

Overpressure Analysis of Girard Point Refinery Accident

Boiling-Liquid Expanding-Vapor Explosion

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1 Introduction

On June 21, 2019, a fire and explosion, see fig. 1.1, occurred at the Girard Point Refinery owned by Philadelphia Energy Solutions¹. One of the three explosions observed that day was from the V1 treater-feed-surge-drum in the refinery's pretreatment unit. The explosion propelled the drum approximately 1,996.6 ft from the blast seat, see fig. 1.2. It is hypothesized that a boiling-liquid expanding-vapor explosion (BLEVE) event provided the energy to generate the blast wave. The Philadelphia Fire Department requested ATF estimate the blast overpressure generated when the tank exploded. This paper is an engineering analysis to estimate the blast overpressure assuming a BLEVE occurred. The analysis is based upon an adiabatic and isentropic energy analysis developed by the Center for Chemical Process Safety².



Figure 1.1: A massive fire burns at Philadelphia Energy Solutions Inc's oil refinery³.



Figure 1.2: Largest portion of the tank that was propelled 1,996.6 ft from the blast seat⁴.

2 Background

2.1 Refinery

The Girard Point Refinery is located in southwest Philadelphia, PA, on the Schuylkill River, see fig. 2.1.⁵ The refinery produced approximately 335,000 bpd of gasoline, and was the largest on the East Coast⁵. The treater-feed-surge-drum, involved in the explosion, is part of the pretreatment process of alkylation used in the production of gasoline.

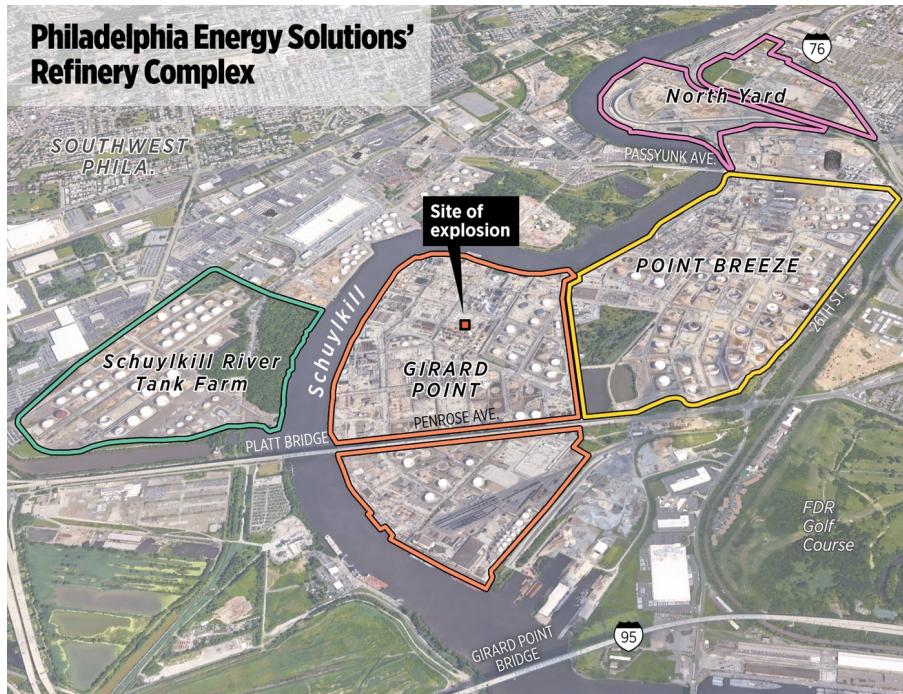


Figure 2.1: Map of Girard Point Refinery show the blast location⁶.

2.2 Treater Feed Surge Tank

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}). These Alkylates are a highly valued component in the production of gasoline because of their high octane and low vapor pressure⁷. The treater-feed-surge-drum (TFSD) was located between the fluid catalytic cracker and the alkylation unit. Surge drums stabilize fluctuations in the flow rate. The TFSD was part of the pretreatment process for alkylation, see fig. 2.2. During pretreatment, also referred to as sweetening, sulfur compounds (hydrogen sulfide, thiophene and mercaptan) are removed to improve color, odor, and oxidation stability.

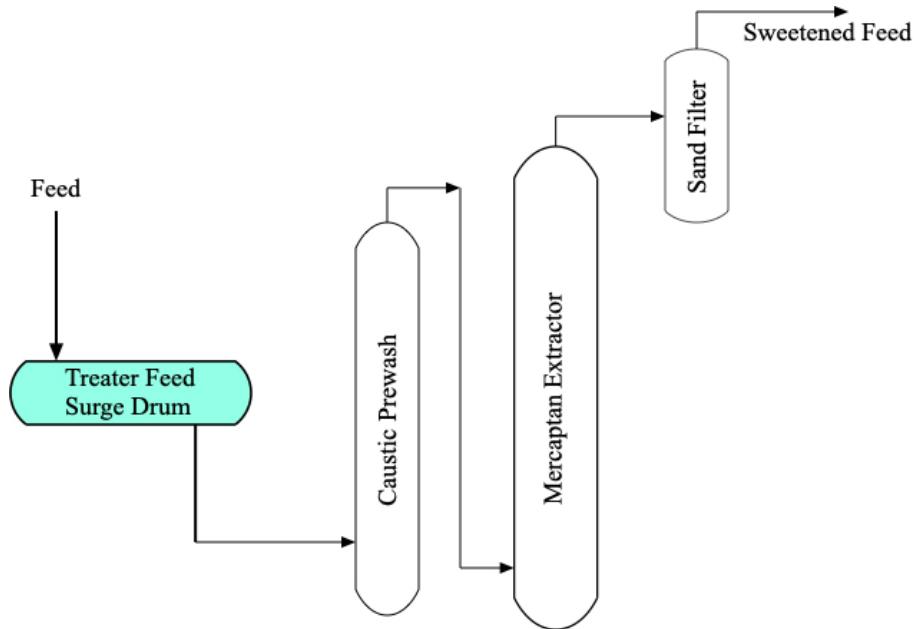


Figure 2.2: Simple flow diagram of the sweetening and treating process where the TFSD was located at the time of the explosion.^{4,8}

The TFSD tank measured 39'-8" in length, not including the heads, see table 2.1 and fig. 2.3 for construction details⁹. At the time of the explosion, the TFSD contained 98,874 lb of butane (50% by volume) and butene (40% by volume) and other lesser constituents, see table 2.2.

Table 2.1: Treater-Feed-Surge-Drum Construction Parameters⁹

Parameter	Value	Units
Type	horizontal	NA
Year Built	1972	NA
Construction Material	A516 Type 70 Steel	NA
Tank Wall Thickness	0.8125	in
Volume	372228	gal
Working Pressure	155	psi
Maximum Temperature	650	°F
Test Pressure	295	psi
Safety Valve	3"x4" 4136	Set at 155 psig

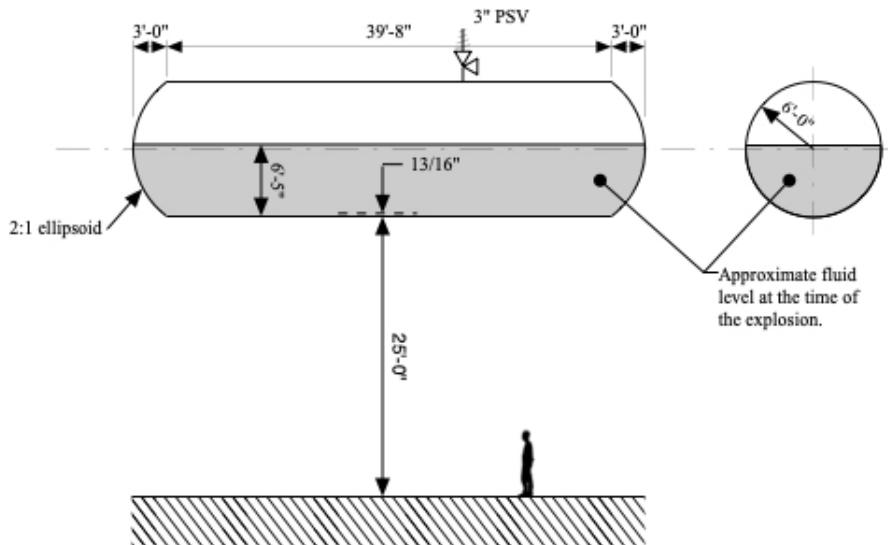


Figure 2.3: Diagram depicting the dimensions of the TFSD tank. The tank was positioned 25 ft above ground level and estimated to contain 20,160 gal (480 bbl) of butane (50% by volume) and butene (40% by volume) at the time of the explosion.⁹

Table 2.2: Sample of Chemical Contents in the Treater-Feed-Surge-Drum Closest to the Time of the Explosion⁹

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
butene	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

2.3 Pressure Relief Valve

The TFSD was fitted with a Consolidated (1906-30LC-1-CC-MS-31-RF-1) 3" x 4" pressure relief valve (PRV). The relief pressure was set to 155 psig and the relief temperature was set to 183.5 °F. The PRV was positioned on the top of the TRFD, see fig. 2.3.

2.4 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 its boiling point but without boiling). The magnitude of the

blast depends on how super-heated the liquid was at failure. As the level of super-heat rises, the portion of liquid that flash-boils rises, thus increasing the energy released. 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 these four forms depends on the specifics of the explosion. Planas-Cuchi et al. found that a *fragile* failure releases 80% of the energy into the blastwave, while a *ductile* 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 small¹⁰. In practice most pressure vessels are designed with materials that are ductile rather than brittle to avoid sudden and catastrophic brittle (fragile) failures¹¹.

3 Notebook Imports

4 Thermodynamic Data

4.1 Pressure at State 1 (Pre-failure State)

The drum (tank) is assumed to fail at 1.21 times the opening pressure of the pressure relief valve (PRV)¹². The PRV was set to open at 15 MPa therefore, the absolute pressure at state 1 (failure state) is given by,

$$p_1 = 1.21 (p_{PRV} + p_{atm}) \quad (4.1)$$

$$p_1 = 1.21 (1500000 + 101325) \quad (4.2)$$

$$p_1 = 1.916 \text{ MPa} \quad (4.3)$$

4.2 Pressure at State 2 (Final Expanded State)

The pressure at state 2 (final expanded state) is standard atmospheric pressure or 0.101 MPa . The other state variables can be determined based on the “saturated” state of the propane inside the tank and the known pressures. The thermodynamic data for states 1 and 2 is summarized in Table (table 4.1).

Table 4.1: Propane Thermodynamic Data for Initial (1) and Final (2) States

State	$P \text{ (kPa)}$	$h_f \left(\frac{\text{kJ}}{\text{kg}} \right)$	$h_g \left(\frac{\text{kJ}}{\text{kg}} \right)$	$v_f \left(\frac{\text{m}^3}{\text{kg}} \right)$	$v_g \left(\frac{\text{m}^3}{\text{kg}} \right)$	$u_f \left(\frac{\text{kJ}}{\text{kg K}} \right)$	$u_g \left(\frac{\text{kJ}}{\text{kg K}} \right)$	$s_f \left(\frac{\text{kJ}}{\text{kg K}} \right)$	$s_g \left(\frac{\text{kJ}}{\text{kg K}} \right)$
1	1937.60325	354584.413136	625197.730383	0.002287	0.022459	350.152477	581.681515	1.503188	2.325970
2	101.32500	100356.292970	525947.893053	0.001722	0.413884	100.181860	484.011098	0.607045	2.449144

5 Internal Energy at States 1 and 2

5.1 Internal Energy at State 1

The internal energy at state 1 (saturated) is calculated from,

$$h = u + pv \quad (5.1)$$

where h is the enthalpy, p is the pressure, and v is the specific volume. Therefore, for state 1 (fluid and gas) we have,

$$u = h - pv \quad (5.2)$$

$$u_{1f} = h_{1f} - p_1 v_{1f} \quad (5.3)$$

$$u_{1f} = 354584.4 - (1937.603 \text{ kPa})(0.002287 \text{ m}^3/\text{kg}) \quad (5.4)$$

$$u_{1f} = 350.15 \text{ kJ/kg} \quad (5.5)$$

$$u_{1g} = h_{1g} - p_1 v_{1g} \quad (5.6)$$

$$u_{1g} = 100356.29 - (101.325 \text{ kPa})(0.001722 \text{ m}^3/\text{kg}) \quad (5.7)$$

$$u_{1g} = 581.68 \text{ kJ/kg} \quad (5.8)$$

and similarly for state 2,

$$u_{2f} = 100.18 \text{ kJ/kg} \quad (5.9)$$

$$u_{2g} = 484.01 \text{ kJ/kg} \quad (5.10)$$

5.2 Internal Energy at State 2

When the drum breaks and the propane at state 1 expands to state 2 (atmospheric pressure) some of the liquid propane vaporizes and some of the gaseous propane condenses. Therefore unlike at the saturated state 1, there is both vapor and fluid present. We can calculate the vapor present using the vapor quality (χ), from,

$$\chi = \frac{v_{tot} - v_f}{v_g - v_f} \quad (5.11)$$

where v is the specific gravity. This equation is also true for the entropy (s), internal energy (u), and enthalpy (h). Using the entropy (s) we can calculate the quality of the saturated liquid and vapor as the propane transitions from state 1 to state 2. Therefore, the liquid vapor quality at state 2 is given by

$$\chi_f = \frac{s_{f1} - s_{f2}}{s_{g2} - s_{f2}} \quad (5.12)$$

$$\chi_f = \frac{1.503188 - 0.607045}{2.449144 - 0.607045} \quad (5.13)$$

$$\chi_f = 0.4865 \quad (5.14)$$

and for the vapor at state 2,

$$\chi_g = \frac{s_{g2} - s_{g1}}{s_{g2} - s_{f2}} \quad (5.15)$$

$$\chi_g = \frac{2.449144 - 2.325970}{2.449144 - 0.607045} \quad (5.16)$$

$$\chi_g = 0.06687 \quad (5.17)$$

We can then calculate the internal energy at state 2 using,

$$u_{2-fluid} = (1 - \chi_f)u_{f2} + \chi_f u_{g2} \quad (5.18)$$

$$u_{2-vapor} = (1 - \chi_g)u_{g2} + \chi_g u_{f2} \quad (5.19)$$

$$u_{2-fluid} = (1 - 0.4865)100.1818 + (0.4865)(484.0111) \quad (5.20)$$

$$u_{2-vapor} = (1 - 0.0668)484.0111 + (0.0668)(100.1818) \quad (5.21)$$

$$u_{2-fluid} = 286.9068 \text{ kJ/kg} \quad (5.22)$$

$$u_{2-vapor} = 458.3459 \text{ kJ/kg} \quad (5.23)$$

6 The Specific Work

The work that the expanding vapor and fluid can perform is the difference between the initial (1) and final (2) states,

$$e_{ex} = u_1 - u_2 \quad (6.1)$$

for the saturated fluid we have,

$$e_{exf} = u_{f1} - u_{2-fluid} \quad (6.2)$$

$$e_{exf} = 350.15 - 286.91 \quad (6.3)$$

$$e_{exf} = 63.25 \text{ kJ/kg} \quad (6.4)$$

and for the vapor,

$$e_{exg} = u_{g1} - u_{2-vapor} \quad (6.5)$$

$$e_{exg} = 581.68 - 458.35 \quad (6.6)$$

$$e_{exg} = 123.34 \text{ kJ/kg} \quad (6.7)$$

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The mass of the fluid at state 1 is 8743.82 kg
The mass of the vapor at state 1 is 222.63 kg
The explosion energy of the fluid at state 1 is 1106018.04 kJ.
The explosion energy of the vapor at state 1 is 54916.44 kJ.
The total energy of the surface explosion is Ex_tot = 1160934.48 kJ.
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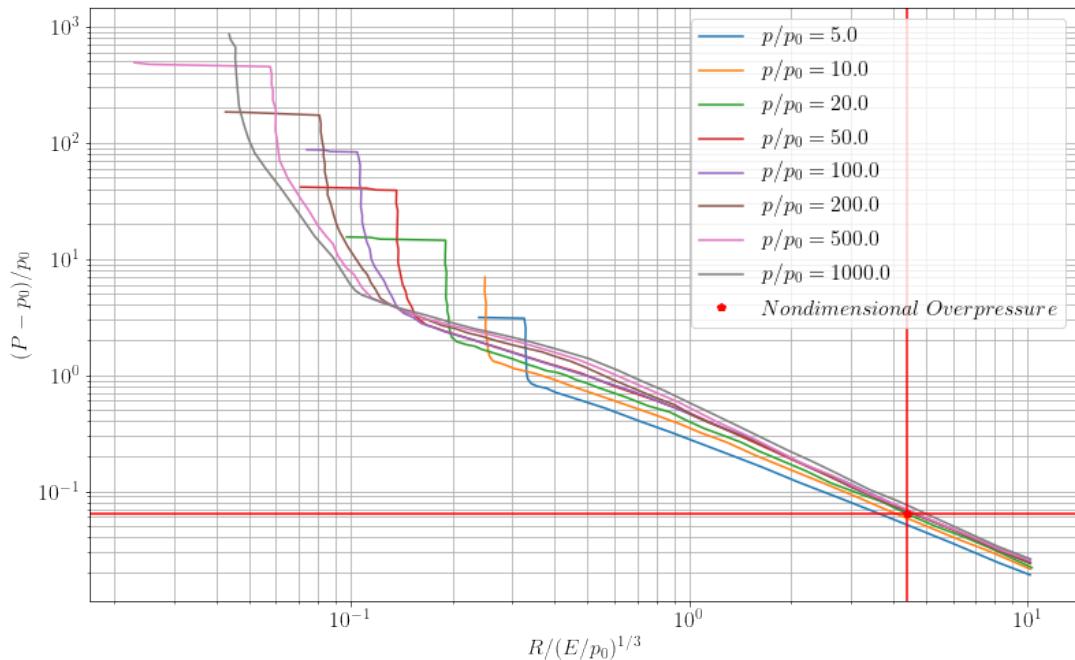
7 The Explosion Energy

The explosion energy is calcu

The non-dimensional range of the receptor is 4.44
 The non-dimensional tank pressure p/p_0 is 19.12

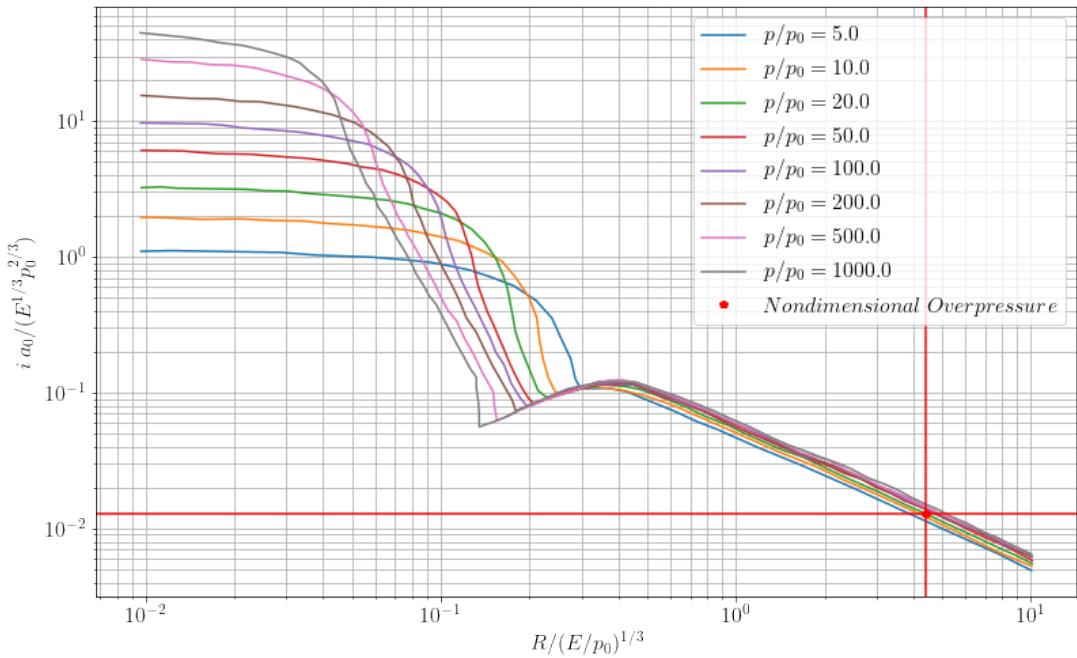
	P	R	w	z
0	3.128611	0.238936	5.0	$p/p_0 = 5.0$
1	3.118639	0.252979	5.0	$p/p_0 = 5.0$
2	3.106715	0.270923	5.0	$p/p_0 = 5.0$
3	3.094836	0.290141	5.0	$p/p_0 = 5.0$
4	3.086942	0.303704	5.0	$p/p_0 = 5.0$

The non-dimensional incident overpressure is 0.064



	I	R	w	z
0	1.098722	0.009641	5.0	$p/p_0 = 5.0$
1	1.110627	0.012128	5.0	$p/p_0 = 5.0$
2	1.098565	0.016701	5.0	$p/p_0 = 5.0$
3	1.088441	0.021905	5.0	$p/p_0 = 5.0$
4	1.078667	0.028533	5.0	$p/p_0 = 5.0$

The non-dimensional incident impulse is 0.013



The incident overpressure is 6488.53 Pa (0.94 psi)

The incident impulse is 86.31 Pa-s (0.01 psi-s)

7.1 Nondimensional Side-on Pressure and Impulse

The nondimensional side-on pressure can be calculated from Figure X and gives a $\bar{P}_s = 0.064$ for an $\bar{R} = 4.4$ and a $p/p_0 = 19.12$. The nondimensional side-on impulse can be calculated from Figure Y and gives a $\bar{i}_s = 0.013$ for an $\bar{R} = 4.4$ and a $p/p_0 = 19.12$.

The side-on pressure and impulse can be calculated from the following:

$$\bar{P}_s - p_0 = (0.064)(101.325 \text{ kPa}) = 6.5 \text{ kPa} \quad (7.1)$$

$$i_s = \frac{(0.013)(101325 \text{ kPa})^{2/3}(1160.9 \text{ E6 J})^{1/3}}{340 \text{ m/s}} = 86.31 \text{ Pa-s} \quad (7.2)$$

8 References

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