Analysis of the Fire and Explosion at the Girard Point Refinery

Boiling Liquid Expanding Vapor Explosion

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Scientia est Potentia.

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1 Introduction

A fire and subsequent explosion occurred at approximately 4:22am on June 21, 2019, at the Philadelphia Energy Solutions Girard Point Refinery, see fig. 1.1[12]. The explosion took place in the V1 treater-feed-surge-drum (TFSD) within the pretreatment unit. The TFSD explosion propelled a 41809.6lb (18964.5kg) piece of the steel drum approximately 2100ft (640m) from the blast seat, see fig. 1.2. It is hypothesized that a boiling-liquid expanding-vapor explosion (BLEVE) event generated the blast wave and broke the drum into fragments. The Philadelphia Fire Department requested ATF estimate the blast overpressure, debris throw, and thermal effects generated when the tank exploded. This paper will estimate these blast parameters assuming a BLEVE occurred. The analysis is based upon an adiabatic and isentropic energy analysis developed by the Center for Chemical Process Safety[7]. Analysis was completed using Jupyter Notebook running Python 3.7 and published using ipypublish[13][14].

Figure 1.1: A view of the Philadelphia Energy Solutions Incs oil refinery on fire June 21, 2019[1].

Figure 1.2: Largest piece of the TFSD was propelled $2100 ft (640 m)$ from the blast seat. The upper image shows the drum fragment in flight moving left to right. The second image shows the drum fragment after striking the edge of the Schuylkill River shoreline.

2 Background

2.1 Refinery

The Girard Point Refinery is the largest refinery on the East Coast, located in southwest Philadelphia, PA, on the Schuylkill River, see fig. 2.1. Prior to the fire and explosion, the refinery produced approximately 335,000 barrels of gasoline per day[15].

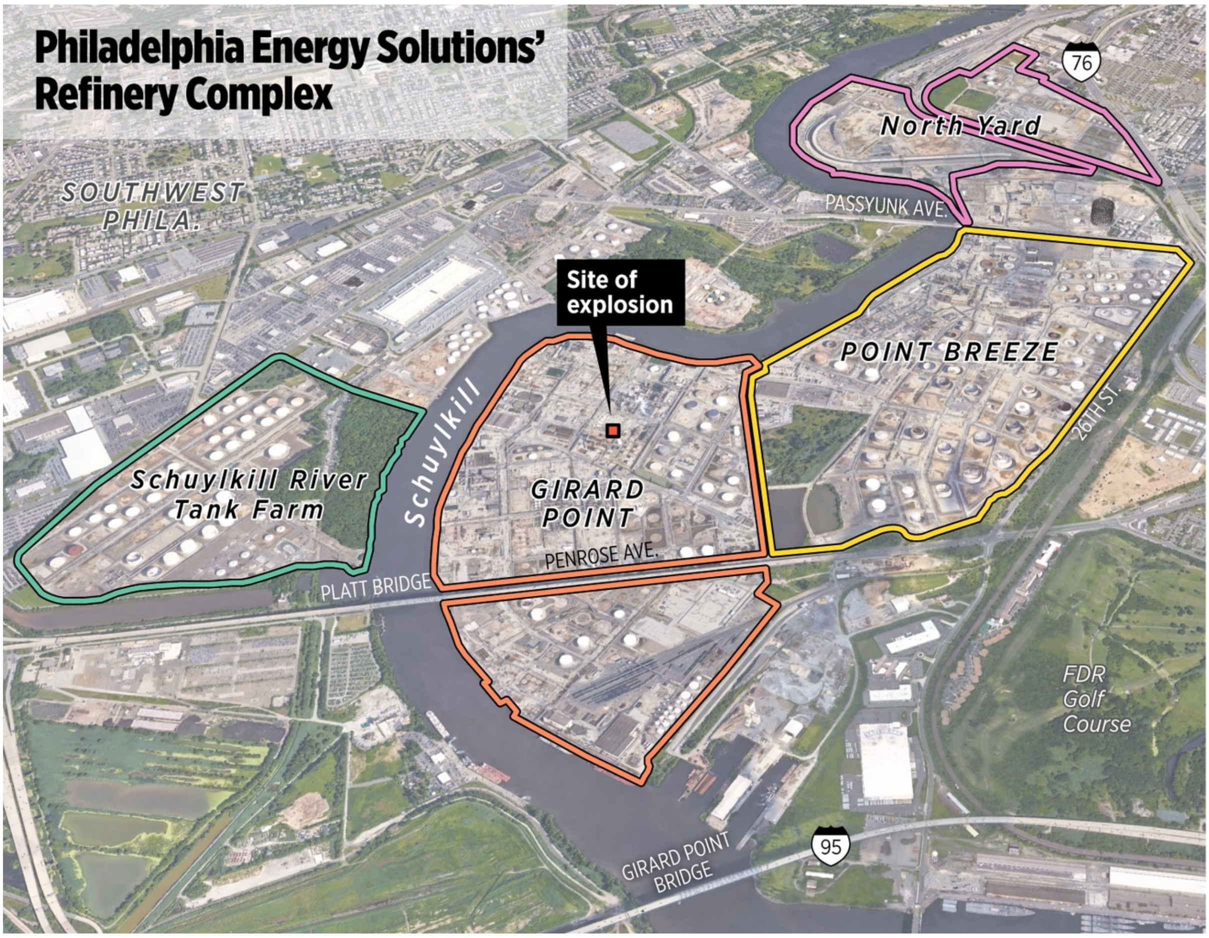

Figure 2.1: Map of Girard Point Refinery showing the blast seat location[2].

2.2 Treater Feed Surge Drum

The TFSD, located between the fluid catalytic cracker and the alkylation unit, was part of the alkylation pretreatment process, see fig. 2.2. The purpose of a surge drum is to stabilize fluctuations in the overall system flow rate. During pretreatment, also referred to as sweetening, sulfur compounds (hydrogen sulfide, thiophene and mercaptan) are removed to improve color, odor, and oxidation stability. Following pretreatment, alkylation generally converts propylene (C_3H_6), butylene (C_4H_8), pentene (C_5H_{10}), and isobutane (C_3H_{10}) to alkane liquids such as isoheptane (C_7H_{16}) and isooctane (C_8H_{16}). Because of their high octane and low vapor pressure, these alkylates are a highly valued component in the production of gasoline[16].

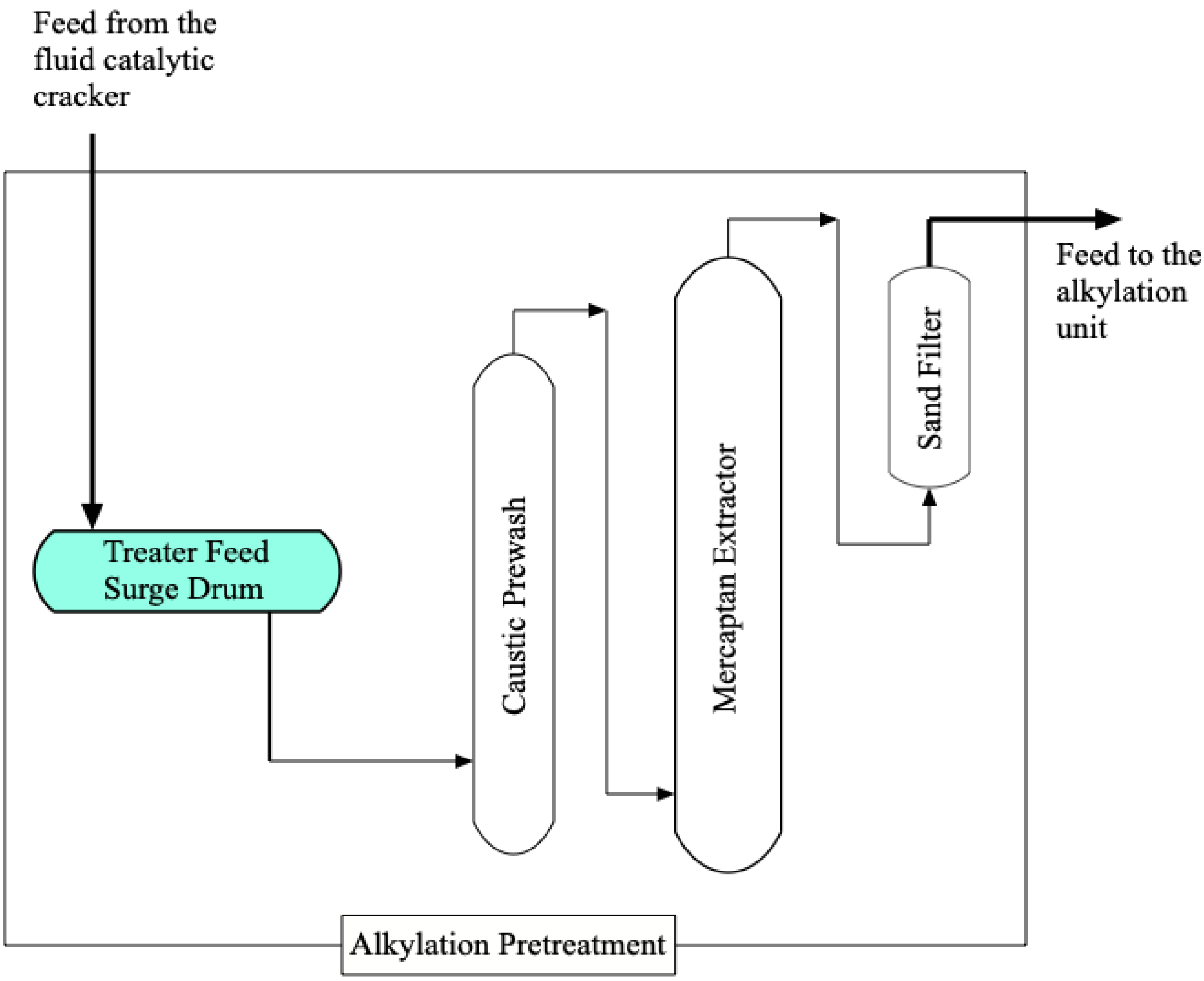

Figure 2.2: Simple flow diagram showing the TFSD in the alkylation pretreatment process[3,4].

The TFSD tank measured $39.66ft$ ($12.09m$) in length, not including the heads, see table 2.1 and fig. 2.3 for construction details[5]. At the time of the explosion, the TFSD contained $20160gal$ ($76.3m^3$) of butane (50% by volume) and butene (40% by volume) and other lesser constituients, see table 2.2 for a complete list of chemicals present.

Table 2.1: Treater-Feed-Surge-Drum Construction Parameters[5]

Parameter	Value	Units
Type	horizontal	NA
Year Built	1972	NA
Construction Material	A516 Type 70 Steel	NA
Tank Wall Thickness	0.8125	in
Volume	37201	gal
Percent Filled	53.3	%
Mass	74660	lb
Safety Valve Set	155	psig

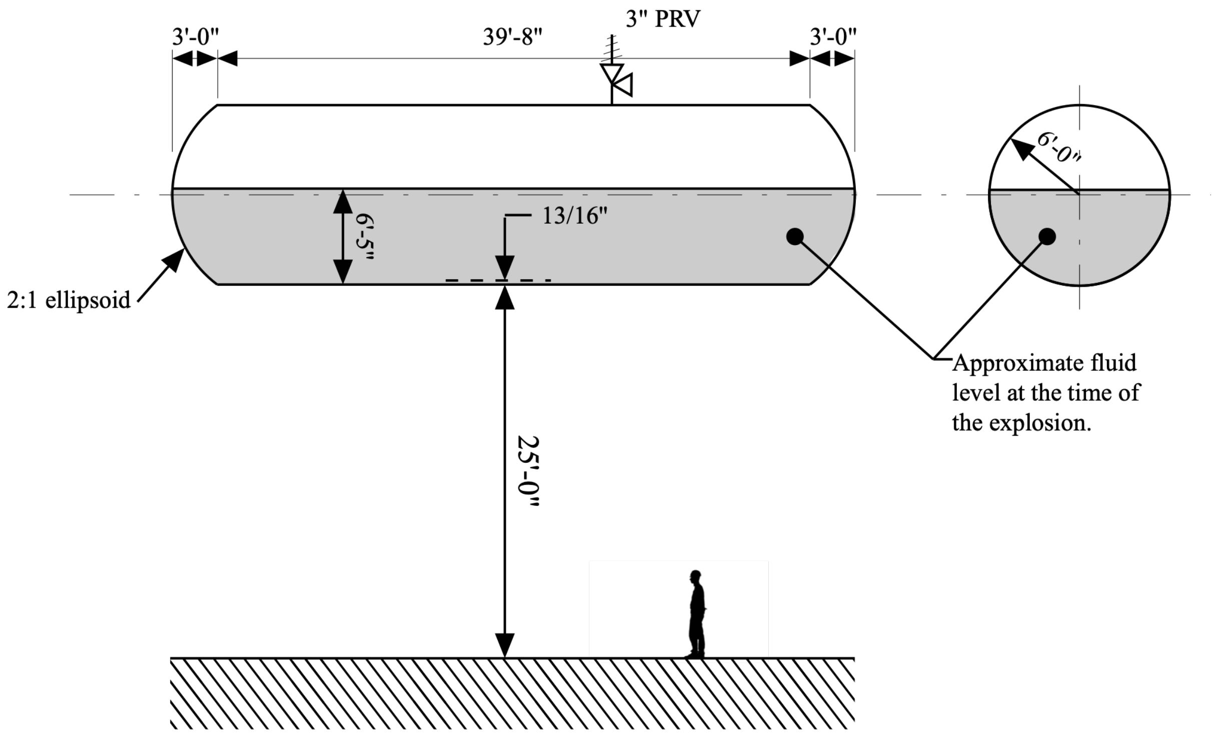

Figure 2.3: Diagram depicting the dimensions of the TFSD tank. The tank was positioned $25ft$ $(7.6m)$ above ground level and estimated to contain $20160gal$ $(76.3m^3)$ (53.3% filled) of butane (50% by volume) and butene (40% by volume) at the time of the explosion.[5]

Table 2.2: Chemical Contents in the Treater-Feed-Surge-Drum at the Time of the Explosion[5]

Chemical	Percent by Volume
methane	0.01
ethylene	0.00
ethane	0.01
propane	0.90
propylene	0.10
isobutane	37.28
nbutane	12.81
butens	40.41
neopentane	0.00
isopentane	3.94
npentane	0.25
butadiene	0.33
benzene	0.00
C5 olefins	3.54
C6 sats	0.33
C7+	0.04

For this analysis, it will be assumed the entire mixture is butane. This assumption avoids partial pressures and multiple energy calculations with different vapor qualities greatly simplifying the analysis. The assumption is reasonable because butane and butene are chemically similar and make up more than 90% of the fluid volume, see table 2.3. A BLEVE assumption is reasonable because, the boiling temperatures for butene $(20.66\,°F\,(-6.3\,°C))$ and butane $(31.1\,°F\,(-1.0\,°C))$ are both well above the tank temperature when exposed to fire.

Table 2.3: Chemical Properties of Butene and Butane[8,9]

Property	Butene	Butane
Molecular Formula	C_4H_8	C_4H_{10}
Molecular Weight	$56.108\frac{g}{mol}$	$58.12g\frac{g}{mol}$
Boiling Point at 760mm Hg	$20.6°F$	$31.1°F$
Flash Point	$-110.0°F$	$-76.0°F$
Density at 25°C, 1 atm	$0.588\frac{g}{cc}$	$0.573\frac{g}{cc}$
$\frac{C_P}{C_V}$ Ratio γ	1.13	1.12

2.3 Pressure Relief Valve

The TFSD was fitted with a Consolidated (1906-30LC-1-CC-MS-31-RF-1) $3in\ x\ 4in$ ($7.63cm\ x\ 10.16cm$) pressure relief valve (PRV). The relief pressure was set to $155psig$ ($1068.7kPa$) and the relief temperature was set to $183.5°F$ ($84.3°C$). The PRV was positioned on the top of the TFSD, see fig. 2.3. It is assumed the PRV functioned as designed.

2.4 Recovered Drum Debris

Three major pieces of the TFSD were identified after the explosion, see fig. 2.4. The largest piece (large-end-cap) was recovered $2100ft$ ($640m$) from the blast seat. It was approximately $22ft$ ($6.7m$) in length, or a little more than half the original tank length, see fig. 2.5. The other end of the TFSD (small-end-cap) was recovered $1761ft$ ($536m$) from the blast seat. It was approximately $5ft$ ($1.5m$) in length, see fig. 2.6. The piece thrown the shortest distance (center-section) was $819ft$ ($249m$) from the blast seat. The center-section piece was heavily damaged and a photographic analysis of the length was not possible. However, based on the original length of the tank after removing the large and small-end-cap lengths, the center-section length is approximately $12ft$ ($3.6m$), see fig. 2.7.

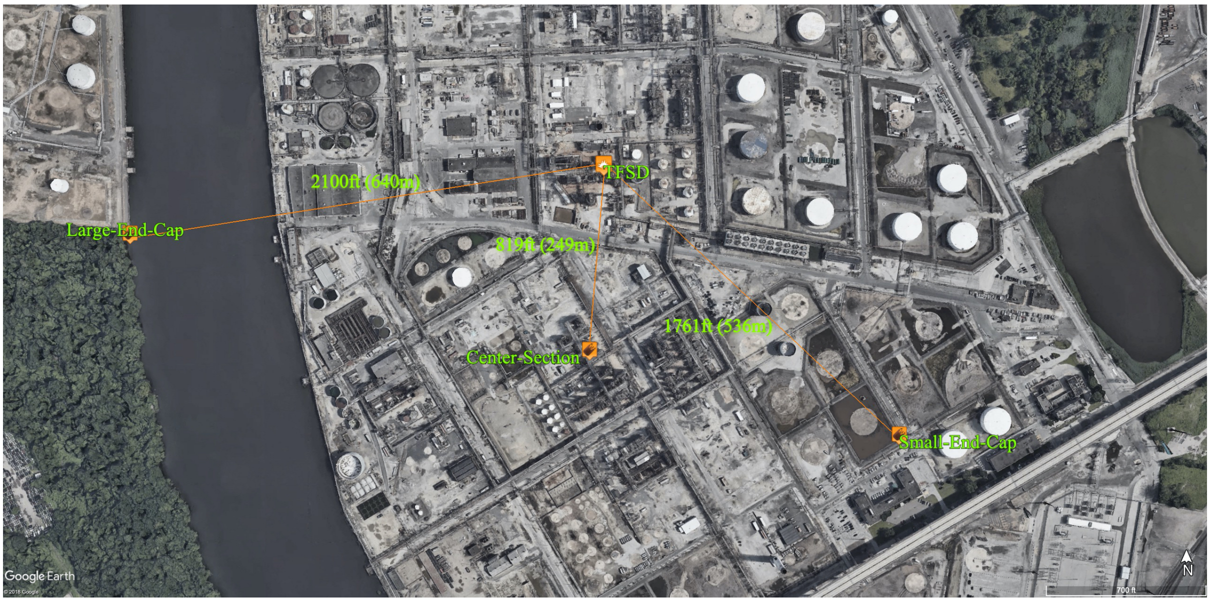

Figure 2.4: Map of Girard Point showing the blast seat and locations of the three main pieces of the TSFD (V-1) recovered.[6]

Figure 2.5: Photograph of the large-end-cap, estimated to be $22ft$ $(6.7m)$ in length based on photographic analysis. In this photograph the tank has been moved from it's original landing location.[6]

Figure 2.6: Photograph of the small-end-cap, estimated to be $5ft$ $(1.5m)$ in length based on photographic analysis.[6]

Figure 2.7: Photograph of the center-section piece, calculated to be $12ft$ ($3.6m$) in length based on the total length of the drum less the lengths of the large and small-end-caps.[6]

The estimated mass of each piece of the TFSD is summarized in table 2.4. The mass calculations are based on the refinery recorded mass of the vessel, $74660lb$ ($33865kg$), multiplied by the percent mass calculated using the following equations,

Ellipsoidal Head:

$$V_{eh} = \frac{\pi D^2 (D/4)}{6} \tag{2.1}$$

Cylinder:

$$V_c = \frac{\pi D^2 l}{4} \tag{2.2}$$

where the drum wall thickness is $0.83in$ ($2.1cm$), the tank diameter is $12ft$ ($3.7m$), and the material density for A516 steel is $7.8g/cc$[4]. The difference in calculated and refinery recorded mass is likely due to other structural components attached to the tank not accounted for in the calculated mass.

Table 2.4: Estimated TFSD Debris Mass[5]

TFSD ID	Cylinder (ft)	Calculated Debris Mass (lb)	Percent Mass Calculated	Refinery Recorded Mass (lb)
Large-End-Cap	22.0	31541.8	0.56	41809.6
Small-End-Cap	5.0	10078.5	0.18	13438.8
Center-Section	12.0	15150.5	0.26	19411.6
Total	39.0	56770.8	1.00	74660.0

2.5 Boiling-Liquid Expanding-Vapor Explosion (BLEVE)

A BLEVE results from the sudden failure of a tank containing a compressed vapor (head space) and a super-heated liquid (a liquid heated above it's boiling point but without boiling). The magnitude of the blast depends on how super-heated the liquid was at failure. There is a direct relationship between the super-heat temperature and the quantity of liquid that flash-boils. Higher volumes of fluid that flash-boil release more energy. Once containment failure occurs, the energy is distributed into four forms:

1. Overpressure wave
2. Kinetic energy of fragments
3. Deformation and failure of the containment material
4. Heat transferred to environment

The distribution of the energy into the these four forms depends on the specifics of the explosion. Planas-Cuchi et al. found that a *brittle*[1] failure releases 80% of the energy into the blastwave, while a *ductile*[2] failure releases 40% of the energy into the blastwave. The remaining energy becomes kinetic energy of the fragments. The heat transfer to the environment is relatively small[17]. In practice, most pressure vessels are designed with materials that are ductile rather than brittle to avoid sudden and catastrophic brittle (fragile) failures[18].

[1] Brittle failure refers to the breakage of a material due to a sudden fracture. When a brittle failure occurs, the material breaks suddenly instead of deforming or straining under load. The fracturing or breaking can occur with only a small amount of load, impact force or shock. Brittle materials absorb less energy before breaking or fracturing, despite the materials having a high strength.

[2] A ductile failure is a type of failure seen in malleable materials characterized by extensive plastic deformation or necking. This usually occurs prior to the actual failure of the material. The term ductile rupture refers to the failure of highly ductile materials. In such cases, materials pull apart instead of cracking.

3 Overpressure and Impulse from the BLEVE

There is a seven step method for calculating the overpressure and impulse from a BLEVE. The method is given in fig. 3.1.

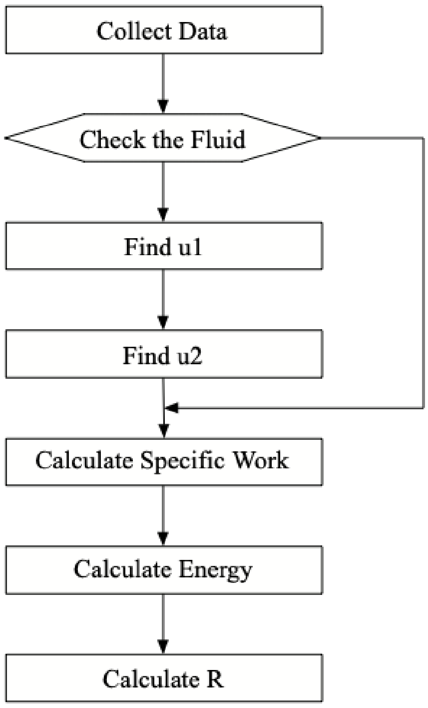

Figure 3.1: Calculation of energy of flashing liquids and pressure vessel bursts filled with vapor or nonideal gas.[7]

3.1 Data Collection

For this analysis the following data will be used:

1. Ambient air pressure, $14.7psi$ $(101.3kPa)$
2. Vessel volume, $37200.63gal$ $(140.82m^3)$
3. Ratio of specific heats of butane (1.12)
4. Distance from the center of the tank to the receptor, $32.81ft$ $(10.00m)$
5. Shape of the vessel is cylindrical, $L/D = 3.29$
6. Speed of sound of air, $1115.49ft/s$ $(340.00m/s)$

3.2 Internal Energy

3.2.1 Pressure at State 1 (Pre-failure State)

The TFSD is assumed to fail at 1.21 times the opening pressure of the pressure relief valve (PRV)[19]. This pressure is based on the American Petroleum Institutes Standard 521 requiring pressure relief valves on pressure vessels to achieve rated flow at 1.21 times the maximum allowable working pressure. The PRV was set to $155.00psi$ $(1068.69kPa)$ therefore, the absolute pressure at state 1 (failure state) is given by,

$$p_1 = 1.21\left(p_{PRV} + p_{atm}\right) \tag{3.1}$$

$$p_1 = 1.21\left(155.00 + 14.70\right) \tag{3.2}$$

$$p_1 = 205.33psia\,(1.42\,MPa) \tag{3.3}$$

3.2.2 Pressure at State 2 (Final Expanded State)

The pressure at state 2 (final expanded state) is standard atmospheric pressure or $14.7psi$ $(101.3kPa)$.

3.2.3 Internal Energy

The internal energy u can be used to estimate the energy released in an explosion. With the gases in the saturated state and knowing the pressures at state 1 (explosion) and state 2 (atmospheric), lookup tables can be used to determine the specific volume v, and the enthalpy h. Combining these two properties with the pressure, the internal energy u can be calculated using,

$$h = u + pv \tag{3.4}$$

where h is the enthalpy, p is the pressure, and v is the specific volume. Therefore, solving for the internal energy u we have,

$$u = h - pv \tag{3.5}$$

3.2.3.1 Internal Energy at State 1 The internal energy at state 1 for saturated liquid butane is,

$$u_{1f} = h_{1f} - (p_1)(v_{1f}) \tag{3.6}$$

$$u_{1f} = 451.46\,kJ/kg - (1415.72\,kPa)(0.002110\,m^3/kg) \tag{3.7}$$

$$u_{1f} = 448.47\,kJ/kg \tag{3.8}$$

and for the saturated vapor butane at state 1 we have,

$$u_{1g} = h_{1g} - (p_1)(v_{1g}) \tag{3.9}$$

$$u_{1g} = 716.93\,kJ/kg - (1415.72\,kPa)(0.027658\,m^3/kg) \tag{3.10}$$

$$u_{1g} = 677.77\,kJ/kg \tag{3.11}$$

and similarly for saturated liquid and vapor butane at state 2,

$$u_{2f} = 198.70\,kJ/kg \tag{3.12}$$

$$u_{2g} = 547.18\,kJ/kg \tag{3.13}$$

All the gas properties are summarized in table 3.1

Table 3.1: Propane Thermodynamic Data for Inital (1) and Final (2) States

State	$P\,(kPa)$	$u_f\left(\frac{kJ}{kg\,K}\right)$	$u_g\left(\frac{kJ}{kg\,K}\right)$	$v_f\left(\frac{m^3}{kg}\right)$	$v_g\left(\frac{m^3}{kg}\right)$	$s_f\left(\frac{kJ}{kg\,K}\right)$	$s_g\left(\frac{kJ}{kg\,K}\right)$	$h_f\left(\frac{kJ}{kg}\right)$	$h_g\left(\frac{kJ}{kg}\right)$
butane-1	1.42E+03	4.48E+02	6.78E+02	2.11E-03	2.77E-02	1.78E+00	2.49E+00	4.51E+02	7.17E+02
butane-2	1.01E+02	1.99E+02	5.47E+02	1.66E-03	3.69E-01	9.96E-01	2.41E+00	1.99E+02	5.85E+02

3.2.3.2 Internal Energy at State 2

When the drum containment fails and the butane at state 1 expands to state 2 (atmospheric pressure), it is no longer at a saturated stated. Some of the liquid vaporizes and some of the vapor condenses. The quality of the vapor and liquid can be used to calculate the unsaturated internal energy at state 2. The vapor quality (χ), can be calculated from,

$$\chi = \frac{s_1 - s_2}{s_{2g} - s_{2f}} \tag{3.14}$$

where s_1 and s_2 are the entropies at the initial state (1) and final state (2) and s_{2g} and s_{2f} are the entropies of the final state (2) of the saturated vapor and fluid respectively. If calculating the quality of the saturated *liquid*, then $s_1 = s_{1f}$ and $s_2 = s_{2f}$ where s_{1f} and s_{2f} are the entropies at the initial (1) and final (2) states of the saturated fluid. Similarly, if calculating the quality of the saturated *vapor* $s_1 = s_{1g}$ and $s_2 = s_{2g}$ where s_{1g} and s_{2g} are the entropies at the initial (1) and final (2) states of the saturated vapor. Therefore, for the saturated liquid butane,

$$\chi_f = \frac{s_{1f} - s_{2f}}{s_{2g} - s_{2f}} \tag{3.15}$$

$$\chi_f = \frac{1.775 - 0.996}{2.411 - 0.996} \tag{3.16}$$

$$\chi_f = 0.552 \tag{3.17}$$

and for the saturated vapor,

$$\chi_g = \frac{s_{1g} - s_{2g}}{s_{2g} - s_{2f}} \tag{3.18}$$

$$\chi_g = \frac{2.495 - 2.410}{2.410 - 0.996} \tag{3.19}$$

$$\chi_g = 0.060 \tag{3.20}$$

The unsaturated internal energy at state 2 can be calculated using,

$$u_{2f} = (1 - \chi_f)u_{2f} + \chi_f u_{2g} \tag{3.21}$$

$$u_{2g} = (1 - \chi_g)u_{2g} + \chi_g u_{2f} \tag{3.22}$$

$$u_{2f} = (1 - 0.552)198.70 + (0.552)(547.18) \tag{3.23}$$

$$u_{2g} = (1 - 0.060)547.18 + (0.060)(198.70) \tag{3.24}$$

$$u_{2f} = 390.89\, kJ/kg \tag{3.25}$$

$$u_{2g} = 526.40\, kJ/kg \tag{3.26}$$

3.3 Specific Work

The specific work done by a BLEVE is the difference in internal energies at state 1 and state 2,

$$e_{ex} = u_1 - u_2 \tag{3.27}$$

For the specific work of the liquid butane,

$$e_{ex-f} = u_{1f} - u_{2f} \tag{3.28}$$

$$e_{ex-f} = 448.47\, kJ/kg - 390.89\, kJ/kg \tag{3.29}$$

$$e_{ex-f} = 57.58\, kJ/kg \tag{3.30}$$

For the specific work of the vapor butane we have,

$$e_{ex-g} = u_{1-g} - u_{2-g} \tag{3.31}$$

$$e_{ex-g} = 677.77\, kJ/kg - 526.40\, kJ/kg \tag{3.32}$$

$$e_{ex-g} = 151.38\, kJ/kg \tag{3.33}$$

3.4 Explosion Energy

The explosion energy is the specific work multiplied by the mass of fluid (liquid or vapor) initially in the TFSD.

$$E_{ex} = e_{ex} m \tag{3.34}$$

Where e_{ex} is the specific work of the fluid (vapor or liquid) and m is the mass of the fluid (vapor or liquid).

However, there are two additional factors that must be considered when estimating the explosion energy. The first, is the ground reflection factor, gnd. If the TFSD were on the ground the reflection factor would be $gnd = 2$ however, the TFSD was located $25ft$ $(7.62m)$ above ground level. For this case, a reflection factor of $gnd = 1.25$ will be assumed. The second factor is estimating the amount of energy lost in fragmenting the tank, $frag$. This reduction in energy can range from $frag = 20\%$-50%[7]. For this calculation, a fragmentation factor of $frag = 40\%$ will be assumed, therefore 60% is available for overpressure and impulse. With these additional factors our explosion energy is,

$$E_{ex} = (gnd)(frag)e_{ex} m \tag{3.35}$$

$$E_{ex} = (1.25)(0.6)e_{ex} m \tag{3.36}$$

$$E_{ex} = 0.75 e_{ex} m \tag{3.37}$$

Because the fluid is present both as a saturated vapor and liquid, the explosion energy for each must be calculated separately and then summed together. For the saturated liquid butane,

$$E_{ex-f} = 0.75(57.58 kJ/kg)(35570.96 kg) \tag{3.38}$$

$$E_{ex-f} = 1536.08 MJ \tag{3.39}$$

and similarly for the saturated vapor,

$$E_{ex-g} = 269.95 MJ \tag{3.40}$$

Therefore the total energy for explosion is,

$$E_{tot} = 1806.03 MJ \tag{3.41}$$

3.5 Non-dimensional Range to the Target

For this analysis, a range of $R = 32.18ft$ $(10m)$ was chosen. However, to use the Baker-Tang overpressure and impulse curves, we must calculate the non-dimensional range to the target from[7],

$$\overline{R} = R\left(\frac{p_0}{E_{tot}}\right)^{1/3} \tag{3.42}$$

where R is the range where you would like the pressure and impulse calculated, p_0 is atmospheric pressure, and E_{tot} is the total explosion energy calculated previously.

$$\overline{R} = 10m\left(\frac{101325Pa}{1806.03x10^6}\right)^{1/3} = 0.38 \tag{3.43}$$

With the non-dimensional range calculated, the Baker-Tang overpressure and impulse curves can be used to calculate the non-dimensional overpressure and impulse.

3.6 Non-dimensional Side-on Pressure and Impulse

The non-dimensional side-on pressure can be calculated from fig. 3.2 and gives a $\bar{P} = 0.950$ for an $\bar{R} = 0.38$ and a $p/p_0 = 13.97 \approx 10$. The non-dimensional side-on impulse can be calculated from fig. 3.3 and gives a $\bar{I} = 0.107$ for an $\bar{R} = 0.38$ and a $p/p_0 = 13.97 \approx 10$.

3.7 Side-on Pressure and Impulse

The dimensional or *real* side-on pressure and impulse can be calculated from the following:

$$P_s = \bar{P}p_0 = (0.950)(101.325\,kPa) = 96.26\,kPa\,(13.96psi) \tag{3.44}$$

$$i_s = \frac{\left(\bar{I}p_0^{2/3}E_{tot}^{1/3}\right)}{a_0} = \frac{(0.107)(101325\,Pa)^{2/3}(1806.03x10^6\,J)^{1/3}}{340\,m/s} = 831.08Pa\text{-}s\,(0.12psi\text{-}s) \tag{3.45}$$

This calculation only accounts for the blast from the expansion of the vessel contents. The blast may be followed by a vapor cloud explosion. In this case, when the expanding contents of the vessel are immediately exposed to fire, there is very little additional overpressure generated. This is because the expanding contents begin burning as soon as the fuel air ratio will support combustion.

3.8 Direct Effects of Blast Overpressure on the Human Body

The direct effects of blast overpressure are due to the positive and negative phases of the shock wave as it passes through the human body. Damage to tissue is due to the shock wave passing through tissue with different densities. These density changes place tissue in compression and tension resulting in hemorrhages and air embolisms. Typical blast over pressure injuries for a human in the open are summarized in table 3.2. A person positioned $32.8ft$ $(10m)$ from the TFSD would experience an absolute pressure of $28.66psia$ $(197603.74Pa)$ and have a 99% chance of fatality. The "threshold for fatality" would occur at a distance of approximately $869.4ft$ $(265m)$.

Table 3.2: Overpressure vs. Human Injury Probability[10]

Overpressure (psig)	Injury
14.5	Threshold for fatality
16.0	50% ear drum rupture
17.5	10% probability for fatality
20.5	50% probability for fatality
25.5	90% probability for fatality
29.0	99% probability for fatality

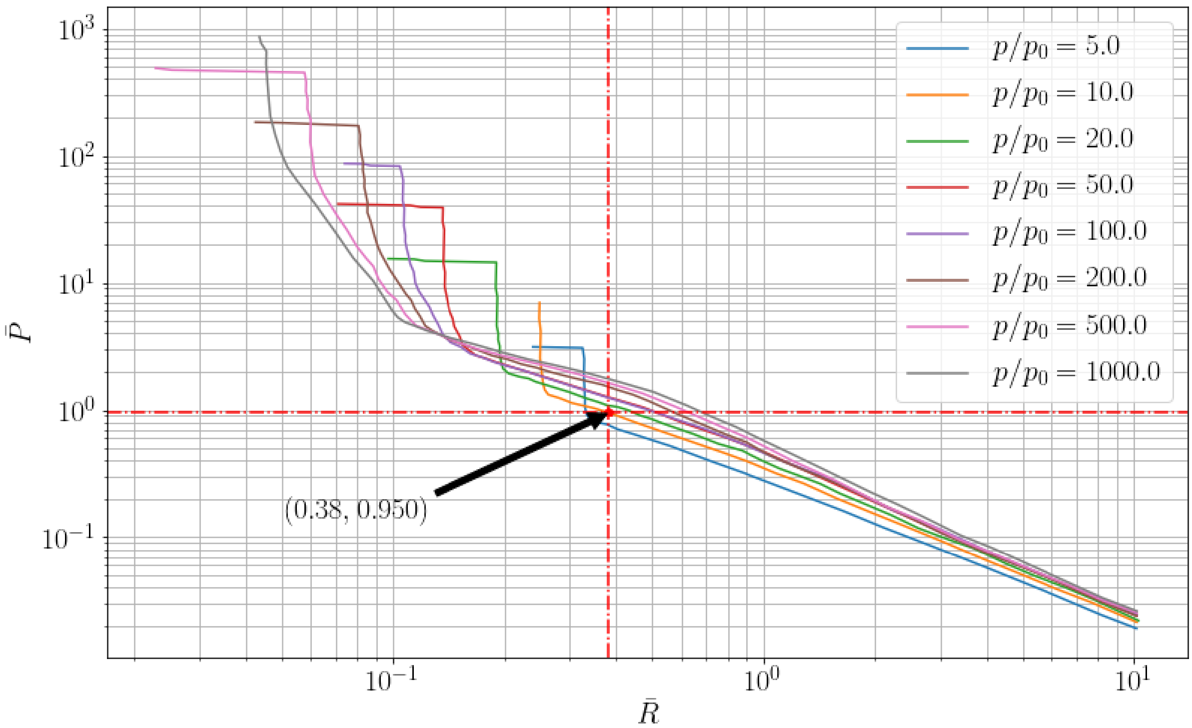

Figure 3.2: Non-dimensional overpressure curves for various vessel internal pressures. The arrow designates the non-dimensional pressure and range point for a butane BLEVE in the TFSD.

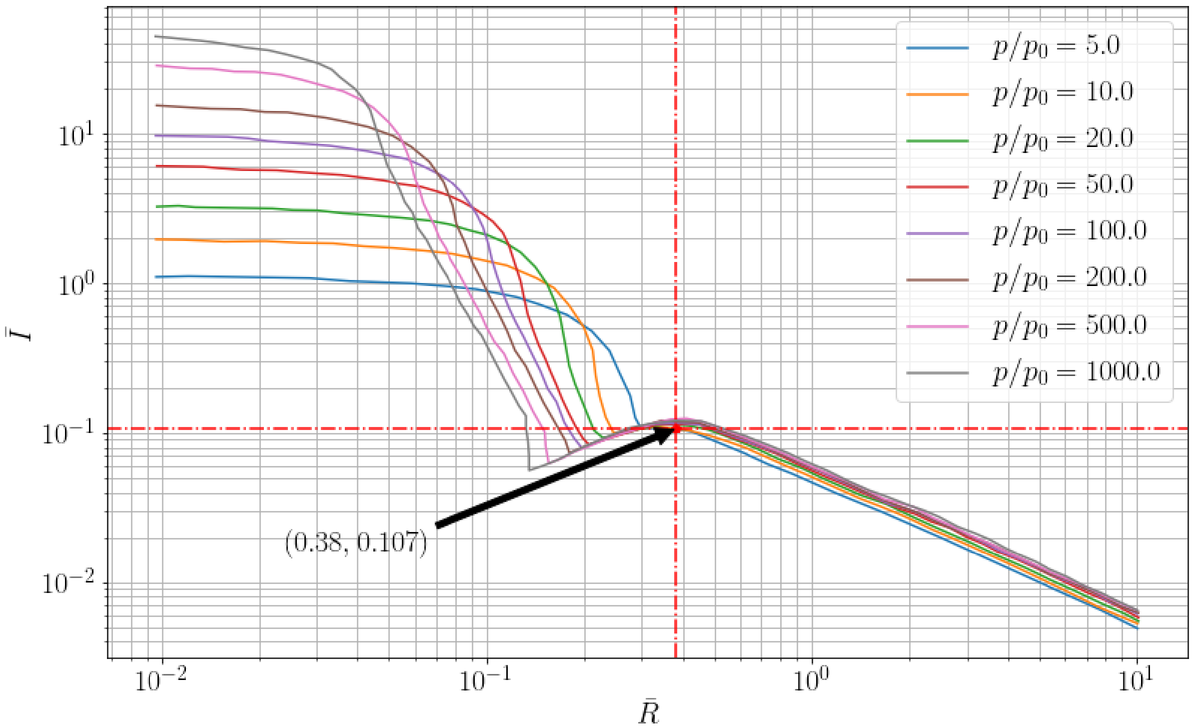

Figure 3.3: Non-dimenstional impulse curves for various vessel internal pressures. The arrow designates the non-dimensional impulse and range point for a butane BLEVE in the TFSD.

4 Debris from the BLEVE

The same explosion energy results developed in the overpressure and impulse calculations can be used for the fragmentation analysis. However, the overpressure energy calculations applied a $grd = 1.25$ ground reflection factor. This factor is not applicable when determining the energy available for fragment throw calculations. However, the $frag = 0.4$ fragmentation factor should be applied. Therefore, the available energy for fragmentation is,

$$E_{ex-f} = 0.4(57.58kJ/kg)(35570.96kg) \tag{4.1}$$

$$E_{ex-f} = 819.24MJ \tag{4.2}$$

and similarly for the saturated vapor,

$$E_{ex-g} = 143.97MJ \tag{4.3}$$

Therefore the total energy for fragmentation is,

$$E_{tot} = 963.22MJ \tag{4.4}$$

4.1 Initial Debris Speed

A conservative method for determining the initial speed of fragments is the empirical method proposed by Moore[20]. The initial velocity is given by:

$$v_i = 1.0092 \left(\frac{E_{tot} G}{M_C} \right)^{0.5} \tag{4.5}$$

where for a cylindrical vessel,

$$G = \frac{1}{1 + M_G/2M_C} \tag{4.6}$$

and M_G is the total gas mass, E_{tot} is the energy, and M_C is the mass of the vessel. For our case we have,

$$v_i = 1.092 \left(\frac{(963.22E6J)(0.60)}{35570.96kg} \right)^{0.5} \tag{4.7}$$

$$v_i = 318.85mph\ (142.54m/s) \tag{4.8}$$

4.2 Debris Throw Ranges

With the initial debris speed calculated and the distances to the three TFSD pieces known, we can calculate the required launch angle. The initial trajectory angle (a_i) can be calculated (neglecting lift and drag forces) using,

$$a_i = asin\left(\frac{Rg}{2v_i^2}\right) \tag{4.9}$$

where R is the horizontal range and g is the acceleration of gravity.

For the initial velocity of $318.85mph$ $(142.54m/s)$ the large-end-cap at a range of $2099.7ft$ $(640m)$ would need a launch angle of 9.0°, the small-end-cap at a range of $1715.8ft$ $(523m)$ would need a launch angle of 7.3°, and the center-section at a range of $816.9ft$ $(249m)$ would need a launch of angle of 3.5°, see fig. 4.1. Therefore, the initial velocity predicted supports the throw ranges observed. The maximum throw range possible (assuming no aerodynamic lift) occurs at a launch angle of 45°. For this case, the maximum throw range would be $6794.9ft$ $(2071.1m)$.

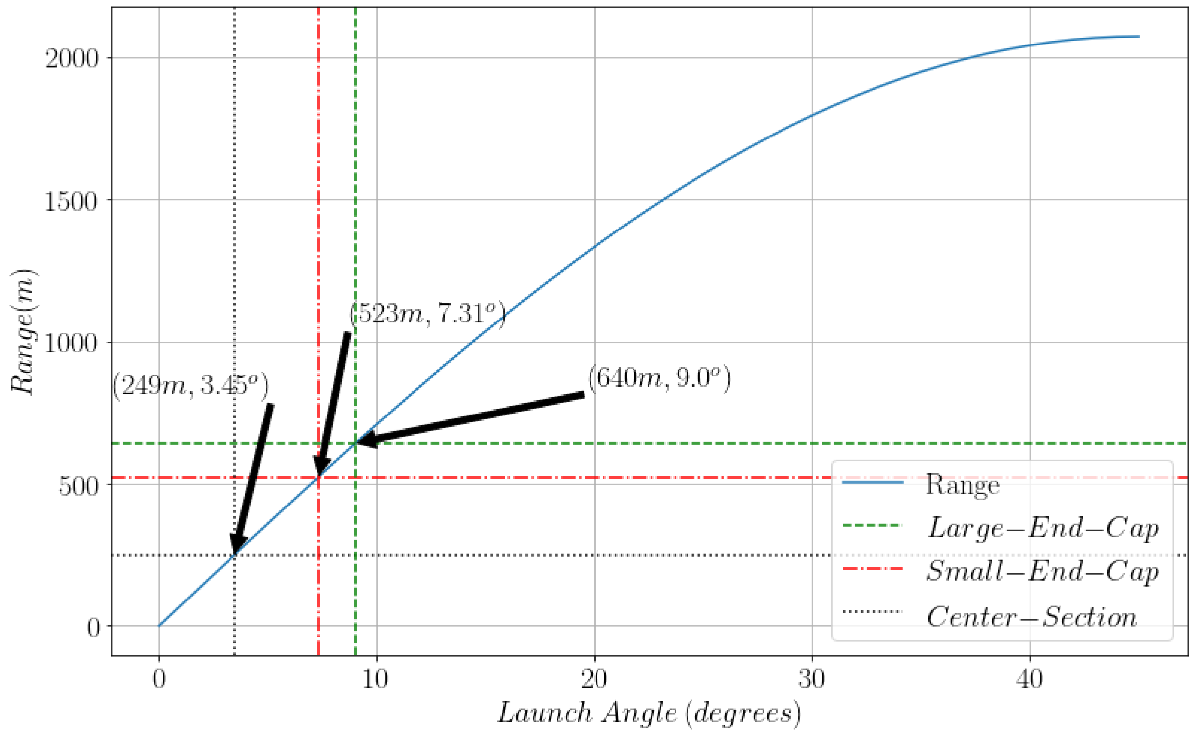

Figure 4.1: Range of debris pieces and calculated launch angle for an initial speed of 318.85mph (142.54m/s).

5 Thermal Radiation from the BLEVE

5.1 Fireball Size and Duration

An estimate for the fireball diameter D_c and duration t_c generated from a BLEVE of $78420.54lb$ $(35570.96kg)$ of liquid butane can be calculated using the equation,

$$D_c = 5.8m_f^{1/3} \tag{5.1}$$

where m_f is the mass of fluid. For this case,

$$D_c = 5.8(35570.96)^{1/3} \tag{5.2}$$

$$D_c = 625.81ft\ (190.75m) \tag{5.3}$$

see fig. 5.1 for a scaled drawing showing the fireball size. The fireball duration t_c can be estimated from,

$$t_c = 0.45m_f^{1/3} \tag{5.4}$$

$$t_c = 0.45(35570.96)^{1/3} \tag{5.5}$$

$$t_c = 14.80s \tag{5.6}$$

Therefore, the fireball from the TFSD would have expanded to $625.81ft$ $(190.75m)$ and then dissipated in $14.8s$.

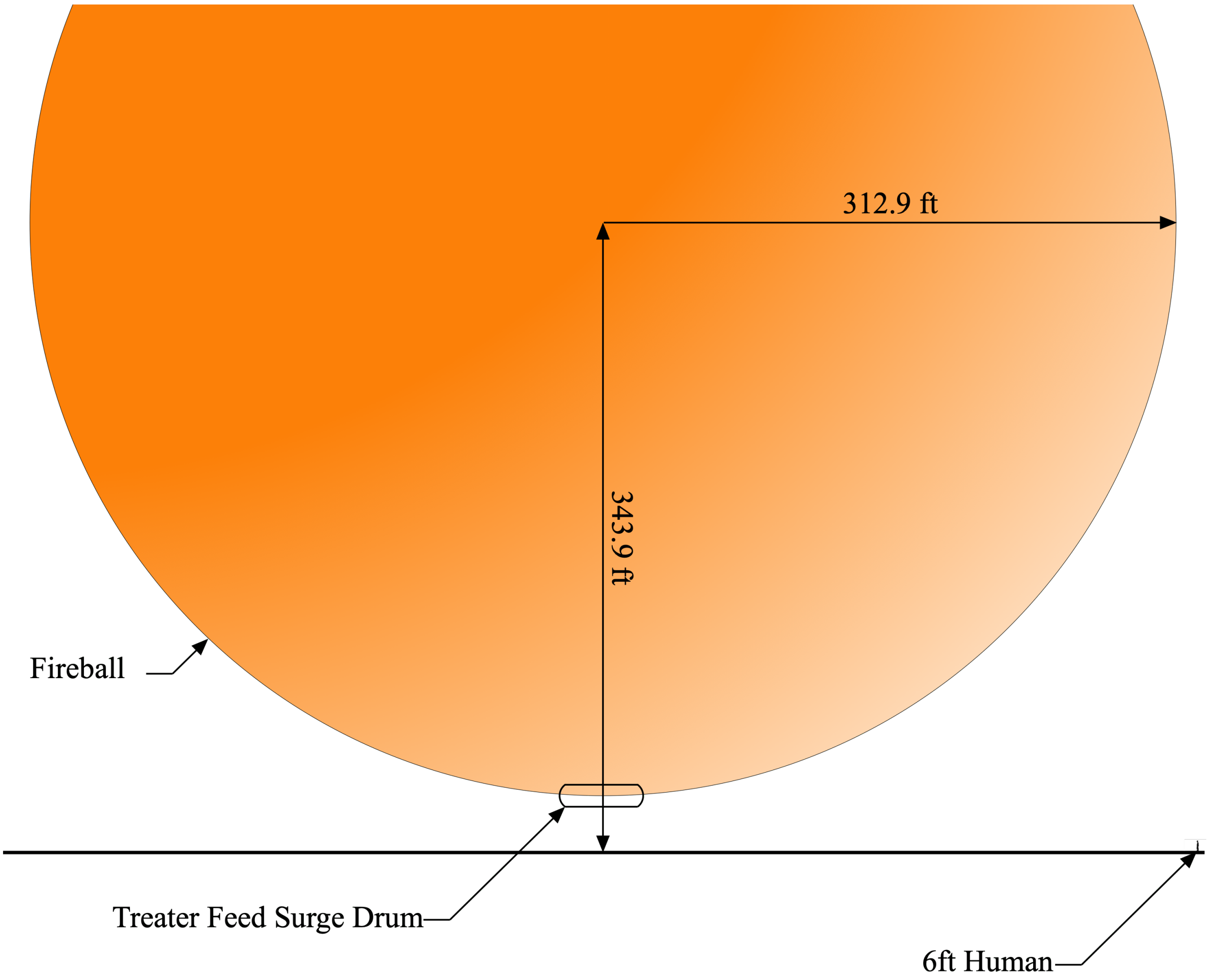

Figure 5.1: Diagram depicting the estimated fireball diameter, $625.8ft$ ($190.7m$), from a butane BLEVE originating from the TFSD tank. The TFSD tank and a 6ft human are shown for scale.

5.2 Thermal Radiation

An estimate for the thermal (infrared) radiation from the BLEVE can be estimated for a standing (vertical) observer some distance from the fireball. The thermal radiation can then be converted to thermal dose units (TDU) to determine the range where the thresholds for pain and 1st, 2nd, and 3rd degree burns would be observed. The critical TDUs are summarized in table 5.1.

Table 5.1: Burn Injury vs. Thermal Dose Relationship[11]

Harm Caused	Mean TDU $((kW/m^2)^{4/3}s)$
Pain	92
Threshold 1st Degree Burns	105
Threshold 2nd Degree Burns	290
Threshold 3rd Degree Burns	1000

To estimate the harm to an observer, the relationship between the emitter (fireball) and the observer (person) must be determined. This relationship is called the view factor and for a spherical emitter and vertical surface can be found from,

$$F_v = \frac{x(D/2)^2}{(x^2 + H^2)^{3/2}} \tag{5.7}$$

where D is the diameter and H is the height to the center of the fireball. The fireball is assumed to be spherical with a height of $H = 343.9ft$ $(104.8m)$ and a diameter $D = 312.9ft$ $(95.4m)$. The range x will be evaluated over a series of distances to determine where critical points of human injury (pain and burns) are predicted to occur, see fig. 5.2.

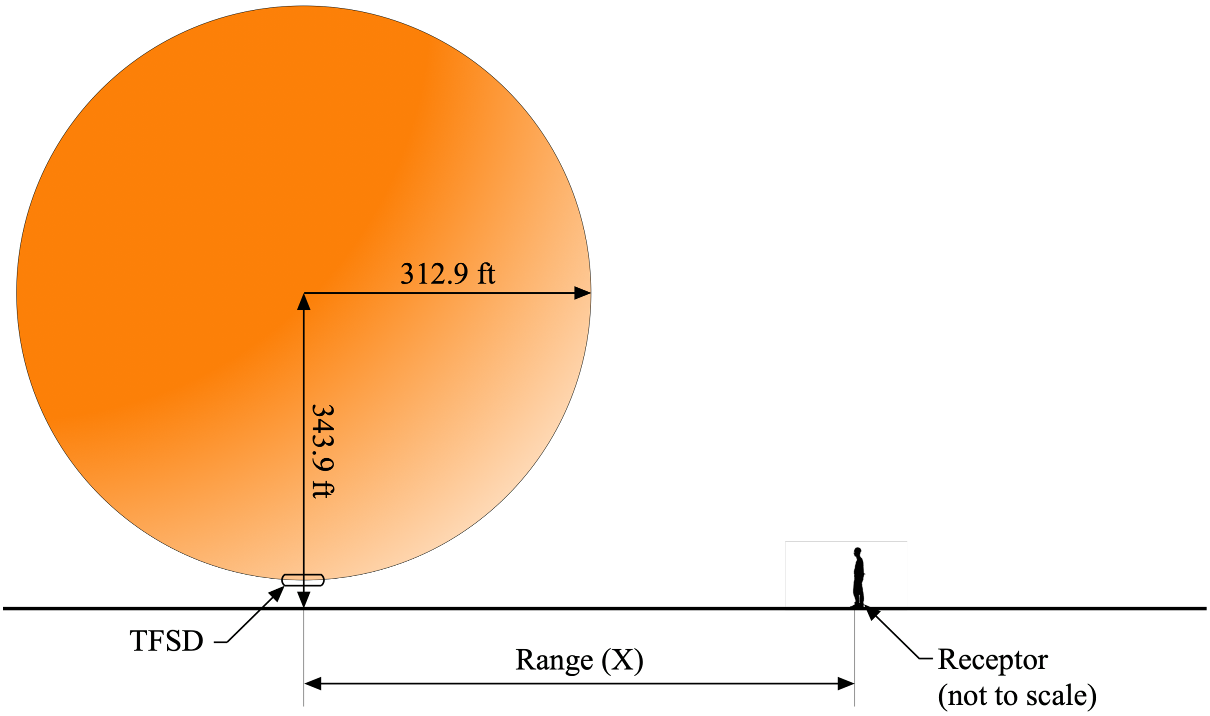

Figure 5.2: Diagram depicting the parameters for calculating the view factor used to estimate the thermal radiation received by the receptor. The receptor (human) is not shown to scale.

Assuming a surface-emissive power of $E = 350kW/m^2$ for the surface of the fireball and an atmospheric transmissivity of $\tau_a = 1$ it is possible to estimate the radiation received by the observer using,

$$q = EF_v\tau_a \tag{5.8}$$

5.3 Thermal Dose Units

Finally, the thermal dose units (TDU) received by the observer can be estimated by assuming they are exposed to the full fireball duration of $t_c = 14.80s$ using[11],

$$TDU = q^{4/3}t_c \tag{5.9}$$

If the range to the observer is varied from $984.3ft$ $(300m)$ to $3280.8ft$ $(1000m)$ we can calculate the view factor (F_v), radiation (q), and thermal dose units (TDU) for the observer. Refer to table 5.2 for a summary of the calculations. We can then compare the critical TDU in table 5.1 to the calculated $TDUs$ at various ranges from the fireball, see fig. 5.3. For the observer to be exposed to 3rd degree burns they would need to be inside of $1312.3ft$ $(400m)$, 2nd degree burns inside of $1968.5ft$ $(600m)$, and 1st degree burns inside of $2952.76ft$ $(900m)$.

Table 5.2: Thermal Dose Units Delivered by the BLEVE to a Human in the Open

Ground Distance (m)	View Factor	Solid Flame Raditation (kW/m^2)	Thermal Dose Units ($(kW/m^2)^{4/3}s$)
300	0.0850	29.7609	1364.9134
350	0.0653	22.8472	959.4496
400	0.0515	18.0111	698.7112
450	0.0415	14.5238	524.4272
500	0.0341	11.9390	403.8322
550	0.0285	9.9761	317.8266
600	0.0242	8.4536	254.8573
650	0.0207	7.2506	207.6883
700	0.0180	6.2847	171.6423
750	0.0157	5.4980	143.6089
800	0.0139	4.8491	121.4662
850	0.0123	4.3078	103.7339
900	0.0110	3.8518	89.3576
950	0.0099	3.4642	77.5724
1000	0.0089	3.1319	67.8145

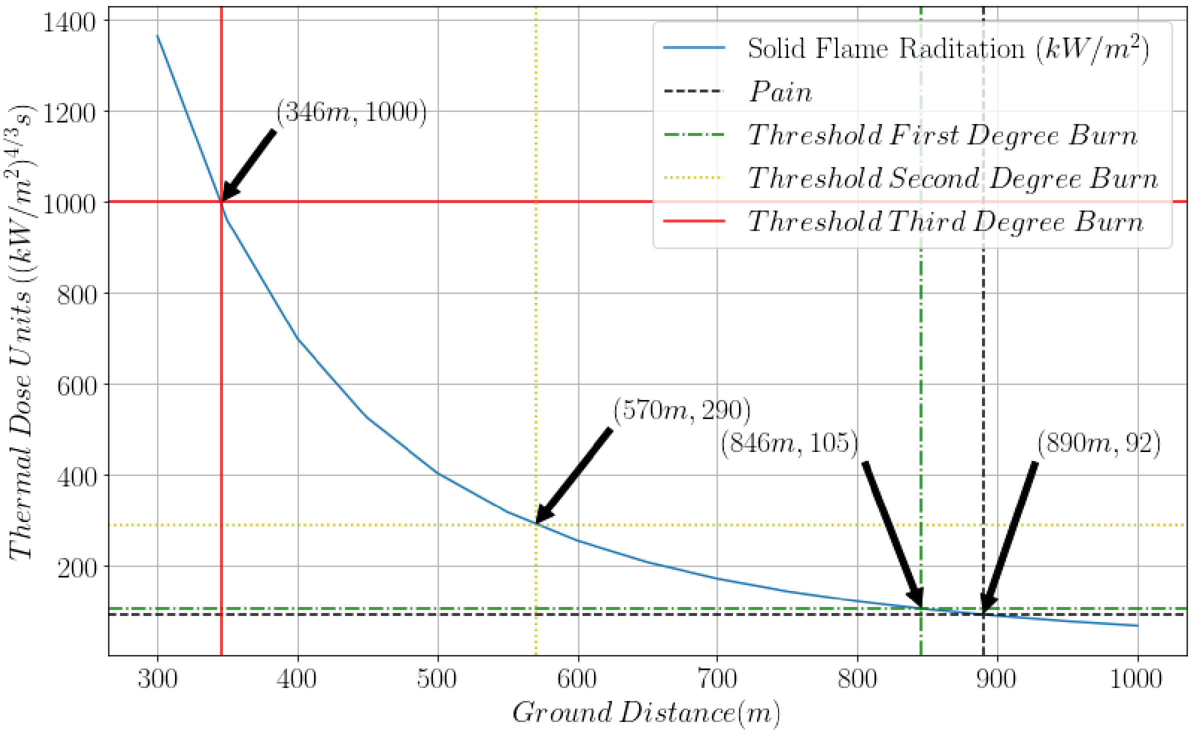

Figure 5.3: The thermal dose units received by a human in the open if exposed to the BLEVE fireball for 14.2s at a range of distances. The pain and 1st, 2nd, and 3rd degree burn thresholds are indicated.

6 Conclusion

The BLEVE analysis indicates the following:

- The calculated overpressure $28.66 psia$ ($197603.74 Pa$) at $32.8 ft$ ($10 m$) would be lethal to a human in the open. The threshold for fatality would be approximately than $869.4 ft$ ($265 m$)
- The large and small-end-caps and the center-section debris had sufficient initial velocity $318.85 mph$ ($142.54 m/s$) to be thrown the distances observed. The maximum throw distance possible would be $6794.9 ft$ ($2071.1 m$).
- The thermal effects would produce 2nd degree burns at $1870 ft$ ($570 m$) and 3rd degree burns at $1135 ft$ ($346 m$).

This BLEVE analysis is based on safety-engineering models therefore, estimates for the consequences are considered conservative. This type of analysis is used during the design phase of a plant to identify process engineering hazards for employees and the public.

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