Loughborough University

23CGB001

Process Design and Safety

Semester 1 2023/24 In-Person Exam paper

This examination is to take place in-person at a central University venue under exam conditions. The standard length of time for this paper is **2 hours**.

You will not be able to leave the exam hall for the first 30 or final 15 minutes of your exam. Your invigilator will collect your exam paper when you have finished.

<u>Help during the exam</u>

Invigilators are not able to answer queries about the content of your exam paper. Instead, please make a note of your query in your answer script to be considered during the marking process.

If you feel unwell, please raise your hand so that an invigilator can assist you.

You may use a calculator for this exam. It must comply with the University's Calculator Policy for In-Person exams, in particular that it must not be able to transmit or receive information (e.g. mobile devices and smart watches are **not** allowed).

Answer **TWO** questions – **ONE** question from Section A and **ONE** question from Section B.

Each question carries 25 marks.

Candidates should show full working for calculations and derivations.

SECTION A: Attempt ONE question

1. The rupture of a process vessel caused the instantaneous release of 1000 kg of toxic phosgene gas at ground level, 1 km upwind of a local village. The release occurred during an overcast night with a windspeed of 2.5 m s^{-1} and ambient temperature of 0 C. N.B. Other relevant data and equations are provided on subsequent pages.

   (a) Describe, with the aid of a neat sketch, what atmospheric stability conditions you would expect and how these will affect the dispersion of this release. [4 marks]

   (b) The gas concentrations downwind of a release can be calculated using Gaussian dispersion models. Determine what type of release occurred and hence explain whether Equation Q1A or Q1B should be used to determine the phosgene concentration in the village. [2 marks]

   (c) Using Table Q1.1 and Figure Q1, determine the atmospheric stability class and the corresponding dispersion coefficients σ_x, σ_y and σ_z. [3 marks]

   (d) Calculate the maximum concentration of phosgene (in ppm) to arrive at the village, assuming that phosgene behaves as an ideal gas under these conditions. [6 marks]

   (e) Show that the phosgene concentration in the village will exceed a concentration of 1000 ppm for a duration of 35.0 s. [6 marks]

   (f) Using the concentrations and duration given above, determine the percentage of villagers expected to be killed as a result of this release. Comment on the accuracy of this approach. [4 marks]

   NOTE: The transformations of percentages to probits are given in Table Q1.2.

   <u>Relevant Data</u>

   Universal gas constant = 8.314 J K^{-1} mol^{-1}

   Molecular weight of phosgene = 98.92 g mol^{-1}

   Atmospheric pressure = 1.013×10^5 Pa

   Compressibility factor = 1

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Q1 Continued/…

Relevant Equations

$$C_{xyz} = \frac{\dot{m}}{2\pi\sigma_y\sigma_z u}\exp\left[-\frac{y^2}{2\sigma_y^2}\right]\left\{\exp\left[-\frac{(z-H_r)^2}{2\sigma_z^2}\right]+\exp\left[-\frac{(z+H_r)^2}{2\sigma_z^2}\right]\right\}$$ Equation Q1A

$$C_{x,y,z,t} = \frac{m}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z} exp\left[-\frac{(x-ut)^2}{2\sigma_x^2}\right]\times exp\left[-\frac{y^2}{2\sigma_y^2}\right]\left\{exp\left[-\frac{(z-H_r)^2}{2\sigma_z^2}\right]+exp\left[-\frac{(z+H_r)^2}{2\sigma_z^2}\right]\right\}$$ Equation Q1B

The probit equation for phosgene lethality is:

$$Y = -19.27 + 3.69 \ln\ Ct$$ Equation Q1C

Where C is concentration in ppmv and t is exposure time in minutes.

All other symbols have their usual meaning as defined in the course.

Table Q1.1: Pasquill stability classes

Surface wind speed m s^{-1}	Daytime insolation			Night conditions	
	Strong	Moderate	Slight	Cloudy	Clear
< 2	A	A – B	B	E	F
2 - 3	A – B	B	C	E	F
3 - 4	B	B – C	C	D	E
4 - 6	C	C – D	D	D	D
> 6	C	D	D	D	D

Table Q1.2: Probit table

%	0	1	2	3	4	5	6	7	8	9
0	-	2.67	2.95	3.12	3.25	3.36	3.45	3.52	3.59	3.66
10	3.72	3.77	3.82	3.87	3.92	3.96	4.01	4.05	4.08	4.12
20	4.16	4.19	4.23	4.26	4.29	4.33	4.36	4.39	4.42	4.45
30	4.48	4.50	4.53	4.56	4.59	4.61	4.64	4.67	4.69	4.72
40	4.75	4.77	4.80	4.82	4.85	4.87	4.90	4.92	4.95	4.97
50	5.00	5.03	5.05	5.08	5.10	5.13	5.15	5.18	5.20	5.23
60	5.25	5.28	5.31	5.33	5.36	5.39	5.41	5.44	5.47	5.50
70	5.52	5.55	5.58	5.61	5.64	5.67	5.71	5.74	5.77	5.81
80	5.84	5.88	5.92	5.95	5.99	6.04	6.08	6.13	6.18	6.23
90	6.28	6.34	6.41	6.48	6.55	6.64	6.75	6.88	7.05	7.33

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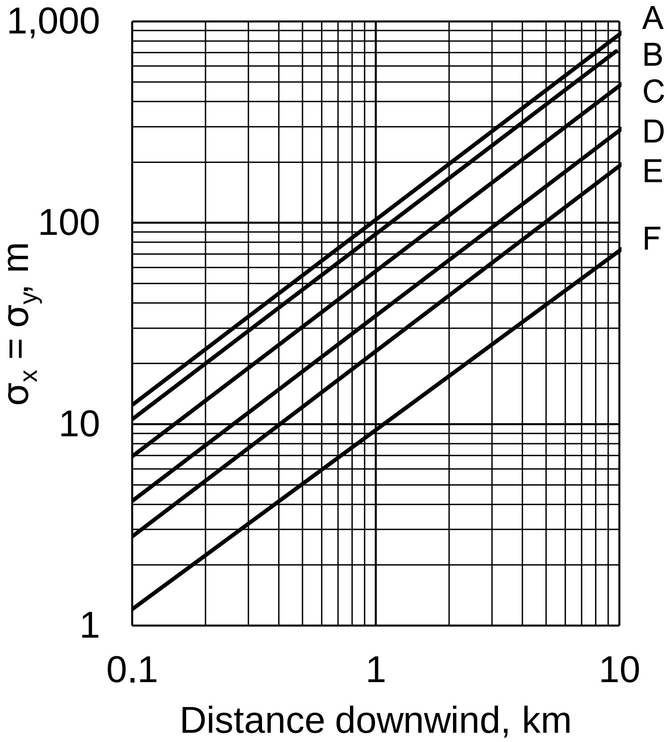
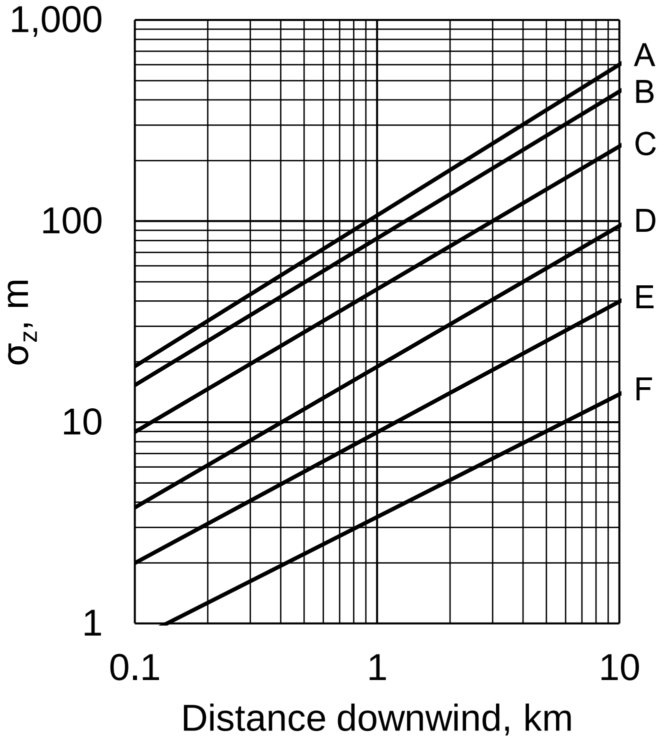
Q1 Continued/…



Pasquill stability class	σ_y (m) or σ_x (m)
A	$0.18x^{0.92}$
B	$0.14x^{0.92}$
C	$0.10x^{0.92}$
D	$0.06x^{0.92}$
E	$0.04x^{0.92}$
F	$0.02x^{0.89}$



Pasquill stability class	σ_z (m)
A	$0.60x^{0.75}$
B	$0.53x^{0.73}$
C	$0.34x^{0.71}$
D	$0.15x^{0.70}$
E	$0.10x^{0.65}$
F	$0.05x^{0.61}$

Figure Q1: Dispersion coefficients for Gaussian dispersion model

2. A 50 m^3 butane sphere is surrounded by a circular bund with a diameter of 8 m. The sphere fails catastrophically, resulting in the release of butane into the bund, which is accidently ignited and burns steadily at a rate of 0.074 kg m^{-2} s^{-1}. The wind speed is 5 m s^{-1}.

(a) Determine the duration of the fire. [3 marks]

(b) Using Equations Q2A and Q2B listed at the bottom of this question, show that the fire reaches flame lengths of 16.5 m and is tilted at an angle of 54.3° from the vertical. [5 marks]

(c) Calculate the total radiative flux from the flame and estimate the flame temperature, assuming that the proportion of heat radiated is 0.3 and that the fire behaves as a black body. [6 marks]

(d) Estimate the incident thermal radiation on a person (1.8 m tall), standing 20 m downwind of the bund wall. Clearly show all your workings, including any appropriate diagram(s). [8 marks]

(e) Using Figure Q2.1 and the provided property data for butane, discuss the potential harm arising from this fire on the person described in part (d). If you did not obtain a value from part (d), you may assume an incident thermal radiation of 15 kW m^{-2}. [3 marks]

<u>Relevant Equations</u>

$$\frac{F_L}{D_P} = 42\left(\frac{\dot{m}_A}{\rho_a (g D_P)^{0.5}}\right)^{0.61} \qquad \text{Equation Q2A}$$

$$\cos\theta = (u^*)^{-0.5} \text{ and } u^* = u\left(\frac{\rho_a}{g D_P \dot{m}}\right)^{\frac{1}{3}} \text{ (if } u^* > 1) \qquad \text{Equation Q2B}$$

<u>Relevant Data</u>

Density of liquid butane = 604 kg m^{-3}

Boiling point of butane = -0.5°C

Density of air at ambient temperature = 1.17 kg m^{-3}

Acceleration due to gravity = 9.81 m s^{-2}

Calorific value of butane = 49.7 MJ kg^{-1}

Stefan-Boltzmann constant = 5.7 x 10^{-8} W m^{-2} K^{-4}

Atmospheric transmissivity = 1

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Q2 Continued/…

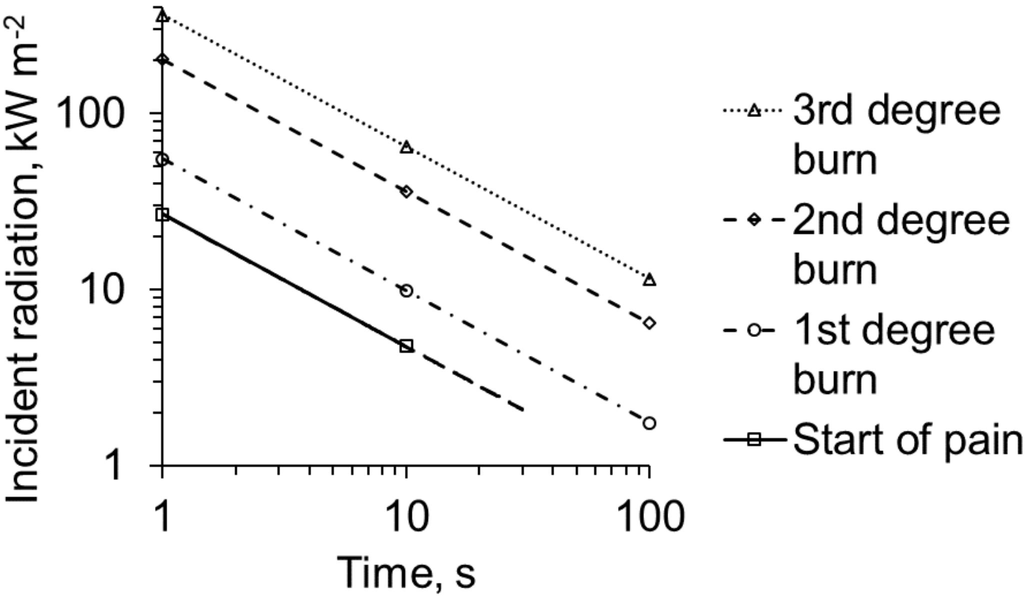

Figure Q2.1: Effect of heat on people

SECTION B: Attempt ONE question

3. LPG is supplied to the storage system represented in Figure Q2.1. In the event of failure of the level control system (Level Transmitter (LT), Level Controller (LC), and Control Valve (CV)), the level in the tank will rise until it is relieved to the flare header (assuming that the inflow exceeds the outflow). The flare header has not been designed to take cold LPG and there is a risk that it could block due to the presence of water. There is also the possibility that it could fail due to brittle fracture. Consequently, an independent High Level Alarm (HLA) is provided to warn the operator. Finally, a trip system is set to operate consisting of a separate High-High Level Switch (HHLS) and a Trip Valve (TV) as depicted in Figure Q3.1.

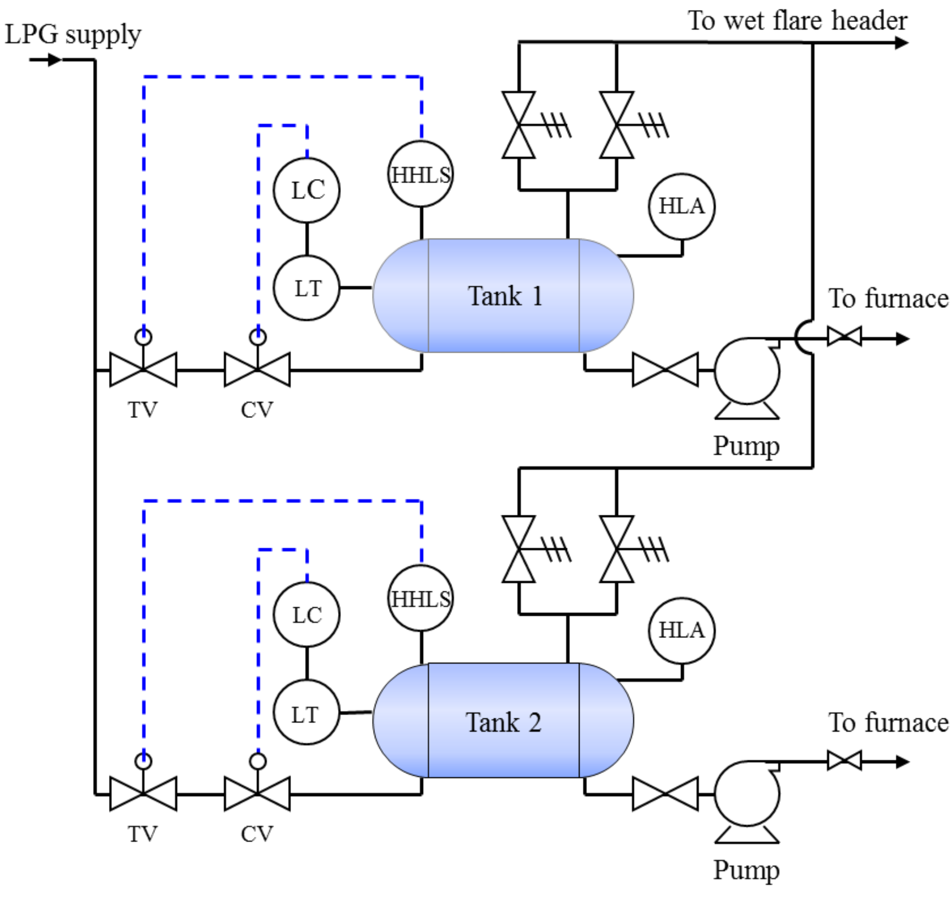

Figure Q3.1

(a) Develop a fault tree for the event **"**LPG enters header" (this may happen if either of the two tanks overflow). [10 marks]

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Q3 Continued/…

(b) Develop an Event Tree following entry of LPG into the header. [10 marks]

The hazard probability can be derived using the following data:

Probability that water will be present in the header	100%
Probability that the line will rupture	40%
Probability that the vapour cloud will ignite	25%
Probability that an employee will be in the area	100%
Probability that a fatality would result from fire/explosion	20%

(c) Assuming that the failure rate of the top event associated with the fault tree of part (a) is 0.005 occurrence per year, determine the fatal accident frequency. Consider that the risk of death to employees should not exceed 3×10^{-5} per year. Does the protective system meet the safety requirement? Justify your answer and provide recommendations. [5 marks]

4. (a) Successful risk reduction in the chemical process industries depends on considering safety during design and operation. Outline the concepts of inherent safety, its goals and the different design approaches that can be adopted to achieve these goals. [10 marks]

(b) A process plant has a twin-channel protective system. Each channel has an individual failure rate, λ, of 0.4 per year. A trip of either channel will return the plant to a safe condition. The time to test (and repair if necessary) each channel is 12 hours and there is a probability of 1 in 1000 that a testing error puts the channel out of service until the next test. The same test interval is used for each channel, but the tests are not performed simultaneously. Dependent failures may be neglected.

(i) Show that the optimum test interval to the nearest number of whole days is 10 days. [9 marks]

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Q4 Continued/…

(ii) Calculate the fractional dead time for the twin channel protection system for a test interval of 10 days. [4 marks]

(iii) Comment on the practicality of a test interval of 10 days and suggest a practical test interval time. [2 marks]

<u>Relevant Data</u>

The fractional dead time (fdt_{comb}) of a twin-channel system tested at the same time interval T, with a test/repair time of t_r is given by Equation Q4–1 below.

The fractional dead times $fdt_{1outof2}$ and $fdt_{1outof1}$ are given by Equations Q4–2 and Q4–3 respectively.

$$fdt_{comb} = \left(fdt_{1outof2}\right)\left(\frac{T-2t_r}{T}\right) + \left(fdt_{1outof1}\right)\left(\frac{2t_r}{T}\right)$$ Equation Q4–1

$$fdt_{1outof2} = \frac{(\lambda T)^2}{3} + 2\left(\frac{\lambda T}{2}\right)P_{TE}$$ Equation Q4–2

$$fdt_{1outof1} = \frac{\lambda T}{2} + P_{TE}$$ Equation Q4–3

END OF PAPER

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