Problem 1 (5 points)
For the systems engineering Vee Diagram below:

1. \( \rho^+ \) (a) Describe the intent of the arrow on the left and the arrow on the right.
2. \( \rho^+ \) (b) How does the Vee relate to the system life cycle?
1. \( \rho^+ \) (c) What aspects of the Vee are the responsibility of the systems engineer?
Systems Engineering Guides the Highest Levels of Analysis and Integration

- Mission Requirements & Priorities
- Develop System Requirements & System Architecture
- Allocate Performance Specs & Build Verification Plan
- Design Components
- Fabricate, Assemble, Code & Procure Parts
- Verify Component Performance
- Component Integration & Verification
- Integrate System & Verify Performance Specs
- System Demonstration & Validation

Integration & Verification Sequence
Decomposition & Definition Sequence

Time and Project Maturity

Systems Engineering Domain
Component Engineering Domain
Problem 2 (6 points)

(a) Draw and label the "Bathtub" Failure Rate Curve.
(b) Explain the meaning of the curve.
(c) Explain the application of the exponential function that models the probability distribution of reliability as it relates to the curve.
Constant Failure Rate:
- Probability Distribution of reliability is an exponential function.
- Although an individual component may not have an exponential reliability distribution, in a complex system with many components the overall reliability may appear as a series of random events and the system will follow an exponential reliability distribution.

The "Bathtub" Failure Rate Curve

Because of burn-in failures and/or inadequate quality assurance practices, the failure rate is initially high, but gradually decreases during the infant period. During the useful life period, the failure rate remains constant, reflecting randomly occurring failures. Later, the failure rate begins to increase because of wear-out failures.
Problem 3 (6 points)
For space system verification, testing is the preferred means for evaluating a system's performance and compliance with requirements. For each of the 3 types of environmental test, describe at least 2 purposes for the test.

(a) Structural dynamics test
(b) Space simulations test
(c) Electromagnetic test
<table>
<thead>
<tr>
<th>Test</th>
<th>Purpose</th>
<th>Equipment/Facilities Required</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration &amp; Shock Testing structural</td>
<td>Ensure product will survive launch</td>
<td>Vibration table and fixture enabling 3-axis testing, and/or</td>
<td>Do low-level vibration survey (a.k.a. modal survey) to determine vibration modes and establish baseline</td>
</tr>
<tr>
<td>Dynamics Test</td>
<td>Comply with launch authority’s requirements</td>
<td>Acoustic chamber</td>
<td>Do high-level random vibration following profile provided by launch vehicle to prescribed levels</td>
</tr>
<tr>
<td></td>
<td>Validate structural models</td>
<td></td>
<td>Repeat low-level survey to look for changes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Compare results to model</td>
</tr>
<tr>
<td>Thermal &amp; Vacuum Testing space</td>
<td>Induce and measure outgassing to ensure compliance with mission</td>
<td>Thermal/vacuum chamber Equipment to detect</td>
<td>Operate and characterize performance at room temperature and pressure</td>
</tr>
<tr>
<td>Simulations Test</td>
<td>requirements</td>
<td>outgassing (e.g. coldfinger or gas analyzer) as needed</td>
<td>Operate in thermal and/or thermal vacuum chamber during hot and cold-soak conditions</td>
</tr>
<tr>
<td></td>
<td>Ensure product will perform in a vacuum under extreme flight temperatures</td>
<td>Instrumentation to measure temperatures at key points on product (e.g. batteries)</td>
<td>Oscillate between hot and cold conditions and monitor performance</td>
</tr>
<tr>
<td></td>
<td>Validate thermal models</td>
<td></td>
<td>Compare results to model</td>
</tr>
<tr>
<td>Electromagnetic Interference/Compatibility (EMI/EMC)</td>
<td>Ensure product does not generate EM energy that may interfere with other spacecraft components or with launch vehicle or range safety signals</td>
<td>Radiated test: Sensitive receiver, anechoic chamber, antenna with known gain</td>
<td>Detect emitted signals, especially at the harmonics of the clock frequencies</td>
</tr>
<tr>
<td>EMI test</td>
<td>Verify that the product is not susceptible to the range and/or launch EM environment</td>
<td>Conduction susceptibility matched “box”</td>
<td>Check for normal operation while injecting signals or power losses</td>
</tr>
</tbody>
</table>
Problem 4 (8 points)
A program has a set of activities (A through G) to accomplish before completion. The diagram below shows the network of these activities and their estimated duration. Answer the following questions:

(a) Designate, by activity letters, the critical path for the program, from program start to program completion. How long is the critical path in days?

\[ A - B - E - G \]
\[ 8 + 8 + 2 + 10 = 28 \text{ days} \]

(b) How much float exists for each of the remaining paths? Designate each path by the activity letters, and express the float in days.

\[ C - D - E - G \]
\[ 7 + 5 + 2 + 10 = 24 \Rightarrow 4 \text{ days float} \]

\[ F - G \]
\[ 10 + 10 = 20 \Rightarrow 8 \text{ days float} \]
Problem 5 (2 points each; 20 points total)

Match definitions with key systems engineering terms, using the word bank below.

WORD BANK:
- a) Gantt chart
- d) trade study
- g) bottoms-up estimating
- j) SEMP
- m) peer review
- p) project plan
- s) event tree
- b) Monte Carlo
- e) demonstration
- h) fault tree
- k) normal distribution
- n) inspection
- q) Taguchi method
- r) milestone chart
- c) technology readiness level
- f) analog model
- i) beta distribution
- l) iconic model
- o) simulation
- p) parametric estimating
- u) mission concept review

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c) A measure used to assess the maturity of evolving materials, devices, components, etc. prior to incorporating into a system.

h) A graphical representation where successive subordinate failure events are identified and logically linked to the top event.

g) Estimate is based on the cost of materials and labor to develop and produce each element, at the lowest level of the WBS possible.

b) A computational algorithm where input parameters are randomly selected.

t) A graphic portrayal of a project that shows the events to be completed on a timeline.

e) Determines conformance to system/item requirements through the operation, adjustment, or reconfiguration of a test article.

Document that

j) Defines for all project participants how the project will be technically managed within the constraints established by the project.

m) A review by individuals selected from outside the project according to their expertise in the applicable disciplines. These reviews help you take advantage of other engineering experience from colleagues who have worked on different missions.

i) The probability distribution function often used in schedule analysis, where a most likely estimate, an optimistic estimate, and a pessimistic estimate are required.

f) A model that behaves like the real system; often used to compare something unfamiliar with something that is familiar.
Problem 6
Design margins calculation (10 points)

The end-of-mission life capability of a spacecraft power system is 200 watts. Your instrument is expected to use 50 watts, including 25% contingency. You are allotted 75 watts by the satellite provider.

5 pts

• What is the instrument’s power contingency in watts?

\[ \% C = \frac{C}{\text{Max Exp} - C} \times 100 \]

\[ \frac{0.25}{50 - C} = C \]

\[ 0.25(50 - C) = C \]

\[ 12.5 - 0.25c = C \]

\[ 12.5 = 1.25c \]

\[ 10 = C \]

Contingency = 10 watts

5 pts

• What is the instrument’s power margin in watts and as a percentage (%)?

\[ \% M = \frac{M}{\text{Max allotted} - M} \times 100 \]

\[ \frac{75 - 50}{75 - (75-50)} = \frac{25}{50} = 50 \% \]

Margin = 25 watts
Problem 7
General questions (4 points each):

(a) What's the difference between PDF and CDF; how are they related?

- Monte Carlo lecture under cost folder (slide 10)
- CDF is the integral of the PDF

(b) What's the difference between Preliminary Design Review (PDR) and Critical Design Review (CDR)?

(c) What is the difference between measures of effectiveness and measures of performance? Give one example of each.

1 point
Preliminary Design Review (PDR)

- The PDR is not a single review but a number of reviews starting with the specific component PDRs, followed by the system-level review.
- The PDR establishes the “design-to” baseline and ensures that it meets the program, project, system, subsystem, or specific component baseline requirements.
- The PDR process should:
  - Establish the ability of the selected design approach to meet the technical requirements (i.e., Verifiability/Traceability);
  - Establish the compatibility of the interface relationships of the specific end item with other interfacing items;
  - Establish producibility of the selected design;
  - Establish the operability of the selected design;
  - Assess compliance with reliability and system safety requirements;
  - Establish the feasibility of the approach;
  - Address status, schedule and cost relationships.

Evaluation Criteria

- Trade studies depend upon having criteria for making decisions based on measure of effectiveness (voice of the customer) and measures of performance (voice of the engineer).

- Example measures of effectiveness
  - Life cycle cost
  - Schedule, e.g., development time, mission duration
  - Technology readiness level (maturity of concept/hardware)
  - Crew capacity
  - Payload Mass

- Example measures of performance
  - Mass
  - Power consumption
  - Specific impulse
  - Consumables required
  - Propellant type
Problem 7 (continued)
General questions (4 points each):

(d) What does it mean to have a closed design?

(e) What is the relationship between the TRL scale and risk?
The design is said to be “closed” when all iterations have converged and all the inputs/outputs to all the model are consistent with each other.

In this case, for example, on the first pass through the $N^2$ diagram you must guess the inputs from $E$ to $D$ (because you have not yet run model $E$). After you run $D$, you use the outputs to run $E$. You will see that the outputs of $E$ probably do not match your guess. Therefore you rerun $D$ using the updated values of the outputs from $E$. The new outputs of $D$ will require you to rerun $E$, and so on. You must continue to iterate until the process converges.
**Intro: Technology Readiness Levels**

- The Technology Readiness Level (TRL) is a NASA-established classification scale against which to measure the maturity of a technology.
  - Describes the state-of-the-art of a given technology
  - Provides a "baseline" from which to advance (ultimately to flight)
- TRLs range from 1 - basic technology research to 9 - full operational capability in space.
- Typically, a TRL of 6 - technology demonstrated in a relevant environment - is required for a flight project development to be approved for implementation.
- TRLs indicate the inherent development risk:
  - A TRL of 1 or 2 represents a situation of relatively high risk
  - TRLs of 3-5 represent moderate risk
  - TRLs of 6-8 represent low risks

**Technology Readiness Level is a Measure of Risk**

Risk can also be translated into cost impact
Problem 8 (15 points)
You are an engineer tasked with estimating the reliability of the communications subsystem for the NEAR spacecraft (schematic shown in Figure 1). Specifically, you are asked to report the probability that the communication subsystem will be capable of successfully transmitting data through the high gain antenna. Recalling all the useful things you learned in your systems engineering class, you use the communication system schematic from in Figure 1 to draw the block diagram shown in Figure 2. Use the block diagram and reliability data shown in Figure 2 to estimate the reliability of the NEAR communications subsystem.

Figure 1. Schematic of communications subsystem for NEAR spacecraft.

Figure 2. Block diagram for reliability calculations.
Problem 9 (10 points)

You are helping design the descent stage for a lunar lander. Although your team’s design uses three identical engines, only two must function for a safe landing. Each engine has a reliability of 0.97. What is the probability that at least 2 of the 3 engines will function properly?

Method 1

\[
R_{2,3} = \frac{3}{2} R^2 (1-R) + R^3
\]

\[
= 3 (0.97)^2 (0.03) + (0.97)^3 = 0.084661 + 0.912673 = 0.997334
\]

Method 2
Workspace for Problem 8

\[ 0.96 \times 0.99 \times 0.97 = 0.9622894 \]

\[ 0.9622894 + 0.9622894 - ( \cdot ) = 0.99873 \]

\[ 0.95 + 0.95 - 0.95 \times 0.95 = 0.9975 \]

\[ 0.9975 \times 0.99893 \times 0.995 = 0.99145 \]