43 m</td>
</tr>
<tr>
<td>Virtual distance to add:</td>
<td>2.30 m</td>
</tr>
<tr>
<td>Effective distance from blast:</td>
<td>20.58 m</td>
</tr>
</tbody>
</table>

Final overpressure calculation using effective distance:

- TNT Mass: 13.83 kg
- Distance from blast: 20.58 m

Calculated Results:

<table>
<thead>
<tr>
<th>Calculated Result</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scaled distance, z:</td>
<td>8.5759 m/kg**(1/3)</td>
</tr>
<tr>
<td>Overpressure Calculation: (only valid for z &gt; 0.0674 and z &lt; 40)</td>
<td></td>
</tr>
<tr>
<td>a+b*log(z):</td>
<td>1.045885</td>
</tr>
<tr>
<td>Overpressure:</td>
<td>18.38 kPa</td>
</tr>
<tr>
<td></td>
<td>2.67 psia</td>
</tr>
</tbody>
</table>

FIGURE 2.66. Spreadsheet output for Example 2.23: Prugh’s method for overpressure from a ruptured sphere.


Solution: The steps listed in the text are followed.

STEP 1: Collect data. The data are already listed in Example 2.23.
STEP 2: Calculate the energy of explosion. The Brode equation, Eq. (2.2.11) is used.

\[
E = \frac{(551 \text{ bar} - 1.01 \text{ bar})(10^5 \text{ Pa/bar})(0.170 \text{ m}^3)}{1.4 - 1} = 23.4 \text{ MJ}
\]

This result must be multiplied by 2 to use the overpressure curves for an open blast. The effective energy is thus 46.9 MJ.

STEP 3: Determine the scaled distance. From Eq. (2.2.15)

\[
\bar{R} = r \left( \frac{P_0}{E} \right)^{\frac{1}{3}} = (18.28 \text{ m}) \left[ \frac{(1.01 \text{ bar})(10^5 \text{ Pa/bar})(\text{N m}^{-2}/\text{Pa})}{46.8 \times 10^6 \text{ J}} \right]^{\frac{1}{3}} = 2.37
\]

STEP 4: Check if \( \bar{R} > 2 \). This is satisfied in this case.

STEP 5: Determine the scaled overpressure from Figure 2.58. The result is 0.098.

STEP 6: Adjust the overpressure for geometry effects. Table 2.24 contains the multipliers for spherical vessels. The multiplier is 1.1. Thus, the effective scaled overpressure is (1.1)(0.098) = 0.108.

STEP 7: Determine the final overpressure. From the definition of the scaled pressure,

\[
p_s = (0.1085)(1.01 \text{ bar}) = 0.110 \text{ bar} = 1.6 \text{ psi}
\]

STEP 8: Check the final pressure. In this case the final pressure is less than the burst pressure of the vessel.

This result is somewhat less than the value of 2.57 psi obtained using Prugh’s method. The solution is readily implemented via spreadsheet, as shown in Figure 2.67.

Example 2.25: Velocity of Fragments from a Vessel Rupture. A 100-kg cylindrical vessel is 0.2 m in diameter and 2 m long. Determine the initial fragment velocities if the vessel ruptures into two fragments. The fragments represent 3/4 and 1/4 of the total vessel mass, respectively. The vessel is filled with helium at a temperature of 300 K, and the burst pressure of the vessel is 20.1 MPa.

For helium,

- Heat capacity ratio, \( \gamma \): 1.67
- Molecular weight: 4

Solution: The procedure detailed in the text is applied.

1. Given:
   - Number of fragments, \( n = 2 \)
   - Total mass of vessel, \( M_c = 100 \text{ kg} \)
   - Mass fraction for each fragment:
     - first fragment = 0.75, second fragment = 0.25
   - Internal burst pressure of vessel, \( P = 20.1 \text{ MPa} \)
   - Volume of vessel, \( V \)

\[
V = \left( \frac{\pi}{4} \right) D^2 L = \frac{3.14}{4} (0.2 \text{ m})^2 (2.0 \text{ m}) = 0.0628 \text{ m}^3
\]
Example 2.24: Baker's Method for Overpressure from a Ruptured Vessel

Input Data:

Vessel burst pressure: 551.43 bar abs
Distance from vessel center: 18.28 m
Vessel volume: 0.17 m$^3$
Final pressure: 1.01325 bar abs
Heat capacity ratio: 1.4
Molecular weight of gas: 29
Gas temperature: 298 K
Speed of sound in ambient gas: 340 m/s

Calculated Results:

Energy of explosion using Brode's equation for constant volume expansion:

- Energy of explosion: 23.39 MJ
- TNT equivalent: 4.99 kg TNT

Effective energy of explosion (x 2): 46.79 MJ

Scaled distance: 2.37

Interpolated scaled overpressure: 0.098591
Interpolated scaled impulse: 0.021681

Vessel shape:

<table>
<thead>
<tr>
<th></th>
<th>Spherical</th>
<th>Cylindrical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overpressure multiplier for vessel shape</td>
<td>1.1</td>
<td>1.6</td>
</tr>
<tr>
<td>Corrected scaled overpressure</td>
<td>0.1085 bar</td>
<td>0.1577 bar</td>
</tr>
<tr>
<td>Actual overpressure</td>
<td>0.1099 bar</td>
<td>0.1598 bar</td>
</tr>
<tr>
<td>Impulse multiplier for vessel shape</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Corrected scaled impulse</td>
<td>0.0217</td>
<td>0.0217</td>
</tr>
<tr>
<td>Actual impulse</td>
<td>39.64 kPa - ms</td>
<td>39.64 kPa - ms</td>
</tr>
</tbody>
</table>

FIGURE 2.67. Spreadsheet from Example 2.24: Baker's method for overpressure from a ruptured vessel.

Ambient pressure, $P_0 = 0.101$ MPa
Absolute temperature of gas in vessel, $T = 300$ K
Heat capacity ratio of gas in vessel, $\gamma = 1.67$
Molecular weight of gas in vessel, $M = 4$

2. Determine speed of sound of gas in vessel using Eq. (2.2.19).

$$a_0 = \left(\frac{TyR_k}{M}\right)^{1/2} = \left[\frac{(300\text{K})(1.67)(8.314\text{J/gm - mole K})(kg\text{ m}^2/s^2)/1\text{J})}{(4\text{ gm/gm - mole})(1\text{ kg/1000 gm})}\right]^{1/2} = 1020\text{ m/s}$$

3. Determine scaled pressure using Eq. (2.2.18).

$$\bar{P} = \frac{(P - P_0)V}{M_c a_0^2} = \frac{(20.1 - 0.1)(\times 10^6 \text{ Pa})(0.0628 \text{ m}^3)(1 \text{ N/m}^2)/\text{Pa})(kg\text{ m}/s^2)/1\text{ N})}{(100 \text{ kg})(1020 \text{ m/s})^2} = 0.012$$

4. Determine the dimensionless velocity from Figure 2.61, or Table 2.25. For $n = 2$, the dimensionless velocity for spheres is 0.079.

5. Determine the unequal fragment correction from Figure 2.62. For mass fraction = 0.75, $K = 1.29$ and for mass fraction = 0.25, $K = 0.63$. 
6. Determine actual velocity for each fragment using Eq. (2.2.20).

For the large fragment,

\[ v_1 = 0.0793K_{a_0} = (0.0793)(1.3)(1020 \text{ m/s}) = 104 \text{ m/s} \]

For the small fragment,

\[ v_1 = (0.0793)(0.635)(1020 \text{ m/s}) = 51.4 \text{ m/s} \]

The large fragment has the greater velocity, which is due to the unequal fragment correction.

This procedure is readily implemented via a spreadsheet, as shown in Figure 2.68. The spreadsheet must be run for each fragment—the output shown is for the large fragment.

Example 2.26: Range of a Fragment in Air. A 100 kg end of a bullet tank blows off and is rocketed away at an initial velocity of 25 m/s. If the end is 2 m in diameter, estimate the range for this fragment. Assume ambient air at 1 atm and 25°C.

**Solution:** The ambient air density is first determined. This is determined using the ideal gas law.

\[
\rho_0 = \frac{PM}{R_g T} = \frac{(1 \text{ atm})(29 \text{ kg/kg-mole})}{[0.082057 \text{ (m}^3\text{ atm)/(kg-mole K)}][298 \text{ K}]} = 1.19 \text{ kg/m}^3
\]

**Example 2.25: Velocity of Fragments from a Vessel Rupture**

<table>
<thead>
<tr>
<th>Input Data:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass of vessel:</td>
<td>100 kg</td>
</tr>
<tr>
<td>Total volume of vessel:</td>
<td>0.0628 m³</td>
</tr>
<tr>
<td>Number of fragments:</td>
<td>2</td>
</tr>
<tr>
<td>Mass fraction of total for fragment:</td>
<td>0.25</td>
</tr>
<tr>
<td>Pressure of gas within vessel:</td>
<td>20.101 MPa</td>
</tr>
<tr>
<td>Ambient gas pressure:</td>
<td>0.101 MPa</td>
</tr>
<tr>
<td>Temperature of gas within vessel:</td>
<td>300 K</td>
</tr>
<tr>
<td>Heat capacity ratio of gas within vessel:</td>
<td>1.67</td>
</tr>
<tr>
<td>Molecular weight of gas within vessel:</td>
<td>4</td>
</tr>
</tbody>
</table>

| Calculated Results: |       |
| Speed of sound of gas within vessel: | 1020 m/s |
| Adjustment factor for unequal mass: | 0.634945 |
| Scaled pressure: | 0.012062 |

Dimensionless velocity for various shapes and numbers:

<table>
<thead>
<tr>
<th>( n )</th>
<th>Spheres</th>
<th>Cylinders</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.079277</td>
<td>0.038977</td>
</tr>
<tr>
<td>10</td>
<td>0.088671</td>
<td>0.125189</td>
</tr>
<tr>
<td>100</td>
<td>0.092694</td>
<td>0.133769</td>
</tr>
</tbody>
</table>

Interpolated dimensionless velocity for actual number of fragments: 0.079277 0.038977

Actual velocity of fragment: 51.37 25.25 m/s

FIGURE 2.68. Spreadsheet output for Example 2.25: Velocity of fragments from a vessel rupture.
The surface area of the fragment is

\[ A_D = \frac{\pi D^2}{4} = \frac{(3.14)(2 \text{ m})^2}{4} = 3.14 \text{ m}^2 \]

We will assume that the fragment flies with its full face area perpendicular to the direction of travel. Other orientations will result in different ranges. For the case where the fragment face is parallel to the direction of travel it is possible that the fragment might "frisbee" as a result of lift generated during its movement.

The drag coefficient, \( C_D \), is determined from Table 2.26. For a round fragment with its face perpendicular to the direction of travel, \( C_D = 0.47 \).

The scaled velocity is determined from Eq. (2.2.29),

\[ \bar{u} = \frac{\rho_0 C_D A_D u^2}{M_g g} = \frac{(1.19 \text{ kg/m}^3)(0.47)(3.14 \text{ m}^2)(25 \text{ m/s})^2}{(100 \text{ kg})(9.8 \text{ m/s}^2)} = 1.12 \]

From Figure 2.63, the scaled fragment range is

\[ \bar{R} = 0.81. \]

The actual range is determined from Eq. (2.2.28)

\[ r = \frac{M_g \bar{R}}{\rho_0 C_D A_D} = \frac{(100 \text{ kg})(0.81)}{(1.19 \text{ kg/m}^3)(0.47)(3.14 \text{ m}^2)} = 46.1 \text{ m} \]

The maximum range is determined from Eq. (2.2.26).

\[ r_{\text{max}} = \frac{u^2}{g} = \frac{(25 \text{ m/s})^2}{9.8 \text{ m/s}^2} = 63.8 \text{ m} \]

The calculation is readily implemented via a spreadsheet, as shown in Figure 2.69. The data of Figure 2.63 is contained within the spreadsheet, but not shown. Also shown on the output is the maximum distance achieved assuming the presence of lift. This is the maximum range for any of the specified values of the lift to drag ratio. Note that with lift it is possible to exceed the maximum range and, in some cases, the increase can be to more than twice the maximum range.

2.2.3.4. DISCUSSION

Strengths and Weaknesses

The main strength of these methods is that they are based mostly on experimental data. The weakness is that many of the approaches are empirical in nature, using correlations based on dimensional or dimensionless groups. Extrapolation outside of the range of the correlations provided may lead to erroneous results. For the purposes of this text, the range of validity may be assumed to be the range provided by the figures and tables.

The energy of explosion methods assume that the explosion occurs from a point source, which is rarely the case in actual process equipment explosions.

Identification and Treatment of Possible Errors

It is very difficult to predict the number of projectiles and where they will be propelled. These methods are more suited for accident investigations, where the number, size and location of the fragments is known.
Example 2.26: Range of a Fragment in Air

Input Data:
- Mass of fragment: 100 kg
- Initial fragment velocity: 25 m/s
- Drag coefficient of fragment: 0.47
- Lift to drag ratio: 0
- Exposed area of fragment: 3.14 m²
- Temperature of ambient air: 298 K
- Pressure of ambient air: 1 atm

Calculated Results:
- Density of ambient air: 1.19 kg/m³
- Scaled velocity of fragment: 1.12

Interpolated values from figure for various lift to drag ratios:

<table>
<thead>
<tr>
<th>Lift to drag ratio</th>
<th>Scaled Range (m)</th>
<th>Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.80622</td>
<td>46.06</td>
</tr>
<tr>
<td>0.5</td>
<td>0.818541</td>
<td>46.65</td>
</tr>
<tr>
<td>1</td>
<td>0.946952</td>
<td>54.10</td>
</tr>
<tr>
<td>3</td>
<td>1.11779</td>
<td>63.87</td>
</tr>
<tr>
<td>5</td>
<td>1.309836</td>
<td>74.84</td>
</tr>
<tr>
<td>10</td>
<td>0.387583</td>
<td>22.14</td>
</tr>
<tr>
<td>30</td>
<td>0.082977</td>
<td>4.74</td>
</tr>
<tr>
<td>50</td>
<td>0.050037</td>
<td>2.86</td>
</tr>
<tr>
<td>100</td>
<td>0.023483</td>
<td>1.34</td>
</tr>
</tbody>
</table>

Interpolated range: 46.06 m
Theoretical max. range (no lift): 63.78 m
Max. possible range (with lift): 74.84 m

Utility
In general, vessels of pressurized gas do not have sufficient stored energy to represent a threat from shock wave beyond the plant boundaries. These techniques find greater application involving in-plant risks.

These types of incidents can result in domino effects particularly from the effects of the projectiles produced. Very few CPQRA studies have ever incorporated projectile effects on a quantitative basis.

Resources
A process engineer should be able to perform each type of calculation in a few hours. Spreadsheet applications are useful.

Available Computer Codes.
- DAMAGE (TNO, Apeldoorn, The Netherlands)
- SAFESITE (W. E. Baker Engineering, Inc., San Antonio, TX)
- QRAWorks (PrimaTech, Columbus, OH)
- SUPERCHEMS (Arthur D. Little, Cambridge, MA)

Several integrated analysis packages contain explosion fragment capability. These include:
2.2.4. BLEVE and Fireball

2.2.4.1. BACKGROUND

Purpose
This section addresses a special case of a catastrophic rupture of a pressure vessel. A boiling liquid expanding vapor explosion (BLEVE) occurs when there is a sudden loss of containment of a pressure vessel containing a superheated liquid or liquified gas. This section describes the methods used to calculate the effects of the vessel rupture and the fireball that results if the released liquid is flammable and is ignited.

Philosophy
A BLEVE is a sudden release of a large mass of pressurized superheated liquid to the atmosphere. The primary cause is usually an external flame impinging on the shell of a vessel above the liquid level, weakening the container and leading to sudden shell rupture. A pressure relief valve does not protect against this mode of failure, since the shell failure is likely to occur at a pressure below the set pressure of the relief system. It should be noted, however, that a BLEVE can occur due to any mechanism that results in the sudden failure of containment, including impact by an object, corrosion, manufacturing defects, internal overheating, etc. The sudden containment failure allows the superheated liquid to flash, typically increasing its volume over 200 times. This is sufficient to generate a pressure wave and fragments. If the released liquid is flammable, a fireball may result.

A special type of BLEVE involves flammable materials, such as LPG. A number of such incidents have occurred including San Carlos, Spain (July 11, 1978), Crescent City, Illinois (June 21, 1970), and Mexico City, Mexico (November 19, 1984).

Films of actual BLEVE incidents involving flammable materials (NFPA, 1994) clearly show several stages of BLEVE fireball development. At the beginning of the incident, a fireball is formed quickly due to the rapid ejection of flammable material due to depressurization of the vessel. This is followed by a much slower rise in the fireball due to buoyancy of the heated gases.


Application
BLEVE models are often required for risk analysis at chemical plants (e.g., Rijnmond Public Authority, 1982) and for major accident investigation (e.g., Mexico City, Pietersen and Huerta, 1985).

2.2.4.2. DESCRIPTION

Description of Technique
The calculation of BLEVE incidents is a stepwise procedure. The first step should be pressure and fragment determination, as this applies to all BLEVE incidents (whether for flammable materials or not). For flammable materials the prediction of thermal intensity from fireballs should also be considered. This requires a determination of the fireball diameter and duration.
AIChE (1994) provides the most up-to-date reference on modeling approaches for BLEVEs.

Blast Effects

Blast or pressure effects from BLEVEs are usually small, although they might be important in the near field (such as the BLEVE of a hot water heater in a room). These effects are of interest primarily for the prediction of domino effects on adjacent vessels. However, there are exceptions. Some BLEVEs of large quantities of nonflammable liquids (such as CO\textsubscript{2}) can result in energy releases of tons of TNT equivalent.

The blast wave produced by a sudden release of a fluid depends on many factors (AIChE, 1994). This includes the type of fluid released, energy it can produce on expansion, rate of energy release, shape of the vessel, type of rupture, and the presence of reflecting surfaces in the surroundings. Materials below their normal boiling point cannot BLEVE.

Baker et al. (1983) discuss pressure wave prediction in detail and provides a sample problem in Chapter 2 of their book. TNO (1979) also provide a physical explosion model, which is used by Pietersen and Huerta (1985) in the analysis of the Mexico City incident. Prugh (1988) presents a method for calculating a TNT equivalent that also incorporates the flash vaporization process of the liquid phase in addition to the vapor phase originally present.

AIChE (1994) states that the blast effect of a BLEVE results not only from the rapid expansion (flashing) of the liquid, but also from the expansion of the compressed vapor in the vessel's head space. They claim that, in many incidents, head-space vapor expansion produces most of the blast effects.

AIChE (1994) describes a procedure developed by Baker et al. (1975) and Tang et al. (1996) for determining both the peak overpressure and impulse due to vessels bursting from pressurized gas. This procedure is too detailed to be described in detail here. The method results in an estimate of the overpressure and impulse due to blast waves from the rupture of spherical or cylindrical vessels located at ground level. The method depends on the phase of the vessel's contents, its boiling point at ambient pressure, its critical temperature, and its actual temperature. An approach is also presented to determine blast pressures in the near-field, based on the results of numerical simulations. These methods are only for the prediction of pressure effects.

Fragments

The prediction of fragment effects is important, as many deaths and domino damage effects are attributable to fragments. The method of Baker et al. (1983) can be used, but specific work on BLEVE fragmentation hazards has been done by the Association of American Railroads (AAR) (1972, 1973) and by Holden and Reeves (1985). The AAR reports that of 113 major failures of horizontal cylindrical tanks in fire situations, about 80% resulted in projected fragments.

Fragments are usually not evenly distributed. The vessel's axial direction receives more fragments than the side directions. Baker et al. (1983) discuss fragment prediction in detail. Figure 2.70 provides data for the number of fragments and the fragment range, based on work by Holden and Reeves (1985). Figure 2.70 shows that roughly 80% of fragments fall within a 300-m (1000-ft) range. Interestingly, BLEVEs from smaller LPG vessels have a history of greater fragment range; one end section at the
Mexico City LPG BLEVE incident traveled 1000 m (3300 ft). The total number of fragments is approximately a function of vessel size. Holden and Reeves (1985) suggest a correlation based on seven incidents, as shown in Figure 2.70.

\[
\text{Number of fragments} = -3.77 + 0.0096 \times \text{(Vessel capacity (m}^3\text{))}
\]  
(2.2.31)

Range of validity: 700–2500 m\(^3\)

Figure 2.70 and the AAR data (Association of American Railroads, 1972, 1973) indicate that a small number of fragments is likely in any BLEVE incident regardless of size. BLEVEs typically produce fewer fragments than high pressure detonations—between 2 and 10 are typical. BLEVEs usually don’t develop the high pressures which lead to greater fragmentation. Instead, metal softening from the heat exposure and thinning of the vessel wall yields fewer fragments.

Normally, propane (LPG) storage tanks are designed for a 250-psig working pressure. A normal burst pressure of four times the working pressure is expected for ASME coded vessels, or 1000 psig. BLEVEs usually occur because of flame impingement on the unwetted portion (vapor space) of the tank. This area rapidly reaches 1200°F and becomes sufficiently weakened that the tank fails at approximately 300–400 psig (Townsend et al., 1974).
Empirical Equations for BLEVE Fireball Diameter, Duration, and Fireball Height

Pitblado (1986) lists thirteen published correlations and compares BLEVE fireball diameters as a function of mass released. The TNO formula (Pietersen and Huerta, 1985) gives good overall fit to observed data, but there is substantial scatter in the source data. All models use a power law correlation to relate BLEVE diameter and duration to mass. Useful formulas for BLEVE physical parameters are (AIChE, 1994):

\[
\text{Maximum fireball diameter (m): } D_{\text{max}} = 5.8 M^{1/3} \tag{2.2.32}
\]

\[
\text{Fireball combustion duration (s):}
\begin{align*}
& t_{\text{BLEVE}} = 0.45 M^{1/3} \text{ for } M < 30,000 \text{ kg} \tag{2.2.33} \\
& t_{\text{BLEVE}} = 2.6 M^{1/6} \text{ for } M > 30,000 \text{ kg} \tag{2.2.34}
\end{align*}
\]

\[
\text{Center height of fireball (m): } H_{\text{BLEVE}} = 0.75 D_{\text{max}} \tag{2.2.35}
\]

\[
\text{Initial ground level hemisphere diameter (m): } D_{\text{initial}} = 1.3D_{\text{max}} \tag{2.2.36}
\]

where \(M\) is the initial mass of flammable liquid (kg). The particular formulas for fireball diameter and duration do not include the volume of oxygen for combustion. This, of course, varies and should affect the size of the fireball.

The initial diameter is used to describe the initial ground level fireball before buoyancy forces lift it.

Radiation

Four parameters used to determine a fireball's thermal radiation hazard are the mass of fuel involved and the fireball's diameter, duration, and thermal emissive power (AIChE, 1994). The radiation hazards are then calculated using empirical relations.

The problem with a fireball typical of a BLEVE is that the radiation will depend on the actual distribution of flame temperatures, the composition of the gases in the vicinity of the fireball (including reactants and products), the geometry of the fireball, absorption of the radiation by the fireball itself, and the geometric relationship of the receiver with respect to the fireball. All of these parameters are difficult to quantify for a BLEVE.

Johnson et al. (1990) completed experiments with fireballs of butane and propane of from 1000 to 2000 kg size released from pressurised tanks. They found average surface emissive radiation of between 320 to 375 kW/m², a fireball duration of from 4.5 to 9.2 s and fireball diameters of 56 to 88 m. AIChE (1994) suggests using an emissive power of 350 kW/m² for large-scale releases of hydrocarbon fuels, with the power increasing as the scale of the release decreases.

The emissive radiative flux from any source is represented by the Stefan–Boltzmann law:

\[
E_{\text{max}} = \sigma T_f^4 \tag{2.2.37}
\]

where \(E_{\text{max}}\) is the maximum radiative flux (energy/area time); \(\sigma\) is the Stefan–Boltzmann constant \((5.67 \times 10^{-11} \text{ kW/m}^2 \text{ K}^4 = 1.71 \times 10^{-9} \text{ BTU/hr ft}^2 \text{ °R}^4)\); and \(T_f\) is the absolute temperature of the radiative source (deg).

Equation (2.2.37) applies only to a black-body and provides the maximum radiative energy flux. For real sources, the emissive power is given by

\[
E = \varepsilon E_{\text{max}} \tag{2.2.38}
\]

where \(E\) is the emissive energy flux (energy/area time) and \(\varepsilon\) is the emissivity (unitless).
The emissivity for a black-body radiator is unity, whereas the emissivity for a real radiation source is typically less than unity.

For fireballs, Beer's law is used to determine the emissivity (AIChE, 1994). This is represented by the following equation:

\[ \varepsilon = 1 - e^{-kD} \]  

(2.2.39)

where \( k \) is an extinction coefficient (1/length) and \( D \) is the fireball diameter (length).

Hardee et al. (1978) measured an extinction coefficient of 0.18 m\(^{-1}\) from LNG fires, but AIChE (1994) reports that this overpredicts somewhat the radiation from fireballs.

Thermal radiation is usually calculated using surface emitted flux, \( E \), rather than the Stefan-Boltzmann equation, as the latter requires the flame temperature. Typical energy fluxes for BLEVEs (200–350 kW/m\(^2\)) are much higher than in pool fires as the flame is not smoky. Roberts (1981) and Hymes (1983) provide a means to estimate surface heat flux based on the radiative fraction of the total heat of combustion.

\[ E = \frac{RMH_c}{\pi D_{\text{max}}^2 r_{\text{BLEVE}}} \]  

(2.2.40)

where

- \( E \) is the radiative emissive flux (energy/area time)
- \( R \) is the radiative fraction of the heat of combustion (unitless)
- \( M \) is the initial mass of fuel in the fireball (mass)
- \( H_c \) is the net heat of combustion per unit mass (energy/kg)
- \( D_{\text{max}} \) is the maximum diameter of the fireball (length)
- \( r_{\text{BLEVE}} \) is the duration of the fireball (time)

Hymes (1983) suggests the following values for \( R \):

- 0.3 for fireballs from vessels bursting below the relief set pressure
- 0.4 for fireballs from vessels bursting at or above the relief set pressure.

AIChE (1994) combines Eq. (2.2.40) with the empirical equation by Robert's (1981) for the duration of the combustion phase of a fireball. This results in an equation for the radiation flux received by a receptor, \( E_r \), at a distance \( L \)

\[ E_r = \frac{2.2 \tau_s R H_c M^{2/3}}{4\pi X_c^2} \]  

(2.2.41)

where

- \( E_r \) is the radiative flux received by the receptor (W/m\(^2\))
- \( \tau_s \) is the atmospheric transmissivity (unitless)
- \( R \) is the radiative fraction of the heat of combustion (unitless)
- \( H_c \) is the net heat of combustion per unit mass (J/kg)
- \( M \) is the initial mass of fuel in the fireball (kg)
- \( X_c \) is the distance from the fireball center to the receptor (m)

The atmospheric transmissivity, \( \tau_s \), is an important factor. Thermal radiation is absorbed and scattered by the atmosphere. This causes a reduction in radiation received at target locations. Some thermal radiation models ignore this effect, effectively assuming a value of \( \tau_s = 1 \) for the transmissivity. For longer path lengths (over 20 m), where absorption could be 20–40%, this will result in a substantial overestimate for received

$$\tau_a = 2.02(P_w X_s)^{-0.69}$$  \hspace{1cm} (2.2.42)

where $\tau_a$ is the atmospheric transmissivity (fraction of the energy transmitted: 0 to 1); $P_w$ is the water partial pressure (Pascals, N/m$^2$); $X_s$ is the path length distance from the flame surface to the target (m).

An expression for the water partial pressure as a function of the relative humidity and temperature of the air is given by Mudan and Croce (1988).

$$P_w = 101325 \times (RH) \exp \left(14.4114 - \frac{532.8}{T_a}\right)$$  \hspace{1cm} (2.2.43)

where $P_w$ is the water partial pressure (Pascals, N/m$^2$); $(RH)$ is the relative humidity (percent); $T_a$ is the ambient temperature (K).

A more empirically based equation for the radiation flux is presented by Roberts (1981) who used the data of Hasegawa and Sato (1977) to correlate the measured radiation flux received by a receptor at a distance, $L$, from the center of the fireball,

$$E_r = \frac{8.28 \times 10^5 M^{0.771}}{X_s^2}$$  \hspace{1cm} (2.2.44)

with variables and units identical to Eq. (2.2.41).

The radiation received by a receptor (for the duration of the BLEVE incident) is given by

$$E_r = \tau_a EF_{21}$$  \hspace{1cm} (2.2.45)

where

- $E_r$ is the emissive radiative flux received by a black body receptor (energy/area time)
- $\tau_a$ is the transmissivity (dimensionless)
- $E$ is the surface emitted radiative flux (energy/area time)
- $F_{21}$ is a view factor (dimensionless)

As the effects of a BLEVE mainly relate to human injury, a geometric view factor for a sphere to a receptor is required. In the general situation, a fireball center has a height, $H$, above the ground. The distance $L$ is measured from a point at the ground directly beneath the center of the fireball to the receptor at ground level. For a horizontal surface, the view factor is given by

$$F_{21} = \frac{H(D/2)^2}{(L^2 + H^2)^{3/2}}$$  \hspace{1cm} (2.2.46)

where $D$ is the diameter of the fireball. When the distance, $L$, is greater than the radius of the fireball, the view factor for a vertical surface is calculated from

$$F_{21} = \frac{L(D/2)^2}{(L^2 + H^2)^{3/2}}$$  \hspace{1cm} (2.2.47)
More complex view factors are presented in Appendix A of AIChE (1994). For a conservative approach, a view factor of 1 is assumed.

Once the radiation received is calculated, the effects can be determined from Section 2.3.2.

Logic Diagram
A logic diagram showing the calculation procedure is given in Figure 2.71. This shows the calculation sequence for determination of shock wave, thermal, and fragmentation effects of a BLEVE of a flammable material.

![Logic Diagram](Image)
Theoretical Foundation
BLEVE models are a blend of empirical correlations (for size, duration, and radiant fraction) and more fundamental relationships (for view factor and transmissivity). Baker et al. (1983) have undertaken a dimensional analysis for diameter and duration which approximates a cube root correlation. Fragmentation correlations are empirical.

Input Requirements and Availability
BLEVE models require the material properties (heat of combustion and vapor pressure), the mass of material, and atmospheric humidity. Fragment models are fairly simplistic and require vessel volume and vapor pressure. This information is readily available.

Output
The output of a BLEVE model is usually the radiant flux level and duration. Overpressure effects, if important, can also be obtained using a detailed procedure described elsewhere (AIChE, 1994). Fragment numbers and ranges can be estimated, but a probabilistic approach is necessary to determine consequences.

Simplified Approaches
Several authors use simple correlations based on more fundamental models. Similarly the Health & Safety Executive (1981) uses a power law correlation to summarize their more fundamental model. Considine and Grint (1984) have updated this to

\[ r_{50} = 22^{0.379} M^{0.307} \]  

(2.2.48)

where \( r_{50} \) is the hazard range to 50% lethality (m), \( t \) is the duration of BLEVE (s), and \( M \) is the mass of LPG in BLEVE (long tons = 2200 lb).

The fragment correlations described for LPG containers are simplified approaches.

2.2.4.3. EXAMPLE PROBLEMS

Example 2.27: BLEVE Thermal Flux. Calculate the size and duration, and thermal flux at 200 m distance from a BLEVE of an isolated 100,000 kg (200 m\(^3\)) tank of propane at 20°C, 8.2 bar abs (68°F, 120 psia). Atmospheric humidity corresponds to a water partial pressure of 2810 N/m\(^2\) (0.4 psi). Assume a heat of combustion of 46,350 kJ/kg.

Solution. The geometry of the BLEVE are calculated from Eqs. (2.2.32)–(2.2.36). For an initial mass, \( M = 100,000 \) kg, the BLEVE fireball geometry is given by

\[
D_{\text{max}} = 5.8 \ M^{1/3} = (5.8)(100,000 \text{ kg})^{1/3} = 269 \text{ m}
\]

\[
r_{\text{BLEVE}} = 2.6 \ M^{1/6} = (2.6)(100,000 \text{ kg})^{1/6} = 17.7 \text{ s}
\]

\[
H_{\text{BLEVE}} = 0.75 \ D_{\text{max}} = (0.75)(269 \text{ m}) = 202 \text{ m}
\]

\[
D_{\text{initial}} = 1.3 \ D_{\text{max}} = (1.3)(269 \text{ m}) = 350 \text{ m}
\]

For the radiation fraction, \( R \), assume a value of 0.3 (Hymes, 1983; Roberts, 1981).

The emitted flux at the surface of the fireball is determined from Eq. (2.2.40),

\[
E = \frac{R \ M \ H}{\pi D_{\text{max}}^2 \ t_{\text{BLEVE}}} = \frac{(0.3)(100,000 \text{ kg})(46,350 \text{ kJ/kg})}{(3.14)(269 \text{ m})^2 (17.7 \text{ s})} = 345 \text{ kJ/m}^2\text{s} = 345 \text{ kW/m}^2
\]
The view factor, assuming a vertically oriented target, is determined from Eq. (2.2.47).

\[ F_{21} = \frac{L(D/2)^2}{(L^2 + H_{BLEVE}^2)^{3/2}} = \frac{(200 \text{ m})(269 \text{ m}/2)^2}{[(200 \text{ m})^2 + (202 \text{ m})^2]^{3/2}} = 0.157 \]

The transmissivity of the atmosphere is determined from Eq. (2.2.42). This requires a value, \( X_a \), for the path length from the surface of the fireball to the target, as shown in Figure 2.72. This path length is from the surface of the fireball to the receptor and is equal to the hypotenuse minus the radius of the BLEVE fireball.

\[
\text{Path Length} = \sqrt{H_{BLEVE}^2 + L^2} - \frac{D_{\text{max}}}{2} = [(202 \text{ m})^2 + (200 \text{ m})^2]^{1/2} - (0.5)(269 \text{ m}) = 150 \text{ m}
\]

The transmissivity of the air is given by Eq. (2.2.42),

\[ \tau_a = 2.02(P_w X_s)^{-0.09} = (202)[(2810 \text{ Pa})(150 \text{ m})]^{-0.09} = 0.630 \]

The received flux at the receptor is calculated using Eq. (2.2.45)

\[ E_r = \tau_a EF_{21} = (0.630)(345 \text{ kW/m}^2)(0.158) = 34.3 \text{ kW/m}^2 \]

This received radiation is enough to cause blistering of bare skin after a few seconds of exposure.

An alternate approach is to use Eq. (2.2.41) or (2.2.44) to estimate the radiative energy received at the receptor. In this case \( X_c \) is the distance from the center of the fireball to the receptor. From geometry this is given by

\[ X_c = \sqrt{(202 \text{ m})^2 + (200 \text{ m})^2} = 284.2 \text{ m} \]

Substituting into Eq. (2.2.41)

\[
E_r = \frac{2.2\tau_s R H_c M^{2/3}}{4\pi X_c^2} = \frac{2.2(0.630)(0.3)(46.35 \times 10^6 \text{ J/kg})(100,000 \text{ kg})^{2/3}}{(4)(3.14)(284.2 \text{ m})^2} = 40.9 \text{ kW/m}^2
\]

**FIGURE 2.72** Geometry for Example 2.27: BLEVE thermal flux.
which is close to the previously calculated value of 34.2 kW/m². Using Eq. (2.2.44)

\[ E_r = \frac{8.28 \times 10^5 M^{0.771}}{X_c^2} = \frac{(8.28 \times 10^5)(100,000 \text{ kg})^{0.771}}{(284.2 \text{ m})^2} = 73.4 \text{ kW/m}^2 \]

which is a different result, more conservative in this case.

This problem is readily implemented using a spreadsheet. The spreadsheet output is shown in Figure 2.73.

**Example 2.28: Blast Fragments from a BLEVE.** A sphere containing 293,000 gallons of propane (approximately 60% of its capacity) is subjected to a fire surrounding the sphere. There is a torchlike flame impinging on the wall above the liquid level in the tank. A BLEVE occurs and the tank ruptures. It is estimated that the tank fails at approximately 350 psig. Estimate the energy release of the failure, the number of fragments to be expected, and the approximate maximum range of the fragments. The inside diameter of the sphere is 50 ft, its wall thickness is \( \frac{3}{4} \) inch, and the shell is made of steel with a density of 487 lb/m³. Assume an ambient temperature of 77°F and a pressure of 1 atm.

**Solution.** The total volume of the sphere is

\[ V = \frac{\pi D^3}{6} = \frac{(3.14)(50 \text{ ft})^3}{6} = 65,450 \text{ ft}^3 = 1854 \text{ m}^3 \]

The volume of liquid is 0.6 \( \times \) 65,450 ft³ = 39,270 ft³. The vapor volume is 65,450 ft³ – 39,270 ft³ = 26,180 ft³. If we assume that pressure effects are due to vapor alone, ignoring any effect from the flashing liquid, and if we assume isothermal behavior and

Click to View Calculation Example

<table>
<thead>
<tr>
<th>Example 2.27: BLEVE Thermal Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input Data:</strong></td>
</tr>
<tr>
<td>Initial flammable mass:</td>
</tr>
<tr>
<td>Water partial pressure in air:</td>
</tr>
<tr>
<td>Radiation Fraction, R</td>
</tr>
<tr>
<td>Distance from fireball center on ground:</td>
</tr>
<tr>
<td>Heat of Combustion of fuel:</td>
</tr>
</tbody>
</table>

| **Calculated Results:** |
| Maximum fireball diameter: | 269.2 m |
| Fireball combustion duration: | 17.7 s |
| Center height of fireball: | 201.9 m |
| Initial ground level hemisphere diameter: | 350.0 m |
| Surface emitted flux: | 344.9 kW/m² |
| Path length: | 149.5 |
| Transmissivity: | 0.630 |

<table>
<thead>
<tr>
<th></th>
<th>Horizontal</th>
<th>Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>View Factor:</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>Received flux:</td>
<td>34.63</td>
<td>34.30 kW/m²</td>
</tr>
</tbody>
</table>

FIGURE 2.73. Spreadsheet output for Example 2.27: BLEVE thermal flux.
an ideal gas, then the energy of explosion due to loss of physical containment alone (i.e., no combustion of the vapor) is given by Eq. (2.2.12)

\[ W = 1.39 \times 10^{-6} V \frac{P_1}{P_0} R_g T_0 \ln \left( \frac{P_1}{P_2} \right) \]

\[ = 1.39 \times 10^{-6} (26,180 \text{ ft}^3) \left( \frac{364.7 \text{ psia}}{14.7 \text{ psia}} \right) \left( \frac{1.987 \text{ BTU}}{\text{lb-mole} \cdot \text{R}} \right) \ln \left( \frac{364.7 \text{ psia}}{14.7 \text{ psia}} \right) \]

\[ W = 3090 \text{ lb TNT} \]

The TNT equivalent could be used with Eq. (2.2.1) and Figure 2.48 to determine the overpressure at a specified distance from the explosion.

The number of fragments is estimated using Eq. (2.2.31).

\[
\text{Number of fragments} = -3.77 + 0.0096 \times \text{(vessel capacity, m}^3\text{)}
\]

\[
= -3.77 + 0.0096 \times (1854 \text{ m}^3)
\]

\[
= 14 \text{ fragments}
\]

The total volume of the \( \frac{3}{4} \)-inch (0.0625 ft) vessel shell is

\[
V = \frac{\pi}{6} \left( D_2^3 - D_1^3 \right) = \frac{3.14}{6} \left[ (50 \text{ ft} + 0.0625 \text{ ft})^3 - (50 \text{ ft})^3 \right] = 246 \text{ ft}^3
\]

The mass of the vessel is \( 246 \text{ ft}^3 \times 487 \text{ lb/ft}^3 = 119,700 \text{ lb} \). If this weight is distributed evenly among 14 fragments, the average weight of each fragment is \( 119,700 \text{ lb}/14 = 8547 \text{ lb} \).

A quick estimate of the initial velocity of the fragments is determined from Eq. (2.2.25):

\[
\frac{u}{6} \frac{PD^2}{W} = 2.05 \sqrt{\frac{PD^2}{W}}
\]

where:

- \( u \) is the initial velocity of the fragment (ft/s)
- \( P \) is the rupture pressure (psig)
- \( D \) is the diameter of the fragment (inch)
- \( W \) is the weight of the fragment (lb)

The average diameter of the fragment is estimated by assuming that each shell fragment is crumbled up into a sphere. Thus, we can determine a fragment diameter by assuming a sphere equal in surface area to the original outer surface area of the fragment. The total surface area of the original vessel is

\[
A = \pi D^2 = (3.14)(50 \text{ ft})^2 = 7854 \text{ ft}^2
\]

The fragment surface area is then, \( 7850 \text{ ft}^2/14 = 561 \text{ ft}^2 \). The equivalent diameter of a sphere with this surface area is

\[
D = \sqrt[3]{\frac{A}{\pi}} = \sqrt[3]{\frac{561 \text{ ft}^2}{3.14}} = 13.36 \text{ ft} = 160 \text{ in.}
\]

Substituting the numbers provided into Eq. (2.2.25)

\[
\frac{u}{6} \frac{(350 \text{ psig})(160 \text{ in.})^3}{8557 \text{ lb}} = 842 \text{ ft/s} = 257 \text{ m/s}
\]
The procedure by Baker is used to calculate the approximate range of a missile under these circumstances

\[ \rho_0 = 1.19 \text{ kg/m}^3 = 0.0740 \text{ lb/ft}^3 \text{ (density of air)} \]
\[ M = 8557 \text{ lb (3,866 kg)} \]
\[ A_D = 561 \text{ ft}^2 \text{ (52.12 m}^2) \]

From Table 2.26 select a drag coefficient for a sphere
\[ C_D = 0.47 \]

The scaled initial velocity in Figure 2.63 can now be calculated,

\[ \frac{\rho_0 C_D A_D u^2}{M g_c} = \frac{(0.0740 \text{ lb/ft}^3)(0.47)(561 \text{ ft}^2)(839 \text{ ft/s})^2}{(8557 \text{ lb}) (32.17 \text{ ft/s}^2)} = 50.4 \]

If it is assumed that the fragment is "chunky," that is,
\[ \frac{C_L A_L}{C_D A_D} = 0 \]

then from Figure 2.63, for a scaled initial velocity of 50.4

\[ \frac{\rho_0 C_D A_D R}{M} = 4.81 \]

Solving for \( R \)

\[ R = \frac{(4.81)(8547 \text{ lb/ft}^3)}{(0.0740 \text{ lb/ft}^3)(0.47)(561 \text{ ft}^2)} = 2106 \text{ ft} = 642 \text{ m} \]

This is the expected range of the fragments. If the fragments were flatter instead of spherical, then the drag coefficient would be larger and the resulting distance would be less.

The spreadsheet implementation of this example is provided in Figure 2.74.

2.2.4.4. DISCUSSION

Strengths and Weaknesses
BLEVE dimensions and durations have been studied by many authors and the empirical basis consists of several well-described incidents, as well as many smaller laboratory trials. The use of a surface emitted flux estimate is the greatest weakness, as this is not a fundamental property. Fragment correlations are subject to the same weaknesses discussed in Section 2.2.3.4.

Identification and Treatment of Possible Errors
The two largest potential errors are the estimation of the mass involved and the surface emitted flux. The surface emitted flux is an empirical term derived from the estimated radiant fraction. While this is not fundamentally based, the usual value is similar in magnitude (but larger) than that used in API 521 for jet flare radiation estimates. A simplified graphical or correlation approach is a check, but these do not allow for differing materials or atmospheric conditions.
Example 2.28: Blast Fragments from a BLEVE

Input Data:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of sphere</td>
<td>15.24 m</td>
</tr>
<tr>
<td>Vessel failure pressure</td>
<td>2514 kPa abs</td>
</tr>
<tr>
<td>Vessel liquid fill fraction</td>
<td>0.6</td>
</tr>
<tr>
<td>Vessel wall thickness</td>
<td>1.905 cm</td>
</tr>
<tr>
<td>Vessel wall density</td>
<td>7800 kg/m(^3)</td>
</tr>
<tr>
<td>Temperature</td>
<td>298 K</td>
</tr>
<tr>
<td>Ambient pressure</td>
<td>101.325 kPa abs</td>
</tr>
<tr>
<td>Drag coefficient of fragment</td>
<td>0.47</td>
</tr>
<tr>
<td>Lift to drag ratio</td>
<td>0</td>
</tr>
</tbody>
</table>

Calculated Results:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of sphere</td>
<td>50.00 ft</td>
</tr>
<tr>
<td>Vessel failure pressure</td>
<td>364.73 psia</td>
</tr>
<tr>
<td>Vessel wall thickness</td>
<td>0.75 in</td>
</tr>
<tr>
<td>Vessel wall density</td>
<td>486.95 lb/ft(^3)</td>
</tr>
<tr>
<td>Temperature</td>
<td>536.40 R</td>
</tr>
<tr>
<td>Total volume of sphere</td>
<td>1853.33 m(^3) = 65447.46 ft(^3)</td>
</tr>
<tr>
<td>Liquid volume</td>
<td>1112.00 m(^3) = 39268.48 ft(^3)</td>
</tr>
<tr>
<td>Vapor volume</td>
<td>741.33 m(^3) = 26178.98 ft(^3)</td>
</tr>
<tr>
<td>Energy of explosion</td>
<td>1401.70 kg TNT = 3090.18 lb TNT</td>
</tr>
<tr>
<td>Number of fragments</td>
<td>14</td>
</tr>
<tr>
<td>Volume of vessel shell</td>
<td>6.96 m(^3) = 245.74 ft(^3)</td>
</tr>
<tr>
<td>Total mass of vessel</td>
<td>54278 kg = 119661 lb</td>
</tr>
<tr>
<td>Average mass of each fragment</td>
<td>3877.03 kg = 8547.25 lb</td>
</tr>
<tr>
<td>Total surface area of sphere</td>
<td>729.66 m(^2) = 7853.79 ft(^2)</td>
</tr>
<tr>
<td>Surface area for each fragment</td>
<td>52.12 m(^2) = 560.99 ft(^2)</td>
</tr>
<tr>
<td>Average diameter of spherical fragment</td>
<td>4.07 m = 13.36 ft</td>
</tr>
<tr>
<td>Initial velocity of fragment</td>
<td>256.76 m/s = 842.39 ft/s</td>
</tr>
<tr>
<td>Density of ambient air</td>
<td>1.19 kg/m(^3) = 0.0740 lb/ft(^3)</td>
</tr>
<tr>
<td>Scaled velocity of fragment</td>
<td>50.41</td>
</tr>
</tbody>
</table>

Interpolated values from figure for various lift to drag ratios:

<table>
<thead>
<tr>
<th>Lift to drag ratio</th>
<th>Scaled Range</th>
<th>Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4.810431</td>
<td>641.99</td>
</tr>
<tr>
<td>0.5</td>
<td>5.299823</td>
<td>707.30</td>
</tr>
<tr>
<td>1</td>
<td>3.964659</td>
<td>529.11</td>
</tr>
<tr>
<td>3</td>
<td>0.77503</td>
<td>103.43</td>
</tr>
<tr>
<td>5</td>
<td>0.490619</td>
<td>65.48</td>
</tr>
<tr>
<td>10</td>
<td>0.238585</td>
<td>31.84</td>
</tr>
<tr>
<td>30</td>
<td>0.079547</td>
<td>10.62</td>
</tr>
<tr>
<td>50</td>
<td>0.051752</td>
<td>6.91</td>
</tr>
<tr>
<td>100</td>
<td>0.023798</td>
<td>3.18</td>
</tr>
</tbody>
</table>

Interpolated range: 642 m = 2106 ft
Theoretical max. range (no lift): 6727 m = 22071 ft
Max. possible range (with lift): 707 m = 2321 ft

FIGURE 2.74. Spreadsheet output for Example 2.28: Blast fragments from a BLEVE.

Utility

BLEVE models require some care in application, as errors in surface flux, view factor, or transmissivity can lead to significant error. Thermal hazard zone calculations will be iterative due to the shape factor and transmissivity which are functions of distance. Fragment models showing the possible extent of fragment flight and damage effects are difficult to use.
Resources Needed
A process engineer with some understanding of thermal radiation effects could use BLEVE models quite easily. A half-day calculation period should be allowed unless the procedure is computerized, in which case much more rapid calculation and exploration of sensitivities is possible. Spreadsheets can be readily applied.

Available Computer Codes
Several integrated analysis packages contain BLEVE and fireball modeling. These include:
- ARCHIE (Environmental Protection Agency, Washington, DC)
- EFFECTS-2 (TNO, Apeldoorn, The Netherlands)
- PHAST (DNV, Houston, TX)
- QRAWorks (PrimaTech, Columbus, OH)
- SUPERCHEMS (Arthur D. Little, Cambridge, MA)
- TRACE (Safer Systems, Westlake Village, CA)

2.2.5. Confined Explosions

2.2.5.1. BACKGROUND

Purpose
Confined explosions in the context of this section (see Figure 2.46) include deflagrations or other sources of rapid chemical reaction which are constrained within vessels and buildings. Dust explosions and vapor explosions within low strength vessels and buildings are one major category of confined explosion that is discussed in this chapter. Combustion reactions, thermal decompositions, or runaway reactions within process vessels and equipment are the other major category of confined explosions. In general, a deflagration occurring within a building or low strength structure such as a silo is less likely to impact the surrounding community and is more of an in-plant threat because of the relatively small quantities of fuel and energy involved. Shock waves and projectiles are the major threats from confined explosions.

Philosophy
The design of process vessels subject to internal pressure is treated by codes such as the Unfired Pressure Vessel Code (ASME, 1986). Vessels can be designed to contain internal deflagrations. Recommendations to accomplish this are contained in NFPA 69 (1986) and Noronha et al. (1982). The design of relief systems for both low strength enclosures and process vessels, commonly referred to as “Explosion Venting,” is covered by Guide for Venting Deflagrations (NFPA 68, 1994). As of this writing both NFPA 68 and NFPA 69 are under revision, with major changes to include updated information from the German standard VDI 3673 (VDI, 1995). Details on the new VDI update are contained in Siwek (1994).

Applications
There are few published CPQRAs that consider the risk implications of these effects; however the Canvey Study (Health & Safety Executive, 1978) considered missile damage effects on process vessels.