Chapter 1

1-1. Essays will vary. Of course, process safety is an important part of an engineering ethics statement.

1-2.

a. This is a bit difficult to classify since it doesn't fit explicitly into the hierarchy. However, it does appear that safety is a core value for this company so it is likely a 5.
b. This is clearly reactive to accidents. It is at level 1.
c. This is a level 3 since it contains the JSA management system.
d. This is likely a level 0 since the faculty member does not participate in the safety program.
e. This is also likely a level 0. Even though the faculty member has made a verbal commitment to the safety program, the faculty member does not do anything.
f. This is at level 4 since the metrics are performance monitoring.
g. This is at level 2 since it is just complying to rules and regulations.
h. This is probably at level 0 since this is disdain for safety.
i. A messy lab or even plant area is a sure indicator of safety problems. If they are unable to keep the lab clean, how can they manage a safety program? This is likely an indication of a 0 on the hierarchy.

1-3.

a. This sends a strong message to the participants at the meeting that safety is NOT the most important thing. This greatly weakens safety culture.
b. If this policy is enacted, it is very likely that eventually no one will wear safety glasses in the lab. Why? Initially, the workers will wear the safety glasses, but over time a number of marginal situations will occur where they really should have worn them and no one alerted them to wear them. As time goes by this marginal boundary will move until eventually no one is wearing safety glasses. This will weaken safety culture over time. This is called normalization of deviations and occurs when people slowly move the acceptable boundary over time without consequence. Eventually the boundary moves far enough that a major incident occurs with major consequences.
c. A safety program and cleanliness go hand in hand. If the workers are not able to keep the laboratory clean, how can they manage a safety program? The faculty member is effectively stating that "No work is ever done in a safe lab!" This weakens the safety culture.
d. Responsibility for safety must be shared at all levels of administration, including the students, faculty member in charge and the university administration. This weakens the safety culture.
e. This strengthens the safety culture, since the plant manager is participating actively in the safety program.
f. Delay in reviewing and implementing safety suggestions sends the hidden message that "your opinions are not valued – we have other important things to do!" Eventually there will be no safety suggestions. This weakens the safety culture.
g. Safety equipment must be provided free of charge to the workers – this is actually an OSHA requirement! This also sends the message to the workers that safety is not important since the lab is not willing to pay the small price for the safety glasses. This weakens the safety culture.

h. The workers must have easy access to the safety equipment – if you make it difficult then the workers will not be inclined to use the safety equipment. This weakens the safety culture.
i. This weakens the safety culture - it sends the message that safety is not important since the lab safety manual is not important.
j. This strengthens the safety culture. The students are the ones that are directly exposed to the hazards in the lab – not the faculty member. So the students should have primary responsibility. The faculty member must insure that the safety program will work by providing the training, resources and management tools to make it work. The faculty member must also continuously audit the students to insure that it is working.

1-4.

a. The worker is the primary person at risk. This is individual risk and voluntary.
b. The primary risk population are the plant workers and the community adjacent to the storage facility. If the workers or the people immediately adjacent to the plant were aware of the plant hazards then the risk would be voluntary. Otherwise it is involuntary. It is likely that the plant workers are more voluntary and the community more involuntary. In both cases this is societal risk.
c. The primary risk population is the driver. For the driver this is individual risk and voluntary. The other drivers on the road are also a primary risk population. This is societal risk and involuntary.
d. In this case the driver is increasing his / her risk since they are not wearing their seat belt – the probability of an accident has not been changed for the driver or the other drivers on the road. The risk to the other drivers has not been changed. The increased risk by the driver is voluntary.
e. The primary risk population is the driver. For the driver this is individual risk and voluntary. The other drivers on the road are also a primary risk population. This is societal risk and involuntary.
f. The primary risk populations are the plane passengers and people injured or killed on the ground. This risk is societal and involuntary.
g. The primary risk populations are the driver, other drivers on the road, potentially people living near the highway, the workers / people at the gas station, and the workers at the refinery. The driver, refinery workers and gas station workers are voluntary risk. The other drivers on the road and the people living near the highway are societal risk and involuntary.
h. The people living near the pipeline are the primary risk community. This is societal and involuntary.
i. The person climbing is the primary risk community. The risk is individual and voluntary.

1-5.

The key to this problem is determining whether an accident has occurred or not. If an accident has occurred it is a lagging indicator. If an accident has not occurred it is leading.

a. This is leading since an accident has not occurred.
b. This is leading since an accident has not occurred.
c. This is lagging, since an insurance claim implies that an accident has already occurred.
d. This is lagging, since visits to a first aid facility implies that an accident has occurred.
e. This is leading since an accident has not occurred.
f. This is leading since an accident has not occurred.

1-6.

a. From Equation 1-2:

$$\text{Worker based fatal injury rate} = \frac{\text{Total number of fatalites during period}}{\text{Total number of employees}} \times 100,000 \text{ workers}$$
$$= \frac{1}{1,000 \text{ workers}} \times 100,000 \text{ workers}$$
$$= 100$$

b. From Equation 1-4:

$$\text{Hours based fatal injury rate} = \frac{\text{Total number of fatalites during period}}{\text{Total hours worked by all employees}} \times 200,000,000 \text{ hours}$$
$$= \frac{1 \text{ fatality}}{(1 \text{ yr})(1,000 \text{ employees})(50 \text{ weeks/yr})(40 \text{ hours/wk})} \times 200,000,000 \text{ hours}$$
$$= \frac{200,000,000 \text{ hours}}{(1 \text{ yr})(2,000,000 \text{ hours})}$$
$$= 100$$

c. From Equation 1-5 :

$$\text{Recordable incidence rate} = \frac{\text{Number of incidents during period}}{\text{Total hours worked by all employees}} \times 200,000 \text{ hours}$$
$$= \frac{1 \text{ recordable incident}}{(1 \text{ yr})(2,000,000 \text{ hours})} \times 200,000 \text{ hours}$$
$$= 0.1$$

d. The part b answer compares to a chemical manufacturing value of 2.0 and the answer for part c compares to a chemical manufacturing value of 2.1. The hours based fatal injury rate is very high and the recordable injury rate very low compared to chemical industry statistics.

e. Return to the equation used for part b. Substitute in the value or 2.0 for the hours based fatal injury rate and calculate the number of years.

$$2.0 = \frac{1 \text{ fatality}}{(1 \text{ yr})(1,000 \text{ employees})(50 \text{ weeks/yr})(40 \text{ hours/wk})} \times 200,000,000 \text{ hours}$$
$$2.0 = \frac{200,000,000 \text{ hours}}{(x \text{ yrs})(2,000,000 \text{ hours})}$$
$$x = 50 \text{ years}$$

f. Return to the equation used for part c. Substitute in the value or 2.1 for the total recordable incidence rate and calculate the number of years.

$$2.1 = \frac{\text{1 recordable incident}}{(x \text{ yrs})(2{,}000{,}000 \text{ hours})} \times 200{,}000 \text{ hours}$$

$$x = 0.048 \text{ years}$$

This is about 17.5 days.

1-7. The deaths per 100,000 people is given by the following equation provided in class:

$$\text{Deaths per 100,000 people} = \frac{\text{Total number of deaths}}{\text{Total people in exposed population}} \times 100{,}000 \text{ people}$$

Substituting the numbers,

$$\text{Deaths per 100,000 people} = \frac{\text{25 deaths}}{325{,}000{,}000 \text{ people}} \times 100{,}000 \text{ people}$$
$$= 0.0077$$

1-8. For the suggested consequence / severity level:

For human health impact, there were multiple fatalities, so this is "catastrophic."
For fire explosion direct cost, there was no explosion or fire, so this is not considered.
For chemical impact, the threshold quantity for MIC from Table 1-15 is 5 kg = 11 lb_m.
We do not know the exact amount of MIC released, but it is certainly greater than 20 times the TQ. Thus, this is "catastrophic."

From Table 1-14, the severity level is "catastrophic" and the safety severity level is 4..

For the likelihood, this is a bit more difficult. Considering that the safeguards were not functioning, the likelihood is somewhere between "likely" and "unlikely."

This results in a risk level of "A." This risk is "unacceptable" and additional safeguards must be implemented immediately. In this case, the existing safeguards should all be brought on-line immediately.

1-9.
a. Anhydrous ammonia: 10,000 lb_m
b. Chlorine: 1,500 lb_m
c. Hydrogen fluoride: 1,000 lb_m
d. Propylene oxide: not listed under this regulation – the regulation does not apply.

1-10. The key is to decide if the incident or consequences have already occurred. If it has, the safeguard is mitigative.
a. Mitigative – the incident has already occurred and the consequence is the loss of production.
b. Mitigative since the hydrocarbon has leaked.
c. Mitigative since the dike contains the spill.

d. Preventive – this prevents the reaction from running away.
e. Mitigative – the leak has already occurred.
f. Mitigative since the liquid has already escaped.
g. Mitigative – the consequence is that the reactor has lost contents.
h. Mitigative – the relief has already opened and discharged material.
i. Preventive – it controls the process within normal operating limits.
j. Mitigative – an incident has already occurred since it is an emergency.
k. Preventive – no consequence or incident has occurred yet.
l. Preventive – this provides more information to the operator to operate the process safely.
m. Mitigative – since the training is designed to mitigate incidents.

1-11. Will accept any one of the following answers:

a. Stakeholder outreach
b. Emergency management
c. Training and performance assurance, process knowledge management, process safety culture, process safety competency.
d. Process safety culture
e. Contractor management
f. Workforce involvement, process safety culture.
g. Incident investigation.
h. Safe work practices
i. Asset integrity and reliability
j. Auditing
k. Operating procedures
l. Management of change
m. Compliance with standards
n. Hazard identification and risk analysis.
o. Process knowledge management
p. Operational readiness
q. Process safety competency
r. Measurement and metrics
s. Management review and continuous improvement
t. Conduct of operations

1-12.

a. Substitute
b. Simplify
c. Moderate
d. Minimize
e. Substitute
f. Moderate or simplify

Problems and Solutions for Chapter 2

Problem 2-1

Using the data provided in Example 2-1, determine the a) mean, and variance, b) frequency as a function of the response, c) number affected as a function of the of the response, and d) show graphs for the frequency and number affected.

Solution 2-1

Note to instructor: A few of these problems are easy, but they give you an opportunity to have the students use the correct tools for making calculations. In this case we are using MathCad, but you can use whatever tool that you prefer.

a) Determine the mean and variance.

x is the response

$$x := \begin{pmatrix} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \end{pmatrix}$$

x =

	0
0	0
1	1
2	2
3	3
4	4
5	5
6	6
7	7
8	8
9	9
10	10

$x_1 = 1$

N is the nuimber with the specific response

$$N := \begin{pmatrix} 0 \\ 5 \\ 10 \\ 13 \\ 13 \\ 11 \\ 9 \\ 6 \\ 3 \\ 3 \\ 2 \end{pmatrix}$$

N =

	0
0	0
1	5
2	10
3	13
4	13
5	11
6	9
7	6
8	3
9	3
10	2

$N_1 = 5$

$$NN := \sum_{i=0}^{10} N_i \qquad NN = 75$$

μ is compuited using Eq. 2-2 and σ is the square root of Equation 2-3.

$$\mu := \frac{\sum_{i=0}^{10} \left(x_i \cdot N_i\right)}{75} \qquad \sigma := \sqrt{\frac{\sum_{i=0}^{10} \left[\left(x_i - \mu\right)^2 \cdot N_i\right]}{\sum_{i=0}^{10} N_i}}$$

$\mu = 4.507$ **μ is Mean** $\sigma = 2.235$

σ squared is the variance $\sigma^2 = 4.997$ **σ is the standard deviation**

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b) determine the frequency as a function of the response

$\mu := 4.51$ $\sigma := 2.24$

$$f(x) := \frac{1}{\left(\sigma \cdot \sqrt{2 \cdot \pi}\right)} e^{-\left(\frac{1}{2}\right)\left[\frac{(x-\mu)}{\sigma}\right]^2}$$

This is Equation 2-1

Where f(x) is the frequency as a function of response.

$N(x) := 75 \cdot f(x)$ Where N(x) is the number of people affected for the specific response..

x =	f(x) =	N(x) =
0	0.023	1.76
1	0.052	3.913
2	0.095	7.13
3	0.142	10.643
4	0.174	13.016
5	0.174	13.042
6	0.143	10.706

7	0.096	7.201
8	0.053	3.968
9	0.024	1.792
10	$8.837 \cdot 10^{-3}$	0.663

c) determine the number affected as a function of the of the response

$$Ntotal := \sum_{x=0}^{10} N(x) \qquad Ntotal = 73.833$$

$$NNormalized(x) := \frac{75 \cdot N(x)}{73.833}$$

$$NtotalNormalized := \sum_{x=0}^{10} NNormalized(x) \qquad NtotalNormalized = 75$$

$$Ftotal := \sum_{x=0}^{10} f(x) \qquad Ftotal = 0.984$$

$$fNormalized(x) := \frac{f(x)}{0.984} \qquad FtotalNormaized := \sum_{x=0}^{10} fNormalized(x)$$

$$FtotalNormaized = 1$$

$$FtotalNormal := \sum_{x=0}^{10} fNormalized(x)$$

NNormalized(x) =

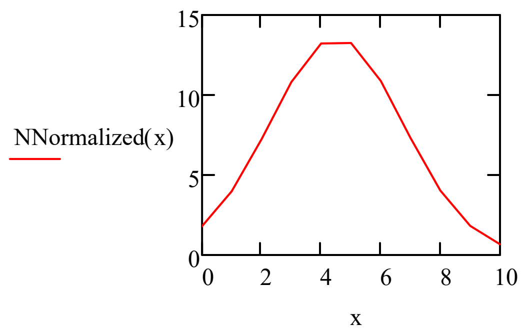
	0
0	1.788
1	3.975
2	7.242
3	10.811
4	13.221
5	13.248
6	10.876

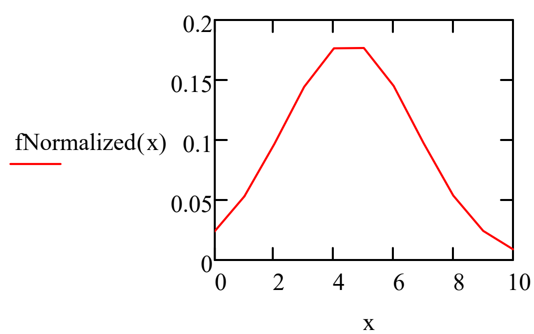
x is the response, and

NNormalized(x) is the number affected as a function of x.

7	7.315
8	4.031
9	1.82
10	0.673

d) show graphs for the frequency and number affected as a function of response.





End of Problem 2-1.

Problem 2-2

Using the data provided in Example 2-1, and a) determine the accumulated frequency between minus infinity and infinity (using Equation 2-1), b) between the mean and infinity (using Equation 2-10, c) between the mean plus the two standard deviations and infinity (Equation 2-1), and d) state your conclusions.

Solution 2-2

a) Determine the accumulated frequency between minus infinity and infinity

$\mu := 4.51$ $\sigma := 2.24$

$$f(x) := \frac{1}{\left(\sigma\cdot\sqrt{2\cdot\pi}\right)} e^{-\left(\frac{1}{2}\right)\left[\frac{(x-\mu)}{\sigma}\right]^2}$$ This is Equation 2-1

$$Freq := \int_{-\infty}^{\infty} f(x)\,dx$$

$Freq = 1$ **Answer to (a) is 1**

$$Freq := \int_{4.51}^{\infty} f(x)\,dx$$

$Freq = 0.5$ **Answer to (b) is 0.5**

$$Freq := \int_{\mu+2\cdot\sigma}^{\infty} f(x)\,dx$$

$Freq = 0.023$ **Answer to (c) is 0.023**

d) State your conclusions. Answer - the results are perfect, indicating the calculations are being done correctly. As proven in statistics courses, 95 % of the results are between the mean and plus or minus 2 standard devialtions. In this case the total frequence is 2 x 0.023 or 4.6 % that is rounded to 5 %.

End of Problem 2-2.

Problem 2-3

Using Equation 2-6 determine the probability for probits of 4.39, 5.25, and 6.23.

Solution 2-3

$Y := 6.23$

$$P := 50\cdot\left[1 + \left[\frac{(Y-5)}{\left|Y-5\right|}\right]\cdot\mathrm{erf}\left(\frac{\left|Y-5\right|}{\sqrt{2}}\right)\right]$$ This is Equation 2-6

$P = 89.065$

Looking at the details as shown below:

$$ErrorF1 := erf\left(\frac{|Y - 5|}{\sqrt{2}}\right)$$

$$ErrorF1 = 0.781$$

$$P1 := 50 \cdot \left[1 + \left[\frac{(Y - 5)}{|Y - 5|}\right] \cdot ErrorF1\right]$$

$$P1 = 89.065$$

If your computing program does not have an error function, then go down the following path:

$$x := \frac{|Y - 5|}{\sqrt{2}}$$

$$x = 0.87$$

$$ErrorF2 := \frac{2}{\sqrt{\pi}} \cdot \left(\int_0^x e^{-t^2} dt\right)$$

$$ErrorF2 = 0.781$$

$$P2 := 50 \cdot \left[1 + \left[\frac{(Y - 5)}{|Y - 5|}\right] \cdot ErrorF2\right]$$

$P2 = 89.065$ $Y = 6.23$ $P = 89.065$ $P1 = 89.065$ $P2 = 89.065$

Results

Probit	P	P1	P2	Table 2-4 Prob.
4.39	27.09	27.09	27.09	27.0
5.25	59.87	59.87	59,87	60.0
6.23	89.07	89.07	89.07	89.0

End of Problem 2-3

Problem 2-4. A blast produces a peak overpressure of 47,000 N/m^2. What fraction of structures will be damaged by exposure to this overpressure? What fraction of people exposed will die as a result of lung hemorrhage? What fraction will have eardrums ruptured? What conclusions about the effects of this blast can be drawn? Repeat this problem with 30,000, 80,000, and 100,000 N/m^2.

Solution.

Note to professor: Problems like this emphasizes the importance of engineers using the appropriate calculation tools.

$Po := 100000$ k1 and k2 are from Table 2-5, and the probit Equation is 2-5

$YS := -23.8 + 2.92 \cdot \ln(Po)$

$YS = 9.818$

$YL := -77.1 + 6.91 \cdot \ln(Po)$

$YL = 2.454$

$YE := -15.6 + 1.93 \cdot \ln(Po)$

$YE = 6.62$

$Y := YS$

$$P := 50 \cdot \left[1 + \left[\frac{(Y-5)}{|Y-5|}\right] \cdot \mathrm{erf}\left(\frac{|Y-5|}{\sqrt{2}}\right)\right]$$ This is Equation 2-6

$P = 100$

$Y := YL$

$$P := 50 \cdot \left[1 + \left[\frac{(Y-5)}{|Y-5|}\right] \cdot \mathrm{erf}\left(\frac{|Y-5|}{\sqrt{2}}\right)\right]$$

$P = 0.545$

$Y := YE$

$$P := 50 \cdot \left[1 + \left[\frac{(Y-5)}{|Y-5|}\right] \cdot \mathrm{erf}\left(\frac{|Y-5|}{\sqrt{2}}\right)\right]$$

$P = 94.738$

Results Probabilities

Overpressure N/m2	Structural	Deaths due to Lung Hemorage	Ear Drum Ruptures
a) 30,000	90.3	0	24.1

b) 47,000	99.9	0	56.5
c) 80,000	100	0	88.3
d) 100,000	100	1.0	94.7

Summary: In all cases the structural damage is significant. Clearly with this amount of distruction everyone in the facility will be affected, and probabily killed..

End of Problem 2-4

Problem 2-5. A volatile substance evaporates from an open container into a room of volume 28.3 m^3. The evaporation rate is 100 mg/min. If the air in the room is assumed to be well mixed, how many m^3/min of fresh air must be supplied to ensure that the concentration of the volatile is maintained below its TLV is 100 ppm? The temperature is 25 deg. C, and the pressure is 1 atm. The volatile molecular weight of 100. Under most circumstances the air in a room cannot be assumed to be well mixed. How would poor mixing affect the quantity of air required?

Solution for 2-5.

Given that in the room d(VC)/dt = Qm-Qv x C and at steady state Qm = Qv x C.

Rearange Eq. 2-7 and knowing Cppm = 100 ppm, P is 1 atm and T is 25 deg C:

$Cppm := 100 \qquad M := 100 \qquad T := 25 + 273 \qquad P := 1$

$T = 298$

$$C := Cppm\cdot\left(\frac{P\cdot M}{T}\right)\cdot\left(\frac{1}{0.08205}\right)$$ This is Equation 2-7

$C = 408.983$ Where C is mg/cu m

Knowing Qm = 100 mg/min, therefore:

$Qm := 100$

$$Qv := \frac{Qm}{C}$$

$Qv = 0.245$ Where Qv is in cu m/min

Clearly, poor mixing would give higher concentrations than the 409 mg/cu m.or 100 ppm. So one should factor in a margin of safety, by increasing the ventilation rate.

End of Problem 2-5.

Problem 2-6.

If 500 workers in a plant are exposed to the following concentrations of ammonia for the given number of hours, how many deaths will be expected?
a to d) 1000 ppm for 1 hr., 2000 ppm for 2 hr., 300 ppm for 3 hr., and 150 ppm for 2 hr.
Repeat this problem with the concentrations given in a., but assume the times are 2, 4, 6, and 2 hours.

Solution 2-6.

Use the data given in Table 2-5:

a to d) Solution

$$Suma := 1000^2 \cdot 60 + 2000^2 \cdot 120 + 300^2 \cdot 180 + 150^2 \cdot 120$$

$$Suma = 5.589 \times 10^8$$

$$Y := -35.9 + 1.85 \cdot \ln(Suma)$$ This is Equation 2--5

$$Y = 1.362$$

$$P := 50 \cdot \left[1 + \left[\frac{(Y-5)}{|Y-5|}\right] \cdot \operatorname{erf}\left(\frac{|Y-5|}{\sqrt{2}}\right)\right]$$ This is Equation 2-6

$P = 0.014$ $\quad$ $Fatalities := 500 \cdot P$ $\quad$ $Fatalities = 6.862$

Repeat with this listed above:

$$Suma := 1000^2 \cdot 120 + 2000^2 \cdot 240 + 300^2 \cdot 360 + 150^2 \cdot 120$$

$$Suma = 1.115 \times 10^9$$

$$Y := -35.9 + 1.85 \cdot \ln(Suma)$$

$$Y = 2.64$$

$$P := 50 \cdot \left[1 + \left[\frac{(Y-5)}{|Y-5|}\right] \cdot \text{erf}\left(\frac{|Y-5|}{\sqrt{2}}\right)\right]$$

$P = 0.913$ $\quad$ $\text{Fatalities} := 500 \cdot P$ $\quad$ $\text{Fatalities} = 456.367$

End of Problem 2-6.

Problem 2-7. Use OSHA data for TLVs and convert TLV in ppm to mg/ m^3 for benzene, chlorine, cyclohexanol, and ethylene oxide. Assume a temp of 25 deg. C and pressure of 1 atm.

Solution 2-7.

Notice:
a) TLVs are on the following site: OSHA Annotated Table Z-1,
https://www.osha.gov/dsg/annotated-pels/tablez-1.html
b) Molecular are computed or found on a Google site; e.g.
Wikepedia..

			Computed below
Chemical	MW	TLV (ppm)	TLV (mg/cu m)
Benzene	78.11	0.5	1.6
Chlorine	70.90	0.5	1.45
Cyclohexanol	100.16	50	204.8
Ethylene oxide	44.05	1	1.80

Rearange Eq. 2-7, and insert the data as shown above.

$T := 25 + 273$ $\quad$ $P := 1$

$Cppm := 0.5$ $\quad$ $M := 78.11$

$$C := Cppm \cdot \left(\frac{P \cdot M}{T}\right) \cdot \left(\frac{1}{0.08205}\right)$$ This is Equation 2-7

$C = 1.597$ mg/cu m

$Cppm := 0.5$ $\quad$ $M := 70.9$

$$C := Cppm \cdot \left(\frac{P \cdot M}{T}\right) \cdot \left(\frac{1}{0.08205}\right)$$

$C = 1.45$ mg/cu m

$Cppm := 50$ $\quad$ $M := 100.16$