A Tutorial on Probabilistic Risk Assessment and its Role in Risk-informed Decision Making

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The material and examples in this tutorial are derived from the following sources:

- NASA PRA Procedures Guide; Version 1.1, August 2002

- NASA PRA Training Modules

- NASA Risk-informed Decision Making Handbook (Draft)
Outline

- Preamble
- A Typical Risk Management Process
- The Concept of Risk-informed Decision Making (NASA’s Perspective)
- Some Key Concepts
- Probabilistic Risk assessment (PRA) Overview
- PRA Methodology Synopsis
- PRA Results of a Real Space System
- Summary
Preamble

- Probabilistic Risk Assessment is a tool that can inform decisions during the entire lifecycle of a program/project
  - Risk analysis of decision alternatives in light of programmatic objectives (to support direction setting decisions)
  - Risk analysis of selected alternatives to set priorities (to support risk management decisions)
- Probabilistic Risk Assessment can play a major role in
  - Design decisions and
  - Operation decisions
A Typical Risk Management Process
A Typical Risk Management (RM) Process

- **Identify** – *Identify* program risk “issues”
- **Analyze** – Estimate the likelihood and consequence components of the risk issues
- **Plan** – *Plan* the *Track* and *Control* actions
- **Track** – *Track* and compile the necessary risk data, measuring how the RM process is progressing
- **Control** – Determine the appropriate *Control* action, execute the decision linked to that action, and verify its effectiveness
- **Communicate and Document** – communicating and documenting all risk information throughout each program phase

**Emphasis on**

- “management” of individual “risks”
- monitoring and accountability for action items associated with “risks”

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A Typical Risk Management Process (Cont.)

- Relies heavily on the application of risk matrices
- Risk "issues" are mapped onto the matrix individually
Origin of Risk Matrix

Risk Matrix Derived from Iso-Risk Curves

Iso-Risk (Equal Risk) Curves

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Cautionary Notes on the Use of Risk Matrix

- A tool for communicating among cognizant and responsible entities
- Presents summary information about the results of an analysis or assessment of particular risks, and places those results in the context of previously established action thresholds
- The purpose of this communication is to coordinate the organizational risk management response
  - Which risks most urgently need management attention?
  - What risks are being elevated?
  - What risks are under control?
- The risk matrix does not add new technical content to the discussion that should occur anyway. It only provides a familiar vehicle for conveying that content. It is not an analysis tool: it is a tool that promotes efficiency in communication.

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Cautionary Notes on the Use of Risk Matrix (Cont.)

- Risks are displayed on a risk matrix in order to frame a discussion of the appropriate current risk management response to those risks
- Traditionally, this has been done by color-coding the cells of the risk matrix, with “red” calling for significant attention, “green” implying that things are under control, and “yellow” in between.
- The thresholds separating different-colored regions are necessarily specific to programs and organizations
  - Risk tolerance is different among different programs
  - Priorities are different among different programs
- Therefore, the likelihood and consequence scales must be specific to the organizational and program context in which a given risk matrix is being used
  - They must be defined unambiguously
Risk-Informing Decisions Making
(Based on NPR 8000.4A)
History of “Risk-Informed”

- Evolved in the mid-1990’s at Nuclear Regulatory Commission in the context of nuclear plant [safety] risk
- Formulation of “risk-informed” may have been a reaction to overzealous advocacy of risk-based regulation: aggressively modifying [admittedly inefficient] traditional approaches to regulation, based on risk model results
What is Risk-Informed Decision Making (RIDM)?

- A risk-informed decision-making process that uses a diverse set of performance measures (some of which are model-based risk metrics) along with other considerations within a deliberative process to inform decision making. *Paragraph A.14 of NASA NPR 8000.4A*

  *Note to Paragraph A.14: A decision-making process relying primarily on a narrow set of model-based risk metrics would be considered "risk-based."

- Decisions are informed by an integrated risk perspective rather than being informed by a set of individual "risk" contributions whose cumulative significance is not understood.

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How Does RIDM Help?

- RIDM is a structured process aimed at achieving success by proactively risk-informing the selection of decision alternatives.
- RIDM tries to foster development of the most robust technical basis for decision-making
  - Couples the attributes of the proposed decision alternatives to the objectives that define success;
  - Considers all attributes of significance to the stakeholders in an integrated manner: technical, safety, schedule and cost;
  - Helps ensure that a broad spectrum of decision alternatives are considered;
  - Involves quantitative assessment of the merits and drawbacks of each proposed decision alternative relative to the stated objectives;
  - Accounts for the uncertainties inherent to each proposed decision alternative to the extent that they impact the achievement of the stated objectives; and
  - Communicates the quantitative assessment of the proposed decision alternatives into the decision environment, where it is deliberated along with other considerations to form a comprehensive, risk-informed basis for alternative selection
- Deliberative process intended to capitalize on tacit organizational knowledge after the analysis / modeling stage
NPR 8000.4A

- The latest version of NPR 8000.4A, Agency Risk Management Procedural Requirements, was issued on December 16, 2008
  - Accessible from NASA Online Directives System (NODIS) Library
    - http://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=8000&s=4A
- This directive evolves NASA’s Risk Management (RM) approach to entail two complementary processes:
  - Risk-informed Decision Making (RIDM)
    - Emphasizes the proper use of risk analysis in its broadest sense to make risk informed decisions that impact all mission execution domains (e.g., safety, technical, cost, and schedule)
    - Formulates recommendations for performance requirements
  - Continuous Risk Management (CRM)
    Focuses on the management of risk associated with implementation of baseline performance requirements

RM ≡ RIDM + CRM
The RIDM Process

- Identification of decision alternatives *(decision context)* and considering a sufficient number and diversity of Performance Measures

- Risk analysis of decision alternatives (uncertainty analysis of performance associated with the alternative)

- Selection of a decision alternative informed by (not solely based on) Risk Analysis Results

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The Continuous Risk Management (CRM) Process

CRM is conducted in the context of performance requirements

Steps in the CRM Process

- **Identify**
  - Identify Risk Contributors (Shortfall in Performance Relative to Baseline Performance Requirements)

- **Analyze**

- **Plan**
  - Decide on Risk Disposition and Handling. Develop and Execute Mitigation Plans. Decide What Will be Tracked

- **Track**
  - Track Observables Relating to Performance Measures (e.g., performance data, schedule variances, etc.)

- **Control**
  - Control Risk by Evaluating Tracking Data to Verify Effectiveness of Mitigation Plans; Make Adjustment to the Plans, and Execute Control Measures

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Key Terms and Concepts Important to RIDM
Performance Measures and Performance Objectives

- A Performance Measure is a metric used to quantify the extent to which a Performance Objective is fulfilled
  - Safety (e.g., avoidance of injury, fatality, or destruction of key assets)
  - Technical (e.g., increase thrust or output, maximize amount of observational data acquired)
  - Cost (e.g., execution within minimum cost)
  - Schedule (e.g., meeting milestones)

- Examples of Performance Objectives and corresponding Performance Measures
  - Maintain Astronaut Health $\rightarrow$ Probability of Loss of Crew ($P(LOC)$)
  - Minimize Cost $\rightarrow$ Cost ($\$$)
  - Maximize Payload Capability $\rightarrow$ Payload Capability (kg)
  - Maximize Public Support $\rightarrow$ Public Support (1 – 5)

- An Imposed Constraint is a limit on the allowable values of the Performance Measure with which it is associated
  - Example: A hard limit on minimum acceptable payload capability
Definition of Risk

- The term “risk”, when used without further qualifications, is very general and applies to a large variety of user contexts.
- In general, risk is uncertainty regarding the future outcome of an undertaking of some kind: a decision alternative, a project, a launch, etc.
- In the context of mission execution, risk is the expression of the potential for performance shortfalls, which may be realized in the future, with respect to achieving explicitly, established and stated performance requirements:
  - The performance shortfalls may be related to any one or more of the following mission execution domains:
    - Safety
    - Technical performance
    - Cost
    - Schedule
Performance Commitment and its Relationship to Risk

- A performance commitment is a performance measure value set at a specified percentile of the performance measure's pdf.
Operational Definition of Risk

• The “triplet” concept of “risk” is operationally useful for defining, analyzing, and managing risk
  – The scenario(s) leading to degraded performance with respect to one or more Performance Measures (e.g., scenarios leading to injury, fatality, destruction of key assets; scenarios leading to exceedance of mass limits; scenarios leading to cost overruns; scenarios leading to schedule slippage);
  – The likelihood(s) of those scenario(s); and
  – The consequence(s) (severity of the performance degradation) that would result if the scenario(s) was (were) to occur
The RIDM Process
RIDM Process Steps

Step 1
- Identification of Alternatives
  Identify Decision Alternatives (Recognizing Opportunities) in the Context of Objectives

Risk Analysis of Alternatives
- Risk Analysis (Integrated Perspective) and Development of the Technical Basis for Deliberation

Risk-Informed Alternative Selection
- Deliberate and Select an Alternative and Associated Performance Commitments Informed by (not solely based on) Risk Analysis

Step 2

Step 3

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RIDM Process – Step 1
Derive Performance Measures from Objectives

- In general, it can be difficult to assess decision alternatives against multifaceted and/or qualitative top-level objectives
- To deal with this situation, objectives are decomposed, using an objectives hierarchy (OH), into a set of lower-level performance objectives that any attractive alternative should have
- A performance measure is then developed for each performance objective, as the quantity that measures the extent to which a decision alternative meets the performance objective
RIDM Process – Step 1
Derive Performance Measures from Objectives (cont.)

- Objectives are decomposed into quantifiable Performance Measures

- Some Performance Measures may have *Imposed Constraints*

- Some Performance Measures are unconstrained but have a desirable direction of goodness

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RIDM Process – Step 1
How is OH Different from Means Objectives?

Objectives Hierarchy

- Explain what is meant by the higher-level objective
- Partition the higher-level objective into its constituent parts
- Don’t impose a solution;
- Are structured in a hierarchy

Means Objectives Network

- Are ways of accomplishing higher-level objectives
- May relate to multiple higher-level objectives;
- Imply a solution;
- Are structured in a network
RlDM Process – Step 1
Compiling Alternatives

Alternative design solutions are generated as part of the Systems Engineering process.

Low-fidelity feasibility assessment (e.g., first-order analysis, engineering judgment) is used to prune the trade tree and narrow the set of alternatives to analyze further.
RIDM Process – Step 2
Risk Analysis of Alternatives

- **Goal:** to develop a risk analysis framework that integrates domain-specific performance assessments and quantifies the performance measures
  - **Risk Analysis** - probabilistic modeling of performance

- **The challenge is to establish a transparent framework that:**
  - Operates on a common set of performance parameters for each alternative
  - Consistently addresses uncertainties across mission execution domains and across alternatives
  - Preserves correlations between performance measures

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RIDM Process – Step 2
Risk Analysis of Alternatives (cont.)

• Setting the risk analysis framework (alternative specific)
RIDM Process – Step 2
Risk Analysis of Alternatives (cont.)

- Quantification via probabilistic modeling of performance

Monte Carlo Shell

Iterate N Times

Decision Alternative i

Risk Analysis Framework & Models

Add Row

Risk Analysis Output

Performance Measure Values for Alternative i

<table>
<thead>
<tr>
<th>Iteration #</th>
<th>Performance Measure 1</th>
<th>...</th>
<th>Performance Measure n</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PM_{1,1}</td>
<td>...</td>
<td>PM_{1,n}</td>
</tr>
<tr>
<td>2</td>
<td>PM_{2,1}</td>
<td>...</td>
<td>PM_{2,n}</td>
</tr>
<tr>
<td>3</td>
<td>PM_{3,1}</td>
<td>...</td>
<td>PM_{3,n}</td>
</tr>
<tr>
<td>N</td>
<td>PM_{N,1}</td>
<td>...</td>
<td>PM_{N,n}</td>
</tr>
</tbody>
</table>

Sampled Performance Parameter Values*

*Sampling is needed for uncertain performance parameters only

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R IDM Process – Step 2
Choosing the analysis methodologies


• Depending on project scale, life cycle phase, etc., different levels of analysis are appropriate. The rigor of analysis should be enough to:
  
  - Assess compliance with imposed constraints
  
  - Distinguish between alternatives

• Iteration is to be expected as part of the analysis process, as analyses are refined and additional issues are raised during deliberations.
RIDM Process – Step 3
Comparing Alternatives in Terms of Candidate Performance Commitments

- **Performance Commitments**
  - A performance commitment is a performance measure value set at a specified percentile of the performance measure’s pdf
  - Performance commitments help to anchor the decision-maker’s perspective to specific performance expectations for each alternative
  - For a given performance measure, the performance commitment is set at the same percentile for all decision alternatives
  - Performance commitments support a risk-normalized comparison of decision alternatives, at a level of risk tolerance determined by the decision maker

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RIDM Process – Step 3
Develop Risk-Normalized Candidate Performance Commitments

Risk Analysis is Conducted on Alternatives A, B and C

Set PM Ordering and Candidate PM Risk Tolerances

Candidate Performance Commitments defined at Candidate PM Risk Tolerances

Candidate Performance Commitments facilitate comparison of performance across a range of risk tolerances

The definition of “high” risk tolerance can vary from one performance measure to another

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RIDM Process – Part 3
Performance Commitments are to be Developed in a Conditional Fashion

a. Risk analysis output for Alternative i

b. PM’s performance commitment set at the specified risk tolerance

c. PM’s performance commitment set at the specified risk tolerance, given compliance with PM’s performance commitment

d. Performance commitments for PM and PM given the specified PM risk tolerances and PM ordering
RIDM Process – Part 3
Summary of How the Concept of Performance Commitment Works

- The inputs to performance commitment development are
  - The performance measure pdfs for each decision alternative
  - An ordering of the performance measures
  - A risk tolerance for each performance measure, expressed as a percentile value

- The decision alternatives are compared by the decision maker in terms of candidate performance commitments that have the same failure probability across alternatives
  - Example (“Low” risk tolerance on previous slide):
    - Alternative B is best at the “low” risk tolerance setting (and Alternative A does not satisfy the imposed constraint)
    - Alternative A has the best reliability at the “low” setting
    - Alternative C has the best Cost & Schedule performance at the “low” setting

- The approach focuses DM attention on the level of program risk being assumed by selection of a given alternative at given commitment levels
Risk-informed Alternative Selection

**Technical Basis for Deliberation**
- Generate candidate performance commitments
- Assess credibility of estimation methods
- Deliberate pros and cons
- Consider performance uncertainty
- Identify contending alternatives
- Iteration

- Deliberate

- Select an Alternative
  - Formulate decision rationale
  - Set the performance commitments

- Document the Decision Rationale
  - Risk analysis results
  - Deliberation summary
  - Decision rationale
  - Performance commitments
  - "Risk List"
  - Dissenting opinions

Additional Risk Analysis, Information Gathering as Needed

*Risk-Informed Selection Report*

*To be defined in formal project management documentation.*
Probabilistic Risk Assessment Overview
Review of Some Key Concepts

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The Concept of a Scenario

A risk scenario contains an IE and (usually) one or more pivotal events leading to an undesired end state.
An Operational Definition for Risk

- Risk is a set of triplets $<S_i, P_i, C_i>$ that answer the questions:
  - What can go wrong? (scenarios, $S_i$)
  - How likely is it? (probabilities, $P_i$)
  - What are the consequences? (adverse effects, $C_i$)

\[ R = \text{RISK} = \{ S_i, P_i, C_i \} \]

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Probability</th>
<th>Consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1$</td>
<td>$p_1$</td>
<td>$C_1$</td>
</tr>
<tr>
<td>$S_2$</td>
<td>$p_2$</td>
<td>$C_2$</td>
</tr>
<tr>
<td>$S_3$</td>
<td>$p_3$</td>
<td>$C_3$</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>$S_N$</td>
<td>$p_N$</td>
<td>$C_N$</td>
</tr>
</tbody>
</table>

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Hazard ≠ Risk

Examples of Hazard and Risk

- **Hazard:** Hydrazine is a hazard because it can result or contribute to loss of spacecraft

- **Risk:** The risk scenario of <Hydrazine leakage AND not detecting the leakage AND damaging flight critical avionics> has probability of 1 in 10,000 to result in a loss of spacecraft
Pivotal Events

- In between IE and end states
  - Represent
    - successes or failures of system/crew responses to the IE
    - occurrence or non-occurrence of external conditions or phenomena
  - Mitigative: reduces the severity of a consequence
  - Aggravating: increases the severity of a consequence

- Hydrazine leaks and
- Leak is not isolated and
- Damage to flight critical avionics

Loss of Spacecraft

Events:
- Building blocks of a scenario
- Declarative sentences used to characterize a scenario
- It is binary: Can only have two mutually-exclusive states (True or False)
- An event is a statement about a piece of equipment, a function, a condition, an outcome, etc.
More on the Concept of Risk Scenarios

- A risk scenario is in effect a conditional statement.
- It is a logical expression that has the following structure:

\[
\text{Occurrence of certain event(s)} \rightarrow \text{undesired end state}
\]

\[
\text{IF} \ (\text{IE} \cap \text{Pivotal Event 1} \cap \text{Pivotal Event 2} \cap \ldots), \ \text{THEN} \ \text{undesired end state is reached}
\]

Where, $\cap$ for “and”

- A risk scenario is often characterized by a minimum set of events. In this case, the undesired end state can be prevented if
  - the IE does not occur  \(<\text{or}>\)
  - one or more pivotal events do not occur
The “Event” Concept

- Events: Building blocks of a scenario
  - declarative sentences used to characterize a scenario
- Each event is a statement about a piece of equipment, a function, a condition, an outcome, etc.
  - It is binary: Can only have two mutually-exclusive states (True or False).
  - Example:

<table>
<thead>
<tr>
<th>Event Description</th>
<th>True</th>
<th>False</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leak is not detected (Failure Space)</td>
<td>Leak is not detected</td>
<td>Leak is detected</td>
</tr>
<tr>
<td>Leak is detected (Success Space)</td>
<td>True</td>
<td>False</td>
</tr>
<tr>
<td></td>
<td>Leak is detected</td>
<td>Leak is not detected</td>
</tr>
</tbody>
</table>
PRA Overview
PRA Methodology Synopsis

Decision Context

Scenario Generation & Probabilistic Modeling

Analysis Results

Metrics

Modeling

Integration

Objectives and Performance Measures

Master Logic Diagram

Fault Tree

Communication and Insights

Uncertainty Characterization

Alternatives

Steady Models

Simulation

Model Parameters

Dynamic Models
Understanding The Decision Context
Decision Context

- If the PRA model is to be used to support decision making, then it should be structured to suit this purpose.
- The performance measures (PMs) are defined according to decisions being supported.
- Identification of PMs is the starting point of the PRA process:
  - They should serve the evaluation of decision options.
  - Ultimately they should be quantified.
- Examples of PMs:
  - $P$(loss of life or injury / illness to crew)
  - $P$(damage to, or loss of, equipment or property)
  - $P$(evacuation)
  - $P$(failure of mission)
  - $P$(damage to environment)
Scenario Structuring

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System Familiarization

- Development of a comprehensive scenario set for a complex facility or mission is a team effort because of
  - the volume of work and
  - diversity of technical discipline involved
- PRA requires detailed knowledge of responses to perturbations
- PRA analysts require an in-depth knowledge of the system and how it operates.
  - knowledge of system dependencies;
  - knowledge of system operability states
- Knowledge of "How it Fails" is derived from "How it Works"
- PRA team should include system experts
Initiating Events (IEs)
Master Logic Diagram (MLD)

- Hierarchical (Top-Down) method for obtaining initiating event groups (CLASS OF THINGS THAT CAN GO WRONG?)
- The highest level of hierarchy is the end state of interest
- Intermediate levels identify systems and subsystems (e.g., thruster module fails)
- Lower levels identify component assemblies and initiating event categories (e.g., filter clogs or propellant leaks)
- Master Logic Diagram is completed when further breakdown produces same system responses as higher level
- An important consideration in the development of a useful MLD is knowing when to stop at a reasonable level
- The “pinch point” occurs when every level below the stopping level has the same consequence as the level above it
Initiating Events: Master Logic Diagram (MLD)

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Event Sequence Diagram (ESD)
Structuring Scenarios

- ESD is useful for identifying accident scenarios
- The method uses forward logic
- An ESD is developed for each initiating event category in the Master Logic Diagram
- Most engineers find ESDs intuitive and easy to understand:
  - Used for communication between PRA analysts and system engineers
- Events may be ordered to reflect dependence:
  - Later events depend on earlier events
- Similarities in system response indicate that different initiating events can be combined
- Scenario modeling is not typically accomplished in a single pass
A Typical ESD

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A Simple Example

- The spacecraft is designed with two redundant sets of thrusters (independent of each other).
- Each propellant distribution module consists of a hydrazine tank, filters, distribution lines, normally-open isolation valves, sensors, heaters, etc. (only components that affect mitigation of leaks are shown).
- When thruster operation is needed, the controller opens the solenoid valves (not shown) to allow hydrazine to flow.
- The controller monitors the pressure of feed-lines via pressure transducers (P1 and P2). It is designed to differentiate between the normal thruster operation and a leak.
- In the event of a leak, isolation valves (V1 and V2) should both close.
- Successful termination of the leak leads to the loss of one but not both, thruster sets.
- Failure to terminate the leak can cause damage to the flight critical avionics and/or damage to scientific equipment:
  - Hydrazine acts as a wire stripper and is corrosive.

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Space mission type: scientific
PMs of interest
- Probability (loss of spacecraft)
- Probability (loss of science data)
Propose design modification, if needed
ESD for Propellant Leak

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Constructing Event Trees for Propellant Leak

- Hydrazine leaks
- Leak detected
- Leak isolated
- No damage to flight critical avionics
- No damage to scientific equipment
- End state

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Fault Tree Modeling of Pivotal Events

- Most popular way to "map" component level failure information to "system level" failure information
- It is a "top-down" analysis
- Used to analyze initiating or pivotal events in terms of more detailed, causal events
- Breakdown continues until either
  - data are available for quantification, or
  - scope of work dictated level of disaggregation.
- Typically, the lowest level (called "basic event" level) is the largest level of assembly for which data are available
Fault Tree Symbols (Basic Events)

PRIMARY EVENT SYMBOLS

BASIC EVENT – A basic initiating fault requiring no further development

CONDITIONING EVENT – Specific conditions or restrictions that apply to any logic gate (used primarily with PRIORITY, AND and INHIBIT gates).

UNDEVELOPED EVENT – An event which is not further developed either because it is of insufficient consequence or because information is unavailable.

HOUSE EVENT – An event which is normally expected to occur.
Fault Tree Symbols (Transfers)

TRANSFER SYMBOLS

TRANSFER IN – Indicates that the next tree is developed further at the occurrence of the corresponding TRANSFER OUT (e.g. on another page)

TRANSFER OUT – Indicates that this portion of the tree must be attached at the corresponding TRANSFER IN
Fault Tree Symbols (Gates)

GATE SYMBOLS

AND – Output fault occurs if all of the input faults occur.

OR – Output fault occurs if at least one of the input faults occur.

COMBINATION – Output fault occurs if n of the input faults occur.

EXCLUSIVE OR – Output fault occurs if exactly one of the input faults occurs.

PRIORITY AND – Output fault occurs if all of the input faults occur in a specific sequence. The sequence is represented by a CONDITIONING EVENT drawn to the right of the gate.

INHIBIT – Output fault occurs if the (single) input fault occurs in the presence of an enabling condition. The enabling condition is represented by a CONDITIONING EVENT drawn to the right of the gate.
Fault Tree Modeling of Pivotal Events (Cont.)

PRA model embodies a collection of various models (logic, reliability, simulation and physical, etc.) in an integrated structure.
The Concept of Cut Sets

- The primary reason for logic-based decomposition of IEs or pivotal events into more detailed causal events (primary events) is the identification of cut sets
- Cut set: A set of primary events whose simultaneous occurrence guarantees the occurrence of the top event (pivotal event)
- Minimal cut set: A cut set containing the minimum subset of primary elements whose simultaneous occurrence guarantees the occurrence of the top event
  - If one were to remove one of the events in a minimal cut set, the top event would not occur
Min Cut Sets for Pivotal Event (Leak not isolated)

Let "T" symbolize "Leak not detected"

The minimal cut sets for event T

\[ T = \text{CN} \cup \text{PP} \cup (\text{P1} \cap \text{P2}) \]

How to read it:

T occurs IF \{ CN occurs OR PP occurs OR P1 and P2 both occur \}

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Examples of Rules of Boolean Algebra

\[ A \cup (A \cap B) = A \]

\[ A \cap A = A \]

\[ A \cup A = A \]
Minimal Cut Sets for Pivotal Event (Leak not Detected)

\[ G_2 = P_1 \cap P_2 \]
\[ G_1 = CN \cup PP \cup G_2 \]
\[ G_1 = CN \cup PP \cup (P_1 \cap P_2) \]

Minimal cut sets
\[ CN \cup PP \cup (P_1 \cap P_2) \]

Minimal cut set: A minimum set of basic elements whose simultaneous occurrence guarantees the occurrence of the top event

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Minimal Cut Sets for Pivotal Event (Leak not isolated)

\[
\begin{align*}
\text{GI1} &= L \cup \text{GI2} \\
\text{GI2} &= /L \setminus \text{GI3} \\
\text{GI3} &= V1 \cup V2 \cup CN \\
\text{GI2} &= /L \setminus (V1 \cup V2 \cup CN) \\
\text{GI1} &= L \cup (/L \setminus V1) \cup (/L \setminus V2) \cup (/L \setminus CN)
\end{align*}
\]

Minimal cut sets
\[
L \cup (/L \setminus V1) \cup (/L \setminus V2) \cup (/L \setminus CN)
\]
One-to-Many Mapping of Scenarios 3, 6, and 9

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Can this scenario occur?

/LD = CN ∪ PP ∪ (P1 ∩ P2)

/LI = L ∪ (/L ∩ V1) ∪ (/L ∩ V2) ∪ (/L ∩ CN)
Conditional Events

<table>
<thead>
<tr>
<th>Hydrazine leaks</th>
<th>Leak detected</th>
<th>Leak isolated</th>
<th>No damage to flight critical avionics</th>
<th>No damage to scientific equipment</th>
<th>End state</th>
</tr>
</thead>
<tbody>
<tr>
<td>IE</td>
<td>LD</td>
<td>LI</td>
<td>A</td>
<td>S</td>
<td></td>
</tr>
</tbody>
</table>

- Intuitively, the likelihood of $/A_1$ should be smaller than $/A_2$

- A pivotal event is always conditional on the occurrence of the IE; and conditional on occurrence or non-occurrence of pivotal events that come before that.
- Characterization of pivotal events as conditional events is essential in order to properly quantify them.

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Probabilistic Modeling

Modeling of Pivotal Events Using Techniques such as Fault Tree

Modeling of Basic Events Using Various Techniques
(Some Examples are Shown Below)

\[ P_T(t) = 1 - e^{-\lambda t} \]
Type of Events that Appear in the Structure of Scenarios

- **Hardware failure**: failure mode(s) of hardware components
  - Example: isolation valve fails to close on demand
- **Software failure**
  - Example: controller program fails to generate isolation signal due to a software error
- **Phenomenological**: a sequence of physical, chemical or biological events
  - Example: Propellant Leak damages critical wire harnesses for avionics
- **Human error**: omission or commission errors
  - Example: Crew fails to isolate the leak after automatic isolation fails
- **Common cause failure (CCF)**: Failure of multiple components due to common physical environment or human interaction
  - Example: common cause failure of both pressure transducers
Data Development

- Events appear in the structure of scenarios are treated as uncertain quantities for which we need probability estimates. Sources of data:
  - **Hardware**
    - Historical data on a similar piece of equipment
    - General engineering knowledge about the equipment or an expert's experience with the equipment
  - **Phenomenological**
    - Experimental and simulation models
    - Expert judgment
  - **Human error**
    - Simulator data
    - Actuarial data
    - Expert judgement
  - **Common cause failure**
    - Parametric models (e.g., beta factor)
Use of Reliability Models to obtain Probability Estimates (an example)

- The simplest and widely-used model based on the assumption of exponential time-to-failure

- Probability of failure:

\[ P_f(t) = 1 - e^{-\lambda t} \]

Example: assume \( \lambda = 0.001 \) per hour

the probability that the device will fail before \( t=1000 \) hours is

\[ 1 - \exp(-1) = 0.632 \]

the probability that the device works for at least 1000 hours is

\[ 1 - 0.632 = 0.368 \]
Uncertainty Expressed as Probability Distribution

Typical uncertainties are associated with

- Numerical values of the parameters used in the model
- Inherent variability of stochastic processes

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Bayes’ Theorem

• The types of information available for the frequency of basic events include:
  – prior knowledge such as general engineering knowledge and the historical information from similar events,
  – the observed data for the event of interest in the system under study
• The Bayesian approach provides a formal mechanism for combing all available information, such as engineering and qualification test data, filed experience, expert judgment, and data from similar systems

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Bayes' Theorem (cont.)

Our prior knowledge about the failure rate

\[ \pi_0(\lambda) \]

Evidence: \( K \) failures in \( t \) hours of operation

\[ L(E | \lambda) = \frac{(\lambda t)^k e^{-\lambda t}}{k!} \]

Model: Poisson

\( K=2; \ t=1000 \) hours

Our model and observed data (evidence \( E \))

Use Bayes' Theorem to combine our prior knowledge and our evidence

\[ \pi_1(\lambda | E) = \frac{\pi_0(\lambda) \cdot L(E | \lambda)}{k} \]

Comparison of Prior and Posterior

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Probability Values Assigned to Basic Events of Example Problem

<table>
<thead>
<tr>
<th>Event Name</th>
<th>probability</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>CN</td>
<td>1.00E-04</td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>1.00E-03</td>
<td></td>
</tr>
<tr>
<td>P2</td>
<td>1.00E-03</td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>1.00E-04</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>1.00E-01</td>
<td>L and /L should add up to unity</td>
</tr>
<tr>
<td>V1</td>
<td>1.00E-03</td>
<td></td>
</tr>
<tr>
<td>V2</td>
<td>1.00E-03</td>
<td></td>
</tr>
<tr>
<td>/L</td>
<td>9.00E-01</td>
<td></td>
</tr>
<tr>
<td>/A1</td>
<td>1.00E-05</td>
<td>Conditional Pr. for the first branch of A</td>
</tr>
<tr>
<td>/A2</td>
<td>1.00E-01</td>
<td>Conditional Pr. for the 2nd &amp; 3rd branch A</td>
</tr>
<tr>
<td>IE</td>
<td>1.00E-02</td>
<td>Frequency per mission</td>
</tr>
</tbody>
</table>
Analysis Results for the Example Problem
Frequency of Leak Initiated Scenarios that Lead to Loss of Vehicle

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description of Scenario</th>
<th>Cut Set</th>
<th>Symbol</th>
<th>Meaning</th>
<th>Probability</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Hydrazine Leak, Isolated Promptly but Avionics Fail Anyway</td>
<td>1</td>
<td>IE</td>
<td>Leak</td>
<td>1.0E-2</td>
<td>1.0E-7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A1</td>
<td></td>
<td>Avionics fail even after successful isolation</td>
<td>1.0E-4</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Hydrazine Leak, Detection Failure Leading to Isolation Failure, Avionics Failure</td>
<td>2</td>
<td>IE</td>
<td>Leak</td>
<td>1.0E-2</td>
<td>1.0E-7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PP</td>
<td></td>
<td>Common cause failure of pressure transducers</td>
<td>1.0E-4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>/A2</td>
<td></td>
<td>Avionics fail after unsuccessful isolation</td>
<td>1.0E-1</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>3</td>
<td>IE</td>
<td>Leak</td>
<td>1.0E-2</td>
<td>1.0E-7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CN</td>
<td></td>
<td>Controller fails</td>
<td>1.0E-4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>/A2</td>
<td></td>
<td>Avionics fail after unsuccessful isolation</td>
<td>1.0E-1</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>4</td>
<td>IE</td>
<td>Leak</td>
<td>1.0E-2</td>
<td>1.0E-9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>P1</td>
<td></td>
<td>Pressure transducer 1 fails</td>
<td>1.0E-3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>P2</td>
<td></td>
<td>Pressure transducer 2 fails</td>
<td>1.0E-3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>/A2</td>
<td></td>
<td>Avionics fail after unsuccessful isolation</td>
<td>1.0E-1</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Hydrazine Leak, Detection Succeeded but Isolation Fails, Avionics Failure</td>
<td>5</td>
<td>IE</td>
<td>Leak</td>
<td>1.0E-2</td>
<td>1.0E-4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>L</td>
<td></td>
<td>Leak occurs upstream of isolation valves</td>
<td>1.0E-1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>/A2</td>
<td></td>
<td>Avionics fail after unsuccessful isolation</td>
<td>1.0E-1</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>6</td>
<td>iE</td>
<td>Leak</td>
<td>1.0E-2</td>
<td>9.0E-7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>/L</td>
<td></td>
<td>Leak occurs downstream of isolation valves</td>
<td>9.0E-1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>V2</td>
<td></td>
<td>Isolation valve V2 fails to close</td>
<td>1.0E-3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>/A2</td>
<td></td>
<td>Avionics fail after unsuccessful isolation</td>
<td>1.0E-1</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>7</td>
<td>IE</td>
<td>Leak</td>
<td>1.0E-2</td>
<td>9.0E-7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>L</td>
<td></td>
<td>Leak occurs downstream of isolation valves</td>
<td>9.0E-1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>V1</td>
<td></td>
<td>Isolation valve V1 fails to close</td>
<td>1.0E-3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>/A2</td>
<td></td>
<td>Avionics fail after unsuccessful isolation</td>
<td>1.0E-1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total</td>
<td>1.02E-4</td>
<td></td>
</tr>
</tbody>
</table>

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Characterizing Frequency of Events as Uncertain Quantities

- We are uncertain about the value of parameter(s) used to model occurrence probability of each event in the right
  - Example: We are uncertain about the value of the failure rate $\lambda$ that we assumed in the exponential failure model of Event "CN"

\[ \Pr(CN) = 1 - e^{-\lambda_{CN}t} \]

- We use log normal distribution to characterize our uncertainty for $\lambda_{CN}$
- Because $\lambda_{CN}$ is uncertain, $\Pr(CN)$ would become uncertain.

- Each distribution defined in the right represents the *uncertainty in the occurrence probability of the event* as a result of uncertainty in the value of a parameter(s) that is used to generate the probability

<table>
<thead>
<tr>
<th>Event</th>
<th>Mean</th>
<th>EF</th>
</tr>
</thead>
<tbody>
<tr>
<td>CN</td>
<td>1.00E-04</td>
<td>10</td>
</tr>
<tr>
<td>P1</td>
<td>1.00E-03</td>
<td>3</td>
</tr>
<tr>
<td>P2</td>
<td>1.00E-03</td>
<td>3</td>
</tr>
<tr>
<td>PP</td>
<td>1.00E-04</td>
<td>5</td>
</tr>
<tr>
<td>L</td>
<td>1.00E-01</td>
<td>3</td>
</tr>
<tr>
<td>V1</td>
<td>1.00E-03</td>
<td>3</td>
</tr>
<tr>
<td>V2</td>
<td>1.00E-03</td>
<td>3</td>
</tr>
<tr>
<td>/L</td>
<td>Dictated by L</td>
<td></td>
</tr>
<tr>
<td>/A1</td>
<td>1.00E-05</td>
<td>5</td>
</tr>
<tr>
<td>/A2</td>
<td>1.00E-01</td>
<td>3</td>
</tr>
<tr>
<td>IE</td>
<td>1.00E-02</td>
<td>4</td>
</tr>
</tbody>
</table>

We assumed all events are log-normally distributed

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Uncertainty Propagation through the Model

A single distribution for \( I_E \)

A single distribution for \( I_A1 \)

A single distribution for \( I_A2 \)

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Example of Risk Results

Probability Distribution for Loss of Vehicle
(Scenarios 3, 6, and 9)

- Mean = 1.04E-04
- 5th Percentile = 5.73E-06
- 50th Percentile = 4.66E-05
- 95th Percentile = 3.74E-04

Values in 10^-3
Frequency Values in 10^-3
Insights

- **One scenario dominates the risk**
  - leak occurs upstream of isolation valves. Because it is not isolable it can damage critical avionics
  - Contribution to risk: 97%

- **Options to reduce risk**

<table>
<thead>
<tr>
<th>OPTIONS</th>
<th>IE: Leak occurs</th>
<th>Leak occurs upstream of isolation valves</th>
<th>Leak damages critical avionics</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Do nothing</td>
<td>0.01</td>
<td>0.1</td>
<td>0.1</td>
<td>1.0E-4</td>
</tr>
<tr>
<td><em>Option 1</em>: Reduce the likelihood of leak between the propellant tank and isolation valves (e.g., change in piping design)</td>
<td>0.01</td>
<td>0.05 (see note below)</td>
<td>0.1</td>
<td>5.0E-5</td>
</tr>
<tr>
<td><em>Option 2</em>: Reduce susceptibility of avionics to leak (e.g., rerouting of wires and fortify wire harnesses)</td>
<td>0.01</td>
<td>0.1</td>
<td>0.01 (see note below)</td>
<td>1.0E-5</td>
</tr>
<tr>
<td>Option 1 and 2</td>
<td>0.01</td>
<td>0.05</td>
<td>0.01</td>
<td>5.0E-6</td>
</tr>
</tbody>
</table>

Note: The numerical values shown in this table are hypothetical.
Summary of PRA Strengths

- Quantifies performance measures
  - Probability of Loss of Crew (LOC)
  - Probability of Loss of Mission (LOM)
  - PRA metrics are integral risk metrics
- Captures dependences and other relationships between sub-systems
- Works within a scenario-based concept of risk that best informs decision-making
  - Identifies contributing elements (initiating events, pivotal events, basic events)
  - Quantifies the risk significance of contributing elements, helping focus on where improvements will be effective
  - Provides a means of re-allocating analytical priorities according to where the dominant risk contributors appear to be coming from
  - Provides a framework for a monitoring / trending program to detect risk-significant adverse trends in performance

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Summary of PRA Strengths (cont.)

- Quantifies uncertainty and ranks contributors to uncertainty
- Supports trade studies by quantifying
  - The most goal-related metrics
  - System interfaces and dependencies
  - Responses to system and function challenges
  - Effects of varying performance levels of different systems
- Can be a powerful tool when used to assist decision-making
PRA Results of a Real Space System

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International Space Station (ISS) Critical End States

12A.1 LOS

7A LOS

12A.1 LOC

7A LOC

12A.1 EVAC

7A EVAC

Probability of Occurrence (per month)

ISS PRA, Dec. 2000

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ISS Non-Critical End States

12A.1 LOSys
7A LOSys
12A.1 LOM
7A LOM
12A.1 COL
7A COL

Probability of Occurrence (per month)

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ISS Risk Drivers

Loss of Station

Loss of Crew

Evacuation

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