Probabilistic Risk Assessment (PRA): Analytical Process for Recognizing Design and Operational Risks

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Safety & Mission Assurance (S&MA)

Prepared for

Equinor Oil & Gas

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Roger L. Boyer Bio

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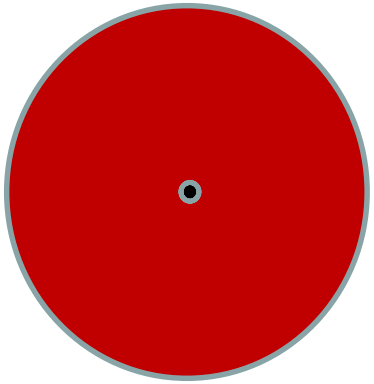
Since 2006, Roger has served as the Chief of the Analysis Branch of the Exploration Division with the National Aeronautics and Space Administration (NASA) at Johnson Space Center (JSC) in Houston, Texas. Roger is responsible for overseeing Probabilistic Risk Assessments (PRAs) and reliability analyses supporting the Space Shuttle, Mars, Constellation, Orion, Commercial Crew, Deep Space Gateway, and new lunar lander programs. He also serves as NASA's Cross Program PRA lead responsible for integrating the various exploration program PRAs (i.e. spacecraft, launch vehicle, human reliability, crew medical, external events, and ground operations) as well as overseeing the development of several new PRA methods for future use and serving on NASA's system safety steering group, human factors technical discipline team, and the integrated medical model steering committee.

Roger's career has evolved from performing deterministic thermal-hydraulic analyses and PRA in the nuclear power industry to advanced automation Fault Detection, Isolation, and Recovery (FDIR) and PRA in the aerospace industry and now working to introduce PRA to the oil and gas industry. The common theme has been promoting and supporting management's risk-informed decision making (RIDM) process from concept to design to operations with high quality risk assessments. He has over 35 years of experience providing both technical analyses and leadership in risk, reliability, thermal-hydraulic and accident analysis, to the nuclear, aerospace, and oil & gas industries.

Roger holds a dual BS in Nuclear and Mechanical Engineering and a MS in Nuclear Engineering from the University of Missouri at Rolla. He is also a Certified Reliability Engineer with the American Society for Quality.

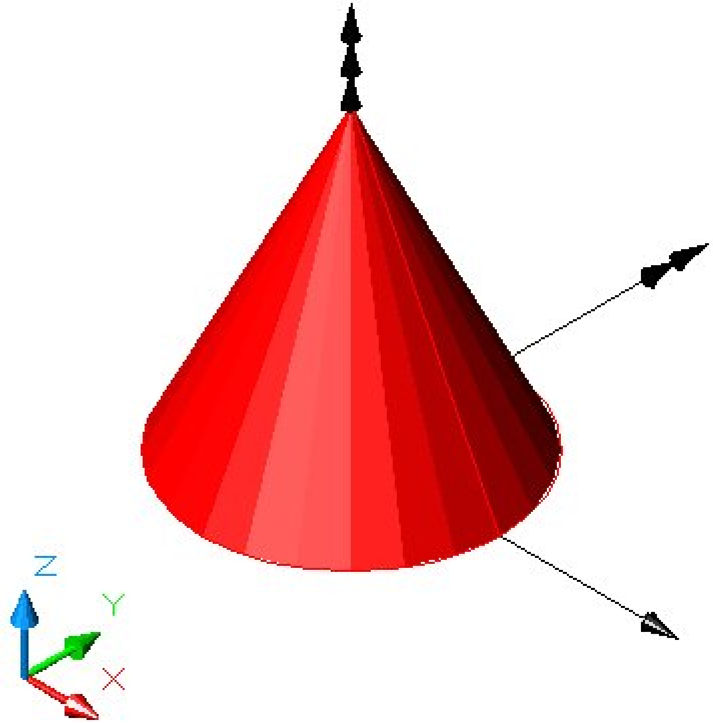
Pop Quiz:
Using different views in analysis

What does this look like?

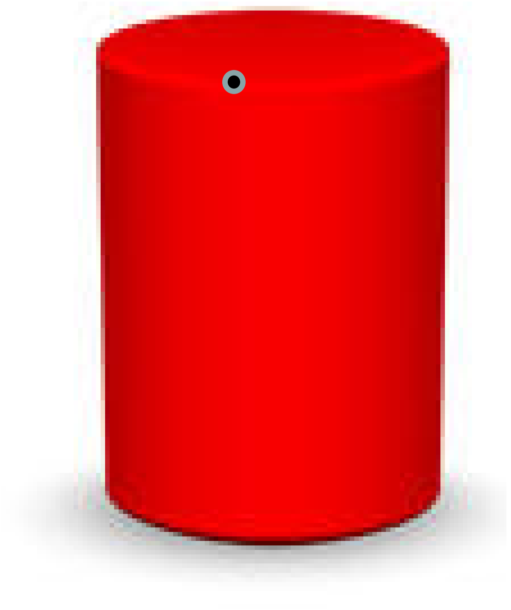


A circle with a dot in the center?
A sphere with a hole through the center?

It could be this…



Or it could be this…



A single view can mislead you…

Conclusion

Probabilistic Risk Assessment (PRA) is a tool to help you assess the risk by looking at systems and operations in a different view both quantitatively and qualitatively.

Given our available budget and time, we must be smart and efficient in how and what we do. That’s where PRA can make a difference.

Questions?

Introduction

- Probabilistic Risk Assessment (PRA) is one of the tools in NASA's Safety & Mission Assurance (S&MA) toolbox. It provides both depth and width in evaluating systems, vehicles, vessels, facilities, and missions.

- NASA continues to get budgets with high expectations from the public. S&MA must continue to do its job with less, thus we have to be smarter and more efficient.

- PRA has been used successfully in several industries, such as commercial nuclear power, aerospace, transportation, chemical, and medical.

- BSEE has hired NASA's Johnson Space Center (JSC) to use its PRA experience to develop a PRA procedures guide for the Oil & Gas industry <u>and</u> to develop several example applications.

Oil & Gas Examples

- **Facility Level Risk Assessment**
  - Deepwater Drilling Operation
  - Shallow Water Drilling Operation
  - Subsea Oil Production
  - Rigs and Platforms

- **System Level Risk Assessment**
  - Blowout Preventer (BOP)
  - Dynamic Positioning System (DPS)
  - Mud Systems

- **Focused risk trade studies between current and proposed process/design. For example:**
  - Evaluate the proposed requirement for additional subsea accumulator bottles in the Well Control Rule for a five year time frame vs. the existing system in API STD-53.
  - Comparing different BOP ram drivers and sealing.
  - Evaluating operational work arounds given an initiating event, such as bolt failure.

What is PRA?

- PRA is a comprehensive, structured, and disciplined approach to identifying and analyzing risk in engineered systems and/or processes. It attempts to quantify rare event probabilities of failures. It attempts to take into account all possible events or influences that could reasonably affect the system or process being studied. It is inherently and philosophically a Bayesian methodology. In general, PRA is a process that seeks answers to three basic questions:

  - ✓ What kinds of events or scenarios can occur (i.e., what can go wrong)?
  - ✓ What are the likelihoods and associated uncertainties of the events or scenarios?
  - ✓ What consequences could result from these events or scenarios (e.g., Loss of Crew, Loss of Mission, Loss of Hydrocarbon Containment, Reactor Core Damage Frequency)?

- There are other definitions and questions that it can help answer.
- The models are developed in “failure space”. This is usually different from how designers think (e.g. success space).
- PRAs are often characterized by (but not limited to) event tree models, fault tree models, and simulation models.

When can PRA be Performed?

NEW DEVELOPMENTS
The ideal time to conduct a PRA is at the beginning of the design process to incorporate the necessary safety and risk avoidance measures throughout the development phase at minimal cost.

EXISTING SYSTEMS
PRA can be applied to existing systems to identify and prioritize risks associated with operations. Risk assessments can evaluate the impact of system changes and help avoid compromises in quality or reliability while increasing productivity.

INCIDENT RESPONSE
In the event of unexpected downtime or an accident, our team can assess the cause of the failure and develop appropriate mitigation plans to minimize the probability of comparable events in the future.

In a nutshell, PRA can be applied from concept to decommissioning during the life cycle, including design and operations.

Some Background

- **In late fifties / early sixties Boeing and Bell Labs developed Fault Trees to evaluate launch systems for nuclear weapons and early approaches to human reliability analysis began**

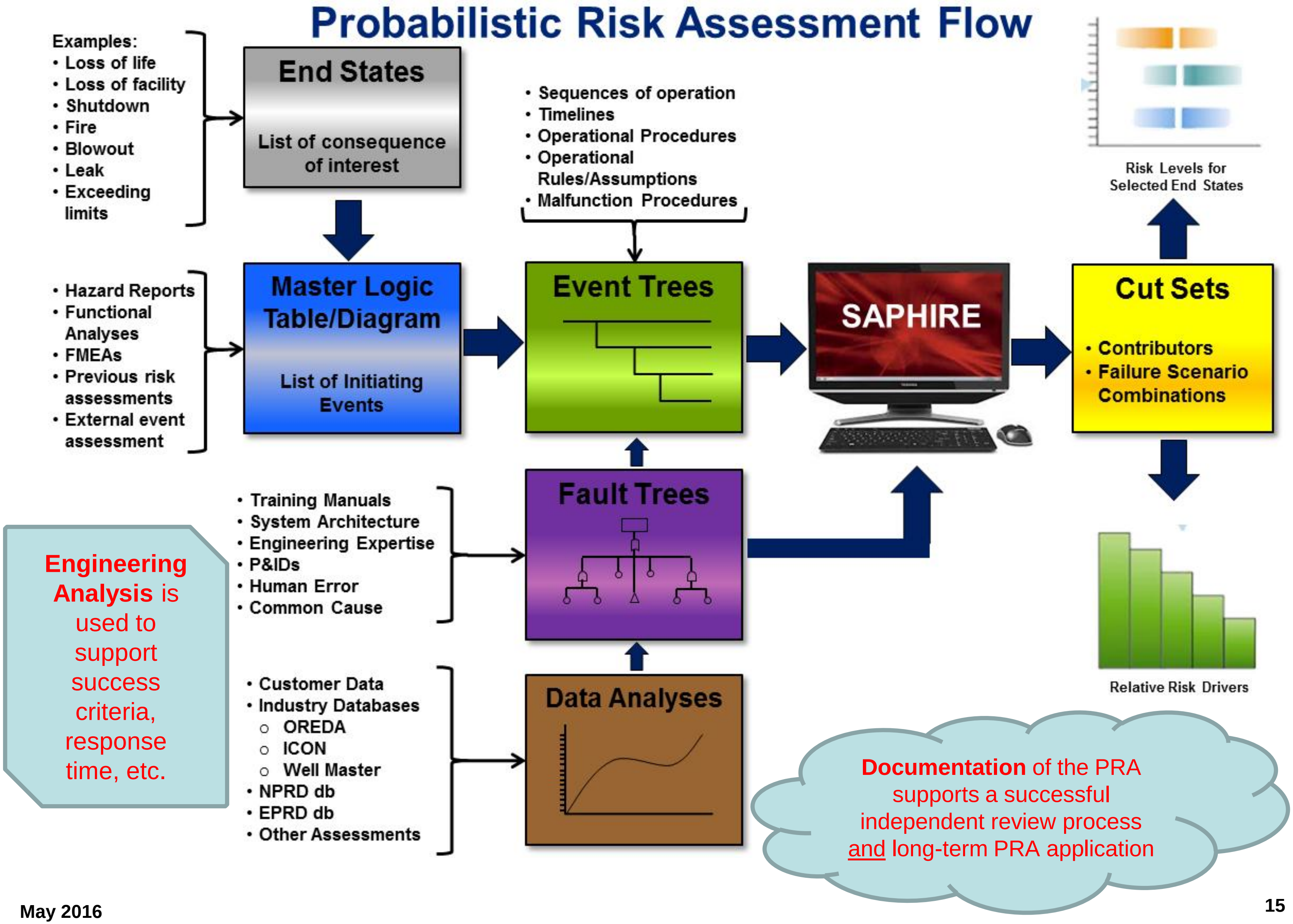
- **NASA experimented with Fault Trees and some early attempts to do Probabilistic Risk Assessment (PRA) in sixties (most notably on the Apollo Program) but then abandoned it and reduced quantitative risk assessment**

- **Nuclear power industry picked up the technology in early seventies and created WASH-1400 (Reactor Safety Study) in mid seventies.**
  - This is considered the first modern PRA
  - Was shelved until Three Mile Island (TMI) incident happened in 1979. It was determined that the WASH-1400 study gave insights to the incident that could not be easily gained by any other means.

- **PRA is now practiced by all commercial nuclear plants in the United States and a large amount of data, methodology and documentation for PRA technology has been developed by the industry and the Nuclear Regulatory Commission (NRC)**
  - All new Nuclear Plants must license their plants based on PRA as well as “Defense In Depth” concepts.
  - The NRC practices its oversight responsibility of the commercial nuclear industry using a “Risk” based approach that is heavily dependent on PRA.
  - SAPHIRE (Systems Analysis Programs for Hands-on Integrated Reliability Evaluations) is a PRA software tool developed by the Idaho National Lab for the U.S. NRC and also used by NASA.

PRA Overview

PRA Process



Probabilistic Risk Assessment Flow

Examples:
- Loss of life
- Loss of facility
- Shutdown
- Fire
- Blowout
- Leak
- Exceeding limits

End States

List of consequence of interest

- Hazard Reports
- Functional Analyses
- FMEAs
- Previous risk assessments
- External event assessment

Master Logic Table/Diagram

List of Initiating Events

- Sequences of operation
- Timelines
- Operational Procedures
- Operational Rules/Assumptions
- Malfunction Procedures

Event Trees

SAPHIRE

Cut Sets

- Contributors
- Failure Scenario Combinations

Risk Levels for Selected End States

Relative Risk Drivers

- Training Manuals
- System Architecture
- Engineering Expertise
- P&IDs
- Human Error
- Common Cause

Fault Trees

- Customer Data
- Industry Databases
  - OREDA
  - ICON
  - Well Master
- NPRD db
- EPRD db
- Other Assessments

Data Analyses

Engineering Analysis is used to support success criteria, response time, etc.

Documentation of the PRA supports a successful independent review process and long-term PRA application

The PRA Team

- **A PRA system analysis team includes both system domain experts and PRA analysts. The key to success is multi-way communication between the PRA analysts, domain experts, and management.**

- **A majority of PRA analysts have engineering degrees with operations and/or design backgrounds in order to understand how systems work and fail. This is essential in developing the failure logic of the vehicle or facility.**

- **Good data analysts understand how to take the available data to generate probabilities and their associated uncertainty for the basic events that the modelers can use or need.**

- **Building or developing a PRA involves:**
  - understanding its purpose and the appropriate modeling techniques,
  - designing how it will serve that purpose,
  - populating it with the desired failure logic and probabilities, and
  - trouble shooting it (nothing works the first time)

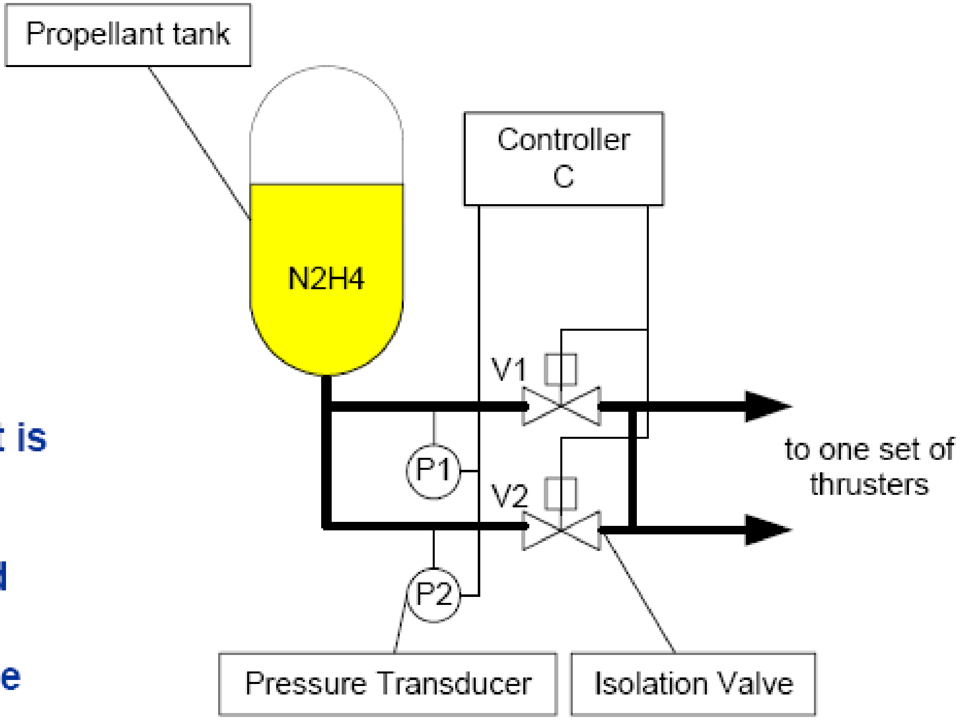
The PRA Team

JSC S&MA Analysis Branch

PRA Development Example

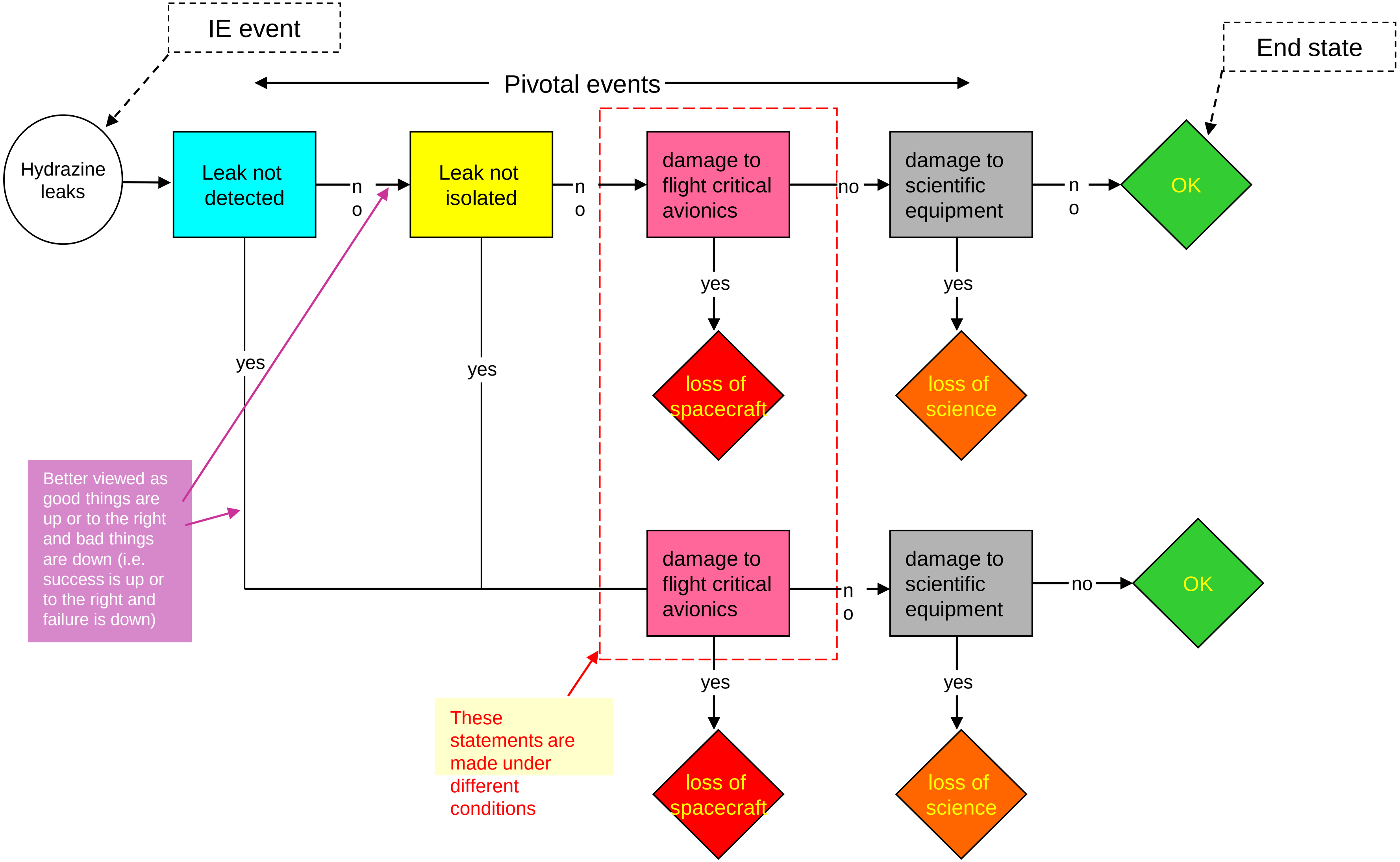
Simple Example of a Small PRA model

- The spacecraft is designed with two redundant sets of thrusters (independent of each other)
- Each propellant distribution module consists 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



Simplified Schematic of Propellant Distribution Module

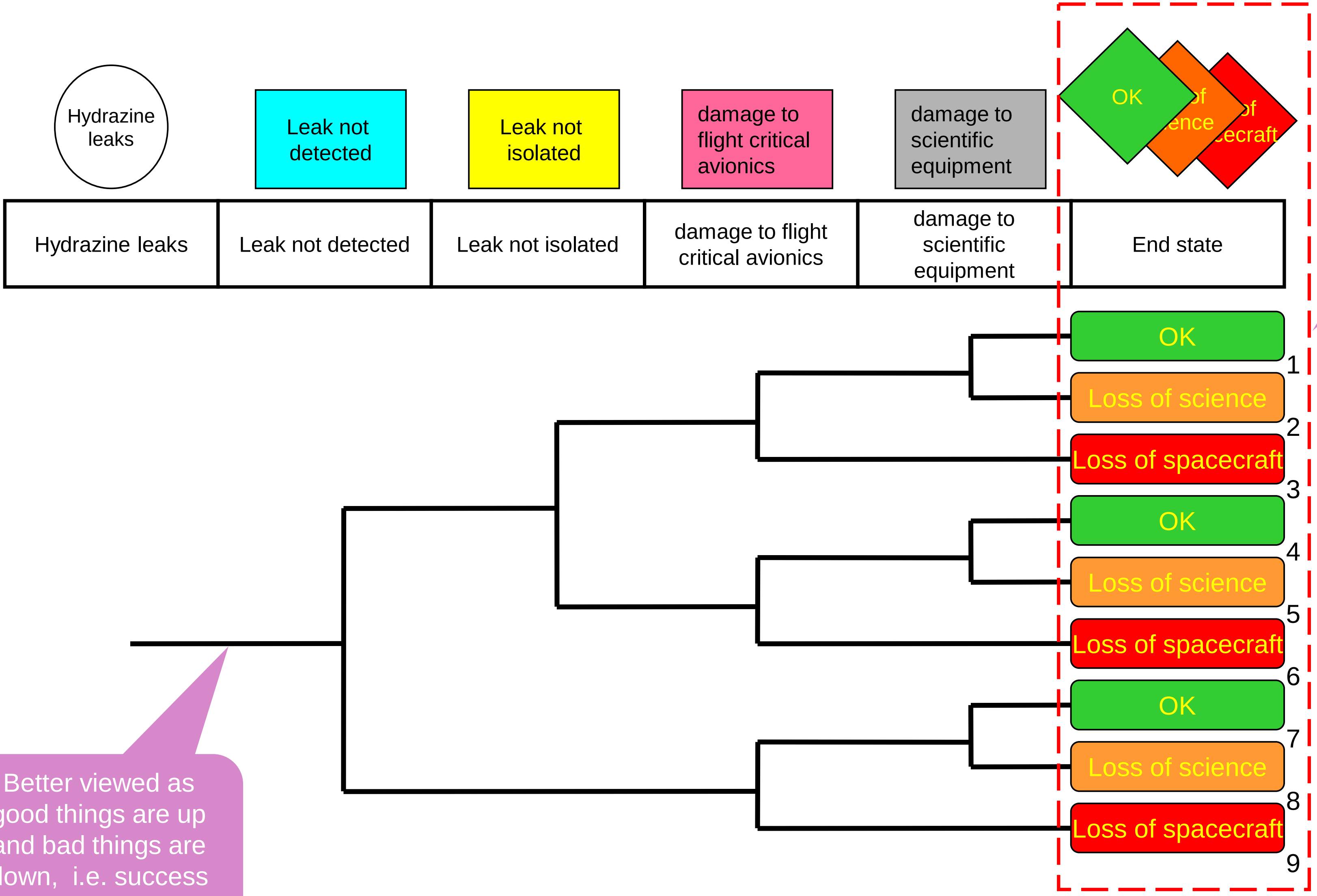
Example of Event Sequence Diagram (ESD)



Better viewed as good things are up or to the right and bad things are down (i.e. success is up or to the right and failure is down)

These statements are made under different conditions

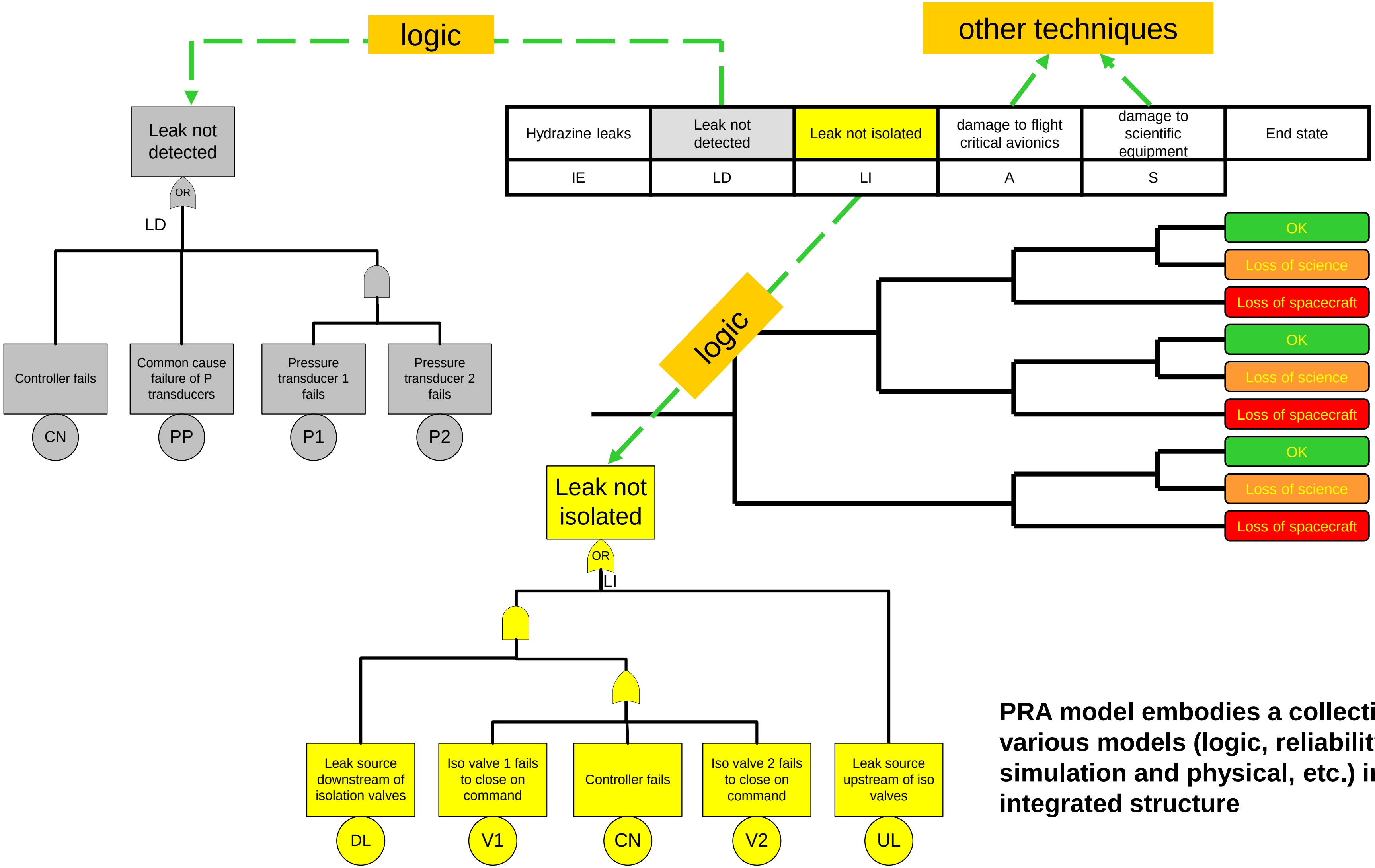
The ESD Translated Into an Event Tree



End states

Better viewed as good things are up and bad things are down, i.e. success up and failure down

Fault Trees Are Attached to the Event Tree



Hydrazine leaks	Leak not detected	Leak not isolated	damage to flight critical avionics	damage to scientific equipment	End state
IE	LD	LI	A	S	

logic
other techniques
logic
Leak not detected
OR
LD
Controller fails
Common cause failure of P transducers
Pressure transducer 1 fails
Pressure transducer 2 fails
CN
PP
P1
P2
OK
Loss of science
Loss of spacecraft
OK
Loss of science
Loss of spacecraft
OK
Loss of science
Loss of spacecraft
Leak not isolated
OR
LI
Leak source downstream of isolation valves
Iso valve 1 fails to close on command
Controller fails
Iso valve 2 fails to close on command
Leak source upstream of iso valves
DL
V1
CN
V2
UL

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

Data Analysis

Types of Data that Exist in the Models

- Functional – A functional failure event is generally defined as failure of a component type, such as a valve or pump, to perform its intended function. Functional failures are specified by a component type (e.g., motor pump) and by a failure mode for the component type (e.g., fails to start). Functional failures are generally defined at the major component level such as Line Replaceable Unit (LRU) or Shop Replaceable Unit (SRU). Functional failures typically fall into two categories, time-based and demand-based. Bayesian update as Shuttle specific data becomes available.

- Phenomenological – Phenomenological events include non-functional events that are not solely based on equipment performance but on complex interactions between systems and their environment or other external factors or events. Phenomenological events can cover a broad range of failure scenarios, including leaks of flammable/explosive fluids, engine burn through, over pressurization, ascent debris, structural failure, and other similar situations.

- Human – Three types of human errors are generally included in fault trees: pre-initiating event, initiating event (or human-induced initiators), and post-initiating event interactions.

- Common Cause – Common Cause Failures (CCFs) are multiple failures of similar components within a system that occur within a specified period of time due to a shared cause.

- Conditional – A probability that is conditional upon another event, i.e. given that an event has already happened what is the probability that successive events will fail

Common Cause Modeling

(More details and examples in Back-up Charts)

- **All large PRAs of complex and redundant machines must include "common cause" effects to be complete and accurate**
- **Common Cause are those conditions that defeat the benefits of redundancy**
  - Not "single point failures"
  - Similar to "generic cause"
- **There are three recognized ways to perform common cause modeling:**
  - The Beta Model
  - The Multiple Greek Letter Model
  - The Alpha Model
- **We use an iterative approach to modeling common cause first the Beta Model approach is used and if it shows up as a risk driver a Multiple Greek Letter Model is used**
- **Generic data from NUREG/CR-5485 for the majority of the events since there are few cases where there is enough Shuttle data to develop Shuttle specific values**
  - RCS Thrusters and ECO sensors are examples of cases where Shuttle specific data is used to calculate the common cause parameters

Unknown and Underappreciated Risks

- **Risk model completeness** has long been recognized as a challenge for simulated methods of risk analysis such as PRA as traditionally practiced.

- These **methods are generally effective** at identifying system failures that result from combinations of component failures that propagate through the system due to the functional dependencies of the system that are represented in the risk model.

- However, they are typically ineffective at identifying system failures that result from **unknown or underappreciated (UU)** risks, frequently involving complex intra- and inter-system interactions that may have little to do with the intentionally engineered functional relationships of the system.

Unknown and Underappreciated Risks (Cont'd)

- Earlier in 2009, the NASA Advisory Council noted the following set of contributory factors:
  - Inadequate definitions prior to agency budget decision and to external commitments
  - optimistic cost estimates/estimating errors
  - inability to execute initial schedule baseline
  - Inadequate risk assessments
  - higher technical complexity of projects than anticipated
  - changes in scope (design/content)
  - Inadequate assessment of impacts of schedule changes on cost
  - annual funding instability
  - eroding in-housetechnicalexpertise
  - poor tracking of contractor requirements against plans
  - Reserve position adequacy
  - lack of probabilistic estimating
  - “go as you can afford” approach
  - lack of formal document for recording key technical, schedule, and programmatic assumptions.

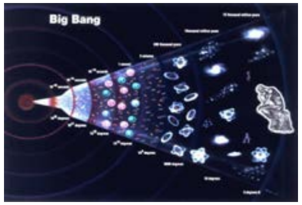
Example Results

Notional PRA Examples

First the Math

1.0E-02 = 0.01	➔	1:100 (Probable)	➔	~Shuttle Mission Risk
1.0E-06 = 0.000001	➔	1:1,000,000 (Improbable)	➔	having 20 coins simulaneously landing on tails
1.0E-12 = 0.000000000001	➔	1:1,000,000,000,000 (ridiculous)		

Time Perspective



1.2 x 10^{14} hours ago
~14 billion years ago

4 x 10^{13} hours ago
~4.5 billion years ago

2 x 10^{12} – 7 x 10^{11} hours ago
~228 – 80 million years ago

4 x 10^{8} hours ago
~46,000 years ago

2.1 x 10^{6} hours ago
~240 years ago

6.3 x 10^{5} hours ago
~72 years ago

Notional Uncertainty Distribution

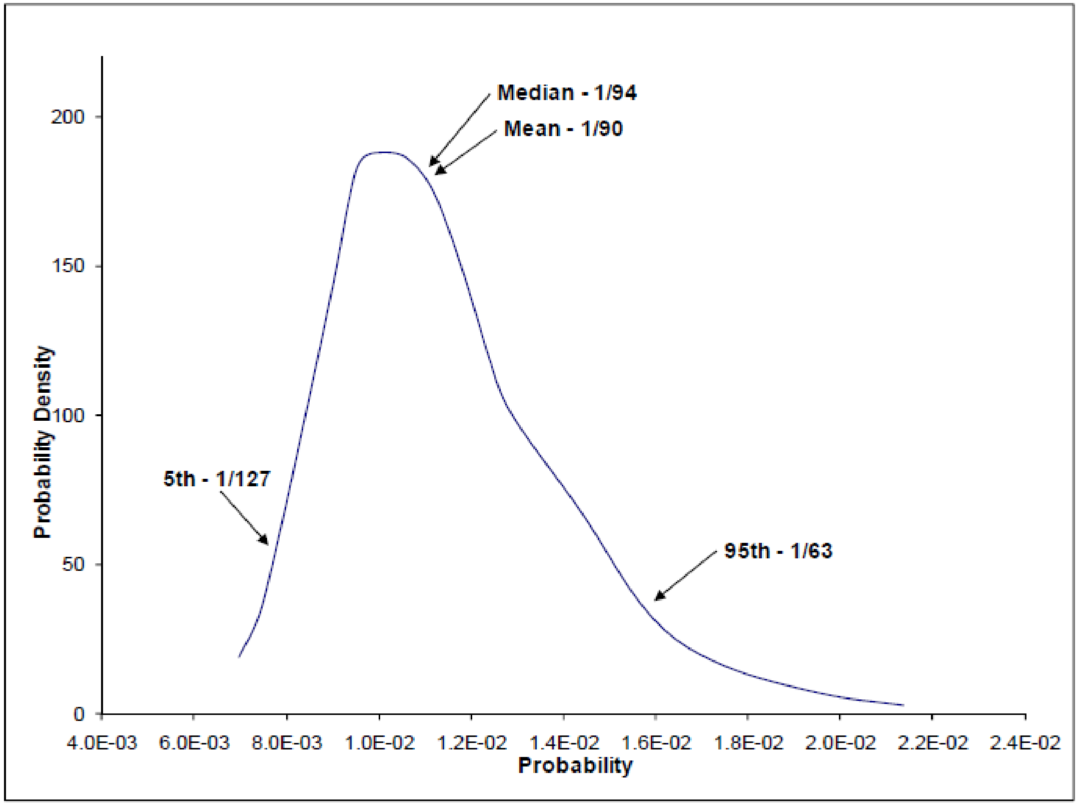
- This distribution is a representation of the uncertainty associated with a PRA's results
- The median is also referred to as the 50th percentile

Mean – 1.1E-02 (1:90)

Median – 1.1E-02 (1:94)

5th percentile – 7.9E-03 (1:127)

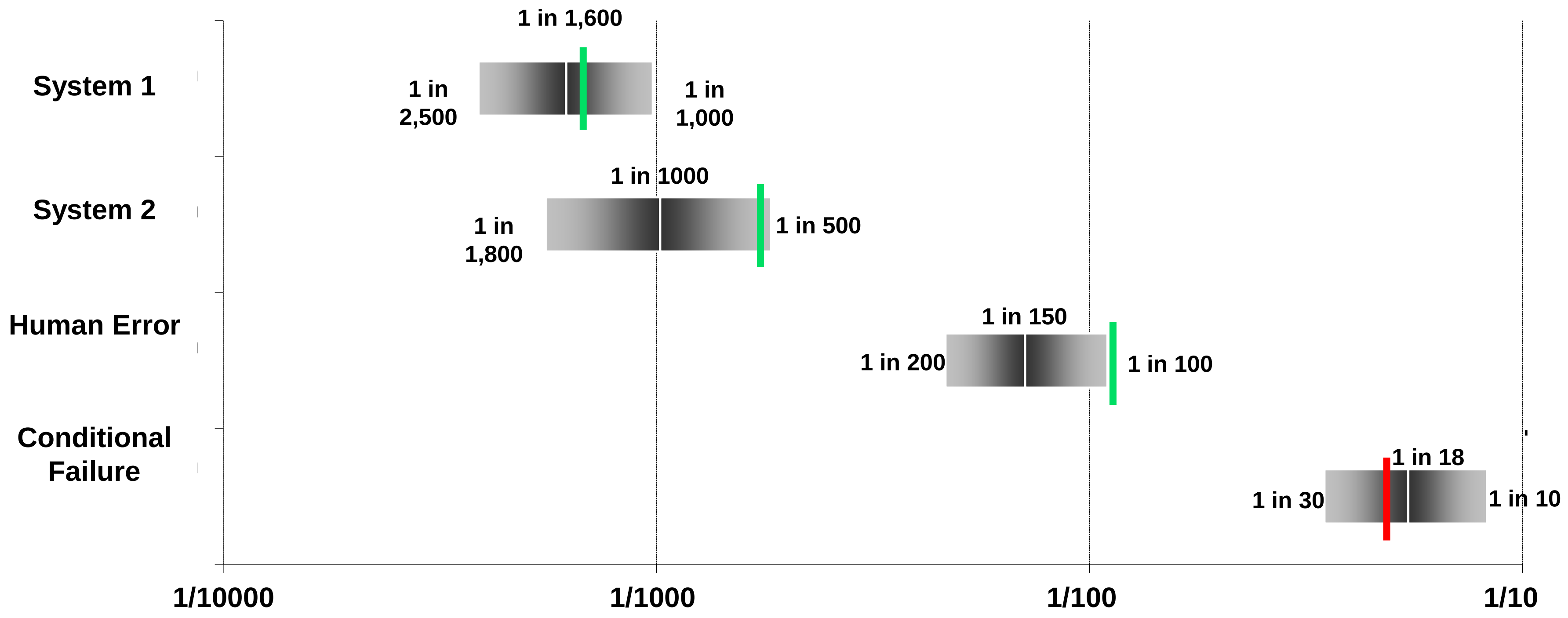
95th percentile – 1.6E-02 (1:63)



- The 5th and 95th percentile are common points on a distribution to show the range that 90% of the estimated risk lies between.
- The mean is a common measure of risk that accounts for uncertainty or this distribution, thus the value or metric used to verify LOC requirements.

Showing Uncertainty wrt Requirements

Notional



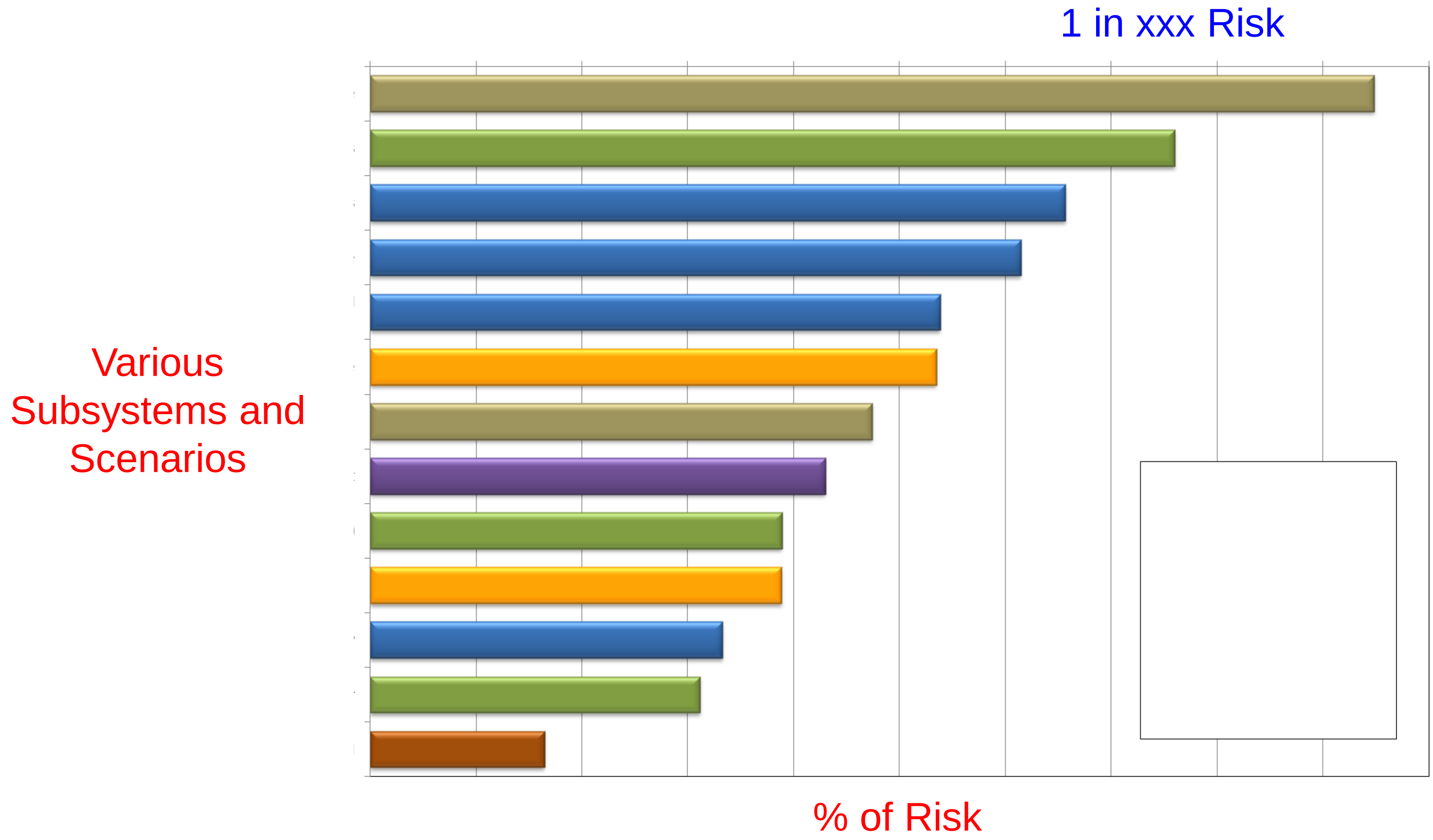
Green Bar shows Requirement Value is met

Red Bar shows Requirement Value is <u>not</u> met

Notional Risk Drivers via Pareto

(e.g. Top 80% of Calculated Risk)

A Pareto chart like this can be made for each project, rig, platform, etc.



In Closing

- **There is much more to know about PRA than what you've seen today. This presentation was to give you insight in order to ask the right questions when you are trying to decide:**
  - whether you need a PRA or not,
  - is it being performed properly and by qualified analysts,
  - is it answering the question(s) you <u>need</u> answered.

- **PRA (with the help of deterministic analyses) identifies <u>and</u> ranks the risk contributors. The FMEA analysts and Reliability Engineers can help solve the problem by focusing on the top risk drivers.**

Backup Charts

Acronyms and Definitions

1. **Cut set:** Those combinations of items that can cause a failure of the type that you are interested in. A “minimum cutset” is the minimum combination of items necessary to cause the failure of interest.
2. **End State:** The consequence of interest that is defined for what your model is supposed to calculate (sometimes will be referred to as a Top event or Figure of merit depending on model type).
3. **Top event (Top):** The top event in a fault tree or a pivotal event in an event tree. If an event tree uses a linked fault tree to calculate a pivotal event then the pivotal event name and Fault tree “Top” name need to be identical.
4. **MLD:** Master Logic Diagram. Used to identify all possible initiators.
5. **Event Tree:** A logic tool that is used to model inductive logic and quantify models using Boolean logic. Can be linked to other event trees and can use fault trees linked to it.
6. **Fault Tree:** A logic tool that is used to build deductive models of equipment or processes and is quantified with Boolean Logic. Can be linked to Event Trees for a linked fault tree model. Built from top down and quantified from bottom up.
7. **PRA:** Probabilistic Risk Assessment: A technique used for evaluating rare events for complex systems or processes. Attempts to account for all possible events that can cause the “end state”, “Top event”, “Figure of Merit”. Uses fault trees, event trees and other methods to “infer” the probability of events of interest. Better definition later.
8. **Rare Event:** An event that has a small probability of happening. From a data point of view, it will have never been seen in practice or seen only rarely. It will not have enough data to be statistically significant. From the “rare event approximation point of view it is a probability that is 0.1 or less.

Acronyms and Definitions

(continued)

9. **LOC: Loss of Crew:** A common “end state”, “top event” consequence, or “Figure of Merit” that we are interested in at NASA.
10. **LOM: Loss of Mission;** A common “end state”, “top event”, consequence, or “Figure of Merit” that we are interested in at NASA.
11. **Risk:** Probability or Frequency, times consequences
12. **“And” gate:** A logic symbol used in Fault Trees that multiplies inputs to it. In Boolean algebra it defines the “intersection” of events that are put into it.
13. **“Or” gate:** A logic symbol used in Fault trees that adds inputs to it. More accurately, in Boolean Algebra” it is the “union” of events that are put into it
14. **Bathtub Curve:** This is a curve shaped like a bathtub that represents infant mortality or break-in failures early in a component or systems life and wear-out or aging late in life with a relatively constant or flat line connecting them. The flat line or constant failure rate implies that failure rates are random and independent of time.
15. **Infant mortality:** The portion on the bathtub curve that is on the front end showing that failure rates are improving (becoming smaller) as time increases.
16. **Aging:** The Portion on the Bathtub curve that is on the back end that shows the failure rates increasing as components wear out or age.
17. **Exponential Distribution:** This is the distribution or equation that we use to represent the flat part of the bathtub curve (constant failure rate) and our PRA models that rely on the failure rates being random with respect to time. For reliability it is e^{-lt} and in failure space, it is $1-e^{-\lambda t}$

Acronyms and Definitions

(continued)

18. **Time Rate of Failure:** Failures that are defined as a rate of failure per time interval (e.g. failures per hour)
19. **Demand Failure:** Failures that are defined as a failure per demand.
20. **Conditional Probability:** This is a probability of occurrence that is pre-conditioned on a specific set of circumstances that precedes it or is concurrent with it.
21. **Frequency:** This is a rate (usually per time but can defined per other parameters such as demands etc.). This is a number greater than 0 but not necessarily less than 1.
22. **Probability:** Dimensionless number between 0 and 1. Describes the likelihood of something happening.
23. **Minimal Cutset:** A "minimum cutset" is the minimum combination of items necessary to cause the failure of interest.
24. **ESD: Event Sequence Diagram:** This is a tool sometimes used to help explain the flow of an event or events and can be directly represented by an event tree. It uses inductive logic. Relatively few computer software programs will quantify ESDs.
25. **Lambda:** This is a rate of failure. Often uses the Greek symbol l. Most of the time this will be a time rate of failure but can also be used to represent a "demand rate of failure".
26. **λ:** Greek letter Lambda often used to show a failure rate.

Acronyms and Definitions

(continued)

27. Lognormal Distribution: This is a distribution of events that if graphed on log paper it would show a normal distribution. It is a distribution often used in the PRA world to define the uncertainty of Lambda (l).
28. EF (Error Factor): This is a parameter used to help define the width of a lognormal distribution. It is defined as the 95th/50th = 50th/5th = Square root of 95th/5th . We will often times approximate a result of an uncertainty evaluation with a Lognormal distribution when it is in fact not a lognormal or any other kind of distribution but a lognormal does a good job of approximating it. In such cases we always try and use the definition of EF= Square root of 95th/5th.
29. Fussel Vessely (FV): Fussel Vesely importance measure. Represents how much of a components failure is contributing to the Top event or end state. Often expressed as a percentage it is not really and will be covered later.
30. Risk Increase Ratio (RIR): This is another importance measure that will tell you how much a Top Event or End State will increase if you set an items probability of failure to 1 and recalculate the end state or top event. It is equivalent to RAW.
31. Risk Achievement Ration (RAW): This is another importance measure that will tell you how much a Top Event or End State will increase if you set an items probability of failure to 1 and recalculate the end state or top event. It is equivalent to RIR.

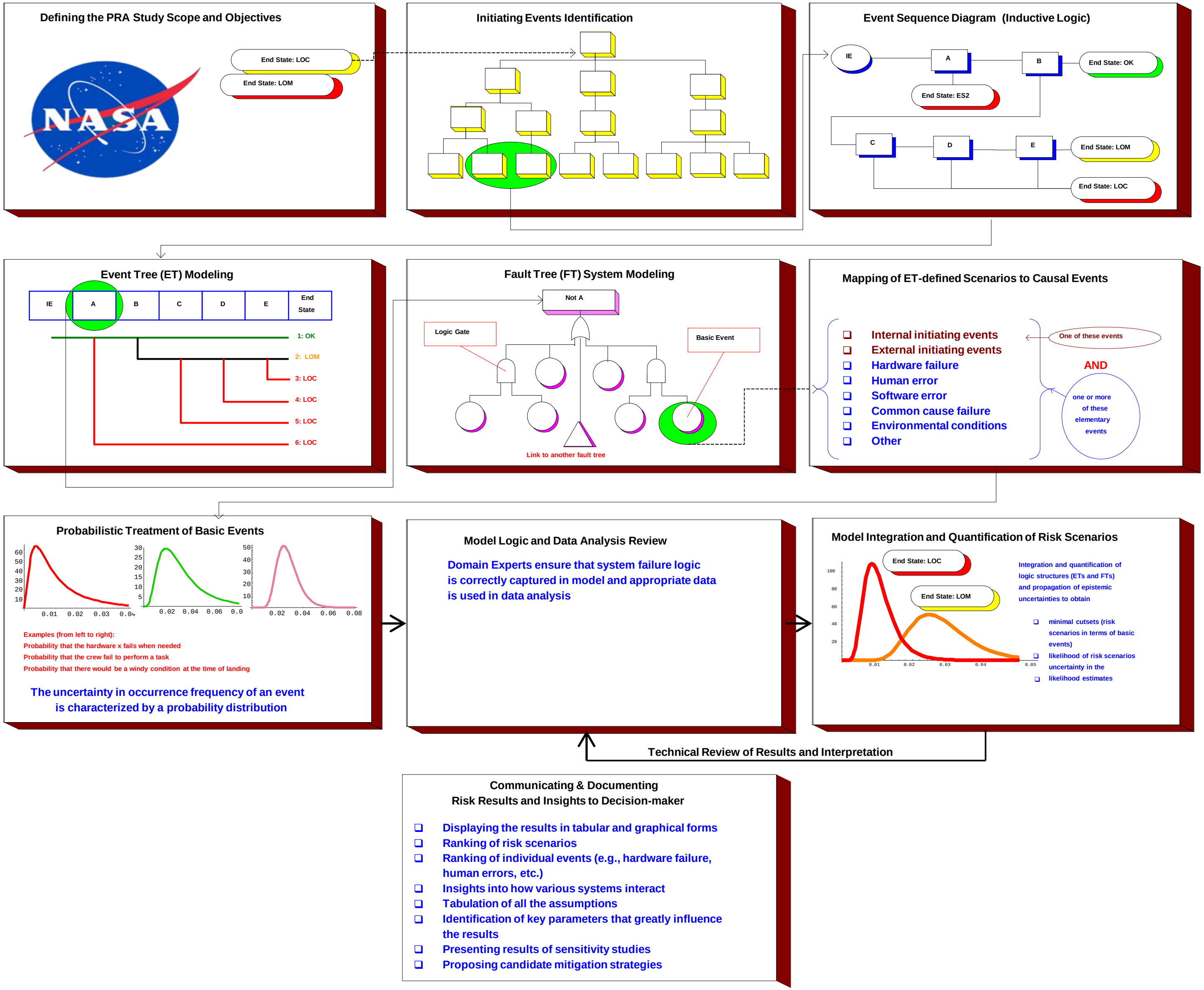
Acronyms and Definitions

(continued)

32. **Risk Reduction Ratio (RRR):** **This is another importance measure that will tell you how much a Top Event or End State will decrease if you set an items probability of failure to 0 and recalculate the end state or top event. It is equivalent to RRW.**
33. **Risk Reduction Worth (RRW):** **This is another importance measure that will tell you how much a Top Event or End State will decrease if you set an items probability of failure to 0 and recalculate the end state or top event. It is equivalent to RRR.**
34. **Common Cause Failure (CCF):** **This is a failure cause that can result in multiple failures of identical redundant equipment within a short time span therefore reducing the advantage of having redundant equipment. (e.g. contaminated lube oil fails multiple pumps in a redundant system).**
35. **Big Stew (BS)** ***extra credit:*** **This is a method defined by the incredibly brilliant Mark Bigler and Mike Stewart in order to model inter-phase dependencies using a linked fault tree model. The only reason Bigler is allowed to have top billing is so we can get a good and memorable Acronym (BS). It is also okay to consider the Big in “Big Stew” to be a modifier of Stew.**

PRA Development Process

PRA Development Process



Defining the PRA Study Scope and Objectives

Initiating Events Identification

Event Sequence Diagram (Inductive Logic)

Event Tree (ET) Modeling

Fault Tree (FT) System Modeling

Mapping of ET-defined Scenarios to Causal Events

- ❑ Internal initiating events
- ❑ External initiating events
- ❑ Hardware failure
- ❑ Human error
- ❑ Software error
- ❑ Common cause failure
- ❑ Environmental conditions
- ❑ Other

One of these events

AND

one or more of these elementary events

Probabilistic Treatment of Basic Events

Examples (from left to right):
Probability that the hardware x fails when needed
Probability that the crew fail to perform a task
Probability that there would be a windy condition at the time of landing

The uncertainty in occurrence frequency of an event is characterized by a probability distribution

Model Logic and Data Analysis Review

Domain Experts ensure that system failure logic is correctly captured in model and appropriate data is used in data analysis

Model Integration and Quantification of Risk Scenarios

Integration and quantification of logic structures (ETs and FTs) and propagation of epistemic uncertainties to obtain

- ❑ minimal cutsets (risk scenarios in terms of basic events)
- ❑ likelihood of risk scenarios uncertainty in the
- ❑ likelihood estimates

Technical Review of Results and Interpretation

Communicating & Documenting
Risk Results and Insights to Decision-maker

- ❑ Displaying the results in tabular and graphical forms
- ❑ Ranking of risk scenarios
- ❑ Ranking of individual events (e.g., hardware failure, human errors, etc.)
- ❑ Insights into how various systems interact
- ❑ Tabulation of all the assumptions
- ❑ Identification of key parameters that greatly influence the results
- ❑ Presenting results of sensitivity studies
- ❑ Proposing candidate mitigation strategies

PRA Development Process (2)

- **Defined the scope of the PRA**
  - Start with the end in mind or the question you want answered. For example, loss of hydrocarbon containment and loss of life failure end states
  - Define mission scope
  - Establish the mission/operational phases and layout the mission level event trees and corresponding top events to be analyzed

- **Develop logic models**
  - Assign top events to system analysts for each subsystem and work with domain experts to develop fault trees
  - System analysts work with data analysts and domain experts to determine level of detail and failure logic (develop fault trees to the level that data exists)
  - Obtain appropriate project office concurrence of system models (fault trees)

PRA Development Process (3)

- **Develop failure data into failure probabilities**
  - Obtain specific failure history or best available generic data
  - Data analysts calculate failure probabilities based on best available data and approved methods

- **Quantify the model, perform sanity checks, re-iterate until Team is in agreement**
  - Quantify the integrated model and perform sanity checks to determine which simplifying model assumptions need to be re-evaluated, where uncertainties need to be narrowed, where additional deterministic analyses are needed

- **Shares results with program and projects**
  - Risk ranking and risk insights
  - Incorporate feedback into PRA and into program/project design/ops
  - Maintain “Living PRA” to represent new program information (data updates) and evolving model scope

Common Cause

Common Cause

- Definition Of Common Cause Failure (CCF)
- Some basics
- Types Of CCF Models
- Examples of common cause
- Deriving common cause parameter values from data
- Examples of Beta’s calculated from real data (NASA and Nuclear)
- Conclusions

Common Cause Modeling

- **All large PRAs of complex and redundant machines must include "common cause" effects to be complete and accurate**
- **Common Cause are those conditions that defeat the benefits of redundancy**
  - Not "single point failures"
  - Similar to "generic cause"
- **There are three recognized ways to perform common cause modeling:**
  - The Beta Model
  - The Multiple Greek Letter Model
  - The Alpha Model
- **We use an iterative approach to modeling common cause first the Beta Model approach is used and if it shows up as a risk driver a Multiple Greek Letter Model is used**
- **Generic data from NUREG/CR-5485 for the majority of the events since there are few cases where there is enough Shuttle data to develop Shuttle specific values**
  - RCS Thrusters and ECO sensors are examples of cases where Shuttle specific data is used to calculate the common cause parameters

Common Cause Modeling (2)

HOW THE BETA MODEL APPROACH WORKS

- **Susceptibility groups (groupings of similar or identical equipment) of redundant trains or components are identified**

- **A common cause basic event is defined for these groups**

- **The common cause basic event failure rate is generated by taking the independent failure rate times a "Beta" factor.**
  - For the beta model it does not matter how many components are in the group
  - The "Beta" factor represents the probability of 2 or more failures given a failure has occurred
    - For this reason, the Beta Model may be conservative for component groups larger than 2.

- **The "Beta" factor is taken from NUREG/CR-5485 and has a different value for "Operating" failures vs. "Demand" failures**
  - Operating failures the "Beta" value is 0.0235
  - Demand failures the "Beta" value is 0.047

Common Cause Modeling (3)

HOW THE MULTIPLE GREEK MODEL APPROACH WORKS

- Similar to the Beta Model except that the Multiple Greek Model takes credit for the full redundancy and therefore can be much more complicated
  - For a 3 component group, there is a “beta” factor and a “gamma” factor where the “beta factor is still the probability of 2 or more failures and the “gamma” factor is the probability of 3 or more failures given 2 or more failures.

Common Cause Definition

- **In PRA, Common Cause Failures (CCFs) are failures of two or more components, subsystems, or structures due to a single specific event which bypassed or invalidated redundancy or independence at the same time, or in a relatively short interval like within a single mission**
  - May be the result of a design error, installation error, or maintenance error, or due to some adverse common environment
  - Sometimes called a generic failure.
- **Common Cause, as used in PRA, is <u>not</u> a single failure that takes out multiple components such as a common power supply to computers or common fluid header to multiple pumps.**
  - Single point failures such as these are modeled explicitly in a PRA

Some Basics on PRA and Common Cause Failures

- **PRA**
  - PRA is used to perform “rare event” analysis
    - If we had 1000 Space Stations operating for 50 years each and we had lost 60 of them we would not need to do a PRA to determine what the loss of station failure rate was
    - However, we have only had one Station operating for ~ 10 years with no loss of station so methods like PRA are needed to estimate this value
  - Most of the components used in space vehicles are designed to be low failure rates and limited numbers of these components mean that an actual failure rate number is difficult to calculate from operational data (uncertainty is high!)
- **Common Cause Parameters**
  - Beta is modeled as a fraction of the total failure rate.
    - Total failure rate = Independent failure rate + common cause failure rate
    - Beta = common cause failure rate / Total failure rate
    - This is ~ to common cause failure rate / independent failure rate (when Beta is small)
  - **If you have a low failure rate for a component, the common cause failure rate will be low too but could still have a high Beta factor**
  - _A failure rate is a rate such as Failures per hour and a Failure probability is derived by the equation of $1-e^{-\lambda t}$ where λ is the failure rate. When lt is a small value the equation can be simplified using the rare event approximation and we get Failure probability ~λt.

Note: **Beta is a parameter of a single modeling method, and there are several modeling methods and variations most work in similar fashion**

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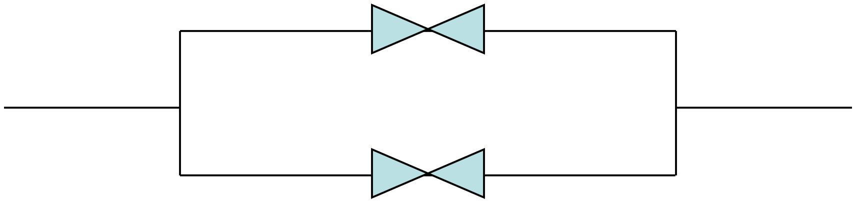
Types Of Common Cause Models

- Common Cause is modeled as a **conditional** probability, i.e. Given that a component has failed, what is the probability that another like component will fail
- Common models used are:
  - Beta (b) model – For a system with multiple like components, Beta factor is used to estimate the probability of failure of **all** components (i.e. two or more)

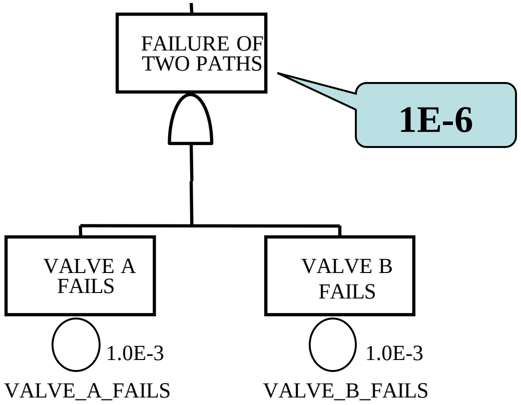
    - Values for Beta can range from 1 to 0.0001 (or less), but more typical values are usually between 0.1 and 0.001
  - Multiple Greek Letter (MGL) model – For systems with 3 or more like components, provides for a more explicit breakdown of possibilities, probabilities of two, three, four, etc. component failures
  - Alpha (a) model – Similar to the MGL model

Example Of Impact Of Modeling Common Cause

A system consisting of two trains:



Without Considering Common Cause



FAILURE OF TWO PATHS

1E-6

VALVE A FAILS

1.0E-3

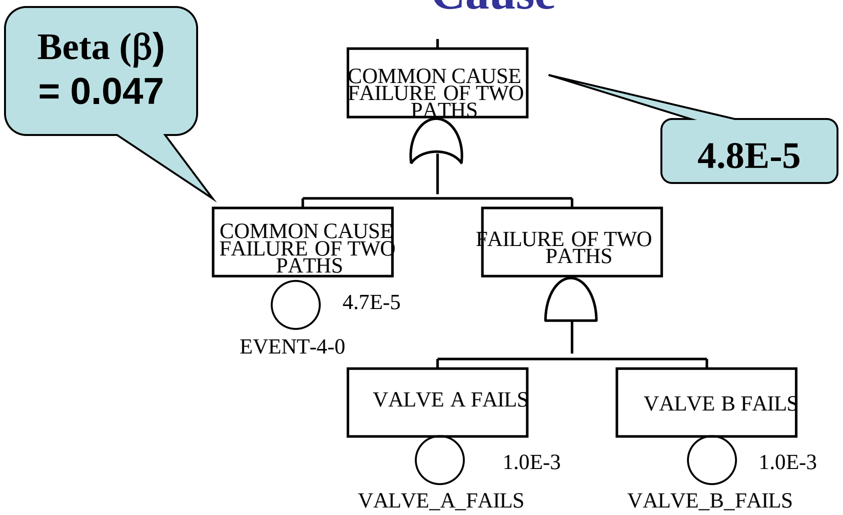
VALVE_A_FAILS

VALVE B FAILS

1.0E-3

VALVE_B_FAILS

Considering Common Cause



Beta (β) = 0.047

COMMON CAUSE FAILURE OF TWO PATHS

4.8E-5

COMMON CAUSE FAILURE OF TWO PATHS

4.7E-5

EVENT-4-0

FAILURE OF TWO PATHS

VALVE A FAILS

1.0E-3

VALVE_A_FAILS

VALVE B FAILS

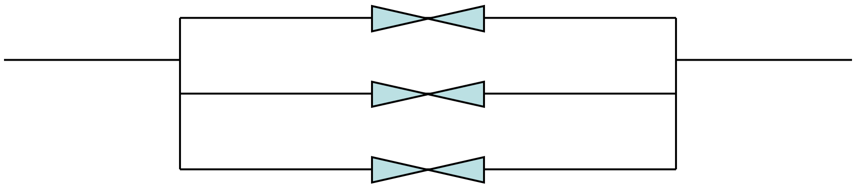
1.0E-3

VALVE_B_FAILS

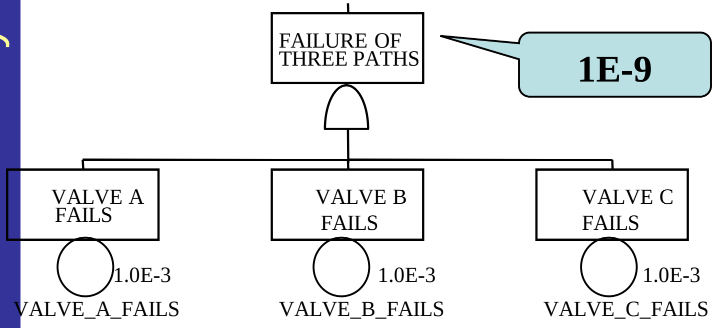
Results in a ~ 4.7E-05 Underestimate of Risk Which is 48 Times the Risk Without Considering Common Cause

Example Of Impact Of Modeling Common Cause

A system consisting of three trains:



Without Considering Common Cause



FAILURE OF THREE PATHS

1E-9

VALVE A FAILS

1.0E-3

VALVE_A_FAILS

VALVE B FAILS

1.0E-3

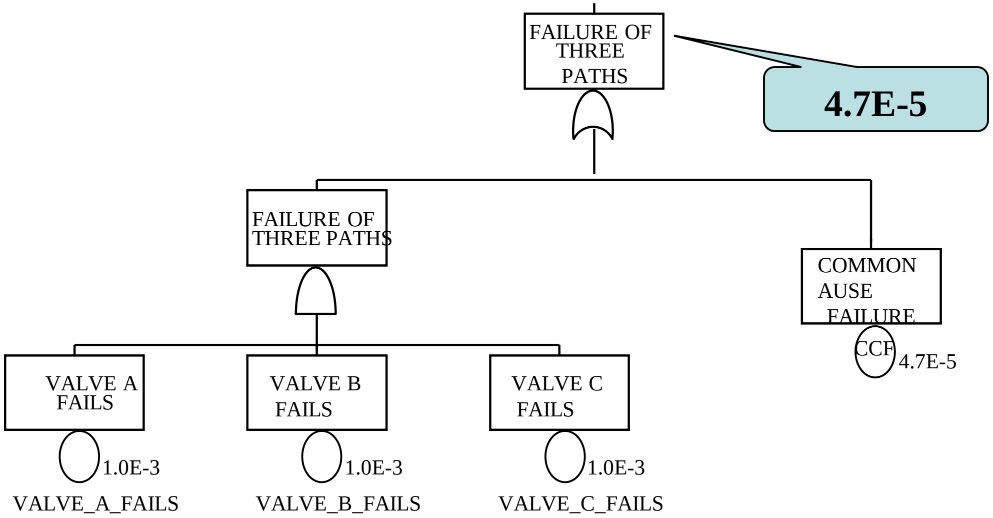
VALVE_B_FAILS

VALVE C FAILS

1.0E-3

VALVE_C_FAILS

Considering Common Cause (Beta Model)



FAILURE OF THREE PATHS

4.7E-5

FAILURE OF THREE PATHS

COMMON AUSE FAILURE

CCF

4.7E-5

VALVE A FAILS

1.0E-3

VALVE_A_FAILS

VALVE B FAILS

1.0E-3

VALVE_B_FAILS

VALVE C FAILS

1.0E-3

VALVE_C_FAILS

Results in a ~ 4.7E-05 Underestimate of Risk Which is 47,000 Times the Risk Without Considering Common Cause

Note: Using a MGL Model Would Reduce Result to 2.6E-05

When Should You Do a PRA?

- **As early in the design process as you can in order to affect the design and corresponding risk with minimal cost impact (i.e. to support Risk Informed Design (RID))**
- **When the risk of losing the project is greater than the company can live with either due to loss of life <u>or</u> for environmental <u>or</u> economic reasons**
- **To support Risk-Informed Decision Making (RIDM) throughout a project’s life cycle from “formulation to implementation” or “concept to decommissioning”**

How much does a PRA cost?

- **As you can also ask, "How much will it cost to not do a PRA?"**
- **The cost of a PRA is a function of the level of detail desired as well as the size/complexity of the item being assessed and the mission life cycle**
  - You should only model to the level of detail that you have data and no further. You may identify that significant risk exists at a sublevel, then your PRA is telling you that you need to study that level further. It may not be a PRA, but a reliability assessment at that time.
  - Modeling a drilling rig is on a different scale than just the Blowout Preventer (BOP). However, understanding the need for a BOP can be important in its design and operation.

Absolute vs Relative Risk?

- **You may have heard, “Don’t believe the absolute risk estimate, just the relative ranking”.**
- **Each event in a PRA is assessed to having a probability of failure (since the PRA is performed in “failure space”).**
  - these failures are combined via the failure logic which is used to determine how they are combined and the resulting scenarios.
  - the failure probabilities of each event are used to establish the probability of each scenario thus ranks the scenarios as well as being added to produce the overall risk.
  - If different approaches and methods are used (which sometimes are needed in full scope PRAs), then the absolutes can be challenged and so may their rankings. This is where experienced PRA analysts earn their pay to help minimize the difference.
- **As a result, some decision makers or risk takers want to know the overall risk, while others want to know how to reduce it by working on the top risk drivers first.**