UNIVERSITI
TEKNOLOGI
PETRONAS

FINAL EXAMINATION
JANUARY 2025 SEMESTER

COURSE	**:**	**CCM5233 – QUANTITATIVE RISK ASSESSMENT**
DATE	**:**	**19 APRIL 2025 (SATURDAY)**
TIME	**:**	**2:30 PM – 5:30 PM (3 HOURS)**

INSTRUCTIONS TO CANDIDATES

1. This is an **OPEN BOOK** exam.
2. Answer **ALL** questions in the Answer Booklet.
3. Begin **EACH** answer on a new page in the Answer Booklet.
4. Indicate clearly answers that are cancelled, if any.
5. Where applicable, show clearly steps taken in arriving at the solutions and indicate **ALL** assumptions, if any.
6. **DO NOT** open this Question Booklet until instructed.

Note :

i. There are **TWELVE (12)** printed pages in this **double-sided** Question Booklet including the cover page and appendices.

1. A storage tank with height of 25 ft and diameter of 9 ft was used to store acetone liquid at 28 °C and 14.7 psi. The density of acetone liquid is 48.8 lb_m/ft^3. The initial acetone liquid level in the storage tank was 18 ft above the tank bottom. Unfortunately, there was a leak with diameter of 0.3 inch at 3 ft above the tank bottom. The acetone liquid began to be released through the leak on the tank. When an engineer detected the leak, the acetone liquid level was 11 ft above the tank bottom. State and justify appropriate assumption.

   a. Determine the instantaneous mass flowrate of the leak when the acetone liquid level in the storage tank was 18 ft above the tank bottom.

   [12 marks]

   b. Estimate the total time the leak was active.

   [14 marks]

2. A plant is storing ethane gas in a tank. Suddenly, 520 kg ethane is leaked from the tank and the ignition of the leaked ethane causes the occurrence of explosion with explosion efficiency of 2%. Unfortunately, there is a residential village which is located at 60 m away from the source of the explosion. In view of this, a safety officer is immediately tasked to carry out an investigation to evaluate the injury and/or death on the residents in the village due to the explosion. Predict the percentage of residents from the village that will experience eardrum ruptures due to the explosion. State and justify appropriate assumption.

[24 marks]

3. A chemical reactor (R1) is used in a continuous process where reactants are fed into the reactor, and the product is withdrawn at a controlled rate. The reactor is equipped with a level control system to prevent overflow as shown in **FIGURE Q3**. The flow control valve (FCV1) regulates the inlet flow, while the level indicating transmitter (LIT) and level indicating controller (LIC) monitor and control the liquid level inside the reactor. Additionally, an operator is assigned to oversee the process and take corrective actions if necessary. If the control system or operator fails, the reactor may overflow, leading to potential hazards. **TABLE Q3** provides failure probabilities of different system components. Develop a fault tree for the top event of "overflow in the reactor (R1)". Estimate the probability of fault tree by referring to relevant failure probabilities specified in the table. Propose suitable preventive measure(s) to reduce the top event probability and demonstrate the effectiveness of the solution. State **ALL** assumptions.

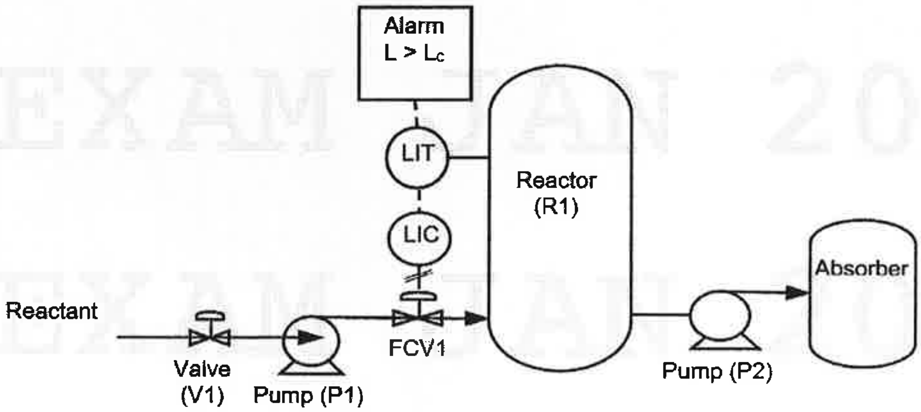

FIGURE Q3: A process at reactor R-1

TABLE Q3: Failure Probability Data

Component	Failure Probability
Pump (P1) stops	0.07
FCV1 fails	0.24
Temperature indicating controller (TIC) fails	0.10
Operator fails	0.31
Alarm fails	0.05

[26 marks]

4. A quantitative risk assessment (QRA) has been conducted at an ammonia storage facility to evaluate the potential consequences of a toxic ammonia leak. The study identifies that in the event of a storage tank failure or pipeline leak, ammonia gas could disperse over a large area, posing significant health and environmental risks. The assessment also reveals that current safety measures may be insufficient in mitigating toxic exposure effectively. Details of the QRA findings are given in **TABLE Q4a**. Based on the findings, various mitigation options have been proposed as shown in **TABLE Q4b**. By using suitable technique, identify the best option to reduce the risk. Discuss the importance of selecting suitable criteria and by giving appropriate example, elaborate how the criteria affecting decision making process in risk analysis.

TABLE Q4a: QRA finding on ammonia release

Projected fatalities	180	Expected cost/fatality	$500,000
Expected injuries	200	Cost/injury	$70,000

TABLE Q4b: Mitigation options for the reduction of ammonia release

Mitigation options	Unit	Estimated Cost/Unit	Toxic reduction
Installing a Scrubber System	1	$50,000	95%
Installing Gas Detection & Alarm System	5	$25,000	70%
Ammonia Absorption using Activated Carbon	2	$30,000	85%

[24 marks]

- END OF PAPER –

Appendix:

$$m_{TNT} = \frac{\eta m \Delta H_c}{E_{TNT}}$$

E_{TNT} = 4686 kJ/kg TNT

$$z_e = \frac{r}{m_{TNT}^{1/3}}$$

$$p_o = p_s \cdot p_a$$

$$Y = k_1 + k_2 lnV$$

Flow of liquid through a hole:

Velocity of fluid exiting the leak through a small hole:

$$\bar{u} = C_o \sqrt{\frac{2 g_c P_g}{\rho}}$$

The mass flow rate Q_m resulting from a hole of area A is given by:

$$Q_m = A\, C_o \sqrt{2 \rho g_c P_g}$$

Flow of liquid through a hole in a tank:

The instantaneous mass flow rate Q_m resulting from a hole of area A is given by:

$$Q_m = \rho C_o A \sqrt{2\left(\frac{g_c P_g}{\rho} + g h_L\right)}$$

The liquid level height in the tank is given by:

$$h_L = h_L^o - C_o\left(\frac{A}{A_t}\right)\sqrt{2\left(\frac{g_c P_g}{\rho} + g h_L^o\right)}\ t + \frac{g}{2}\left(C_o \frac{A}{A_t} t\right)^2$$

The time t_e for the vessel to empty to the level of the leak is given by the equation below:

$$t_e = \frac{1}{C_o g}\left(\frac{A_t}{A}\right)\left[\sqrt{2\left(\frac{g_c P_g}{\rho} + g h_L^o\right)} - \sqrt{\frac{2 g_c P_g}{\rho}}\right]$$

Flow of gas/vapour through a hole:

The maximum mass flow rate of any vapour/gas, $(Q_m)_{choked}$ at any point during the isentropic expansion:

The mass flow rate Q_m at any point during the isentropic expansion

$$Q_m = C_0 A P_0 \sqrt{\frac{2 g_c M}{R_g T_0}\frac{\gamma}{\gamma - 1}\left[\left(\frac{P}{P_0}\right)^{2/\gamma} - \left(\frac{P}{P_0}\right)^{(\gamma+1)/\gamma}\right]}$$

$$(Q_m)_{choked} = C_0 A P_0 \sqrt{\frac{\gamma g_c M}{R_g T_0}\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}}$$

$$\frac{P_{\text{choked}}}{P_0} = \left(\frac{2}{\gamma+1}\right)^{\gamma/(\gamma-1)}$$

g_c = gravitational constant = 32.174 ft-lb$_m$/(lb$_f$·sec^2)

g = local gravitational acceleration = 32.174 ft/sec^2

TABLE A1: Unit conversion

Quantity	Equivalent Values
Mass	1 kg = 1000 g = 0.001 metric ton = 2.20462 lb_m = 35.27392 oz 1 lb_m = 16 oz = 5×10^{-4} ton = 453.593 g = 0.453593 kg
Length	1 m = 100 cm = 1000 mm = 10^6 microns (μm) = 10^{10} angstroms (Å) = 39.37 in = 3.2808 ft = 1.0936 yd = 0.0006214 mile 1 ft = 12 in = 1/3 yd = 0.3048 m = 30.48 cm
Volume	1 m^3 = 1000 L = 10^6 cm^3 = 10^6 mL = 35.3145 ft^3 = 220.83 imperial gallons = 264.17 gal = 1056.68 qt 1 ft^3 = 1728 in^3 = 7.4805 gal = 0.028317 m^3 = 28.317 L = 28,317 cm^3
Force	1 N = 1 kg.m/s^2 = 10^5 dynes = 10^5 g.cm/s^2 = 0.22481 lb_f 1 lb_f = 32.174 lb_m.ft/s^2 = 4.4482 N = 4.4482 × 10^5 dynes
Pressure	1 atm = 1.01325×10^5 N/m^2 (Pa) = 101.325 kPa = 1.0325 bar = 1.01325 × 10^6 dynes/cm^2 = 760 mmHg at 0°C (torr) = 10.333 m H_2O at 4°C = 14.696 lb_f/in^2 (psi) = 33.9 ft H_2O at 4°C = 29.921 in Hg at 0°C
Energy	1 J = 1 N.m = 10^7 ergs = 10^7 dyne.cm = 2.778 × 10^{-7} kW.h = 0.23901 cal 0.7376 ft.lb_f = 9.486 × 10^{-4} Btu
Power	1 W = 1 J/s = 0.23901 cal/s = 0.7376 ft.lb_f/s = 9.486× 10^{-4} Btu/s = 1.341×10^{-3} hp

TABLE A2: Ideal gas constant R_g

1.9872 cal/gm-mole K
1.9872 Btu/lb-mole°R
8.3143 J/mol K
10.731 psia ft^3/lb-mole°R
8.3143 kPa m^3/kg-mole K = 8.314 J/gm-mole K
0.83143 bar m^3/kg-mole
82.057 cm^3 atm/gm-mole K = 8.2057×10^{-5} m^3 atm/mol K
0.082057 L atm/gm-mole K = 0.082057 m^3 atm/kg-mole K
21.9 (in Hg) ft^3/lb-mole°R
0.7302 ft^3 atm/lb-mole°R
1,545.3 ft lb_f/lb-mole°R
8.314×10^3 kg m^2/kg-mole s^2 K

TABLE A3: Heat of combustion for selected hydrocarbons

Compound	Formula	Heat of combustion (kJ/mol) Lower[a]	Upper[b]	Flammability limit[c] vol. % fuel in air LFL	UFL	Flash point temperature[d] °C	Autoignition temperature[d] °C
Paraffin hydrocarbons							
Methane	CH_4	−802.3	−890.3	5.0	15.0	−188	600
Ethane	C_2H_6	−1428.6	−1559.8	3.0	12.5	−135	515
Propane	C_3H_8	−2043.1	−2219.9	2.1	9.5	−104	450
Butane	C_4H_{10}	−2657.5	−2877.5	1.8	8.5	−60	405
Isobutane	C_4H_{10}	−2649.0	−2869.0	1.8	8.4	−83	460
Pentane	C_5H_{12}	−3245.0	−3536.6	1.4	7.8	−40	260
Isopentane	C_5H_{12}	−3240.3	−3527.6	1.4	7.6	−57	420
Neopentane	C_5H_{12}	−3250.4	−3514.1	1.4	7.5	−65	450
Hexane	C_6H_{14}	−3855.2	−4194.5	1.2	7.5	−23	234
Heptane	C_7H_{16}	−4464.9	−4780.6	1.0	7.0	−4	223
2,3-Dimethylpentane	C_7H_{16}	−4460.7	−4842.3	1.1	6.7	−15	337
Octane	C_8H_{18}	−5074.1	−5511.6	0.8	6.5	13	220
Nonane	C_9H_{20}	−5685.1	–	0.7	5.6	31	206
Decane	$C_{10}H_{22}$	−6294.2	−6737.0	0.8	5.4	46	208
Olefins							
Ethylene	C_2H_4	−1322.6	−1411.2	2.7	36.0	−136	450
Propylene	C_3H_6	−1925.7	−2057.3	2.0	11.0	−108	455
1-Butene	C_4H_8	−2541.2	−2716.8	1.6	9.3	−79	384
2-Butene	C_4H_8	−2534.4	−2708.2	1.8	9.7	−74	324
1-Pentene	C_5H_{10}	−3129.7	−3361.4	1.5	8.7	−18	273
Acetylenes							
Acetylene	C_2H_2	−1255.6	−1299.6	2.5	80.0	−18	305

TABLE A4: Heat capacity ratio (γ) for selected gases[a]

Gas	Chemical formula or symbol	Approximate molecular weight (*M*)	Heat capacity ratio $\gamma = C_p/C_v$
Acetylene	C_2H_2	26.0	1.30
Air	–	29.0	1.40
Ammonia	NH_3	17.0	1.32
Argon	Ar	39.9	1.67
Butane	C_4H_{10}	58.1	1.11
Carbon dioxide	CO_2	44.0	1.30
Carbon monoxide	CO	28.0	1.40
Chlorine	Cl_2	70.9	1.33
Ethane	C_2H_6	30.0	1.22
Ethylene	C_2H_4	28.0	1.22
Helium	He	4.0	1.66
Hydrogen	H_2	2.0	1.41
Hydrogen chloride	HCl	36.5	1.41
Hydrogen sulfide	H_2S	34.1	1.30
Methane	CH_4	16.0	1.32
Methyl chloride	CH_3Cl	50.5	1.20
Natural gas	–	19.5	1.27
Nitric oxide	NO	30.0	1.40
Nitrogen	N_2	28.0	1.41
Nitrous oxide	N_2O	44.0	1.31
Oxygen	O_2	32.0	1.40
Propane	C_3H_8	44.1	1.15
Propene (propylene)	C_3H_6	42.1	1.14
Sulfur dioxide	SO_2	64.1	1.26

[a]Crane Co., *Flow of Fluids Through Valves, Fittings, and Pipes*, Technical Paper 410 (New York: Crane Co., 2009), *www.flowoffluids.com*.

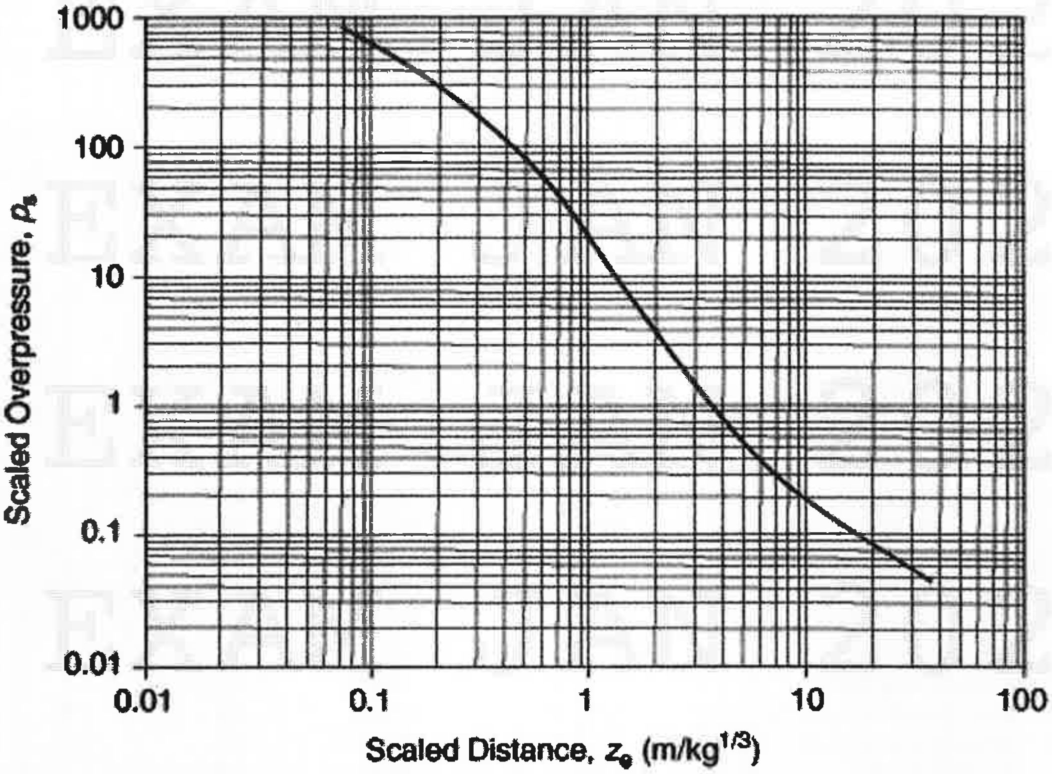

FIGURE A1: Correlation between scaled overpressure and scaled distance

TABLE A5: Transformation from percentages to Probits

%	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
%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
99	7.33	7.37	7.41	7.46	7.51	7.58	7.65	7.75	7.88	8.09

[a]D. J. Finney, *Probit Analysis* (Cambridge: Cambridge University Press, 1971), p. 25. Reprinted by permission.

TABLE A6: Probit correlations for a variety of exposures

Type of injury or damage	Causative variable	Probit parameters k_1	Probit parameters k_2
Fire[1]			
Burn deaths from flash fire	$t_e I_e^{4/3}/10^4$	−14.9	2.56
Burn deaths from pool burning	$t I^{4/3}/10^4$	−14.9	2.56
Explosion[1]			
Deaths from lung hemorrhage	p^o	−77.1	6.91
Eardrum ruptures	p^o	−15.6	1.93
Deaths from impact	J	−46.1	4.82
Injuries from impact	J	−39.1	4.45
Injuries from flying fragments	J	−27.1	4.26
Structural damage	p^o	−23.8	2.92
Glass breakage	p^o	−18.1	2.79
Toxic release[2]			
Ammonia deaths	$\Sigma C^{2.0}T$	−35.9	1.85
Carbon monoxide deaths	$\Sigma C^{1.0}T$	−37.98	3.7
Chlorine deaths	$\Sigma C^{2.0}T$	−8.29	0.92
Ethylene oxide deaths[3]	$\Sigma C^{1.0}T$	−6.19	1.0
Hydrogen chloride deaths	$\Sigma C^{1.0}T$	−16.85	2.0
Nitrogen dioxide deaths	$\Sigma C^{2.0}T$	−13.79	1.4
Phosgene deaths	$\Sigma C^{1.0}T$	−19.27	3.69
Propylene oxide deaths	$\Sigma C^{2.0}T$	−7.42	0.51
Sulfur dioxide deaths	$\Sigma C^{1.0}T$	−15.67	1.0
Toluene	$\Sigma C^{2.5}T$	−6.79	0.41

t_e = effective time duration (s)
I_e = effective radiation intensity (W/m^2)
t = time duration of pool burning (s)
I = radiation intensity from pool burning (W/m^2)
p^o = peak overpressure (N/m^2)
J = impulse (N s/m^2)
C = concentration (ppm)
T = time interval (min)

[1]Selected from Frank P. Lees, *Loss Prevention in the Process Industries* (London: Butterworths, 1986), p. 208.
[2]CCPS, *Guidelines for Consequence Analysis of Chemical Releases* (New York: American Institute of Chemical Engineers, 1999), p. 254.
[3]Richard W. Purgh, "Quantitative Evaluation of Inhalation Toxicity Hazards," in *Proceedings of the 29th Loss Prevention Symposium* (American Institute of Chemical Engineers, July 31, 1995).