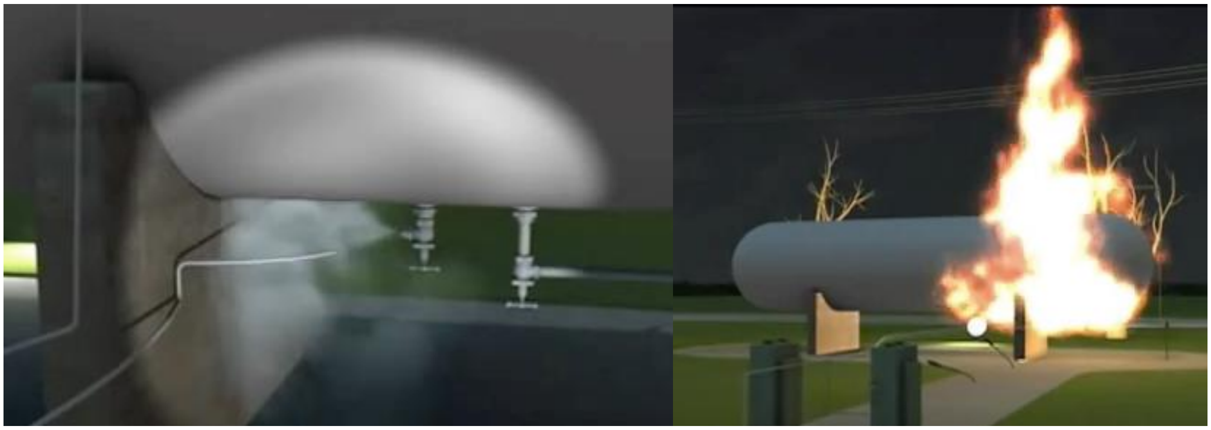
Heat and Mass Transfer
Safety Module 3: *Propane Fire, Herrig Brothers Poultry Farm, April 9, 1998*

Problem Statement: Teenagers joyriding on an all-terrain vehicle (ATV) drove into gas lines attached to a carbon steel propane tank. The crash severed the lines from the tank, which contained 10,000 gallons of propane, causing the propane to leak from the bottom of the tank. The leaked gas traveled to a hot propane vaporizer and ignited, engulfing the tank in flames. The fire surrounding the tank heated and softened the tank's steel upper portion. The softened steel coupled with the increase in propane vapor pressure caused the tank to rupture and explode, killing 2 firefighters, injuring 7, and causing damage to the farm's buildings.



Watch the Video: (*https://www.youtube.com/watch?v=R2Ez7lkjg1Y*)(Time 0:00 – 2:30)

Incident Report Available At: (*https://www.csb.gov/file.aspx?DocumentId=5609*)
(Pages 5-10, 42-45)

(a) It is important that chemical engineers understand what the accident was, why it happened and how it could have been prevented in order ensure similar accidents may be prevented. Applying a safety algorithm to the accident will help achieve this goal. In order to become familiar with a strategy for accident awareness and prevention, view the Chemical Safety Board video and read the incident report on the propane fire at Herrig Brothers Poultry Farm and fill out the following algorithm. See definitions on the last page. If necessary, view the incident report.

Safety Analysis of the Incident

Activity: ______________________________

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Hazard: ______________________________

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Incident: ______________________________

Initiating Event: ______________________________

Preventative Actions and Safeguards: ____________________

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Contingency Plan/ Mitigating Actions: ____________________

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Lessons Learned: ____________________

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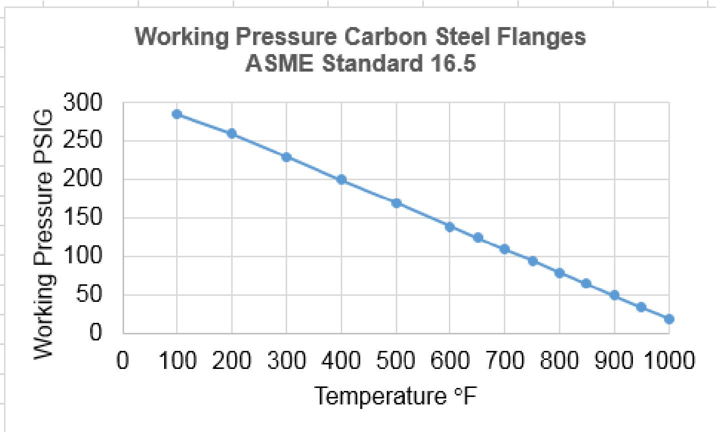
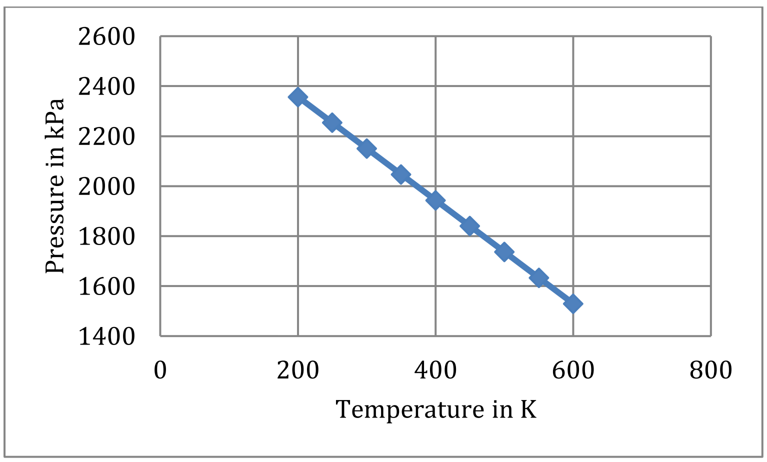
Additional Information





Pressure vs. Temperature, in ASME standard and in SI units

Using Linear Least Square regression, the equation for Working Pressure (P in Pa) vs temperature (T in K) for Carbon steel[1] is obtained as

$$P(Pa) = 2771275.65 - 2068.70T(K) \quad \text{(i)}$$

Time taken for the BLEVE to occur after the leaking propane ignited was about 23 min (pg. 36, Section 4.5.1 of Incident report). T_l is temperature of liquid propane, T_g is temperature of propane vapor, T_f is flame temperature and T_s is temperature of steel tank.

[1] https://www.engineeringtoolbox.com/ansi-flanges-pressure-temperature-d_342.html

Tank properties	
Outer diameter (D)	9 ft (2.74 m)
Length (L)	42 ft (12.8 m)
Thickness of wall (δ)	0.5 inch (0.0127 m)
Initial temperature (T_o)	298 K
Steel	
Heat capacity (C_s)	0.4733 kJ/kgK
Density (ρ_s)	7820 kg/m^3
Conductivity (k_s)	34 W/mK
Liquid Propane	
Heat capacity (C_l)	2.7378 kJ/kgK
Density (ρ_l)	490.46 kg/m^3
Convective heat transfer coefficient (h_l)	100 W/m^{2}K
Propane vapor	
Heat capacity (C_g)	2.0134 kJ/kgK
Density (ρ_g)	20.5330 kg/m^3
Convective heat transfer coefficient (h_g)	10 W/m^{2}K
Flame	
Flame temperature (T_f)	1000 K
Convective heat transfer coefficient of air (h_f)	50 W/m^{2}K
Antoine equation[2] for propane	$\log_{10}(P)= 4.53678-1149.36/(T+24.906)$ P= vapor pressure (bar), T=temperature (K)
Ideal Gas Law[3]	PV=nRT

Solve parts (b) through (d) for the following **initial conditions**.

1. Tank is completely filled with liquid propane.

   Assume T_s=T_l and that propane vapors do not form upon heating of liquid propane under this storage conditions. Pressure exerted by liquid propane is obtained using Antoine equation.

2. Tank is completely filled with propane vapor.
   Propane vapor is initially at its saturation pressure. Use Ideal Gas Law for propane vapor. Propane liquid and vapor are at same temperature at all times. Take T_s=T_l for calculations.

3. (EXTRA CREDIT) Tank is equally filled with propane liquid and propane vapor (by volume).

   Propane vapor is initially at its saturation pressure. Use Ideal Gas Law for propane vapor. Propane liquid and vapor are at same temperature at all times, i.e., T_g=T_l. Also, take T_s=T_l for calculations. To evaluate temperature and time of tank rupture, use pressure exerted by liquid propane which is obtained using Antoine equation. Solve this part for zero and non-zero (2kg/s) rate of vaporization of liquid propane.

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[2] https://webbook.nist.gov/cgi/cbook.cgi?ID=74-98-6

[3] https://en.wikipedia.org/wiki/Ideal_gas_law

Enthalpy of vaporization of liquid propane ΔH_v is 368.52 kJ/kg. Perform energy balance on the tank by considering heat transfer to liquid propane only.

Assume entire cylindrical surface of tank is exposed to fire and that liquid/ gas phase(s) are well mixed. Effect of expansion of steel tank due to heating is negligible.

(b) Calculate the heat flux into the storage tank using the temperature of the fire on the outside of the storage tank and outside heat transfer coefficient and the heat transfer coefficient on the inside above and below the liquid level.

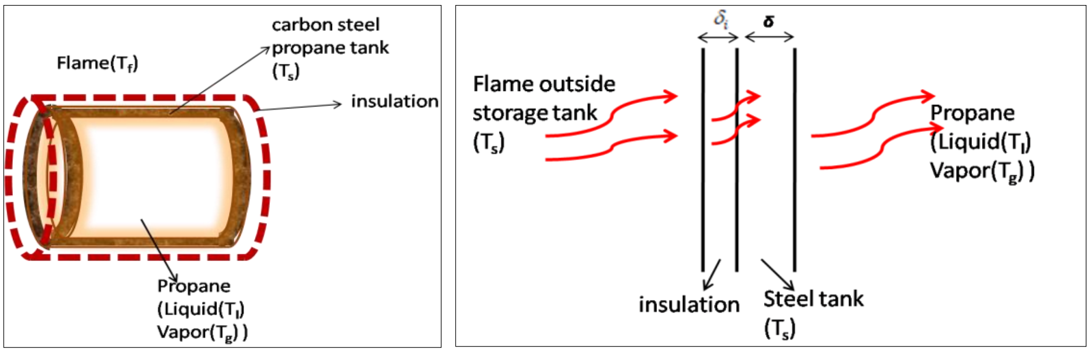


Figure 3.1. Schematic of heat flow across the tank with insulation

When energy flows through several mediums in contact across a surface of area, A, with overall temperature difference, ΔT, the net energy flow, Q is defined using overall heat transfer coefficient, U. Refer Eq. (15-17)[4]*. (Here $\Delta T=T_f-T_g$ or T_f-T_l)*

$$Q = UA\Delta T \qquad \text{(b-1)}$$

Overall heat transfer coefficient, U, for energy transfer from flame outside the storage tank to the contents inside the tank can be calculated using

$$\frac{1}{U} = \sum_{i=1}^{m} \frac{1}{h_i} + \sum_{j=1}^{n} \frac{\delta_j}{k_j} \qquad \text{(b-2)}$$

Where m and n are the number of mediums across which convective and conductive heat transfer occur, respectively. h_i is the convective heat transfer coefficient of medium i. δ_j and k_j are the thickness and conductivity of mediums across which conduction occurs.

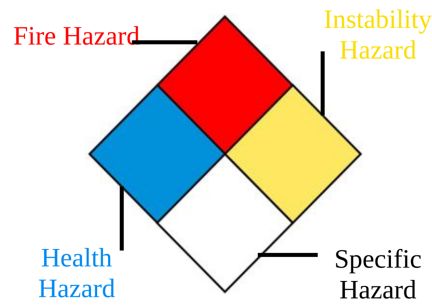
(Hint: Flame heats up the storage tank continuously until it ruptures. T_l, T_g and T_s will therefore vary with time. To account for time variation, perform energy balance using quasi steady-state analysis.)

(c) Calculate the rates of temperature increase of the gas space and the liquid space inside the storage tank. Given that: $\frac{dT_l}{dt} = \alpha_1 \cdot (T_f - T_o) \cdot e^{-\alpha_1 t}$

(d) Estimate the time and temperature at which the storage tank ruptured.

[4]Welty, J.R., Rorrer, G.L., and Foster, D.G. (2013). Fundamentals of Momentum, Heat, and Mass Transfer (6th. Ed.), Oregon and Rochester, New York: Wiley, 230

(e) Review the information in the NFPA Diamond tutorial. After reviewing the information, visit the CAMEO Chemicals website and fill out the blank NFPA Diamond to the right for propane.

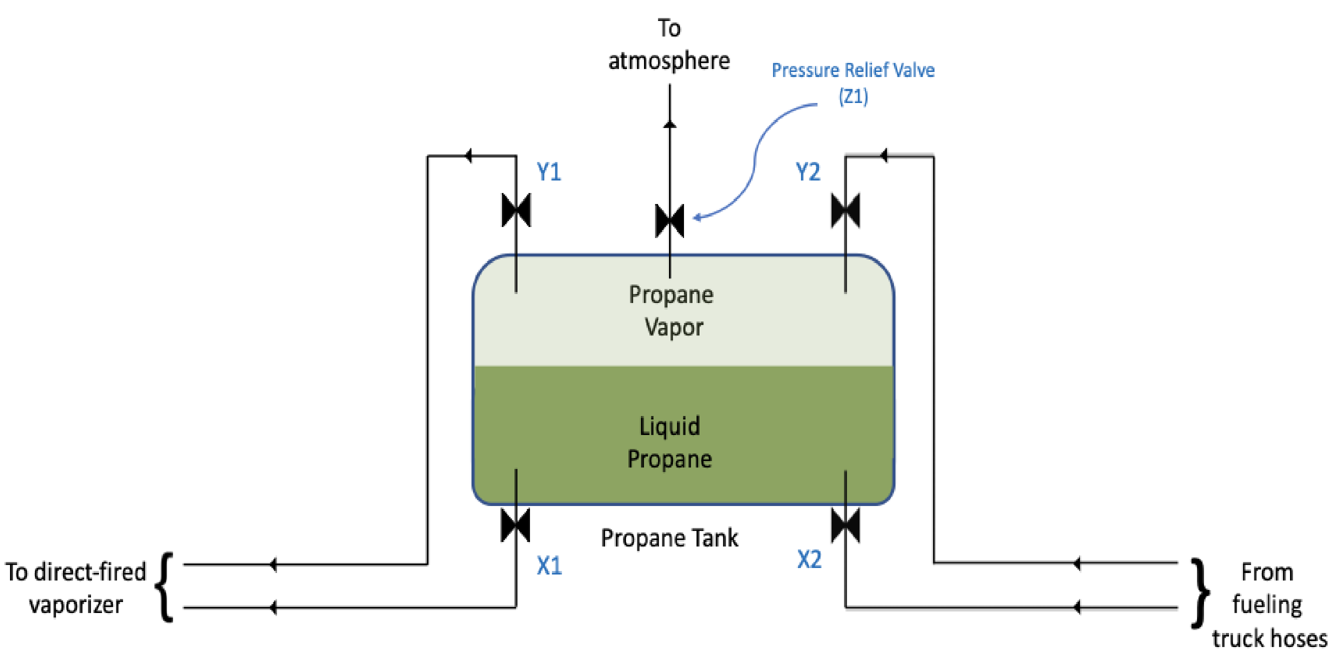


Parts (f)-(h) are based on industry practices used to assess process safety. For more information on process safety and its importance in chemical engineering, please visit the University of Michigan SafeChE website here. *It is recommended that professors only assign 1-2 of the following parts due to the similar nature of the questions.*

(f) Review the explanation of the components of a BowTie diagrams found here. After reviewing the information, create a BowTie diagram for the Propane Fire incident at Herrig Brothers Poultry Farm.

(g) A HAZOP study is structured analysis of process design to identify potential vulnerabilities in a facility. Review the background on how to conduct a HAZOP study here before completing one for the following system. It is important to note that not all guidewords and parameters will be relevant for different systems. Some information is given here for guidance:

System to consider: Tank containing liquid and vapor propane and its adjacent valves



Valves X1, X2, Y1, Y2 are excess flow valves, which are designed to automatically close when the flow through the valve exceeds a predetermined rate, (i.e. the closing rating). Valve Z1 is a pressure relief valve that vents propane vapor to the atmosphere when the pressure inside the cylinder exceeds the set pressure. Note that all the liquid and vapor lines in the system use *above-ground piping*. The liquid and vapor lines on the left go to a direct-fired vaporizer, while those on the right are connected to fueling truck hoses.

Process parameters to consider: Temperature, Pressure, Leak of Propane

(i) Fill out the HAZOP chart as shown in the tutorial. Some other information has been filled out here for you.

Guideword + Parameter = Deviation	**Causes**	**Consequences**	**Safeguards**	**Recommendations**
More (High) Temperature of the Tank	A fire in the close vicinity of the tank			
More (High) Pressure of the Tank	Increase of temperature in and around the tank			
Other (*Leak)* of Propane from the tank and/or the above-ground piping				

(ii) Write a short conclusion on some takeaways from completing a HAZOP for this system and recommendations you would make.

(h) A Layers of Protection Analysis (LOPA) is a semi-quantitative study to identify available safeguards and determine if the safeguards sufficiently protect against a given risk. Review the background on how to conduct a LOPA study here before filling the table out for the system described in this module. Some information is given for guidance:

- Assume that the farm can only accept a moderate risk
- Per the CSB report, the explosion had a catastrophic impact of 2 fatalities and 7 injuries

LOPA Study for Propane Tank Explosion		
Initiating Event	Cause:	Third-party intervention (external impact by vehicle)
	Consequence:	Leakage of propane from the damaged pipelines and tank, leading to the formation of an ignitable vapor cloud
	FOIE:	

IPL(s)	Description of IPL_1, IPL_2, ...	
	PFD = PFD_1 x PFD_2 x ...	
MCF	MCF = FOIE x PFD	
	Category of MCF:	
Severity	Impact:	2 fatalities and 7 injuries
	Category:	
Risk	Type of risk:	
	Acceptable / Unacceptable?	
If risk evaluated above is unacceptable, please continue below:		
Proposed IPL(s) (P-IPL(s))	Description of P-IPL_1, P-IPL_2, ...	
	P-PFD = P-PFD_1 x P-PFD_2 x ...	
MCF	MCF = FOIE x PFD x P-PFD	
	Category of MCF:	
Risk	Type of risk:	
	Acceptable / Unacceptable?	

(i) Describe what was the most unsettling to you about the incident.

Wolfram

Click here to download Wolfram CDF Player for free.

Click here to view CDF installation tutorial.

Click here to download Wolfram code for this module.

The sliders and graphs in this Wolfram section represent the scenario where the tank is equally filled with propane liquid and propane vapor by volume (Case 3). The rate of vaporization of liquid propane is assumed to be zero.

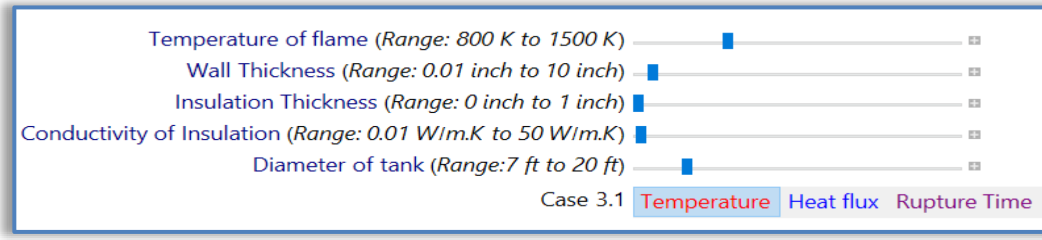


Fig. 3.2 Wolfram sliders

Wolfram Graph Outputs:

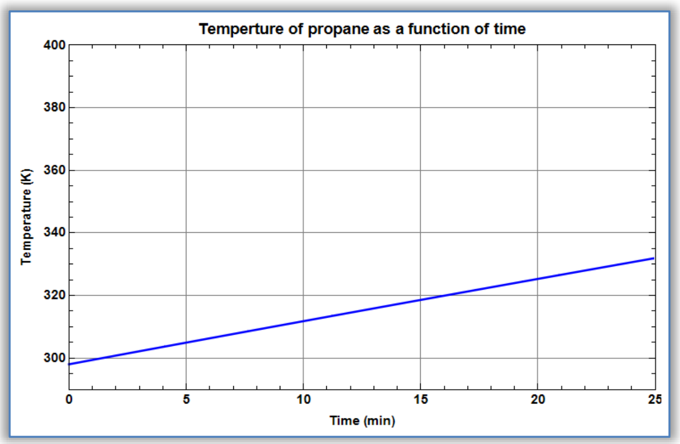


Fig. 3.3 Temperature vs. Time

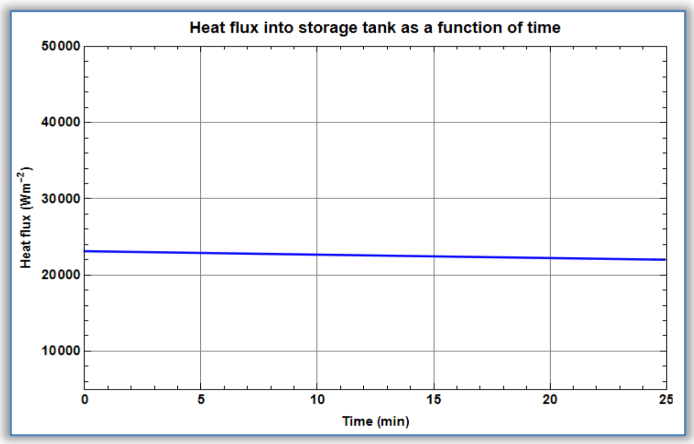


Fig. 3.4 Heat Flux vs. Time

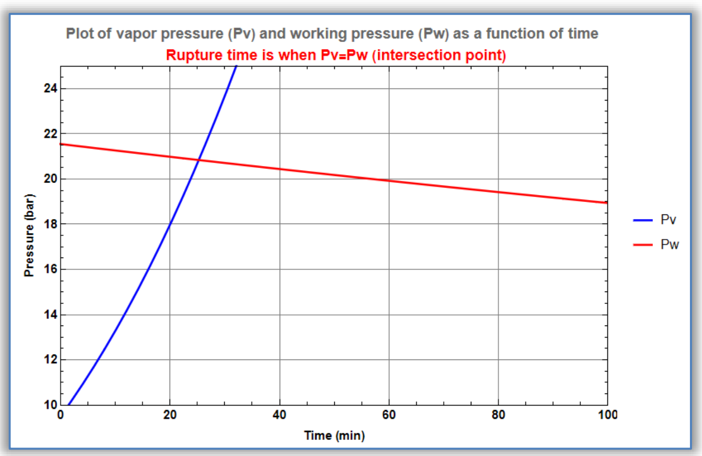


Fig. 3.5 Pressure vs. Time and Rupture Point

Questions:

i. Describe how heat flux into the storage tank changes by varying the wall thickness. Why does the heat flux decrease with time?

ii. Describe how the temperature profile of propane varies with changes in flame temperature and tank diameter.

iii. Vary the sliders for tank diameter and wall thickness and note how the time to rupture changes.

iv. Consider the propane storage tank with a diameter of 10 ft and a wall thickness of 4 in. In the event of a fire, fire fighters can be expected to put out the flame within 40 min, thus preventing a potential explosion of the tank. Given insulation with a conductivity of 0.1 W/mK, determine the minimum thickness of insulation so that the time for rupture is at least 40 min for any flame temperature.

v. Write a set of conclusions based on completing the previous parts.

Definitions

Activity: The process, situation, or activity for which risk to people, property or the environment is being evaluated.
Hazard: A chemical or physical characteristic that has the potential to cause damage to people, property, or the environment.
Incident: What happened? Description of the event or sum of the events along with the steps that lead to one or more undesirable consequences, such as harm to people, damage to property, harm to the environment, or asset/business losses.
Initiating Event: The event that triggers the incident, (e.g., failure of equipment, instrumentation, human actions, flammable release, etc.). Could also include precursor events, (e.g., no flow from pump, valve closed, inadvertent human action, ignition). The root cause of the sum events in causing the incident.
Preventative Actions and Safeguards: Steps that can be taken to prevent the initiating event from occurring and becoming an incident that causes damage to people, property, or the environment. Brainstorm all problems that could go wrong and then actions that could be taken to prevent them from occurring.
Contingency Plan/ Mitigating Actions: These actions occur after the initiating event. They are steps that reduce or mitigate the incident after the preventative action fails and the initiating event occurred.
Lessons Learned: What we have learned and can pass on to others that can prevent similar incidents from occurring
BowTie Diagram: A qualitative hazard analysis tool through which potential problems and consequences associated with a hazard are studied through a pictorial representation. Necessary preventive and mitigating barriers are determined to reduce the process safety risk.
Hazard and Operability Study (HAZOP): A qualitative hazard analysis tool that uses a set of guide words to determine whether deviations from design or operating intent can lead to undesirable consequences. The existing safeguards are evaluated and if required, actions are recommended to mitigate the consequences.
Layer of Protection Analysis (LOPA): A semi-quantitative study that determines initiating event frequency, consequence severity, and likelihood of failure of independent protection layers (IPLs) to calculate the risk of a scenario. If the existing risk is intolerable, then additional IPLs are suggested to bring down risk to an acceptable level.

Module Specific for Propane Fire at Herrig Bros. Poultry Farm

Boiling Liquid Expanding Vapor Explosion (BLEVE)[†]: A BLEVE occurs when a vessel containing a liquid at a temperature above its atmospheric boiling point ruptures. The subsequent BLEVE is an explosive vaporization of a large fraction of the vessel contents that can be followed by combustion or explosion of the vaporized cloud. BLEVE occurs when an external heat source heats the contents of the vessel thereby increasing the vapor pressure in the vessel and reducing its structural integrity.

[†] From Crowl, D. A. and J.F. Louvar, *Chemical Process Safety with Applications*, Prentice Hall, Upper Saddle River, NJ.

Table of Nomenclature:

Symbol	**Description**	**Unit**
U	Overall heat transfer coefficient	$W/m^2.K$
h_i	is the convective heat transfer coefficient of medium *i*	$W/m^2.K$
δ_j	thickness of mediums across which conduction occurs	m
k_j	conductivity of mediums across which conduction occurs	W/m.K
ΔH_v	Enthalpy of vaporization	kJ/mol
T_l	temperature of liquid propane	K
T_g	temperature of propane vapor	K
T_f	flame temperature	K
T_s	temperature of steel tank	K