NPRE 457
Safety Analysis of Nuclear Reactor Systems
Fall 2017

<table>
<tr><th>Number</th><th>Date Assigned</th><th>Due Date</th><th>Description</th></tr>
<tr><td>1</td><td>8/28</td><td>9/6</td><td>Consider a design goal of 10^{-7} [LOCAs / (reactor.year)] for the failure likelihood of a Loss Of Coolant Accident (LOCA) in the next generation of nuclear power plants.
Calculate the yearly frequency of a LOCA occurrence for:
a. 100 reactors in service in the USA,
b. 400 reactors operational globally.</td></tr>
<tr><td>2</td><td>8/30</td><td>9/6</td><td>a) Briefly describe the difference in terminology between the natural events:
1. Hurricanes,
2. Typhoons,
3. Cyclones.
b) Identify the 10 most devastating known natural disasters in terms of human casualties and order them in a descending order.</td></tr>
<tr><td>3</td><td>9/1</td><td>9/8</td><td>1. The difference between two Richter scale magnitudes is given by:
$$\Delta M = \log_{10}\frac{M_2}{M_1}$$
Estimate the ratio of the actual magnitude (9.0M) to the design-basis magnitude (8.6M) for the Fukushima March 11, 2011 earthquake.
2. The relationship between the intensity (E) and magnitude (M) scales can be expressed as:
$$\frac{E_2}{E_1} = 10^{1.5(M_2 - M_1)}$$
Estimate the ratio of the actual intensity to the design-basis intensity for the Fukushima March 11, 2011 earthquake.</td></tr>
<tr><td>4</td><td>9/6</td><td>9/13</td><td>List the names of the known scales used to describe the severity of natural disasters.

Describe the difference in the wind speeds and the effects on human structures between a category IV and a category V hurricane on the Saffir- Simpson scale.

Estimate the risk to individuals in the USA population from the different types of traffic accidents shown in the table.
Use the appropriate units.
<table>
<tr><th>Consequences</th><th>Number/year</th><th>Risk</th></tr>
<tr><td>Fatalities in traffic crashes</td><td>41,059</td><td></td></tr>
<tr><td>Injuries in traffic crashes</td><td>2,491,000</td><td></td></tr>
<tr><td>Alcohol related deaths</td><td>12,998</td><td></td></tr>
<tr><td>Speeding related deaths</td><td>13,040</td><td></td></tr>
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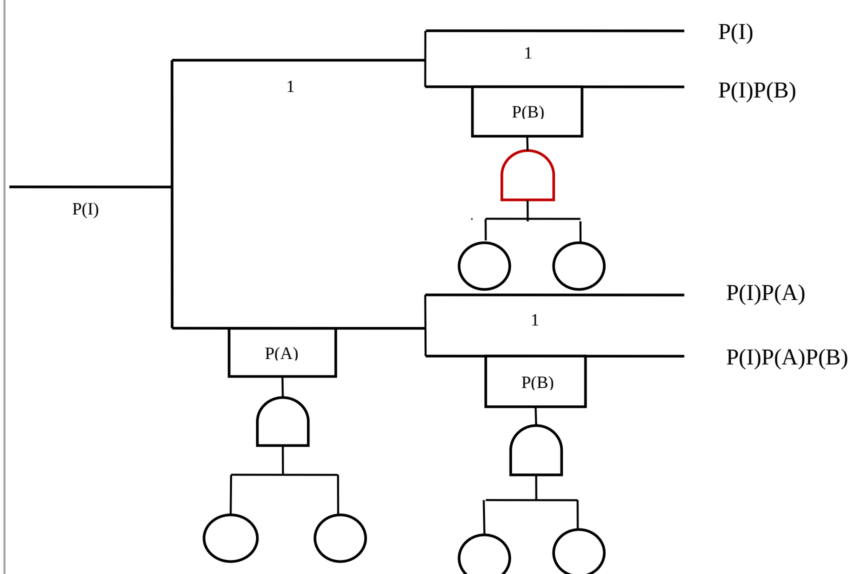
</td></tr>
</table>

5	9/8	9/15	List the initiating events usually leading to the occurrence of man-made accidents. Identify and classify the initiating events resulting in the following accidents: 1. Space orbiter Challenger, 2. Space orbiter Columbia. 3. Titanic sinking, 4. Bhopal chemical plant, 5. Hindenburg dirigible, 6. Macombo oil well blowout, 7. Texas City oil refinery fire, 8. Exxon Valdez tanker oil spill, 9. Costia Concordia cruise ship sinking, 10. Chicago fire.
6	9/11	9/11	Plot (using a plotting routine, e. g. Excel) the discrete probability distributions representing the following random variables: 1. Flipping a coin, 2. Throwing a 6-faced die, 3. Throwing a hypothetical 8-faced die. Identify the probable outcomes and their associated probabilities and the associated units, if any. Consider a hypothetical single die with 7 faces instead of 6. 1. What is the random variable describing the probable outcomes from throwing the die and their associated probability distribution? 2. Calculate its mean value, or mathematical expectation, or first moment. 3. Calculate its second moment. 4. Calculate its variance. 5. Calculate the standard deviation.
7	9/13	9/20	Consider a component that fails at a constant rate λ and its probability density function: (pdf): $\lambda e^{-\lambda t}$. 1. Prove that the pdf satisfies the normalization condition. 2. Calculate the mean time to failure: $\bar{t} = \frac{\int_0^\infty t.\lambda e^{-\lambda t} dt}{\int_0^\infty \lambda e^{-\lambda t} dt}$. If the fuzzy variable Y = “tolerable” is represented by the discrete membership function: $\mu_Y = \begin{pmatrix} 1.0 & 1.0 & 1.0 \\ 0 & 5 & 10 \end{pmatrix}$, Calculate the performance level of the security: g = X *is* Y = Failure rate *is* tolerable, for the following discrete probability density functions representing X = “failure rate” : a) $p_{X1} = \begin{pmatrix} 0.1 & 0.8 & 0.1 \\ 0 & 5 & 10 \end{pmatrix}$

			b) $p_{X2} = \begin{pmatrix} 0.2 & 0.6 & 0.2 \\ 5 & 10 & 15 \end{pmatrix}$ c) $p_{X3} = \begin{pmatrix} 0.3 & 0.4 & 0.3 \\ 10 & 15 & 20 \end{pmatrix}$ Plot the discrete functions and discuss the obtained results for the security performance levels.
8	9/15	9/22	Prove that the power law for the energy release in an earthquake: $P(E)dE = \frac{E_0}{E^2} dE,\ \ E \geq E_0\,,$ is a probability density function. Briefly explain: 1. Black Swan event, 2. Critical states, 3. Fingers of instability, 4. Minsky moment. *Self-Organized Criticality Experiment:* A home experiment is proposed by Per Bak, Chao Tang and Kurt Wiesenfeld, to test the concepts of self-organized critical equilibrium. One uses a shoe box and a cup or two of sand, sugar, salt or rice or wheat kernels. The experimenter would wet the sand with a small amount of water, then gather it into the steepest slope in one corner of the shoe box. The threshold slope or angle of repose is larger for wet sand than it is for dry sand. As the water is allowed to evaporate, one would observe a sequence of slides, some very small, and some quite large occurring at random positions in the pile. The evaporation process can be accelerated by placing the shoe box on a warm surface or in direct sunlight, preferably at the beach. Dropping individual or collections of grains of sand or kernels of wheat can also precipitate local avalanches. Describe your setup of the experiment and your observations and relate them to the described theory. Include a photograph of the setup if possible.
9	9/18	9/25	An insurance company requires a 20 percent overhead on the premiums it collects from its customers. If the payment to a beneficiary is $100,000 and it collects $1,200 per year in premiums, what is the probability of death in the year that the insurance company used to calculate the collected premium? Compare the result to the case of breakeven for the actuarial risk. In terms of perceived risk versus objective risk assessment, estimate the distance travelled by a car at a speed of 65 miles / hour during the 4.6 seconds taken by a texting event.
10	9/20	9/27	$Radon^{222}$ as a daughter in the decay chain of uranium is gaseous at room temperature. It is an inert or noble gas that does not interact chemically in the body. However it decays into Pb^{210} which attaches itself to vegetation such as tobacco leaves as a solid and subsequently decays into Po^{210} which emits an energetic alpha particle with 5.3 MeV of energy. The inhalation of these two isotopes in the particulate matter of cigarettes smoke delivers to the average smoker a radiation dose equivalent or effective dose of 8 rems (radiation equivalent man) per year to the basal cells of the bronchial tissue. The “cancer dose” is the total radiation dose that if spread through a population would cause one additional cancer death and is considered to be approximately 2,000 rems. Calculate the ensuing radiological risk in units of cancer deaths per year in a population of one million smokers.
11	9/22	9/29	For the Emergency Core Cooling System (ECCS) for a Pressurized Water Reactor (PWR) system the annualized cost of the Engineered Safety Feature (ESF) is: $C = 1.5 \times 10^6$ [$/year] The existing risk from n identified accident sequences is:

			$$\sum_{i=1}^{n} \mathrm{f_i R_i} = 1.0\times10^{5}[\text{person.rem/year}]$$ The risk from m accident sequences after implementation of the ESF is: $$\sum_{i=1}^{m} \mathrm{f_i^{'} R_i^{'}} = 3.0\times10^{4}[\text{person-rem/year}]\,]$$ Estimate the cost-benefit ratio, clearly showing its units.
12	9/25	10/2	Calculate the likelihood risk indices for: a) Obtaining a value of “heads” in the flip of a coin. b) Obtaining a value of “six” in the throw of a single die. c) Playing Russian Roulette with a six-shooter handgun.
13	9/27	10/4	1. List the four conditions for the existence of “Risk.” 2. Consider a component that fails at a constant rate λ and its probability density function: (pdf):): $\lambda e^{-\lambda t}$. a) Derive the expression for the cumulative distribution function (cdf). b) Derive the expression for the complementary cumulative distribution function (ccdf) or risk profile, or Farmer’s curve. c) Plot the pdf, cdf and ccdf. using $\lambda = 2$.
14	9/29	10/4	Construct the truth tables for the two binary and the one unary operations of the Boolean Algebra: $B\{[0,1], \wedge, \vee, \bar{\ }, 0, 1\}$ where: $\wedge$ means the lesser of, $\vee$ means the greater of, $\bar{\ }$ means the opposite of. Use Venn diagrams to prove the L10 de Morgan law or axiom of a Boolean Algebra.
15	10/2	10/4	Graph then construct a table of combinations for the gating network given by the Boolean expression: (X1+X2).X3 Use Zadeh diagrams and membership functions to prove the L10 de Morgan law or axiom of a de Morgan or Fuzzy Algebra.
16	10/6	10/13	Use Kosko's interpretation of fuzzy sets as points on the unit interval, unit square, unit cube and unit hypercube to graphically show: 1. On the unit interval, the point A:{1/3}, A^c, A OR A^c, A AND A^c. 2. In the unit square, the fuzzy set A:{2/3,1/4}, A^c, A OR A^c, A AND A^c. 3. In the unit cube, the fuzzy set, A:{1/4,1/2,2/3}, A^c, A OR A^c, A AND A^c. 4. For the case of the four dimensional hypercube set, A:{1/3, 1/4, 1/2, 3/4}, calculate A^c, A OR A^c, A AND A^c.
17	10/9	10 16	For the cases of n=2 and n=3 prove that the summation and the product formulae for the probability of the union of n events are equivalent. Use Venn diagrams to prove the formulae for n = 2 and n =3.
18	10/11	10/18	For the Fault Tree for the control rod or latch mechanism of a control rod, consider the following failure probabilities: $P(A)=P(B)=P(C)=P(D)=P(E)=10^{-3}$ calculate the error in the estimate of the probability of failure of the top event generated by the use of the small probabilities approximation. Recalculate the error for the following failure probabilities:

			P(A)=P(B)=P(C)=P(D)=P(E)=0.1 Discuss the results.
19	10/13	10/20	Consider the Boolean expression for a Fault Tree: T=A+(B.C.D)+(E.F.G) 1. Graphically construct the corresponding Fault Tree. 2. Analytically deduce the expression for the “operational” tree as the complement of the Fault Tree, and show it graphically. 2. Calculate the probability of failure for the top event for probabilities of failures of the basic events equal to 10^{-2}. 3. Show how you can reduce the top event failure probability by modifying the design. Show your suggestion graphically and write its Boolean expression. 4. Compare the failure probability of the modified design to that of the original one. 5. Calculate the possibility of failure for the top event for the following possibilities of failures of the basic events: $\Pi(A)=10^{-2}$, $\Pi(B)=\Pi(C)=\Pi(D)=\Pi(E)=\Pi(F)=\Pi(G)=10^{-3}$.
20	10/16	10/23	An initiating event for an accident occurs with a probability $P(I)=10^{-3}$. To mitigate that type of accident the system was designed with three Engineered Safety Features (ESFs). The probabilities of failure of these ESFs are: $P(A) = 10^{-2}$, $P(B) = 10^{-3}$, and $P(C) = 10^{-4}$. a. Construct the event tree that describes this system. b. Using the small probabilities approximation, calculate the probabilities of failure for each of the different accident sequences in the Event Tree. c. If we consider that we have a possibilistic rather than a probabilistic Event Tree, calculate the possibilities for the different accident sequences for: $\pi(I)=10^{-3}, \pi(A)=10^{-2}, \pi(B)=10^{-3}, \pi(C)=10^{-4}$.
21	10/18	10/25	 1. In the shown coupled event and fault tree, if the probabilities of failure of the basic events are all equal to 10^{-3}, and the probability of the initiating event is 10^{-4}, calculate the probabilities of the different accident sequences. 2. If one uses the same values as possibilities of failure, estimate the possibilities of the different accident sequences. Consider the Boolean expression that represents a Fault Tree: $$T = A+(B.C.D)+(E.F)$$ 1. Derive the expression for the Operational Tree as the complement: T’. 2. Graph the Fault Tree.

<table>
<tr><td></td><td></td><td></td><td>3. Graph the Operational Tree.
4. Calculate the probability of the top event T in the Fault Tree, using the small probabilities approximation, given the following probabilities:
$P(A)=P(B)=P(C)=P(D)=P(E)=P(F)=10^{-3}.$
5. Calculate the possibility of the top event T in the Fault Tree, given the following possibilities:
$\Pi(A)=10^{-3},\Pi(B)=10^{-3},\Pi(C)=10^{-4},\Pi(D)=10^{-5},\Pi(E)=10^{-4},\Pi(F)=10^{-3}.$</td></tr>
<tr><td>22</td><td>10/20</td><td>10/27</td><td>1. Use a plotting routine (e. g. Excel) to display the decay curves $N(t)/N_0$ of the following long lived fission products of safety concern:
1. Sr^{90}
2. Cs^{137}
Describe their safety concerns.
2. Write the formula for the effective half-life in terms of the biological and the physical half-lives.</td></tr>
<tr><td>23</td><td>10/23</td><td>10/30</td><td>The soil to plant transfer ratio for Cs^{137} for tropical fruit grown on the Bikini Atoll in the Marshall Islands ranges between 2 to 40. For crops grown on USA continental soils this factor ranges between the much smaller values of 0.005 to 0.5.
1. Calculate the specific activity of Cs^{137} in a contaminated soil in [Bq/gm] if the percentage weight of the isotope in the soil is 0.01 percent.
2. Calculate the corresponding ranges of the specific activities of Cs^{137} of plants grown in contaminated tropical and continental soils in Bq/gm.</td></tr>
<tr><td>24</td><td>10/25</td><td>11/1</td><td>1. Identify the health physics concerns from the following fission products that could potentially be released in a nuclear reactor accident:
<table>
<tr><th>Isotope</th><th>Half life</th><th>Health Concern</th></tr>
<tr><td>Sr^{90}</td><td>28 a</td><td></td></tr>
<tr><td>Cs^{137}</td><td>33 a</td><td></td></tr>
<tr><td>I^{131}</td><td>8 d</td><td></td></tr>
<tr><td>Kr^{87}</td><td>78 m</td><td></td></tr>
</table>
2. Calculate the effective half-lives in terms of the physical and biological half-lives of the following fission products of safety concern:
a. Sr^{90}
b. Cs^{137}
c. I^{131}
d. T^3</td></tr>
<tr><td>25</td><td>10/27</td><td>11/3</td><td>A nuclear power reactor is operated according to the following power history:
1. Operation at a power level of 3,000 MWth for 1 year, followed by,
2. Operation at a power level of 1,500 MWth, for 6 months, followed by a scram (shut-down).
Using the analytical formulae derived in the class, or the Systems Analysis Handbook graphs, determine the decay heat power:
1. Six minutes after shutdown,
2. One day after shutdown,
3. One month after shutdown.
Hint: The decay heat generation adds up for different operational periods.</td></tr>
<tr><td>26</td><td>10/30</td><td>11/3</td><td>The relation for the decay heat power versus time P(t) from the fission products assuming an infinite irradiation period is given in the reference: “Decay Heat Power in Light Water Reactors,” ANSI/ANS-5.1, published by the American Nuclear Society (ANS) as:
$$\frac{P(t)}{P_0}=A.t^{-a}$$
where t is the time after shutdown in seconds., and:</td></tr>
</table>

			$A = 0.0603$, $a = 0.0639$ for $0<t<10$ s $A = 0.0766$, $a = 0.1810$ for $10<t<150$ s $A = 0.1300$, $a = 0.2830$ for $150<t<4\times10^6$ s. 1. Derive an expression for the total energy release between the times t_1 and t_2. 2. For a power reactor producing P_0 = 3,000 MWth, calculate the total energy release from the decay heat within 1 day after shutdown in MegaJoules (MJs).
27	11/1	11/3	From Euler's equation: $dp = -\rho V dV$ Derive the expression for Bernoulli's law suggesting that the sum of the static and kinetic pressures is a constant between two points at steady-state in an inviscid flow without body forces. A wind rotor airfoil is placed in the air flow at sea level conditions with a free stream speed of 10 m/s. The density at standard sea level conditions is 1.23 kg/m^3 and the pressure is 1.01 x 10^5 Newtons / m^2. At a point along the rotor airfoil the pressure is 0.90 x 10^5 Newtons / m^2. By applying Bernoulli's equation estimate the wind speed at this point.
28	11/6	11/13	

Assignments Policy

Assignments will be turned in at the beginning of the class period, one week from the day they are assigned.
The first five minutes of the class period will be devoted for turning in, and returning graded assignments.
Late assignments will be assigned only a partial grade. Please try to submit them on time since once the assignments are graded and returned to the class, late assignments cannot be accepted any more.
If you are having difficulties with an assignment, you are encouraged to seek help from the teaching assistants (TAs) during their office hours. Questions may be emailed to TA's, but face-to-face interaction is more beneficial.
Although you are encouraged to consult with each other if you are having difficulties, you are kindly expected to submit work that shows your individual effort. Please do not submit a copy of another person's work as your own. Copies of other people's assignments are not conducive to learning, and are unacceptable.
For further information, please read the detailed assignments guidelines.