Reaction Engineering and Design

Safety Module 2b: *Synthron Runaway Reaction*[1†]

Problem Statement:

On January 31, 2006, a vapor cloud explosion killed one worker and injured fourteen people at the Synthron, LLC facility in Morganton, NC. The explosion destroyed the facility and damaged buildings in the nearby community. Following investigation, the CSB issued a final report (found below) which explains how a runaway reaction caused the explosion[1].

The product that was being manufactured at the time of the incident was a liquid acrylic polymer industrially known as Modarez MFP-BH. In planning for the polymerization of the MFP-BH batch, managers at the facility made several changes in reaction conditions that increased the potential for a dangerous runaway reaction. The customer ordered 12% more MFP-BH than was polymerized in a standard reaction, and Synthron decided to scale up the recipe to produce a single batch rather than running two half-batches. This decision was made to save time and effort, but the changes in conditions increased the total amount of monomer in the reactor by 45%, increased the concentration of the monomer by 27%, and increased the atmospheric boiling point of the mixture of the mixture by almost 5°C. These changes were a result of modified solvent amounts, and they combined to increase the heat output from the reaction to at least 2.3 times greater than the standard recipe.

Although the chemists, manager, and superintendent on-site all reviewed the changes in solvent quantities and the potential changes in boiling point that would result, they did not recognize the impact that increased monomer could have on the reaction rate or total rate of heat release. This oversight proved deadly, as a runaway reaction occurred, which resulted in the vapor cloud release and eventual explosion.

Synthron Video: (*https://www.youtube.com/watch?v=sRuz9bzBrtY*) *Note:* Only 2:00-7:00 is relevant for this problem.

Synthron Incident Report: (*https://www.csb.gov/file.aspx?DocumentId=5619*)

Synthron polymer reaction

[1†] Adapted from the problem by Ronald Willey, Seminar on a Nitroaniline Reactor Rupture. Prepared for SAChE, Center for Chemical Process Safety, American Institute of Chemical Engineers, New York (1994). Also see Process Safety Progress, vol. 20, no. 2 (2001), pp. 123–129. The values of ΔH_{Rx} and UA were estimated from the plant data of the temperature–time trajectory in the article by G. C. Vincent, Loss Prevention, 5, 46–52.

[1] "The First Responder," Volume 12, Issue 1. Jan 31, 2008. <https://www.aristatek.com/Newsletter/JAN08/JAN08ts.aspx>

(a) It is important that chemical engineers understand what the accident was, why it happened and how it could have been prevented in order to 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 Synthron explosion and fill out the following Safety Algorithm for the incident. See definitions on the last page. If necessary, view the Synthron incident report.

Safety Analysis of Synthron Incident

Activity: ______________________________

____

Hazard: ______________________________

____

Incident: ______________________________

____

Initiating Event: ______________________________

____

Preventative Actions and Safeguards: ______________________________

____

Contingency Plan/ Mitigating Actions: ______________________________

____

Lessons Learned: ______________________________

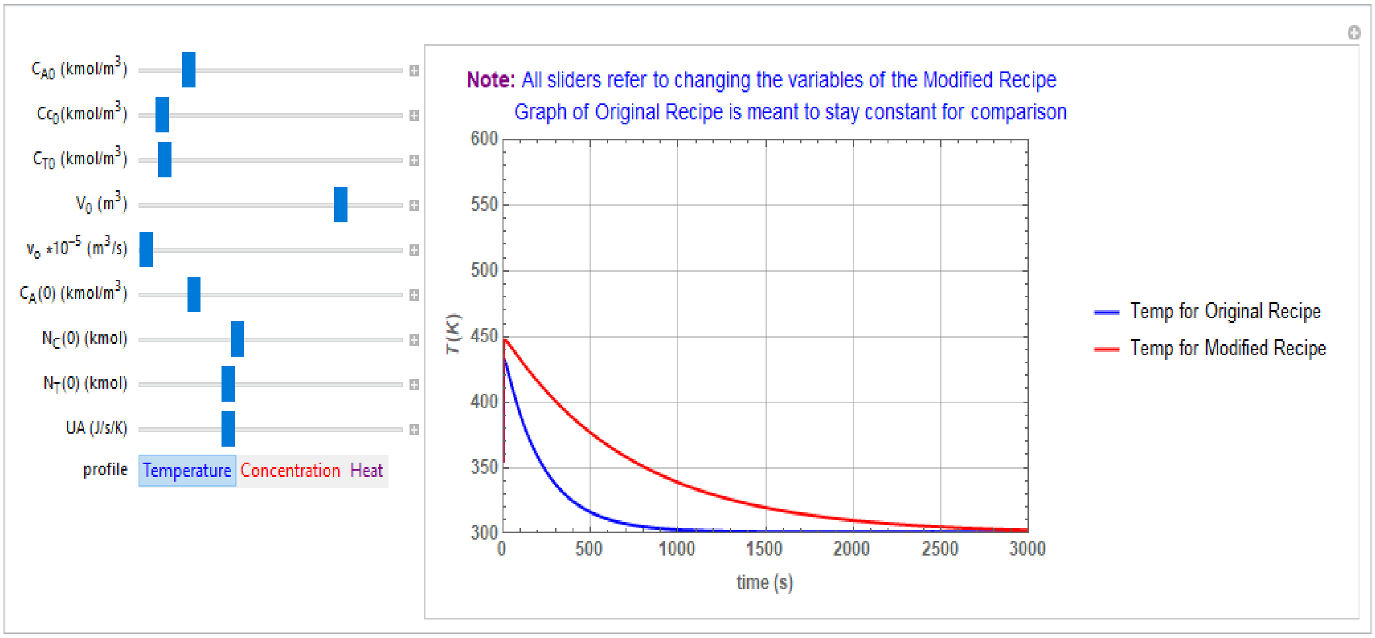
____

For parts (b) through (e), download the following files based off software preferences. Wolfram, Polymath, and MATLAB code can be found at the following link: *http://www.umich.edu/~elements/5e/13chap/live.html*

Note: Due to the complexity of the problem, it is advised to use Wolfram or MATLAB, so the proper graphs are already provided. If Polymath is your preferred method, please be sure to read the notes at the top of the file to avoid confusion.

For more information on the derivations, definitions, and calculations used in the plots for this incident, please review the Synthron Safety Module Case Study from the *Elements of Chemical Reaction Engineering* website here.

Sample temperature-time trajectory using Wolfram:



Note: All sliders refer to changing the variables of the Modified Recipe
Graph of Original Recipe is meant to stay constant for comparison

b.) Describe and discuss the original recipe temperature-time trajectory.

c.) What is the critical initial volume of reactants (V_o) above which the reactor will explode? For the sake of simplicity, assume the reactor will explode if the contents of the reactor remain above 350 K at 500 s after the start of the reaction, as the lack of cooling will result in an unsafe pressure increase.

d.) Vary two parameters of your choice that you think will have the most effect on the explosion and describe what you find.

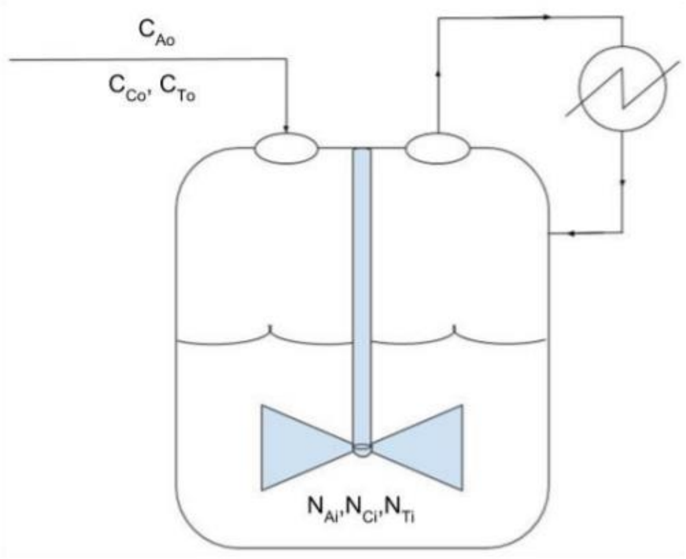
e.) Write a set of conclusions after completing the previous questions.

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 Synthron reaction incident.

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: The semi-batch reactor vessel and the heat exchanger used to cool the vapor that was allowed to leave the reactor.



Process Parameters to Consider: Temperature, Pressure, Level, Composition, Heat Exchanger Flow ______

(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**
________ Level	Charging more feed from the original recipe than usual			
Other Composition *Than* Usual	Changing usual feed recipe and/or feeding all at once rather than continuously			
________Temperature	1.High reaction rates due to high initial concentrations 2. Insufficient heat exchange due to fouling			
________Pressure				
Less (or *No*) Heat Exchanger Coolant Flow				

(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, explain why the situation is not hazardous, and describe another consequence that could occur. *HINT: Consider process efficiency*

(iii) 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 plant can only accept a moderate risk
- Assume that the reaction involved in this process is carried out 100 times per year
- Per the incident report, the explosion killed one worker, injured 14 more, and bankrupted the company

LOPA Study for Synthron Runaway Explosion		
Initiating Event	Cause:	Operator error (charging more feed than usual)
	Consequence:	Unexpected heat release leading to reaction runaway and dangerous pressure increase inside the reactor
	FOIE:	
IPL(s)	Description of IPL$_1$, IPL$_2$, ...	Pressure relief valve
	PFD = PFD$_1$ x PFD$_2$ x ...	
MCF	MCF = FOIE x PFD	
	Category of MCF:	
Severity	Impact:	Killed a worker and injured 14 more. Damages were severe enough to bankrupt the company
	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 this incident.

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.

---

[i] In collaboration with Zach Gdowski, University of Michigan