NPRE 457
Safety Analysis of Nuclear Reactor Systems
Fall 2024

1. Please read the assigned-reading lecture-notes chapters.
2. Then answer the corresponding written assignment,
3. For questions about the assignments, please access the teaching assistants by email:
https://www.mragheb.com/NPRE%20402%20ME%20405%20Nuclear%20Power%20Engineering/talist.htm
4. Submit the corresponding written assignment through email to https://canvas.illinois.edu
5. Please use either the Word or pdf formats
6. In case of internet "rationing" (e. g. to health and government authorities), instability, or collapse through overload, please read the lecture notes and submit the corresponding assignments. Already-taken tests and submitted assignments would be used in assessing the final grade.

Threat of Nuclear War:
https://www.youtube.com/watch?v=HSC7Lp1nvx8
https://www.youtube.com/watch?v=M7hOpT0lPGI

Regrettably, some 3,278 colleges and universities across the USA have been impacted by the Covid-19 pandemic, with many temporarily closing their campuses and switching to online classes, affecting more than 22 million students.
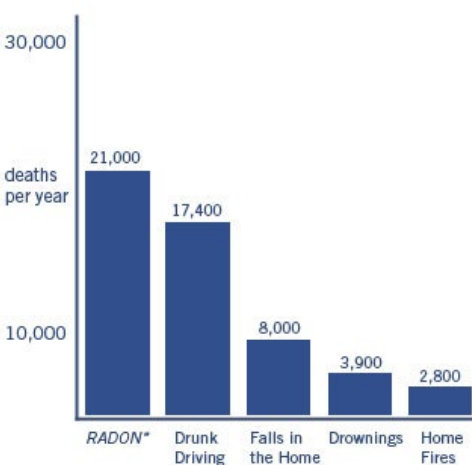
To all and everyone we wish good health and well-being.

Number	Date Assigned	Due Date	Description
1	8/26	8/2	**Reading assignment** **Preface** **Written Assignment** Generate the corresponding fraction of land area required to provide for the energy needs in the USA using different energy options. Hint: The USA existing power flux is 0.4 Watts / m^2 _(see table below)_
2	8/28	8/4	**Reading assignment** **1. Overview** **Written Assignment** For a rare failure event in chemical reaction vessels with a design failure likelihood of 10^{-4} failures / (vessel.year), calculate the frequency of occurrence for: a. 100 vessels in service, b. 1,000 vessels in service.

Energy option	Power flux [Watts / m^2]	Fraction of Land area needed
Energy crops, biomass, plants	0.5	
Wind power	2.5	
Solar Photo Voltaic panels, (PV)	5.0-20.0	
Concentrated thermal solar power, deserts	15.0-20.0	
Nuclear electricity	1,000.0	

			For a Loss Of Coolant Accident (LOCA) likelihood of 10^{-5} [occurrences / (reactor.year)], calculate the frequency of occurrence for: a. 97 reactors in service in the USA, b. 448 reactors globally.

3	8/30	8/6	**Reading Assignment**
			2. Natural Disasters and Man Made Accidents
			Written Assignment
			Estimate the risk to individuals in the USA population of 345 million persons from the different types of traffic accidents shown in the table. Use the appropriate units.
			
			Identify the 10 most devastating known natural disasters in terms of human casualties and order them in a descending order.
			
			Briefly describe the differences between the natural events:
			   1. Hurricanes,
			   2. Typhoons,
			   3. Cyclones.

4	9/4	9/11	**Reading Assignment** **2. Natural Disasters and Man Made Accidents** **Written Assignment** The difference between two Richter Scale magnitude measurements 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.
5	9/6	9/13	**Reading assignment** **2. Natural Disasters and Man Made Accidents** **Written Assignment** List the names of the scales used to describe the expected damage from the following natural hazards: 1. Astral impacts, 2. Earthquakes, 3. Hurricanes, 4. Tornadoes. For each scale, list the description of the expected maximum damage level.

Table (within row 3):

Consequences	fatalities / year	Risk
Fatalities in traffic crashes	41,059	
Injuries in traffic crashes	2,491,000	
Alcohol related deaths	12,998	
Speeding related deaths	13,040	

6	9/9	9/16	**Reading assignment** **2. Natural Disasters and Man Made Accidents** **Written Assignment** Identify any: 1. Design flaws, 2. Equipment failures, 3. Human errors, 4. Natural Events. In the following accidents: 1. Challenger space shuttle accident, 2. Columbia space shuttle accident.
7	9/11	9/18	**Reading Assignment** **3. Safety Definitions and Terminology** **Written Assignment** If the fuzzy variable Y = "tolerable" is represented by the discrete membership function: $$\mu_Y = \begin{bmatrix} 1.0 & 1.0 & 1.0 & 0.0 & 0.0 \\ 0 & 5 & 10 & 15 & 20 \end{bmatrix}$$ Calculate the performance levels of the information granule: g = X *is* Y = "Failure rate" *is* "tolerable", for the following discrete probability density functions representing X = "failure rate" : a) $p_{X1} = \begin{bmatrix} 0.1 & 0.8 & 0.1 & 0.0 & 0.0 \\ 0 & 5 & 10 & 15 & 20 \end{bmatrix}$ b) $p_{X2} = \begin{bmatrix} 0.0 & 0.2 & 0.6 & 0.2 & 0.0 \\ 0 & 5 & 10 & 15 & 20 \end{bmatrix}$ c) $p_{X3} = \begin{bmatrix} 0.0 & 0.0 & 0.3 & 0.4 & 0.3 \\ 0 & 5 & 10 & 15 & 20 \end{bmatrix}$ Plot the discrete functions and discuss the obtained results for the security performance levels.
8	9/13	9/20	**Reading Assignment** **3. Safety Definitions and Terminology** **Written Assignment** Define: "Information granule" Define: "Performance Level" Write the discrete and continuous forms of the mathematical expressions of the performance level.
9	9/16	9/23	**Reading Assignment** **4. Accidents Occurrence** **Written Assignment** Identify on a diagram the different modes of stability. 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 (pdf). Hints: Apply the normalization condition for a pdf.

			An earthquake by definition must have a minimum energy release E_0. Carry out the shoe box experiment suggested by Per Bak, Chao Tang and Kurt Wiesenfeld, to test the concepts of self-organized critical equilibrium. Describe your observations.
10	9/18	9/25	**Reading Assignment** **4. Accidents Occurrence** **Written Assignment** Briefly explain: 1. Black Swan event, 2. Critical states, 3. Fingers of instability, 4. Minsky moment.
11	9/20	9/27	**Reading Assignment** **5. Risk Quantification** **Written Assignment** Consider a component that fails at a constant rate λ and a probability density function (pdf): $\lambda e^{-\lambda t}$. 1. Prove that the pdf satisfies the normalization condition. 2. Derive the expression for the mean time to failure or the first moment of the pdf. $$\overline{t} = \frac{\int_0^\infty t.\lambda e^{-\lambda t}\, dt}{\int_0^\infty \lambda e^{-\lambda t}\, dt}$$ An insurance company requires an overhead on the premiums it collects from its customers. If the payment to a beneficiary is \$100,000 and it collects \$1,000 per year in premiums, what is the probability of death in the year that the insurance company used to calculate the collected premium if the overhead charge is: 1. 10 percent 2. 20 percent. 3. 30 percent? Compare the result to the case of breakeven for the actuarial risk.
12	9/23	9/30	**Reading Assignment** **5. Risk Quantification** **Written Assignment** 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. List the objectives of the typical risk assessment methodology. Write a paragraph about the source and the properties of Radon gas. Use the following diagram to estimate the individual risk of death per year from different sources for a USA population of 325 million persons.

			30,000 deaths per year 21,000 17,400 10,000 8,000 3,900 2,800 _RADON*_ Drunk Driving Falls in the Home Drownings Home Fires

13	9/25	9/30	**Reading Assignment**
			6. Incidence and Likelihood Risk and Safety Indices
			Written Assignment
			Describe the difference between:
			    1. Incidence risk indices,
			    2. Likelihood risk indices.
			
			1. 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.

14	9/27	9/30	**Reading Assignment** **7. The Risk Assesment Methodology** **Written Assignment** List the conditions for the existence of "Risk". For the _discrete_ random variable of the outcomes from throwing a single die, plot: 1. The probability distribution as a function of the outcomes x_i. 2. The cumulative distribution function (cdf) as a function of the outcomes x_i. 3. The complementary cumulative density functions as a function of the outcomes x_i. Use the same scale for comparison, and briefly explain the meaning conveyed by each one of these plots. Hint: For a discrete probability distribution, Cumulative distribution function: $$cdf(x) = \sum_{x_i \le x} p_i(x)$$ Complementary cumulative distribution function $ccdf(x) = 1 - cdf(x)$ In Probabilistic Risk Assessment (PRA), risk profiles are generated for likelihoods as a function of outcomes. Consider the probability (likelihood) density function (pdf): $\lambda \exp(-\lambda t)$ for the time t to failure of a component with a constant failure rate λ. Derive expressions for, then use a plotting routine to plot the following: 1. The probability density functions as a function of t. 2. The cumulative distribution functions (cdf) as a function of t. 3. The complementary cumulative density function (ccdf) as a function of t. This is designated as the Farmer's Curve or the Risk Profile. Use the same scale for comparison, and briefly explain the meaning conveyed by each one of these plots. Hint: For a _continuous_ pdf: f(x)dx,

			Cumulative distribution function: $$cdf(x) = \int_0^x f(x)dx$$ Complementary cumulative distribution function $$ccdf(x) = 1 - \int_0^x f(x)dx = \int_x^\infty f(x)dx = 1 - cdf(x)$$
	First Midterm		**Monday September 30**
15	10/2	10/9	**Reading Assignment** **8. Risk and Safety Ethics** **Written Assignment** If the expected maximum loading on a structural member is about 1,000 kgs, a prudent designer would use an ignorance factor of ?, and a safety factor of ?. Then the design load would be ? kgs. The concept of acceptable risk defines the professional and ethical dimension of the engineering profession. Because of the element of uncertainty involved in risk, a bias or predisposition in favor of one set of values or another is inevitable. Explain the difference between the observed two sets of values, biases or orientations: 1. The Good Science (GS) approach 2. The Respect for Persons (RP) approach
16	10/4	10/11	**Reading Assignment** **8. Risk and Safety Ethics** **Written Assignment** Under the doctrine of informed consent, list the ethical value judgments affecting the acceptance of risk. Consider the Good Science (GS) and Respect for Persons (RP) orientations to risk acceptance. Relate them to the Precautionary Principle pertaining to the acceptance of risk. List 8 causes of the disparity between the experts and members of the public concerning the perception of risk.
17	10/7	10/14	**Reading Assignment** **9. The Source Term** **Watch the video recording:** **https://mediaspace.illinois.edu/media/t/1_crltskjl/353320142** **or:** **https://youtu.be/sAUVNNDJees** **Written Assignment** Calculate the effective half-lives in terms of the radioactive and biological half-lives of the following fission products of safety concern: a. Sr^{90} b. Cs^{137} c. I^{131} d. T^3 Identify the health physics concerns from the following fission products that could potentially be released in a nuclear reactor accident: <table><tr><td>Isotope</td><td>Half life</td><td>Health Concern</td></tr></table>

			<table><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>
18	10/9	10/16	**R**eading Assignment **11. Decay Heat Generation in Fission Reactors** **Written Assignment** 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 1,000 MWth, for 6 months, followed by a scram (shut-down). Using the analytical formulae derived in the class, determine the decay heat power: 1. Six minutes after shutdown 2. One day after shutdown.
19	10/11	10/18	**R**eading Assignment **11. Decay Heat Generation in Fission Reactors** **Written Assignment** 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: 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<4x10^6 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).
20	10/14	10/21	**R**eading Assignment **12. Cost Effectiveness Analysis** **Written Assignment** For the Emergency Core Cooling System (ECCS) addition as an Engineered Safety Feature (ESF) to a PWR, reconstruct in detail the following from the lecture data: 1. The radiological risk before the addition of the ESF. 2. The radiological risk after the addition of the ESF. 3. Estimate the cost effectiveness ratio. 4. Reach a recommendation as to whether it is cost effective to implement it or not according to the Nuclear Regulatory Commission (NRC) criteria.
21	10/16	10/23	Plot a graph describing the economic concept of the law of diminishing returns as applied to risk assessment.

Generate the level of Risk against the cost of risk reduction or Cost-Effectiveness graph for the case of an automobile safety design where extra safety measures are being introduced seeking reduced risk levels. Use tentative values for the entries in the table.

Risk Reduction Measure	Risk Reduction ratio	Cost of Risk Reduction [$]
Seat belts	1/2	$200
Anti-lock brakes	---	---
Front air bags	---	---
Side air bags	---	---
Backup camera	---	---
Front collision avoidance radar	---	---
Lane change sensor	---	---

For the following radiological quantities, fill out the table showing the corresponding units and their abbreviations.

Radiological quantity	Conventional System Unit	SI System Unit
Effective dose, dose equivalent		
Absorbed dose		
Activity		
Exposure		

22	10/18	10/25	**Reading Assignment** **10. Environmental Remediation of Radioactive Contamination** **Written Assignment** 1. Compare the soil-to-plant transfer ratio for the fission product isotope Cs^{137} in an island coral contaminated soil to that of a continental clay contaminated soil. 2. Describe the remediation action used to reduce the uptake of Cs^{137} by plants growing in an island coral contaminated soil.
23	10/21	10/28	**Reading Assignment** **10. Environmental Remediation of Radioactive Contamination** **Written Assignment** The soil to plant transfer ratio for Cs^{137} for tropical fruit grown on the Bikini Island ranges between 2 to 40. For crops grown on 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.
24	10/23	10/30	**Reading Assignment** **13. Boolean Algebra** **Written Assignment** Use Venn diagrams to prove the L10 de Morgan law or axiom of a Boolean Algebra.
25	10/25	11/1	**Reading Assignment** **13. Boolean Algebra** **Written Assignment** Consider the "two-element" Boolean Algebra:

			$B[\{0,1\}, \wedge, \vee, \overline{}, 0, 1\}$ where: $\wedge$ means the lesser of, $\vee$ means the greater of, $\overline{}$ means the opposite of. Fill up the following operation or truth tables: $\begin{array}{c\|c} \overline{} & \\ \hline 0 & \\ 1 & \end{array}$ $\begin{array}{c\|cc} \wedge & 0 & 1 \\ \hline 0 & \\ 1 & \end{array}$ $\begin{array}{c\|cc} \vee & 0 & 1 \\ \hline 0 & \\ 1 & \end{array}$
26	10/28	11/1	**Reading Assignment** **14. Fuzzy de Morgan Algebra** **Written Assignment** Use Zadeh diagrams to prove the L10 de Morgan law or axiom of a de Morgan Fuzzy Algebra. Use Kosko's interpretation of fuzzy sets as points on the unit interval, unit square, unit cube and unit hypercube to analytically calculate, and 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).
27	11/30	11/1	**Reading Assignment** **15. Probabilistic and Possibilistic Fault Tree Analysis** **Written Assignment** 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. Write a one-page summary of the article on the construction of "Expert Systems" in the field of Applied Artificial Intelligence: Dan Rehfeldt and Magdi Ragheb, "Building Expert Systems in Prolog on the Explorer Machine," TI Professional Computing, Vol. 3, No. 6, pp. 12-27. June 1986. What kind of logic does it use?
	11/1	Friday November 1st	**Second midterm exam, during class period**
28	11/4	11/11	**Reading Assignment** **15. Probabilistic and Possibilistic Fault Tree Analysis** **Written Assignment** 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.

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.
3. Calculate the probability of failure for the top event for probabilities of failures of the basic events equal to 10^{-2}.
4. Show how you can reduce the top event failure probability by modifying the design. Show your suggestion graphically and write its Boolean expression.
5. Compare the failure probability of the modified design to that of the original one.

29	11/6	11/13	**Reading Assignment** **16. Event Tree Analysis** **Written Assignment** 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: $$\pi(I)=10^{-3}, \pi(A)=10^{-2}, \pi(B)=10^{-3}, \pi(C)=10^{-4}$$ In the shown coupled event and fault tree, if the probabilities of failure of the basic events are all equal to 10^{-4}, and the probability of the initiating event is 10^{-5}, calculate the probabilities of the different accident sequences. If one uses the same values as possibilities of failure, estimate the possibilities of the different accident sequences.
30	11/8	11/15	**Reading Assignment** **21. Fluid Mechanics Equations** **Written Assignment** 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 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 velocity 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 velocity at this point.
31	11/11	11/18	**Reading Assignment** **22. Safety Computational Fluid Dynamics** **Written Assignment** List the four basic relationships that define Computational Fluid Dynamics (CFD) for single phase flow. List the variables used in a numerical CFD one phase flow computational scheme together with their units in the conventional cgs (centimeter, gram, sec) system of units. In CFD, the discretization of the energy conservation equation proceeds as follows. The specific internal energy can be calculated based on the work done on the slab assuring conservation of energy through the thermodynamic relation: $dE = -pdV, \Delta E \simeq -p\Delta V$ $E^{n}_{j-\frac{1}{2}} - E^{n-1}_{j-\frac{1}{2}} = ?$ $E^{n}_{j-\frac{1}{2}} = ?$
32	11/13	11/20	**Reading Assignment** **23. Loss of Coolant Accident, LOCA** **Written Assignment** What does the acronym "LOCA" stand for? Write a one-page comparison for the PWR design of: a) The large-break LOCA, b) The small-break LOCA.
33	11/15	11/22	**Reading Assignment** **23. Loss of Coolant Accident, LOCA** **Written Assignment** Consider a model of the Small-break Loss of Coolant Accident (LOCA). If the water evaporation volumetric rate as a result of decay heat generation in a typical Light Water Reactor (LWR), Loss of Coolant Accident (LOCA) is 0.01 m^3/sec, its effective wetted core area is 3 m^2, and its core height is 4 m. 1. Calculate the core uncovery rate in cm/sec. 2. If the core is half filled with water, estimate the time in minutes for total core uncovery
34	11/18	12/2	
35	11/20	12/2	
36	11/22	12/2	
37	12/2	12/9	
38	12/4	12/11	
39	12/6	12/11	

40	12/9	12/11	
41	12/11	12/16	
	12/16		**NPRE 457 Fall 2024 Third Exam** **7:00pm-10:00pm., Monday Dec. 16**

Assignments Policy

Assignments will be turned in at the beginning of the class period, one week from the day they are assigned.

They need to be submitted earlier when tests are scheduled.

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 e-mailed to the 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.