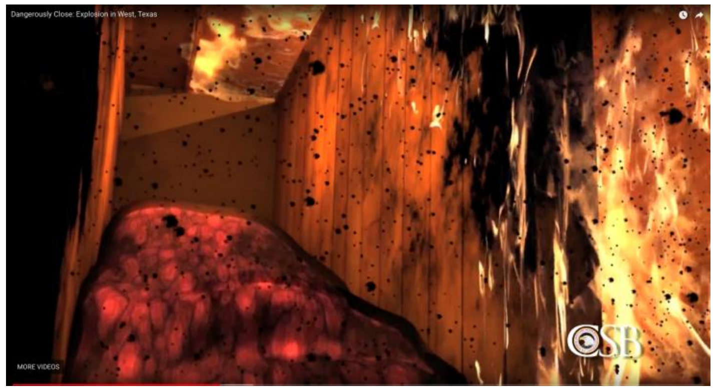
Mass and Heat Transfer Radiant and Convective Heat Transfer
[i]**Safety Module 2:** *West Fertilizer Explosion and Fire, West, TX, April 17, 2013*

Problem Statement: On April 17th, 2013, the West Fertilizer Company in West, TX was storing ammonium nitrate and other flammable and explosive materials in a 12,000 ft^2 building constructed of combustible material (mostly wood.) After a fire started in the building, 30 tons of ammonium nitrate heated up and eventually detonated killing 15 people, injuring over 260 others, damaging over 150 nearby homes and businesses, and causing the loss of hundreds of millions of dollars for the town. This was one of the worst disasters in United States history.



Watch the Video: (*https://www.youtube.com/watch?v=pdDuHxwD5R4*)

Incident Report Available At: (*https://www.csb.gov/file.aspx?DocumentId=5983*)
(Pages:16-18, 60-64, and 243-245)

(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 on the West Fertilizer explosion and fill out the following algorithm. See definitions on the last page. If necessary, view pages 16-18, 60-64, and 243-245 of the incident report.

Safety Analysis of the Incident

Activity: ______________________________

____

Hazard: ______________________________

____

Incident: ______________________________

Initiating Event: ______________________________

Preventative Actions and Safeguards: ______________________________

____

Contingency Plan/ Mitigating Actions: ______________________________

____

Lessons Learned: ______________________________

____

Additional Information:

The main bin used to store NH_4NO_3 was 8 ft (2.4384m) wide, 20 ft (6.096 m) long and 30 ft (9.144 m) high. The flame temperature, T_{flame} =2000K and temperature of NH_4NO_3 surface, $T_{surface}$ = 298K respectively. The density of solid NH_4NO_3, $\rho = 1725\, kg/m^3$, and the convective heat transfer coefficient of air at 2000K is 1 $Wm^{-2}K^{-1}$. Heat capacity, C_P, of NH_4NO_3 =1.05 *kJ/ (kg. °C)*

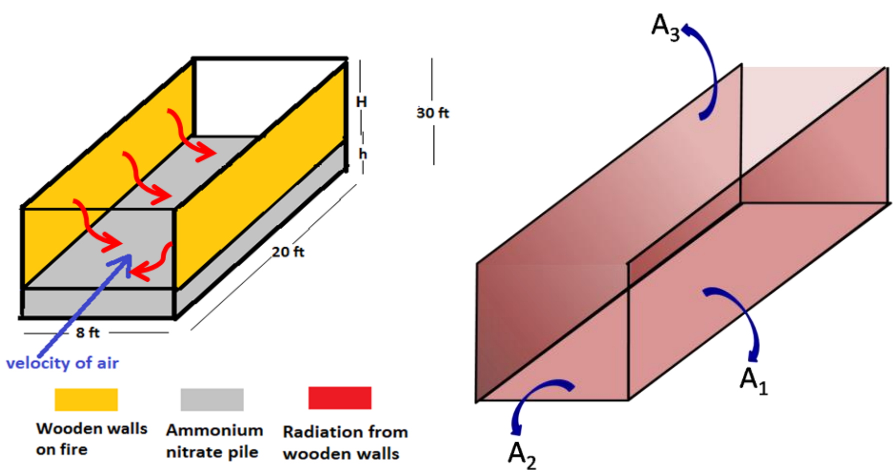


Figure 2.1. Schematic of NH_4NO_3 storage bin

(b) Calculate the **radiant energy flux** to the surface of NH_4NO_3 pile.

Energy flux radiated, $\dot{q_{rad}}$*, by a black body at temperature, T is given by Eq. (15-13)*[1]

$$\dot{q} = \sigma T^4 \tag{b-1}$$

Where σ is the Stefan-Boltzmann constant, which is equals $5.676 * 10^{-8}\, W/m^2 \cdot K^4$. *Radiant energy flux emitted by surface i which is incident on surface j with view factor* $F_{i,j}$ *is given by,*

$$\dot{q_{rad,\iota}} = F_{i,j}\sigma(T_i^4 - T_j^4) \tag{b-2}$$

[1] 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, 228

Assume that NH_4NO_3 pile is horizontal and covers the entire floor. Energy flux is from the two wooden walls along the length of NH_4NO_3 pile. (Hint: First evaluate the height of wooden walls above the NH_4NO_3 pile. Then evaluate the view factors relating the surface of NH_4NO_3 pile and the wooden walls.)

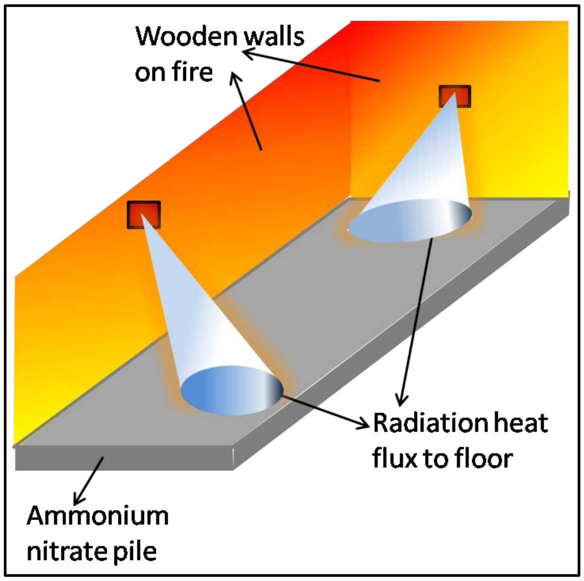


Figure 2.2. Radiation heat flux from walls to floor

(c) At around 175 °C, ammonium nitrate violently decomposes in to ammonia and nitrogen oxides by following reaction:

$$NH_4NO_3 \leftrightarrow 2NH_3 + HNO_3$$

$$NH_4NO_3 \rightarrow 2NO_2 + 2H_2O$$

The above reaction liberates enormous heat and leads to pressure buildup which causes explosion of NH_4NO_3.Calculate the time it takes for ammonium nitrate to explode since it is exposed to fire.

The amount of energy, Q (kJ), absorbed by a substance is given by

$$Q = mC_P\Delta T \qquad \text{(c-1)}$$

where m is the mass, C_P is the heat capacity, &ΔT is the temperature difference of the substance.

Rate of heat transfer, q (kJ/s)to a substance given by

$$q = \dot{q}_{net} * A_2 \qquad \text{(c-2)}$$

where $\dot{q}_{net}$ is the net heat flux and A_2 is the exposed area of the substance

Time, t(s) taken by substance to absorb Q (kJ) can be calculated by

$$t = \left(\frac{Q}{q}\right) \qquad \text{(c-3)}$$

Assume Ammonium Nitrate explodes when it reaches a temperature of 175 °C(448 K)

(d) Estimate the **convective heat flux** from the gas flame to the solid NH_4NO_3 and compare with the radiant energy flux obtained in part (e) of this module.

$$\dot{q}_{conv} = h(T_{flame} - T_{surface})$$

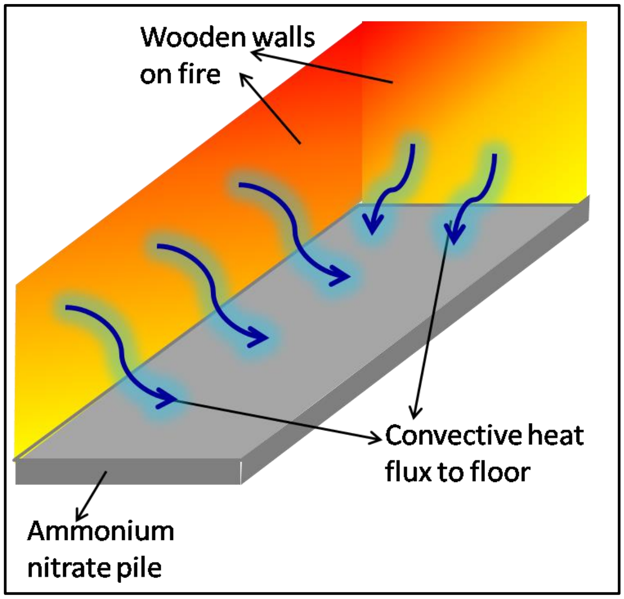
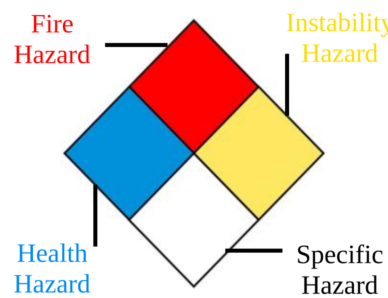


Figure 2.3. Convective heat flux from walls to floor

(e) List some of the equipment used in process industry where radiative heat flux is dominant over convective heat flux.[1,2]

(f) 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 ammonium nitrate.



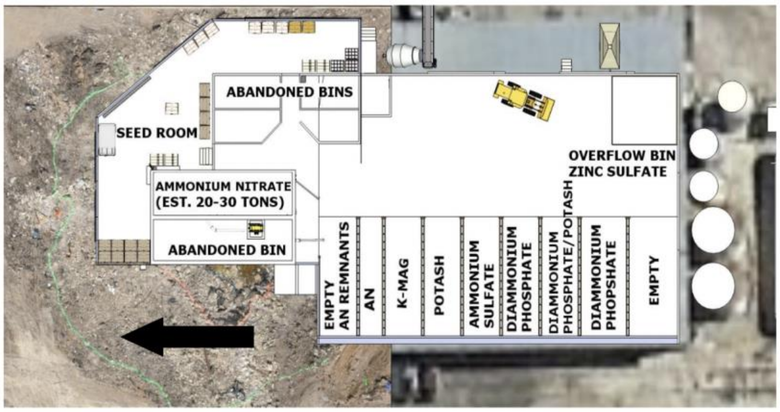
Parts **(g)-(i)** are based on industry practices used to assess process safety. For more information on process safety and its importance in chemical engineering, please visit the University of Michigan SafeChE website here. *It is recommended that professors only assign 1-2 of the following parts due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

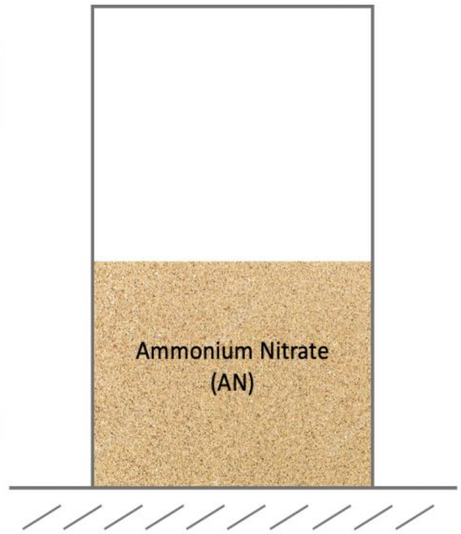
(g) Review the explanation of the components of a BowTie diagrams found here. After reviewing the information, create a BowTie diagram for the West Fertilizer incident

[1] http://www.thermopedia.com/content/796/
[2] https://www.sciencedirect.com/topics/engineering/radiative-heat-transfer

(h) 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: The bin containing granular ammonium nitrate. The walls of the bin are made of a combustible material, and one side of the bin is opened to allow for loading and unloading.





Process parameters to consider: Temperature, Composition

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

Guideword + Parameter = Deviation	**Causes**	**Consequences**	**Safeguards**	**Recommendations**
More (Higher) Temperature				
Ammonium nitrate *as well as* Contaminants	Contamination by other fertilizers present near the bin containing AN			
	A fire in the vicinity that caused soot and ash to land on the AN			

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

(i) 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 CSB report, the explosion at West Fertilizer caused a catastrophic impact of 15 fatalities and more than 260 injuries

LOPA Study for West Fertilizer Fire and Explosion		
Initiating Event	Cause:	Fire in the West Fertilizer building
	Consequence:	Detonation and explosion of ammonium nitrate in the storage bins
	FOIE:	
IPL(s)	Description of IPL_1, IPL_2, ...	None
	$PFD = PFD_1 \times PFD_2 \times ...$	
MCF	MCF = FOIE x PFD	
	Category of MCF:	
Severity	Impact:	15 fatalities, more than 260 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 $P\text{-}IPL_1$, $P\text{-}IPL_2$, ...	
	$P\text{-}PFD = P\text{-}PFD_1 \times P\text{-}PFD_2 \times ...$	
MCF	MCF = FOIE x PFD x P-PFD	
	Category of MCF:	
Risk	Type of risk:	
	Acceptable / Unacceptable?	

(j) 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.

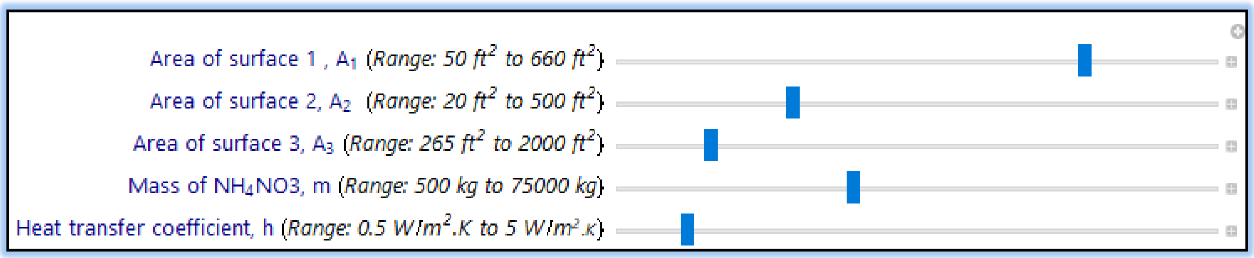


Fig. 2.4 Wolfram sliders

Wolfram graphs:

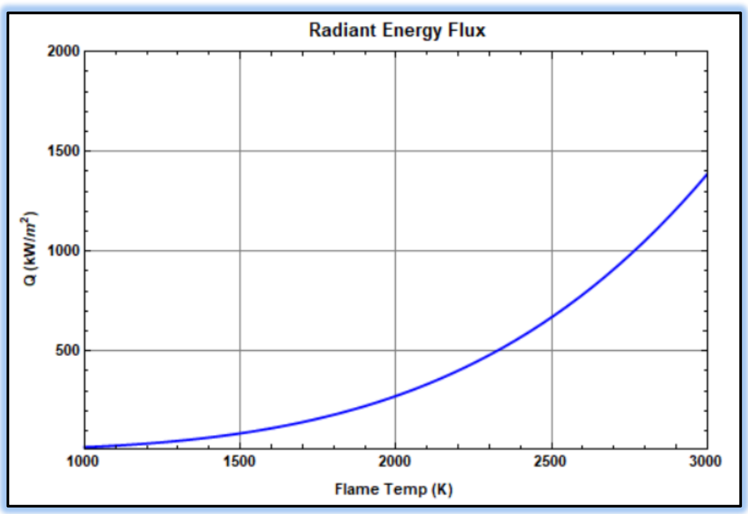


Fig. 2.5 Radiant energy flux vs. temperature

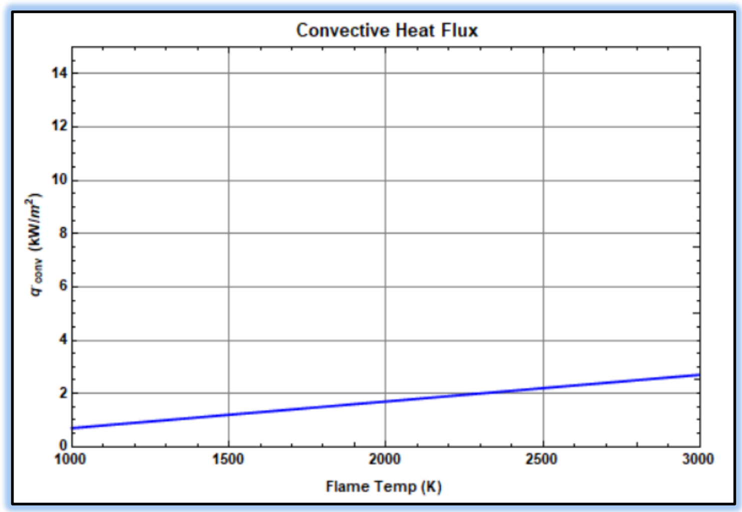


Fig. 2.6 Convective energy flux vs. flame temperature

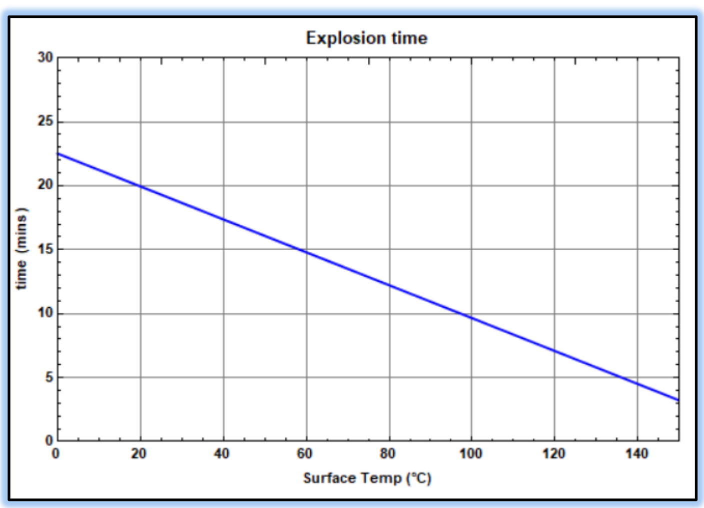


Fig. 2.7 Time to explode vs. surface temperature

Questions

(i) Vary the sliders for A_1, A_2, and A_3 (refer to additional information and Fig. 2.1 for the definitions and values of A_1, A_2 and A_3) and describe how the radiation flux changes. Consider the general case where A_1, A_2, and A_3 are all independent.

(ii) Determine the convective heat flux from the gas flame to the solid NH_4NO_3 from the Wolfram plot when the flame temperature is 2000 K . Vary the slider for heat transfer coefficient h and describe how q_{conv} changes.

(iii) Vary the slider for m (mass of NH_4NO_3) and describe how the time required to explode varies.

(iv) Write a set of conclusions from your experiments in (i), (ii) and (iii).

Table of Nomenclature:

Symbol	**Description**	**Unit**
m	Mass of NH_4NO_3	kg
C_p	Heat capacity	kJ/kg-K
q_{net}	Net heat flux	$kJ/m^2.s$
q	Rate of heat transfer	kJ/s
Q	Amount of energy	kJ
σ	Stephan Boltzmann Constant	$W/m^2.K^4$

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 to West Fertilizer Explosion and Fire

View Factor: View factor, F_{ij}, is the fraction of radiant energy emitted by surface *i* which is incident on surface *j*.

---

[i]In collaboration with K. S. Reshma, Indian Institute of Technology Bombay and Marina Miletic, Miletic Consulting.