Process Dynamics and Control

†**Safety Module 2:** *Buncefield Explosion and Fire, England, December 11, 2005*

Problem Statement: Tank 912 at the Buncefield oil storage depot was being filled with fuel. The tank had an automatic tank gauge (ATG) system for monitoring the fuel filling operation. Due to failure of the level gauge, the system stopped registering the level of fluid in the tank. ATG alarms did not go off when the fluid reached sufficiently high level. There was an independent high-level switch whose function was to automatically close the valve when the fluid level rose beyond ATG alarm level. This switch also failed to ring the alarm and did not initiate the shutdown of filling of the tank.

Eventually the tank overfilled, and large quantities of fuel overflowed from the top of this tank. Subsequently the secondary containment and the tertiary drainage systems also failed. As a result of this overflow, a vapor cloud was formed which ignited and caused a massive explosion and a fire that lasted for five days.

Watch the Video: (https://www.youtube.com/watch?v=Ghbb-ENOaEs)

Incident Report Available At: (*http://www.hse.gov.uk/comah/buncefield/buncefield-report.pdf*)

(Relevant pages: 4, 10-15, 21-25, 30)

(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. To become familiar with a strategy for accident awareness and prevention, view the Chemical Safety Board video on the Buncefield explosion and fill out the following algorithm. See definitions on the last page. If necessary, view the incident report.

Safety Analysis of the Incident

Activity: ____

____

Hazard: ____

____

Incident: ____

Initiating Event: ____

Preventative Actions and Safeguards: ____

____

Contingency Plan/ Mitigating Actions: ____

____

Lessons Learned: ____

____

(b) Modify the schematic of the storage tank in Figure 2.1 to incorporate an automatic closure of the control valve and generate an alarm when the fuel has reached ‘high’ level, instead of just an alarm by the automatic gauge system, i.e., implement an Automatic Overfill Prevention System (AOPS).

(Hint: Connect Safety Instrumented System (SIS) to transmitter which then forwards fuel level to the control room and regulates the sounding of alarms and closure of control valve.)

LT	*Level Transmitter*	*Transmitting fuel level from gauge*
LI	*Level Indication*	*Indicates level of fluid in the tank (in control room)*
LAH	*Level Alarm High*	*High fuel level alarm (in control room).*
LAHH	*Level Alarm High-High*	*High-High level alarm (In control room).*
LS	*Level Switch*	*Independent high-level switch (IHLS)*
HS	*Hand Switch*	*Emergency Shutdown button (in control room)*

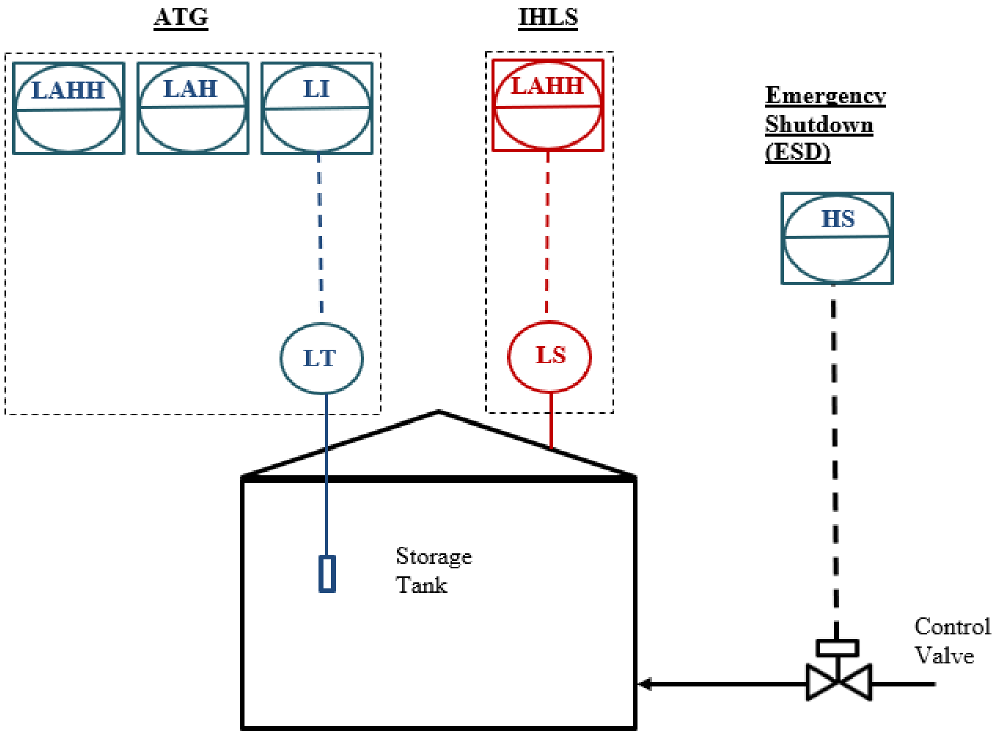


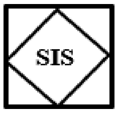
Figure 2.1 Control System in place for overfill prevention.

The schematic of the control system for preventing overfill being used in Buncefield is shown in Figure 1. The ATG provides automatic and continuous information on liquid level in the tank, which is transmitted (via LT) to the control room. It was also used to generate alarms situated in the control room. These three 'high level' alarms were
1) 'user high' which could be set by the supervisor to indicate that intervention was required
2) 'high' level – set at a level in the tank below its maximum working level
3) 'high-high' level – set below the level at which the IHLS was intended to operate.
If one these alarms was sounded, then the control room supervisor would direct closure of the control valve manually. This is known a Manual Overfill Prevention System (MOPS).

IHLS is for automatic closure of valves on any pipeline importing fuel as well as for sounding an audible alarm when fuel level has reached a set value, higher than the ATG alarm levels.

HS is for emergency closure of the control valve. Though in this case, it had never been wired, so it was of no use!!!

The Safety Instrumented Systems are used to monitor the condition of values and parameters of a plant (in this case fuel level) within the operational limits and, when risk conditions occur (threat of overfill), they must trigger alarms and place the plant in a safe condition or even at the shutdown condition.



Symbol for Safety Instrumented system (SIS)

(c) Suppose that addition to ATG, the storage tank is attached with a sight glass, as shown in the figure below, for visual inspection of the fuel level in the tank.

I. Derive transfer functions relating height of fuel in storage tank, h_1, and height of fuel in sight glass, h_2, to fuel flow rate at the inlet, q_i.
The flow through exit valve, q_e, and lower pipe connecting the tank and sight glass, q_s, can be taken to be linearly related to fuel levels via resistances, R_e and R_s respectively.

$$h_1 = q_e R_e \rightarrow q_e = {}^{h_1}\!/_{R_e}$$
$$h_1 - h_2 = q_s R_s \rightarrow q_s = {}^{h_1 - h_2}\!/_{R_s}$$

II. Taking the valve connecting the tank and the sight glass to be closed ($R_s \rightarrow \infty$), what will be the transfer function relating h_1 and q_i? Compare this transfer function with the one obtained in part I for h_1 and q_i.

III. How can sight glass be used as a layer of safety for cases where gauge in the tank gets stuck and thereby high fuel level alarms don't go off, as was the case in Buncefield explosion?

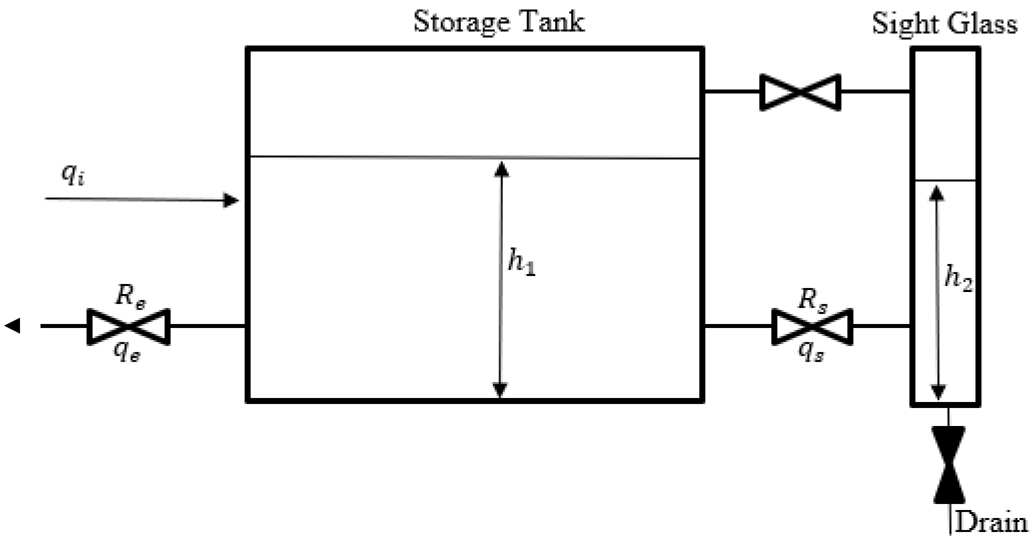
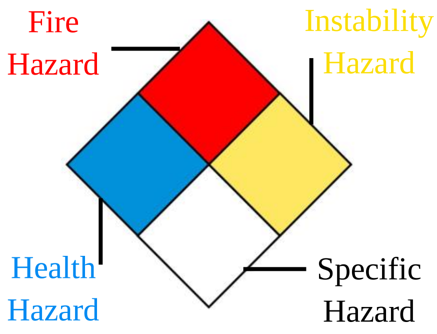


Figure 1.2 Storage tank with sight glass.

(d) 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 octane.

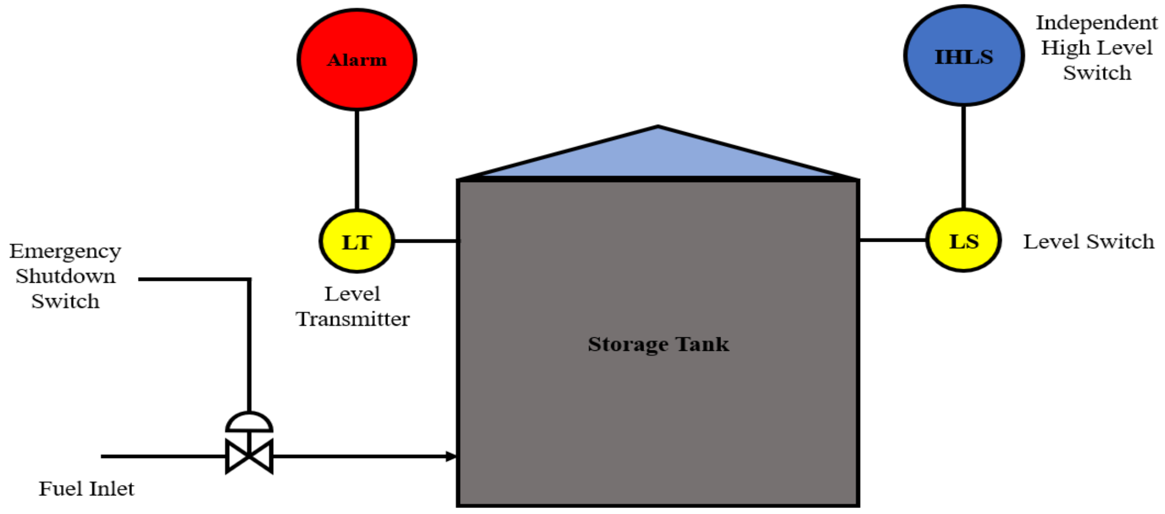


Parts **(e)-(g)** are based on industry practices used to assess process safety. For more information on process safety and its importance in chemical engineering, please visit the University of Michigan SafeChE website here. *It is recommended that professors only assign 1-2 of the following parts due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

(e) Review the explanation of the components of a BowTie diagrams found here. After reviewing the information, create a BowTie diagram for the Buncefield explosion.

(f) 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 912 and its automatic tank gauging (ATG) system receiving fuel



Process parameters to consider: Flow to storage tank, Level in storage tank

(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 Flow to the tank	Large changes in the flow rate from the source			
More Level in the tank	Failure of the level gauge			
	More flow into the tank			

(ii) When conducting a HAZOP, you will often find combinations of guidewords and parameters that describe a possible situation for the system that is not hazardous. For the given process parameters, give an example and explain why the situation is not hazardous.

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

(g) 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 plant can only accept a moderate risk
- Per the incident report, the Buncefield explosion injured over 40 people and resulted in damages of $750 million

LOPA Study for Buncefield Explosion		
Initiating Event	Cause:	Instrument failure (LG Failure)
	Consequence:	Overflow leading to release of flammable material
	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:	Serious injuries and $750 million in business losses
	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?	

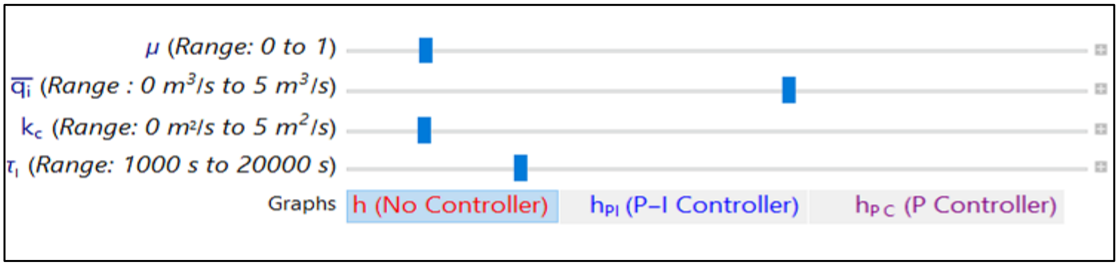
(h) Describe what was the most unsettling to you about the incident.

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.



μ (Range: 0 to 1)

$\overline{q_i}$ (Range : 0 m^3/s to 5 m^3/s)

k_c (Range: 0 m^2/s to 5 m^2/s)

τ_I (Range: 1000 s to 20000 s)

Graphs [✓ h (No Controller)] h_{PI} (P–I Controller) h_{PC} (P Controller)

Figure 2.3 Wolfram sliders.

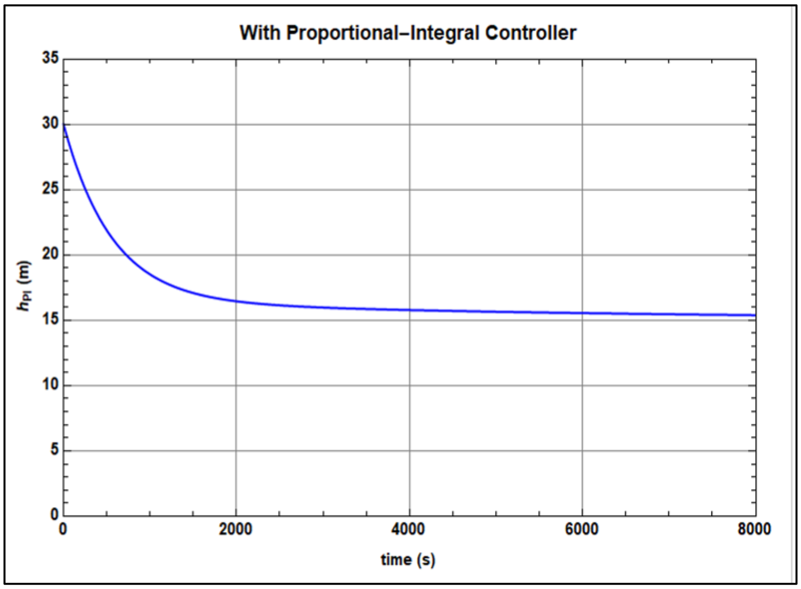


Figure 2.4 Height of fuel in the storage tank when a PI controller is used.

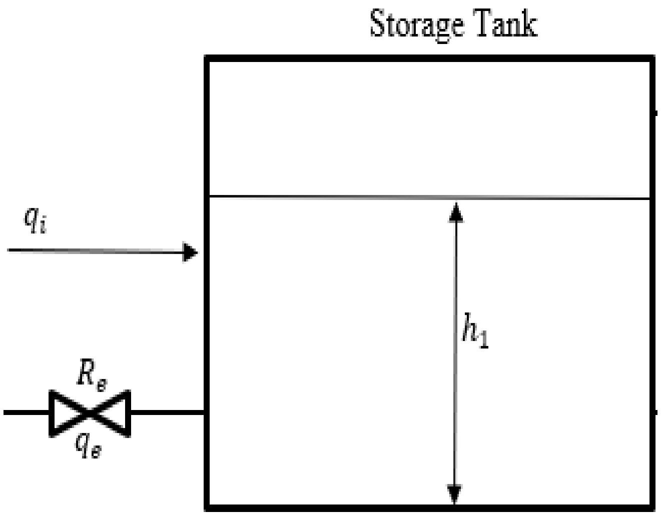


Figure 3.5 Storage tank without sight glass

Consider the storage tank shown in Figure 2.5. Suppose the outlet flow rate (q_e) varies as $q_e = \mu h$, where μ is the fractional opening of the exit valve. Answer the following questions for this setup:

(i) Vary $\overline{q_\iota}$ and μ and explain how these variables affect the height of fuel (h) in the storage tank. (Use the 'h (No Controller)' graph)

(ii) It was decided to use a PI controller to control the height of the fuel in the tank by manipulating q_i. Using the initial setting of $\overline{q_\iota}$ and μ, find the values of k_c and τ_I at which height in the tank has an offset of 20% at 500 secs and no offset at 2000 secs. (Use the 'h_{PI} (P-I Controller)' graph)

(iii) How would the controller behaviour change if the proportional controller had been used instead of a PI controller (Use the 'h_{PC} (P Controller)' graph). Using the initial setting of $\overline{q_\iota}$ and μ , find the value of k_c that achieves 5% offset.

(iv) Write a set of conclusions based on your experiments through (i) to (iii).

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.

Table 2.1 Nomenclature

Symbol	Description	SI Unit
q_i	Inlet flow rate of fuel	m^3s^{-1}
$\overline{q_\imath}$	q_i (0) (Steady state value of q_i)	m^3s^{-1}
μ	Fractional opening of the exit valve	---
h	Height of fuel in storage tank	m
h_{PC}	Height of fuel in storage tank when proportional controller is used	m
h_{PI}	Height of fuel in storage tank when PI controller is used	m
k_c	Controller gain (a tuning parameter)	m^2s^{-1}
τ_i	Integral Time Constant	s

[†] In Collaboration with Kshitiz Parihar, Indian Institute of Technology Bombay