

**24CGB001**  
Process Design and Safety

Semester 1 2024/25

In-Person Exam paper

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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.

Help during the exam

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 **THREE** questions in total. Answer **BOTH** questions in **SECTION A** and **ONE** question from **SECTION B**.

Candidates should show full working for calculations and derivations.

## SECTION A: Attempt BOTH questions

1. Explain the concept of inherent safety and provide one example for each of the four inherently safer design strategies. Discuss the best point in the design lifecycle at which inherently safer design should be considered. [10 marks]
2. LPG is pumped to a storage vessel from which it is supplied continuously to a process plant as shown in Figure Q2. The level control system in the storage vessel comprises a Level Transmitter (LT), a Level Controller (LC) and a Control Valve (CV). In the event of failure of the level control system, the inflow is assumed to always exceed the outflow, and hence the level of LPG in the storage vessel will rise. An independent high level protection system is provided, comprising a High Level Switch (HLS), a Solenoid Valve (SV) and a Trip Valve (TV). If the high level protection system fails, then the level will continue to rise until it is relieved to the LPG header. It can be assumed that the probability of the relief valve operating on demand is 1.
  - (a) Draw the fault tree. [10 marks]
  - (b) Determine the frequency at which LPG enters the header from the LPG storage vessel. The failure rates of the components in the level control and high level protection systems are provided below. [5 marks]

### Level Control System

Level Transmitter (LT)	0.25/year
Level Controller (LC)	0.1/year
Control Valve (CV)	0.2/year

### High Level Protection System

High Level Switch (HLS)	0.25/year
Solenoid Valve (SV)	0.15/year
Trip Valve (TV)	0.1/year

The high-level protection system is proof tested every 6 months.

Formula list :  $f dt = \frac{\lambda T}{2}$

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Q2 Continued/...

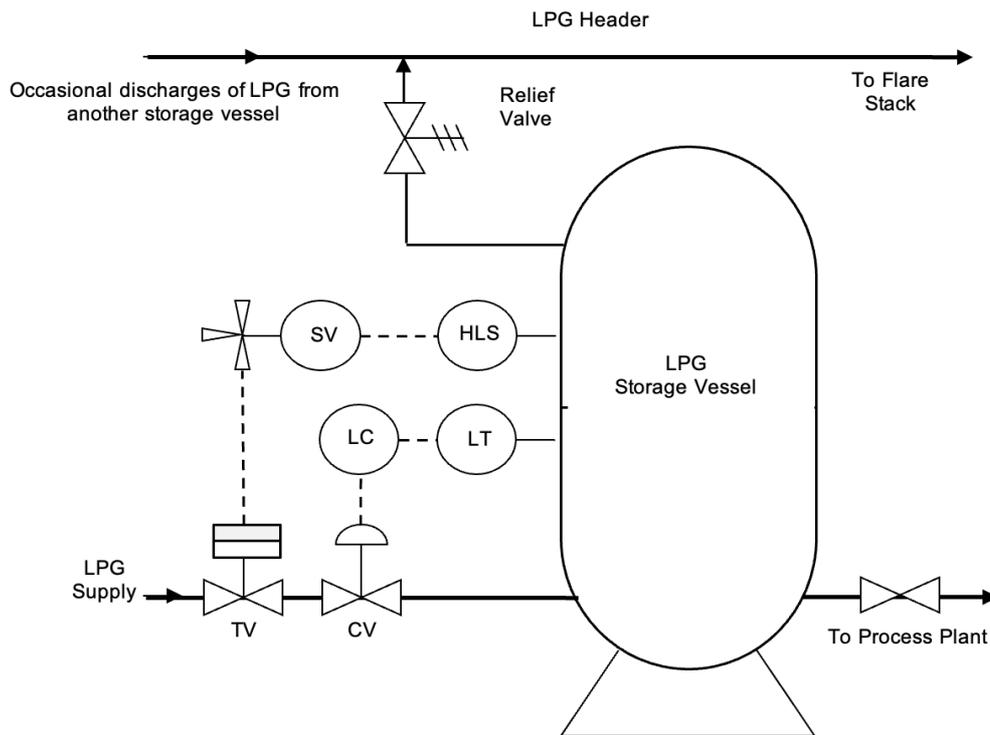


Figure Q2. P&ID of the LPG storage vessel

## SECTION B: Attempt ONE question

3. A spherical storage tank is used to store 50 tonnes of liquid butane above its ambient boiling point of  $-1^{\circ}\text{C}$ . A pool fire develops below the tank causing the temperature of the tank to increase. When the temperature inside the sphere reaches  $70^{\circ}\text{C}$ , the tank ruptures catastrophically, causing the explosive vaporization of the liquid butane and immediate combustion of the resulting flammable cloud (BLEVE).

The latent heat of vaporisation for butane is  $0.386 \text{ MJ kg}^{-1}$ , its heat of combustion is  $49.5 \text{ MJ kg}^{-1}$ , and its liquid heat capacity is  $2.278 \text{ kJ kg}^{-1} \text{ K}^{-1}$ .

- (a) Estimate the amount of butane that will be vaporised during the initial release. [3 marks]
- (b) Using Table Q3.1, determine the diameter, duration and height of the resulting fireball. [4 marks]
- (c) Assuming that 30% of the heat is emitted as radiation, estimate the maximum radiative heat release from the fireball. Treating the fireball as a black body, calculate the corresponding surface emissive power and flame temperature. [7 marks]
- (d) The storage sphere was located at a distance of 500 m from the control room. Assuming an atmospheric transmissivity of 0.7, estimate the maximum incident radiation at the control room. Calculate the resulting thermal dose and use Table Q3.2 to describe the expected impact on people. [6 marks]
- (e) Using Figure Q3.1, and assuming an explosion efficiency of 5%, estimate the expected overpressure at the control room building arising from this explosion. Discuss the expected impact from this explosion. [5 marks]

### Data

Stefan-Boltzmann constant,  $\sigma = 5.7 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$

Explosion energy of TNT,  $E_{TNT} = 4652 \text{ kJ kg}^{-1}$

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**Table Q3.1** Empirical factors for fireball sizing

Fuel	a	b	c	d
Hydrocarbons <sup>1</sup>	6.36	0.325	2.57	0.167
Hydrocarbons <sup>2</sup>	5.8	0.333	0.45	0.333
n-pentane	5.25	0.314	1.07	0.181
Propane	5.88	0.333	1.09	0.167
Butane	5.72	0.303	0.45	0.333
LPG	6.48	0.325	0.852	0.26

<sup>1</sup>Vapour cloud; <sup>2</sup>bursting of pressure vessel

**Table Q3.2** Thermal dose limits (kW<sup>1.33</sup> s m<sup>-2.66</sup>)

Start of pain	80
1 <sup>st</sup> degree burns	210
2 <sup>nd</sup> degree burns	1200
3 <sup>rd</sup> degree burns	2600

### Relevant equations

Diameter of fireball (m),  $D_{FB} = a \times m^b$

Duration of fireball (s),  $t_{FB} = c \times m^d$

Height of fireball (m),  $H_{FB} = 1.25D_{FB}$

Surface area of a sphere (Asp) =  $4\pi r^2$

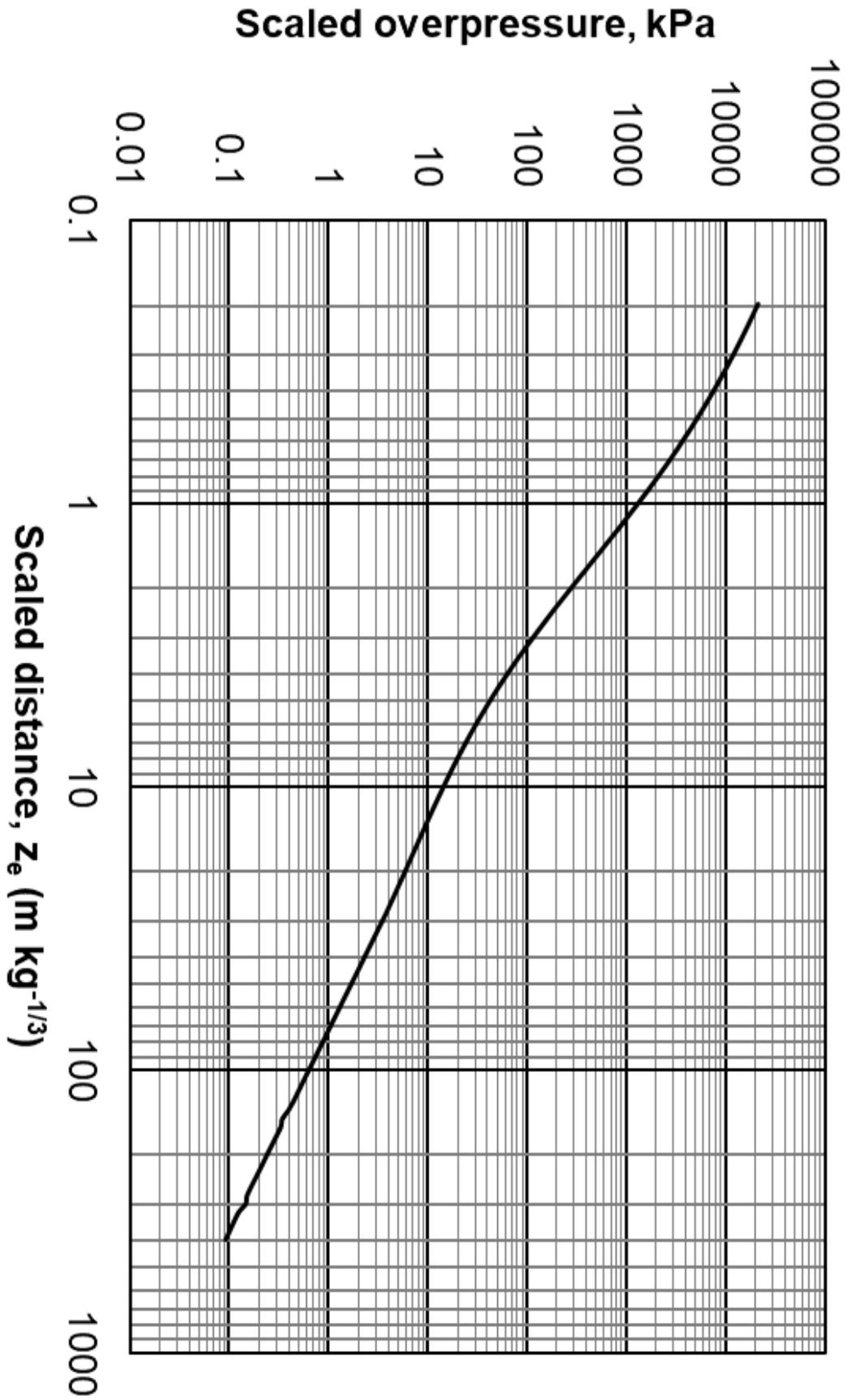
Equivalent mass of TNT (kg),  $m_{TNT} = \frac{\eta m \Delta H_C}{E_{TNT}}$

Scaled distance (m kg<sup>-1/3</sup>),  $z_e = \frac{r}{m_{TNT}^{1/3}}$

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Q3 Continued/...

Figure Q3.1 Peak overpressure vs scaled distance for explosion of TNT close to ground



4. A leak develops from the stem of a valve ( $d = 3 \text{ mm}$ ) on a liquid toluene line, operating at 7 barg, and located inside a laboratory building. The leak results in the formation of a liquid pool, which subsequently starts to evaporate.
- (a) Estimate the liquid leak rate from the valve. You may assume a radial gap width around the stem of the valve of 0.125 mm. The coefficient of discharge is unknown. [6 marks]
- (b) The leak is stopped after 15 minutes. Estimate the surface area of the pool, if the substrate material is concrete (typical pool depth of 5 mm). [3 marks]
- (c) Calculate the maximum rate of evaporation from the pool If the initial liquid temperature is  $25^\circ\text{C}$ . [4 marks]
- (d) The occupational exposure limit (OEL) for toluene is  $188 \text{ mg m}^{-3}$ . If the laboratory has a volume of  $500 \text{ m}^3$ , estimate the duration to reach this OEL. Clearly state your assumptions. [2 marks]
- (e) The toluene pool is ignited and burns at a constant burning rate,  $\dot{m}_A$ , of  $0.085 \text{ kg m}^{-2} \text{ s}^{-1}$  until the fuel has been fully consumed. Estimate the duration and height (flame length) of the fire. The temperature of ambient air inside the building is  $20^\circ\text{C}$ . [4 marks]
- (f) The combustion results in the formation of 0.2 g of carbon monoxide per g of fuel burnt. Estimate the volumetric concentration of carbon monoxide in the laboratory. [3 marks]
- (g) The carbon monoxide dose to loss of consciousness is 27,000 ppm minute. Using Haber's rule, determine the time to loss of consciousness. Comment on your results. [3 marks]

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#### Q4 Continued/...

##### Data

Density of liquid toluene,  $\rho_{\text{Toluene}} = 867 \text{ kg m}^{-3}$

Molecular weight of toluene,  $M_{\text{toluene}} = 91.1 \text{ g mol}^{-1}$

Molecular weight of water,  $M_{\text{water}} = 18 \text{ g mol}^{-1}$

Molecular weight of carbon monoxide,  $M_{\text{CO}} = 28 \text{ g mol}^{-1}$

Mass transfer coefficient of water,  $K_{\text{water}} = 0.83 \text{ cm s}^{-1}$

Universal gas constant,  $R = 8.314 \text{ J mol}^{-1} \text{ K}^{-1}$

Saturation pressure for toluene at 25°C,  $P^{\text{sat}} = 3.8 \text{ kPa}$

Density of ambient air,  $\rho_{\text{air}} = 1.2 \text{ kg m}^{-3}$

Acceleration due to gravity,  $g = 9.81 \text{ m s}^{-2}$

##### Relevant equations

Leak rate from liquid release ( $\text{kg s}^{-1}$ ),  $\dot{m} = C_d A \rho \sqrt{2 \left( \frac{P_1 - P_2}{\rho} + g h_L \right)}$

Initial rate of evaporation from a liquid pool ( $\text{kg s}^{-1}$ ),  $\dot{m} = \frac{MKAP^{\text{sat}}}{R_u T_L}$

Mass transfer coefficient ( $\text{cm s}^{-1}$ ),  $K = K_0 \left( \frac{M_0}{M} \right)^{1/3}$

Flame length of a pool fire,  $\frac{F_L}{D_P} = 42 \left( \frac{\dot{m}_A}{\rho_a (g D_P)^{0.5}} \right)^{0.61}$

Where  $\rho_a$  is density of ambient air,  $\text{kg m}^{-3}$

END OF PAPER

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