Analysis of Boiling Liquid Expanding Vapor Explosion (BLEVE) Events at DOE Sites

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Abstract

Several DOE standards and/or orders require the analysis of hypothetical releases of hazardous materials. The consequences of such releases for nonnuclear facilities are reported in safety analysis reports (SARs) (DOE Order 5481.1B), basis for interim operation (BIO) analyses (DOE Standard 3011-94), and/or emergency response planning hazard assessments (DOE Order 151.1). For flammable materials such as liquefied petroleum gas (LPG) or propane stored as pressurized liquefied materials (i.e., stored as liquids in pressurized vessels), a boiling liquid expanding vapor explosion (BLEVE) event may prove to be a credible accident scenario.

A BLEVE occurs when a vessel containing a superheated liquid (e.g., propane) catastrophically fails, usually as a result of external fire exposure (i.e., a pool fire under the vessel or a jet- or torch-type fire impinging on the vessel walls). The fire pressurizes the vessel, causing the relief valve to open, which allows the pressurized vapor to escape. As the liquid level in the vessel decreases, the flames impinge on the vessel wall above the liquid level. The vessel wall rapidly heats up due to the poor heat transfer provided by the vapor on the inner side of the vessel wall. The wall weakens and then tears, resulting in a sudden catastrophic failure of the vessel.

The consequences of a BLEVE event are (1) the overpressure blast wave that is generated as a result of the rapid expansion of the superheated liquid, (2) the fireball thermal radiation generated as a result of the rapid combustion of the released flammable material, and (3) the potential vessel fragments that may be propelled as missiles. BLEVE events have the potential for causing injury and/or facility damage at significant distances from the source of the BLEVE.

The standard techniques for evaluating the thermal radiation from BLEVE events assume that the radiant heat flux is constant over the duration of the BLEVE fireball. This assumption leads to overly conservative predictions of hazard zones for injuries (i.e., second-degree burns). More recent techniques have been developed that account for the time-dependent nature of thermal radiation generated by a BLEVE fireball, leading to a more realistic assessment of hazard zones associated with burn injuries.

This paper presents the most recent analysis techniques for evaluating the blast (overpressure, impulse, etc.), time-dependent thermal radiation, and missile generation consequences of a BLEVE event. As an illustration of the methodology, a simple case study is presented for a typical size propane storage vessel. The methodology and case study provide analysts with a simple, yet technically defensible, realistic approach for analyzing BLEVE events for SARs, BIOs, hazard assessments, or other analyses.

1. Introduction

Several DOE standards and/or orders require the analysis of hypothetical releases of hazardous materials. The consequences of such releases for nonnuclear facilities are reported in safety analysis reports (SARs) (DOE Order 5481.1B), basis for interim operation (BIO) analyses (DOE Standard 3011-94), and/or emergency response planning hazard assessments (DOE Order 151.1). Table 1 presents excerpts from these orders/standards.

Table 1 Excerpts from DOE Standards/Orders Requiring Consequence Analyses

DOE Reference	Reference Title	Consequence Analysis Language
Order 5481.1B	*Safety Analysis and Review System*	Safety analysis is performed "to systematically identify the hazards of a DOE operation, to describe and analyze the adequacy of the measures taken to eliminate, control, or mitigate identified hazards, and to ***analyze and evaluate accidents*** and their associated risks." One of the objectives of the safety analysis preparation and review process is to ensure that "***potential consequences are analyzed***."
Standard 3011-94	*Guidance for Preparation of DOE 5480.22 (TSR) and DOE 5480.23 (SAR) Implementation Plans*	Safety analysis is performed "to provide assurance that hazards associated with processes at a facility have been identified, that characterization has been made of the ***potential impacts*** that deviations from normal operating parameters and conditions can have on facility workers, onsite workers, and the public...For scenarios resulting in a significant impact outside the facility, the extent of detail incorporated in the analysis must ensure that a ***qualitative or semi-quantitative determination of the consequences*** and frequencies of the identified scenarios can be made."
Order 151.1	*Comprehensive Emergency Management System*	Hazard assessment is performed to ensure that the "release of or loss of control of hazardous materials (radiological and non-radiological) [is] ***quantitatively analyzed***...Assumptions, methodology, models, and evaluation techniques used in the hazard assessment [must] be documented."

In recent years, more attention has focused on the hazards associated with nonradioactive materials. Boiling liquid expanding vapor explosion (BLEVE) events, resulting from failure of liquified petroleum gas (LPG) storage vessels or tank trucks, can pose a risk to facility workers and property. While in some cases it may be possible to *qualitatively* evaluate the consequence of hypothetical releases of hazardous materials, BLEVE events generally require a *quantitative* analysis to thoroughly understand the scope of the consequences. This paper summarizes methods for evaluating the consequences of a BLEVE event and presents a simple case study illustrating the methods.

2. Description of a BLEVE Event

A BLEVE occurs when a vessel containing a superheated liquid (e.g., propane) catastrophically fails, usually as a result of external fire exposure (i.e., a pool fire under the vessel or a jet- or torch-type fire impinging on the vessel walls). The fire pressurizes the vessel, causing the relief valve to open, which allows the pressurized vapor to escape. As the liquid level in the vessel decreases, the flames impinge on the vessel wall above the liquid level. The vessel wall rapidly heats up due to the poor heat transfer provided by the vapor on the inner side of the vessel wall. The wall weakens and then tears, resulting in a sudden catastrophic failure of the vessel. BLEVE events have also been known to occur as a result of vessel failure from mechanical impact, corrosion, overpressurization, or metallurgical failure.

The consequences of a BLEVE event are (1) the overpressure blast wave that is generated as a result of the rapid expansion of the superheated liquid, (2) the fireball thermal radiation generated as a result of the rapid combustion of the released flammable material, and (3) the potential vessel fragments that may be propelled as missiles. BLEVE events have the potential for causing injury and/or facility damage at significant distances from the source of the BLEVE.

According to the Center for Chemical Process Safety (CCPS 1994), the effects of a BLEVE event will be determined by the condition of the container's contents and its walls at the instant of vessel failure. The blast and fragmentation consequences of a BLEVE event depend directly on the internal energy of the vessel's contents, which is a function of the material's thermodynamic properties and mass.

The pressure of the vessel's contents at the time of failure is a function of the conditions leading to vessel failure. For failures resulting from fire exposure, the internal failure pressure for vessels with safety relief valves may be as much as 20% above the safety valve setpoint. For vessels without safety relief valves or improperly sized relief valves, the internal failure pressure may be the maximum design pressure of the vessel, accounting for factors of safety that may be incorporated in the design. In this paper, we examine the methodology for evaluating the consequences of BLEVE events resulting from LPG vessels (with safety valves) that fail due to fire exposure. The methodology may be expanded, however, to failures resulting from other causes.

3. BLEVE Blast Effects Methodology

The blast wave associated with a BLEVE event is estimated by calculating the total work done by the superheated liquid as it expands from its initial condition at the time of vessel failure to atmospheric conditions. For storage vessels with properly sized relief valves, it is assumed that the failure pressure of the vessel is 1.21 times the relief valve set pressure. This approach is recommended by the CCPS (1994). Assuming an isentropic expansion, the total work (W) done by the superheated liquid during the expansion process is given by the following:

(1) $$W = -\Delta U$$

where ΔU is the change in the internal energy of the expanding fluid. The specific internal energy (u) at a specific state may be obtained directly from thermodynamic tables, or it may be calculated if the specific enthalpy (h), pressure (p), and specific volume (υ) are known:

(2) $$u = h - p\upsilon$$

The change in the internal energy (ΔU) is then estimated from the following:

(3) $$\Delta U = m_{f,2}u_{f,2} + m_{g,2}u_{g,2} - m_{f,1}u_{f,1} - m_{g,1}u_{g,1}$$

where $m_{f,i}$ and $m_{g,i}$ are the liquid and vapor masses, respectively, at state i, and $u_{f,i}$ and $u_{g,i}$ are the liquid- and vapor-specific internal energies, respectively, at state i. The mass of liquid and vapor at the final state is estimated from the following:

(4) $$m_{f,2} = (1 - x_f)\, m_{f,1} + (1 - x_g)\, m_{g,1}$$

(5) $$m_{g,2} = x_f\, m_{f,1} + x_g\, m_{g,1}$$

(6) $$x_f = \frac{s_{f,1} - s_{f,2}}{s_{g,2} - s_{f,2}}$$

(7) $$x_g = \frac{s_{g,1} - s_{f,2}}{s_{g,2} - s_{f,2}}$$

where x_f is the fraction of the initial liquid mass that flashes to vapor, x_g is the fraction of the initial vapor mass that does not condense during the expansion, and $s_{f,i}$ and $s_{g,i}$ are the liquid- and vapor-specific entropies, respectively, at state i. If entropy data are not available, x_f and x_g can be estimated assuming an isenthalpic expansion:

(8) $$x_f = \frac{h_{f,1} - h_{f,2}}{h_{g,2} - h_{f,2}}$$

(9) $$x_g = \frac{h_{g,1} - h_{f,2}}{h_{g,2} - h_{f,2}}$$

where $h_{f,i}$ and $h_{g,i}$ are the liquid- and vapor-specific enthalpies, respectively, at state i.

The peak side-on overpressure (P_S) for a BLEVE event at a specific distance from the event can be estimated from the curve presented in Figure 1 (CCPS 1994).

The blast wave generated by a BLEVE event may cause building damage or personnel injury. Personnel may be injured as a result of direct or indirect effects of a BLEVE. Direct effects result from direct exposure to the blast wave or thermal radiation generated from a BLEVE. For example, eardrum rupture can occur from direct exposure to excessive overpressures. Table 2 presents criteria (Eisenberg et al. 1975) for assessing the likelihood of eardrum rupture occurring as a result of exposure to blast wave overpressures.

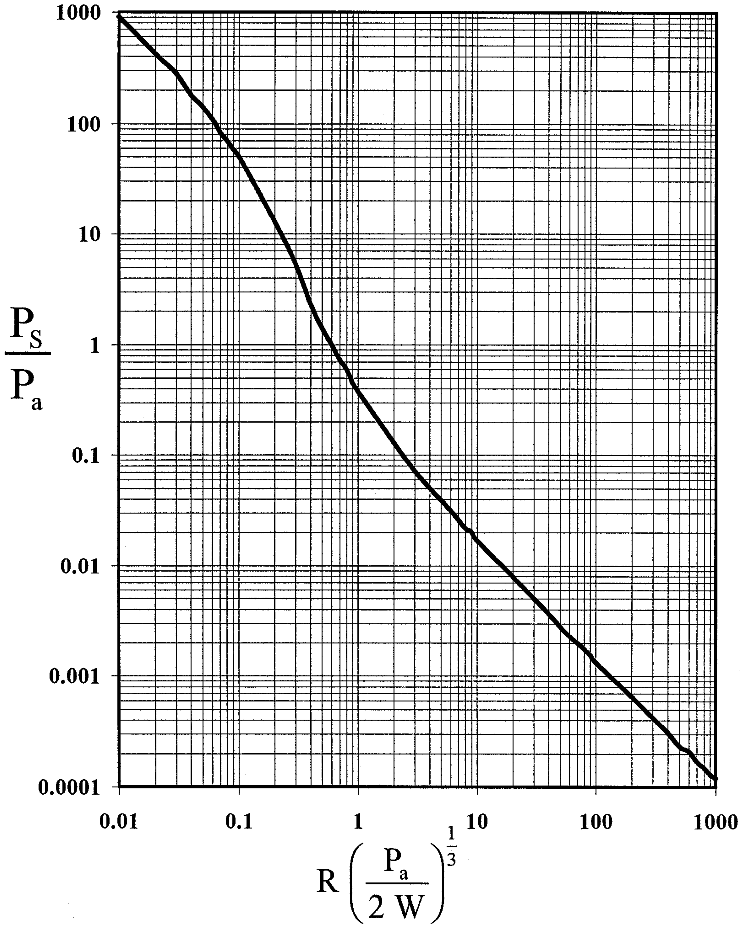

Figure 1 Dimensionless Overpressure vs Distance Curves for BLEVE Events

Table 2 Eardrum Rupture Criteria for Exposure to Blast Overpressures

Likelihood of Eardrum Rupture	Peak Overpressure (psi)
90%	12.2
50%	6.3
10%	3.2
1%	1.9

Indirect effects of a BLEVE include injuries resulting from building damage (e.g., collapse of a wall or roof) or flying fragments. Table 3 (CCPS 1996) describes the types of damage that may occur to various building types as a result of exposure to various levels of peak side-on overpressure and the vulnerability (probability of serious or fatal injury) of occupants within the building type. The data in Table 3 assume a long positive phase duration to help ensure conservatism during risk screening.

4. BLEVE Thermal Radiation Effects Methodology

The thermal radiation generated from a BLEVE fireball is estimated using a solid flame model that assumes that the fireball is a spherical ball that rises into the air as the flammable material is burned. The time-dependent diameter and height of the fireball and the duration of the fireball are estimated using empirical relationships. The duration of combustion (t_d) for the BLEVE fireball may be estimated from the following (Martinsen and Marx 1999):

(10) $$t_d = 0.9\, M_{FB}^{\frac{1}{4}}$$

where t_d is in sec and M_{FB} is the mass of released flammable material in the fireball in kg.

The fireball diameter is time-dependent. Based on experimental observations, the fireball tends to reach its maximum diameter during the first third of the fireball duration. At this point, the fireball tends to rise into the air and the diameter remains constant until the fireball dissipates. Martinsen and Marx (1999) present the following equation for estimating the fireball diameter during the growth phase:

(11) $$D(t) = 8.664\, M_{FB}^{\frac{1}{4}}\, t^{\frac{1}{3}} \quad \text{for } 0 \le t \le \frac{1}{3} t_d$$

where D(t) is in m, M_{FB} is in kg, and t is in sec. At the end of the growth period, the fireball is assumed to achieve its maximum diameter (D_{max}) as given by the following equation (Roberts 1981-1982):

(12) $$D_{max} = 5.8\, M_{FB}^{\frac{1}{3}} \quad \text{for } \frac{1}{3} t_d < t \le t_d$$

where D_{max} is in m. The initial ground flash radius (R_{flash}) associated with a BLEVE fireball is approximated using the following relationship (CCPS 1999):

(13) $$R_{flash} = 0.65\, D_{max}$$

where R_{flash} is in m. This radius represents the distance that may be engulfed in flames during the initial development of the BLEVE fireball.

The height of the center of the fireball is also time-dependent. Based on experimental observations (Martinsen and Marx 1999) the center of the fireball rises at a constant rate from its lift-off position to three times the lift-off position during the last two-thirds of the fireball duration. This leads to the following equations for the height of the center of the fireball (H_{FB}):

(14) $$H_{FB}(t) = \frac{D(t)}{2} \quad \text{for } 0 \le t \le \frac{1}{3} t_d$$

Table 3 Peak Side-on Overpressure Damage/Vulnerability Criteria for Various Types of Buildings

Building Type	Peak Side-on Overpressure (psi)	Type of Damage	Occupant Probability of Serious Injury or Fatality
Wood-frame trailer or shack	1	Isolated buildings overturn. Roof and walls collapse.	0.1
	2	Near-total collapse.	0.4
	5	Buildings completely destroyed.	1
Steel-frame/ metal siding pre-engineered building	1.25	Metal siding anchorage failure.	0.1
	1.5	Sheeting ripped off, and internal walls damaged. Danger from falling objects.	0.2
	2.5	Building frame stands, but cladding and internal walls destroyed as frame distorts.	0.4
	5	Building completely destroyed.	1
Unreinforced masonry bearing wall building	1	Partial collapse of walls that have no breakable windows.	0.1
	1.25	Walls and roof partially collapse.	0.2
	1.5	Complete collapse.	0.6
	3	Building completely destroyed.	1
Steel or concrete frame with unreinforced masonry infill or cladding	1	Failure of incident face.	0.1
	1.5	Walls blow in.	0.2
	2	Roof slab collapses.	0.4
	2.5	Complete frame collapse.	0.6
	5	Building completely destroyed.	1
Reinforced concrete or masonry shear wall building	4	Roof and wall deflect under loading. Internal walls damaged.	0.1
	6	Building has major damage and collapses.	0.4
	12	Building completely destroyed.	1

$$H_{FB}(t) = \frac{3 D_{max} t}{2 t_d} \quad \text{for } \frac{1}{3} t_d < t \le t_d \tag{15}$$

where H_{FB} is in m.

The thermal radiation emitted from the surface of the fireball is also time-dependent. The fireball surface emitted flux is assumed to be constant during the growth period, and then is assumed to linearly decrease from its maximum value to zero during the last two-thirds of fireball duration. The maximum surface emitted thermal flux (E_{max}) during the growth phase is given by the following (Martinsen and Marx 1999):

$$E_{max} = 0.0133\, f\, H_c\, M_{FB}^{\frac{1}{12}} \quad \text{for } 0 \le t \le \frac{1}{3} t_d \tag{16}$$

where E_{max} is in kW/m^2, f is the radiant heat fraction, H_c is the net heat of combustion of the flammable material in kJ/kg, and M_{FB} is in kg. The radiant heat fraction (f) is given by the following (Roberts 1981-1982):

$$f = 0.27\ P_B^{0.32} \tag{17}$$

where f is dimensionless, and P_B is the burst pressure of the vessel in MPa. Fire research suggests that the maximum surface emitted flux E_{max} will not exceed some upper limit ranging from 300 to 450 kW/m^2. A value of 400 kW/m^2 is suggested as a limiting value (Martinsen and Marx 1999). Therefore, the lesser of the surface emitted flux given by Equation 16 or 400 kW/m^2 should be used. During the last two-thirds of the fireball duration, the surface emitted flux (E_S) is given by the following:

$$E_S(t) = E_{max}\left[\frac{3}{2}\left(1 - \frac{t}{t_d}\right)\right] \quad \text{for } \frac{1}{3} t_d < t \le t_d \tag{18}$$

The thermal flux incident upon a target object is a function of the geometric view factor between the fireball and the target. The most conservative approach assumes that the target area is normal to the surface of the fireball as the fireball rises into the air, as illustrated in Figure 2.

For a target at ground level, the maximum geometric view factor (F) for a spherical emitter is given by the following equation (CCPS 1999):

$$F(x,t) = \frac{D(t)^2}{4\left[H_{FB}(t)^2 + x^2\right]} \tag{19}$$

where F is dimensionless and D, H_{FB}, and x are in m.

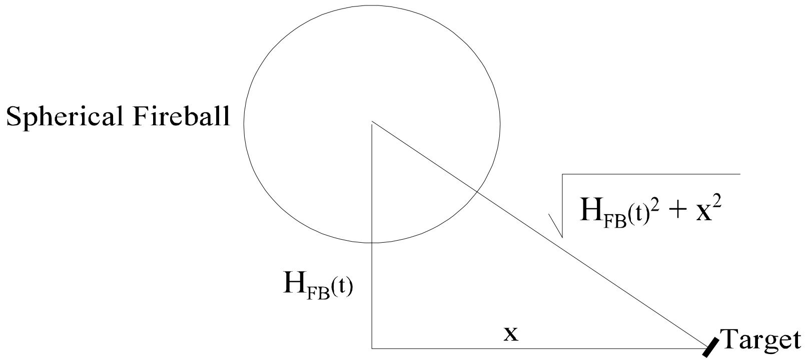

Figure 2 Assumed Orientation of a Ground-level Target to the Fireball Surface

The atmospheric transmissivity (τ) between the fireball and the target is estimated from the following equation (CCPS 1999):

(20)
$$\tau(x,t) = 2.02 \left\{ R\,P_v \left[\sqrt{H_{FB}(t)^2 + x^2} - \frac{D(t)}{2} \right] \right\}^{-0.09}$$

where τ is dimensionless, R is the fractional relative humidity (e.g., for 70% relative humidity, R is 0.7), and P_v is the saturated vapor pressure of water at the ambient temperature in Pa. The saturated vapor pressure of water at various ambient temperatures is summarized in Table 4 (American Institute of Chemical Engineers 1998).

Table 4 Saturated Vapor Pressure of Water as a Function of Temperature

Saturated Vapor Pressure of Water at Various Temperatures					
Temp. (°C)	**Vapor Pressure (Pa)**	**Temp. (°C)**	**Vapor Pressure (Pa)**	**Temp. (°C)**	**Vapor Pressure (Pa)**
1	660	18	2060	30	4250
2	705	19	2200	31	4500
4	813	20	2340	32	4760
6	935	21	2490	33	5040
8	1070	22	2650	34	5330
10	1230	23	2810	35	5630
11	1310	24	2990	36	5950
12	1400	25	3170	37	6280
14	1600	26	3360	38	6630
15	1710	27	3570	39	7000
16	1820	28	3780	40	7390
17	1940	29	4010	41	7790

The thermal flux (I_{th}) at a target is given by the following equation (CCPS 1999):

(21)
$$I_{th}(x,t) = \tau(x,t)\,F(x,t)\,E_S(t)$$

where I_{th} is in kW/m^2. Personnel injuries resulting from exposure to a BLEVE fireball are dependent upon the thermal dose (I_{dose}) or the integral of the thermal flux over the duration of the fireball:

$$I_{dose}(x) = \int_0^{t_d} I_{th}(x,t)\,dt \tag{22}$$

where I_{dose} is in kJ/m^2. Table 5 (Prugh 1994) summarizes the type of injury that may result from various thermal dose levels.

Table 5 Thermal Dose Injury Criteria

Injury Description	Thermal Dose (kJ/m^2)
Third-degree burns (99% fatal)	1,200
Third-degree burns (50% fatal)	500
Third-degree burns (1% fatal)	250
Second-degree burns (blisters)	150
First-degree burns (sunburn)	100
Threshold of pain	40

5. BLEVE Missile Effects Methodology

BLEVE events often generate large vessel fragments that may be propelled long distances. In fact, in many cases, the longest reaching hazard associated with a BLEVE event is projectiles or rocket-type fragments. The fragments associated with a BLEVE are generally not evenly distributed. The vessel's axial direction usually receives more fragments than the side directions, but it is not unusual for a vessel to pivot or spin during failure. Therefore, fragments can be launched in any direction. The trajectory of the propelled fragments can also be changed by bouncing off terrain or structures.

According to Birk (1995), as a crude approximation, projectile ranges can be related to the fireball radius. The following is suggested as a guide:

- 80 to 90% of rocketing fragments fall within 4 times the fireball radius
- Severe rocketing fragments may travel up to 15 times the fireball radius
- In very severe, rare cases, rocketing fragments may travel up to 30 times the fireball radius

Birk (1995) suggests that personnel should be evacuated to beyond 15 to 30 times the fireball radius, if possible. Birk (1995) also stresses that the above guidelines are based on limited data and should be considered as approximate.

6. Case Study Description

As a case study, consider a 10,000-gal capacity propane storage tank with a safety relief valve that has a relief pressure of 250 psig. For this case study, it is assumed that the storage tank is filled to 80% of volume capacity (i.e., 8,000 gal). The storage tank is assumed to be engulfed in flames, resulting in a BLEVE event. The ambient temperature is assumed to be 70 °F, and the relative humidity is assumed to be 70%. The net heat of combustion for propane is 19,944 Btu/lb.

7. Case Study Blast Effects Analysis

The 10,000-gal propane storage vessel is assumed to fail at an internal pressure of 1.21 times the setpoint of the safety relief valve (250 psig), or 320 psia. The saturation temperature of propane at 320 psia is approximately 144 °F. This defines the initial conditions for calculation of the change in the internal energy. The final conditions of the propane are atmospheric pressure (14.7 psia) and the normal boiling point of propane (-44 °F). Table 6 summarizes the thermodynamic data for propane at the initial and final conditions (Perry 1984).

Table 6 Thermodynamic Data for Propane Case Study

Condition	Temp. (°F)	Pressure (psia)	h_f (Btu/lb)	h_g (Btu/lb)	ν_f (ft^3/lb)	ν_g (ft^3/lb)	s_f (Btu/lb-R)	s_g (Btu/lb-R)
1 (initial)	144	320	300.0	409.2	0.0381	0.311	1.153	1.337
2 (final)	-44	14.7	181.2	365.1	0.0276	6.696	0.925	1.367

First, the masses of liquid and vapor and the initial and final states are determined. The initial liquid and vapor masses are given by the following:

$$m_{f,1} = \frac{8{,}000 \ \text{gal} \times 0.1337 \ \frac{\text{ft}^3}{\text{gal}}}{0.0381 \ \frac{\text{ft}^3}{\text{lb}}} = 28{,}100 \ \text{lb}$$

$$m_{g,1} = \frac{2{,}000 \ \text{gal} \times 0.1337 \ \frac{\text{ft}^3}{\text{gal}}}{0.311 \ \frac{\text{ft}^3}{\text{lb}}} = 900 \ \text{lb}$$

The final liquid and vapor masses are estimated by first calculating the liquid flash fraction (x_f) and the fraction of the initial vapor mass that does not condense (x_g) from Equations 6 and 7:

$$x_f = \frac{1.153 - 0.925}{1.367 - 0.925} = 0.516$$

$$x_g = \frac{1.337 - 0.925}{1.367 - 0.925} = 0.932$$

The final liquid and vapor masses are then given by Equations 4 and 5:

$$m_{f,2} = (1 - 0.516)(28{,}100 \text{ lb}) + (1 - 0.932)(900 \text{ lb}) = 13{,}700 \text{ lb}$$

$$m_{g,2} = (0.516)(28{,}100 \text{ lb}) + (0.932)(900 \text{ lb}) = 15{,}300 \text{ lb}$$

The specific internal energies (u) at the initial and final states are estimated from Equation 2 as follows:

$$u_{f,1} = 300.0 \frac{\text{Btu}}{\text{lb}} - \left(320 \frac{\text{lbf}}{\text{in}^2}\right)\left(144 \frac{\text{in}^2}{\text{ft}^2}\right)\left(0.0381 \frac{\text{ft}^3}{\text{lb}}\right)\left(\frac{1 \text{ Btu}}{778 \text{ ft-lbf}}\right) = 297.7 \frac{\text{Btu}}{\text{lb}}$$

$$u_{f,2} = 181.2 \frac{\text{Btu}}{\text{lb}} - \left(14.7 \frac{\text{lbf}}{\text{in}^2}\right)\left(144 \frac{\text{in}^2}{\text{ft}^2}\right)\left(0.0276 \frac{\text{ft}^3}{\text{lb}}\right)\left(\frac{1 \text{ Btu}}{778 \text{ ft-lbf}}\right) = 181.1 \frac{\text{Btu}}{\text{lb}}$$

$$u_{g,1} = 409.2 \frac{\text{Btu}}{\text{lb}} - \left(320 \frac{\text{lbf}}{\text{in}^2}\right)\left(144 \frac{\text{in}^2}{\text{ft}^2}\right)\left(0.311 \frac{\text{ft}^3}{\text{lb}}\right)\left(\frac{1 \text{ Btu}}{778 \text{ ft-lbf}}\right) = 390.8 \frac{\text{Btu}}{\text{lb}}$$

$$u_{g,2} = 365.1 \frac{\text{Btu}}{\text{lb}} - \left(14.7 \frac{\text{lbf}}{\text{in}^2}\right)\left(144 \frac{\text{in}^2}{\text{ft}^2}\right)\left(6.696 \frac{\text{ft}^3}{\text{lb}}\right)\left(\frac{1 \text{ Btu}}{778 \text{ ft-lbf}}\right) = 346.9 \frac{\text{Btu}}{\text{lb}}$$

The change in the internal energy (ΔU) and the total work (W) done by the superheated liquid during the expansion process are given by Equation 3:

$$\Delta U = (13{,}700)(181.1) + (15{,}300)(346.9) - (28{,}100)(297.7) - (900)(390.8) = -9.285 \times 10^5 \text{ Btu}$$

$$W = 9.285 \times 10^5 \text{ Btu} \quad \text{or } 7.225 \times 10^8 \text{ ft-lbf}$$

Using the overpressure curve presented in Figure 1, the overpressure as a function of distance may be determined, as shown in Figure 3. Table 7 presents the maximum distances associated with various likelihoods of eardrum rupture, and Table 8 summarizes the maximum distances to various types of building damage.

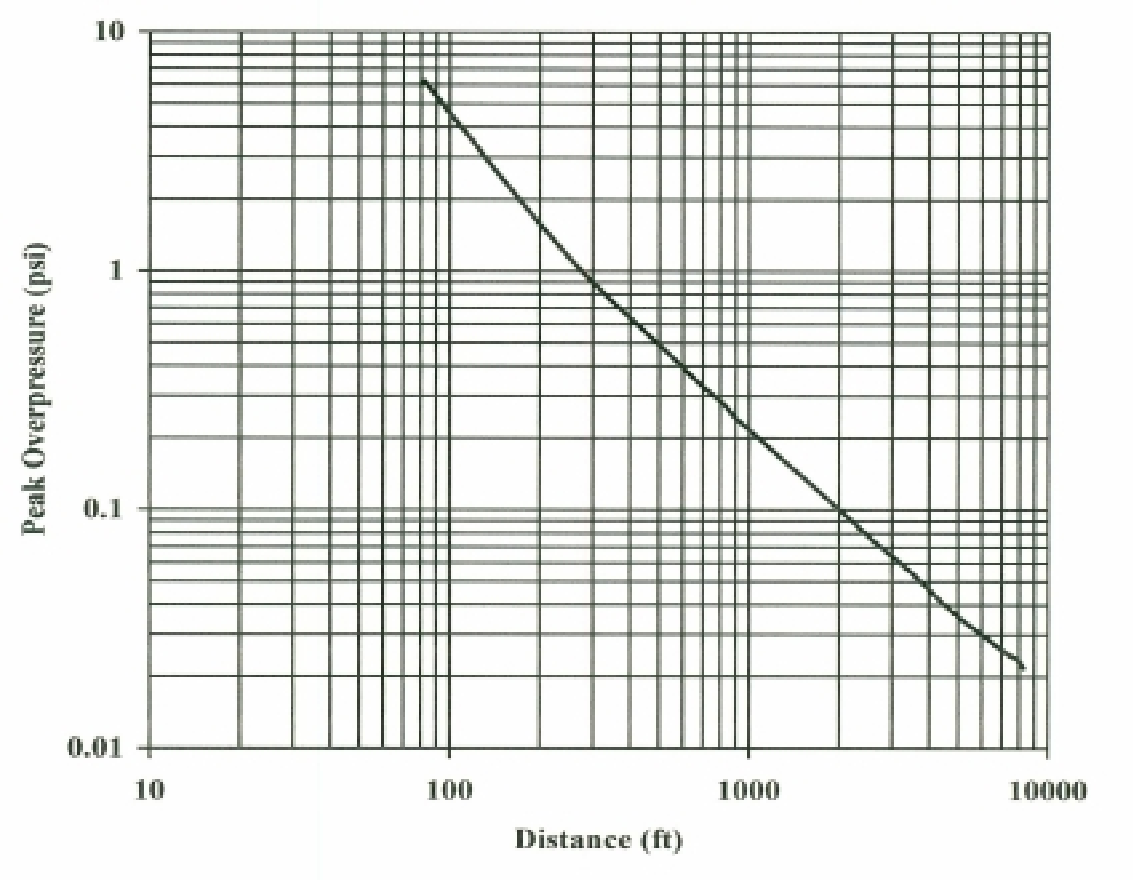

Figure 3 Peak Overpressure vs. Distance for a BLEVE of a 10,000-gal Propane Tank

Table 7 Eardrum Rupture Distances for a BLEVE of a 10,000-gal Propane Tank

Likelihood of Eardrum Rupture	Maximum Distance (ft)
90%	58
50%	82
10%	126
1%	177

7. Case Study Thermal Effects Analysis

The first step in assessing the thermal effects is to determine the duration (t_d) of combustion for the BLEVE fireball based on the total fireball mass (29,000 lb or 13,166 kg) from Equation 10:

$$t_d = 0.9\left(13{,}166 \text{ kg}\right)^{\frac{1}{4}} = 9.64 \text{ sec}$$

Table 8 Damage/Vulnerability Distances for a BLEVE of a 10,000-gal Propane Tank

Building Type	Maximum Distance (ft)	Type of Damage	Occupant Probability of Serious Injury or Fatality
Wood-frame trailer or shack	274	Isolated buildings overturn. Roof and walls collapse.	0.1
	171	Near-total collapse.	0.4
	95	Buildings completely destroyed.	1
Steel-frame/ metal siding pre-engineered building	235	Metal siding anchorage failure.	0.1
	207	Sheeting ripped off, and internal walls damaged. Danger from falling objects.	0.2
	148	Building frame stands, but cladding and internal walls destroyed as frame distorts.	0.4
	95	Building completely destroyed.	1
Unreinforced masonry bearing wall building	274	Partial collapse of walls that have no breakable windows.	0.1
	235	Walls and roof partially collapse.	0.2
	207	Complete collapse.	0.6
	131	Building completely destroyed.	1
Steel or concrete frame with unreinforced masonry infill or cladding	274	Failure of incident face.	0.1
	207	Walls blow in.	0.2
	171	Roof slab collapses.	0.4
	148	Complete frame collapse.	0.6
	95	Building completely destroyed.	1
Reinforced concrete or masonry shear wall building	109	Roof and wall deflect under loading. Internal walls damaged.	0.1
	84	Building has major damage and collapses.	0.4
	58	Building completely destroyed.	1

The time-dependent fireball diameter [D(t)] during the growth phase of the fireball is then estimated from Equation 11:

$$D(t) = 8.664\left(13{,}166 \text{ kg}\right)^{\frac{1}{4}} \ t^{\frac{1}{3}} \quad \text{for } 0 \leq t \leq 3.21 \text{ sec}$$

$$D(t) = 92.81 \ t^{\frac{1}{3}} \quad \text{for } 0 \leq t \leq 3.21 \text{ sec}$$

The maximum fireball diameter (D_{max}) at the end of the growth period is given by Equation 12:

$$D_{max} = 5.8\left(13{,}166 \text{ kg}\right)^{\frac{1}{3}} \quad \text{for } 3.21 < t \leq 9.64 \text{ sec}$$

$$D_{max} = 137 \text{ m} = 449 \text{ ft} \quad \text{for } 3.21 < t \leq 9.64 \text{ sec}$$

The initial ground flash radius (R_{flash}) associated with the BLEVE fireball is given by Equation 13:

$$R_{flash} = 0.65 \text{ (137 m)} = 89 \text{ m or 292 ft}$$

The time-dependent height of the center of the fireball [$H_{FB}(t)$] may be calculated from Equations 14 and 15 for the fireball growth and postgrowth phases, respectively:

$$H_{FB}(t) = 46.41 \ t^{\frac{1}{3}} \quad \text{for } 0 \leq t \leq 3.21 \text{ sec}$$

$$H_{FB}(t) = \frac{3\left(137 \text{ m}\right)t}{2\left(9.64 \text{ sec}\right)} \quad \text{for } 3.21 < t \leq 9.64 \text{ sec}$$

$$H_{FB}(t) = 21.32 \ t \quad \text{for } 3.21 < t \leq 9.64 \text{ sec}$$

The radiant heat fraction (f) for the BLEVE fireball is estimated from Equation 17, assuming a vessel burst pressure of 2.21 MPa (320 psia), as determined in Section 7:

$$f \ = \ 0.27 \ \left(2.21 \text{ MPa} \right)^{0.32} \ = \ 0.348$$

The maximum surface emitted thermal flux (E_{max}) during the fireball growth phase is given by the lessor of Equation 16 or 400 kW/2m^2. Equation 16 gives the following:

$$E_{max} \ = \ 0.0133 \left(0.348 \right) \left(46{,}390 \ \frac{\text{kJ}}{\text{kg}} \right) \left(13{,}166 \text{ kg} \right)^{\frac{1}{12}} \quad \text{for } 0 \le t \le 3.21 \text{ sec}$$

$$E_{max} \ = \ 473 \ \frac{\text{kW}}{\text{m}^2} \quad \text{for } 0 \le t \le 3.21 \text{ sec}$$

Since Equation 16 estimates that the maximum surface emitted thermal flux during the growth phase is greater than 400 kW/m^2, the surface emitted thermal flux is assumed to be limited to 400 kW/m^2.

The time-dependent surface emitted flux [$E_S(t)$] during the postgrowth phase of the fireball is estimated from Equation 18:

$$E_S(t) \ = \ 400 \ \frac{\text{kW}}{\text{m}^2} \left[\frac{3}{2} \left(1 - \frac{t}{9.64 \text{ sec}} \right) \right] \quad \text{for } 3.21 < t \le 9.64 \text{ sec}$$

$$E_S(t) \ = \ 600 \ - \ 62.24 \, t \quad \text{for } 3.21 < t \le 9.64 \text{ sec}$$

The time-dependent fireball height, diameter, and surface flux are shown in Figure 4.

For a target at ground level, the time- and distance-dependent maximum geometric view factor F(x, t) may be estimated from Equation 19 by substituting the appropriate relationships for D(t) and $H_{FB}(t)$:

$$F(x,t) \ = \ \frac{2{,}153.9 \, t^{\frac{2}{3}}}{\left[2{,}153.9 \, t^{\frac{2}{3}} + x^2 \right]} \quad \text{for } 0 \le t \le 3.21 \text{ sec}$$

$$F(x,t) \ = \ \frac{4{,}692}{\left[454.5 \, t^2 + x^2 \right]} \quad \text{for } 3.21 < t \le 9.64 \text{ sec}$$

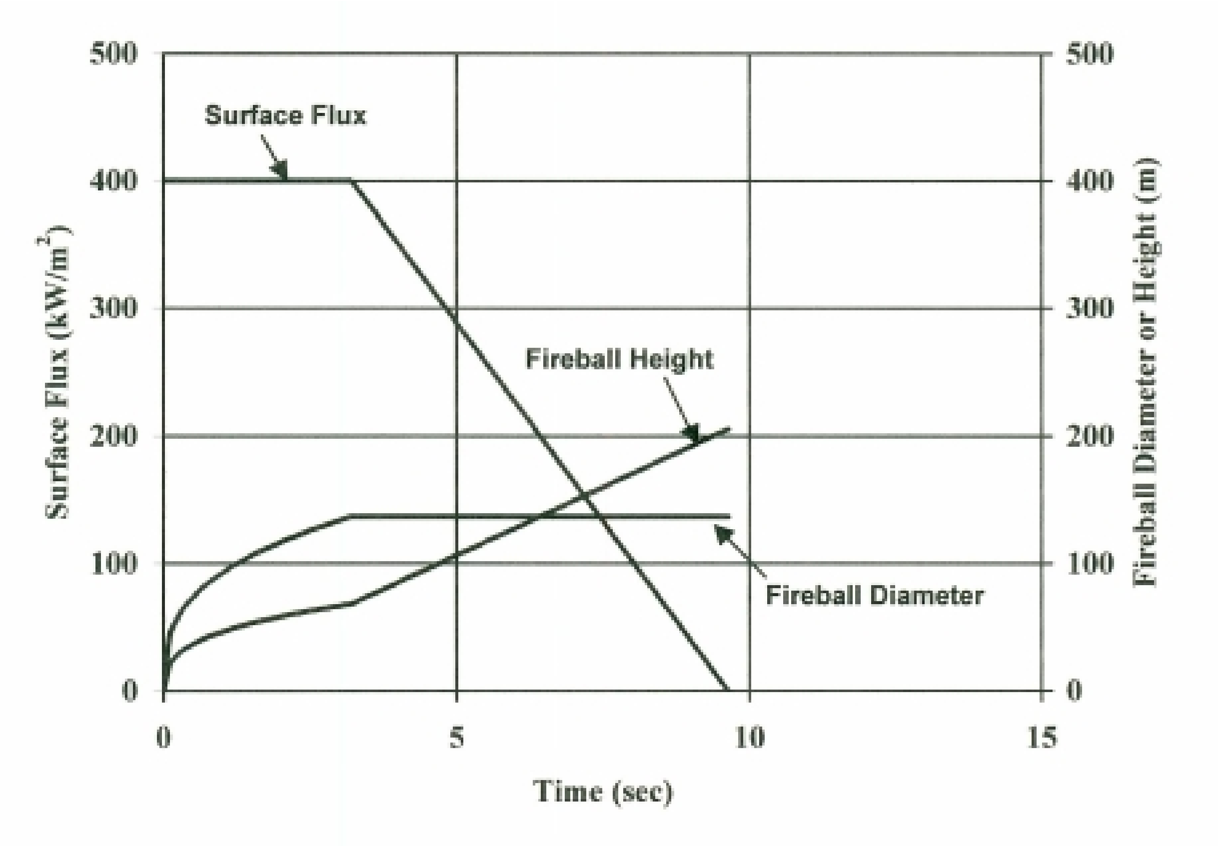

Figure 4 Surface Flux, Fireball Height, and Fireball Diameter for a BLEVE of a 10,000-gal Propane Tank

For a target at ground level, the time- and distance-dependent atmospheric transmissivity $\tau(x, t)$ may be estimated by substituting the appropriate relationships for D(t) and $H_{FB}(t)$ into Equation 20. The relative humidity is 70% (0.7), and the saturated vapor pressure of water P_v at 70 °F is 2,534 Pa (interpolated from Table 4).

$$\tau(x,t) = 1.03 \left[\sqrt{2{,}153.9\, t^{\frac{2}{3}} + x^2} - 46.41\, t^{\frac{1}{3}}\right]^{-0.09} \quad \text{for } 0 \le t \le 3.21 \text{ sec}$$

$$\tau(x,t) = 1.03 \left[\sqrt{454.5\, t^2 + x^2} - 68.5\right]^{-0.09} \quad \text{for } 3.21 < t \le 9.64 \text{ sec}$$

The time-dependent thermal flux and thermal dose may be estimated from Equations 21 and 22 by substituting the appropriate relationships for $\tau(x, t)$, F(x, t), and $E_S(t)$. The thermal dose as a function of distance for a ground-level target is presented in Figure 5. Figure 5 also shows the thermal dose for a more traditional method, which assumes that the thermal flux is constant (400 kW/m^2) during the duration of the fireball. It is apparent from Figure 5 that the traditional method significantly overestimates the thermal dose compared to the time-dependent method (Martinsen and Marx 1999). Table 9 summarizes the distances to various types of burns for the BLEVE fireball event.

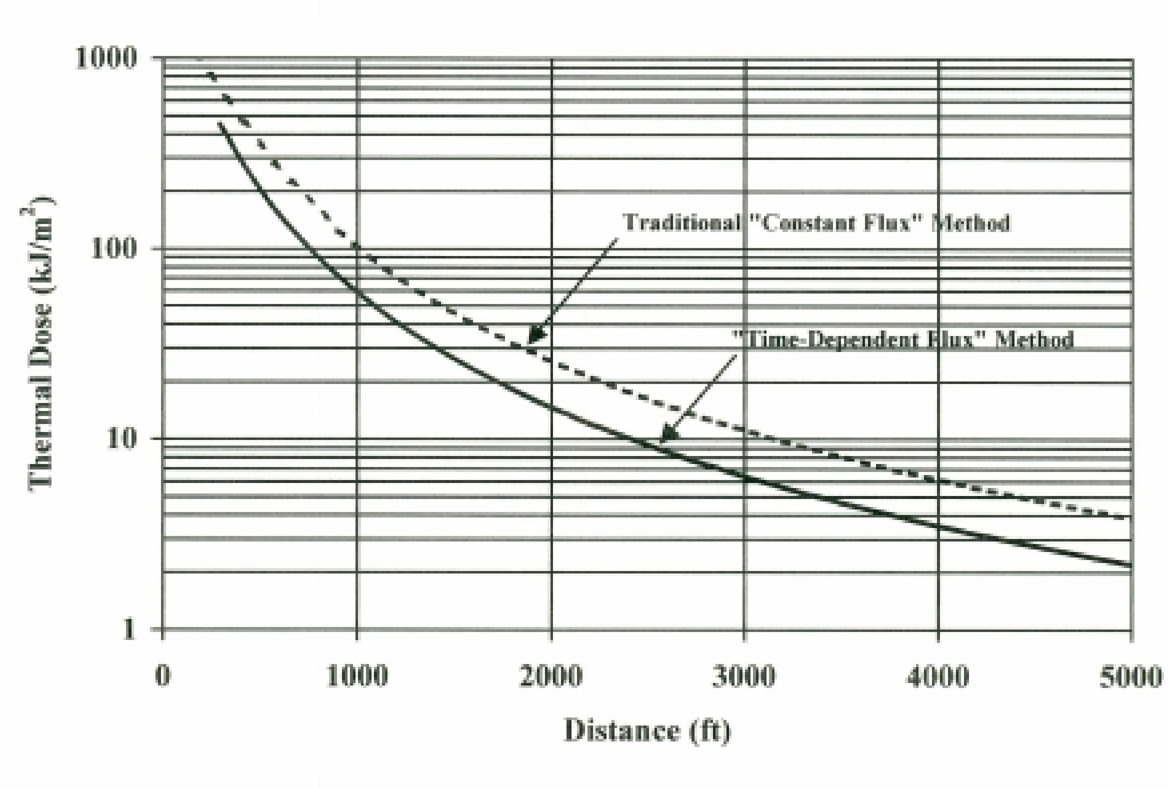

Figure 5 Thermal Dose vs. Distance for a BLEVE of a 10,000-gal Propane Tank

Table 9 Maximum Distances to Various Types of Burns for a BLEVE Fireball of a 10,000-gal Propane Tank

Injury Description	Maximum Distance (ft)
Third-degree burns (99% fatal)	292*
Third-degree burns (50% fatal)	292*
Third-degree burns (1% fatal)	444
Second-degree burns (blisters)	604
First-degree burns (sunburn)	758
Threshold of pain	1,221

* This calculated distance is less than the distance associated with the initial ground flash. Therefore, the ground flash distance is used.

8. Case Study Missile Effects Analysis

The maximum fireball radius estimated for a BLEVE of the 10,000-gal propane storage tank is approximately 449 ft, based on Equation 12. Applying the guidelines from Birk (1995):

- 80 to 90% of rocketing fragments should fall within 1,800 ft
- Severe rocketing fragments may travel up 6,740 ft
- In very severe, rare cases, rocketing fragments may travel up to 13,470 ft

9. Conclusions and Observations

For the case study evaluated, a 10,000-gal propane storage tank filled to 80% capacity was assumed to be involved in a BLEVE event. The blast effects associated with the case study indicate that building damage may occur up to 270 ft from the event, depending upon the building type. Personnel within a building may suffer serious injury. Direct exposure of personnel to the blast wave may cause eardrum rupture at distances ranging from 58 ft (90% likelihood) to 177 ft (1% likelihood). Direct exposure to thermal radiation from the BLEVE fireball may cause second-degree burns up to approximately 600 ft from the storage vessel. The traditional constant flux approach estimates that the distance to second-degree burns is approximately 820 ft (37% greater distance than the time-dependent flux approach). Approximately 80 to 90% of the rocketing fragments associated with the BLEVE event would fall within 1,800 ft of the vessel, with severe rocketing fragments traveling up to 6,740 ft.

The methods presented in this paper provide a simple, yet technically defensible approach for evaluating the consequences of BLEVE events. The methods can be useful in satisfying SAR, BIO, or emergency response planning requirements. The methods can also be useful in performing siting studies for placement of LPG tanks at DOE facilities. In addition, the methods may be used to evaluate BLEVE events for various liquid fill levels to investigate the consequences of BLEVE events occurring at different times during venting of the safety relief valve.

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