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THE PAST, PRESENT, AND FUTURE OF PRA

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11/01/2023; RAMS XV Training Summit

Agenda

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01 Overview

02 What is PRA?

03 Differences between PRA and Reliability

04 History of PRA

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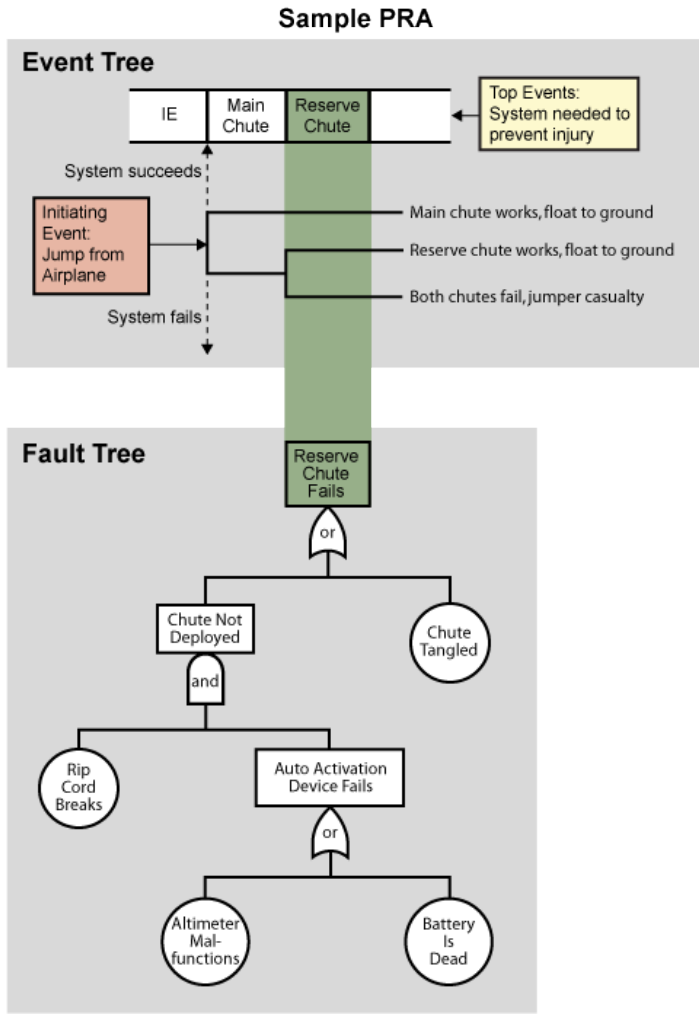
01 Overview

- Probabilistic Risk Assessment (PRA)/Probabilistic Safety Assessment (PSA) serves as a cornerstone for understanding and managing complex risks.
- Used across a wide array of industries, PRA’s history is based in weapons development, nuclear safety, and human spaceflight.
- As we approach a new era defined by emerging technologies—small modular reactors, advancements in artificial intelligence, or the establishment of lunar bases—our comprehension of PRA's past and present equips us to effectively navigate the future of risk assessment and management.

02 What is Probabilistic Risk Assessment?

- A systematic method for assessing three questions:
  1. What can go wrong?
  2. How likely it is?
  3. What might the consequences might be?
- When used correctly, PRA can positively impact design changes by pointing out risk drivers early on in the design process, which could potentially lower costs (design changes happen sooner than later) or improve safety.
- These questions allow the analyst to understand likely outcomes, sensitivities, areas of importance, system interactions, and areas of uncertainty, which can be used to identify risk-significant scenarios.
- "Probabilistic in Nature" - rare events.
  - "Loss of Mission/Vehicle/Crew"
  - "Core Damage Frequency"



03 PRA and Reliability

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PRA

- System scenario-based risk assessment.
- The results of the PRA are used to identify the major contributing elements (i.e., initiating events, pivotal events, and basic events) to the overall risk and quantify the risk significance of these contributing elements, helping focus on where improvements will be effective.
- PRA Tools:
  - Event Trees, Fault Trees, Data Analysis
  - Bayesian Inference
  - Uncertainty Analysis
  - Common Cause Modeling
  - Reliability Analysis
  - CDF, LERF, LOC, LOM, LOV – Figures of Merit

Reliability

- Broad design discipline concerned with loss of function.
- Reliability analysis involves evaluating component failure mechanisms in assessing critical design and process drivers.
- The reliability figure of merit is the probability that an item will perform its intended function for a specified mission profile.
- RAM VII Training Summit Presentation – "The Similarities and Differences between Reliability Engineering and Probabilistic Risk Assessment (PRA)," Dr. Fayssal Safie

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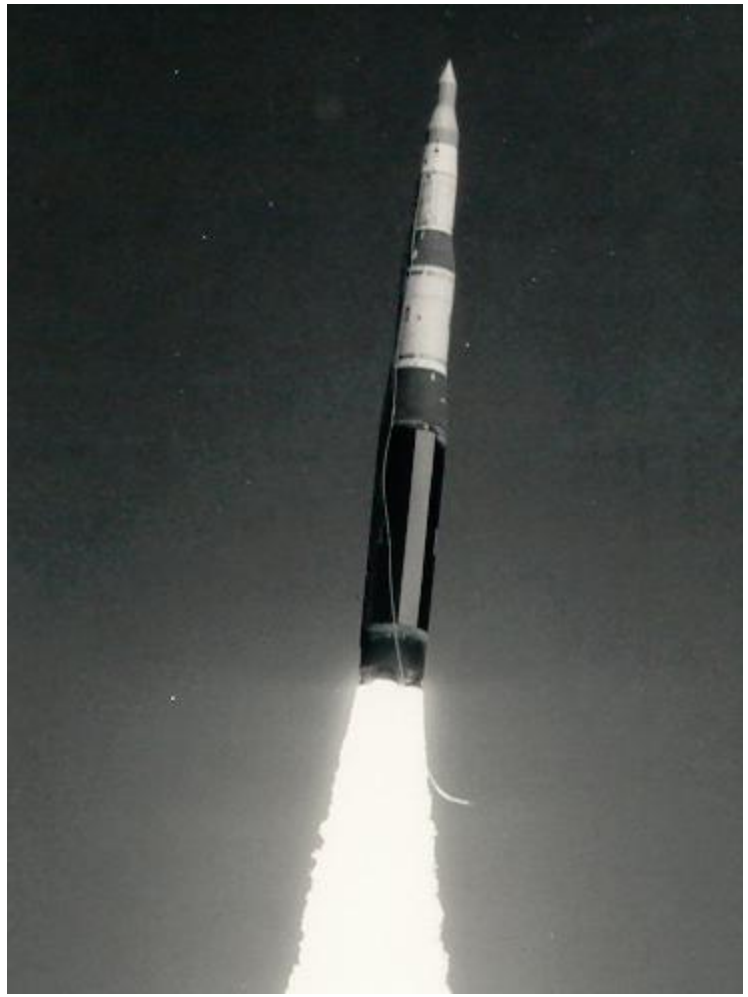
A BRIEF HISTORY OF PRA

1957; WASH-740

- Post WW-1, greater emphasis on reliability engineering with qualitative comparisons in systems.
- WW-2 German V-1 Flying Bomb achieved a 60% reliability with high level quantitative analysis.
- 1949, Reactor Safeguard Committee expresses concern with possibility and consequences of runaway reactions, desire for information on accident probabilities.
- Hanford staff recommend “bottom up” methodology for calculating probabilities based on concept of accidents as chains of events (1953).
- WASH-740, "Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants" (also known as "The Brookhaven Report"), estimated the maximum credible accident for a reactor with no containment as 1 in 100,00 to 1 in 1 Billion.
  - 3400 deaths
  - $7 billion in property damage (~$73 billion in 2023)

1962; Bell Labs Fault Tree Analysis



- Fault tree analysis (FTA) was originally developed in 1962 at Bell Laboratories by H.A. Watson, under a U.S. Air Force Ballistics Systems Division contract to evaluate the Minuteman I Intercontinental Ballistic Missile (ICBM) Launch Control System
- Dave Haasl, then at Boeing, recognized the value of this tool and led a team that applied FTA to the entire Minutemen Missile System
- Use spread at Boeing, and FTA was then used during the design of commercial aircraft

1975; Wash-1400

- WASH-1400, 'The Reactor Safety Study', was a report produced in 1975 for the Nuclear Regulatory Commission by a committee of specialists led by Professor Norman Rasmussen.
  - Built off work done by Dr. Ian Wall at General Electric (GE).
- Dr. Rasmussen was a physicist who, at the time, was the head of the nuclear engineering department at the Massachusetts Institute of Technology, known as the “father of PRA”
- WASH-1400 considered the course of events that might arise during a serious accident at a (then) large modern Light water reactor. It estimated the radiological consequences of these events, and the probability of their occurrence, using a fault tree/event tree approach
  - 60 People, 3 Years, ~4 Million Dollars (~23 million in 2023)
- Two plants, Surry (PWR) and Peach Bottom (BWR), used as basis for study
- Results:
  - Accident likelihoods higher than previously assumed (around 6x10-5 /ry vs. 1x10-8) but consequences are lower
  - Risk can be dominated by less severe, more likely scenarios (SLOCA>LLOCA)
- The 1975 WASH-1400 report was not well recognized in our community received, however, the 1979 Three Mile Island core melt led to re-consideration of PRA tool.

1980; Indian Point PRA and NUREG-0492

- Union of Concern Scientist launch petition to close Indian Point pending resolution of safety issues.
- Indian Point Probabilistic Safety Study 1980-1982 quantified the risk and assessed severe accident management alternatives.
- Reviews by Sandia National Lab (SNL) and Brookhaven National Lab (BNL) provided basis for the Atomic Safety Licensing Board decision to allow for continued plant operation.
- A similar study for Zion Nuclear Plant (between Chicago and Milwawkee) kicked off widespread use of PRA in Nuclear industry.
- 1981; NUREG-0492, Fault Tree Handbook is published:
  - “This handbook has been developed not only to serve as text for the System Safety and Reliability Course, but also to make available to others a set of otherwise undocumented material on fault tree construction and evaluation”

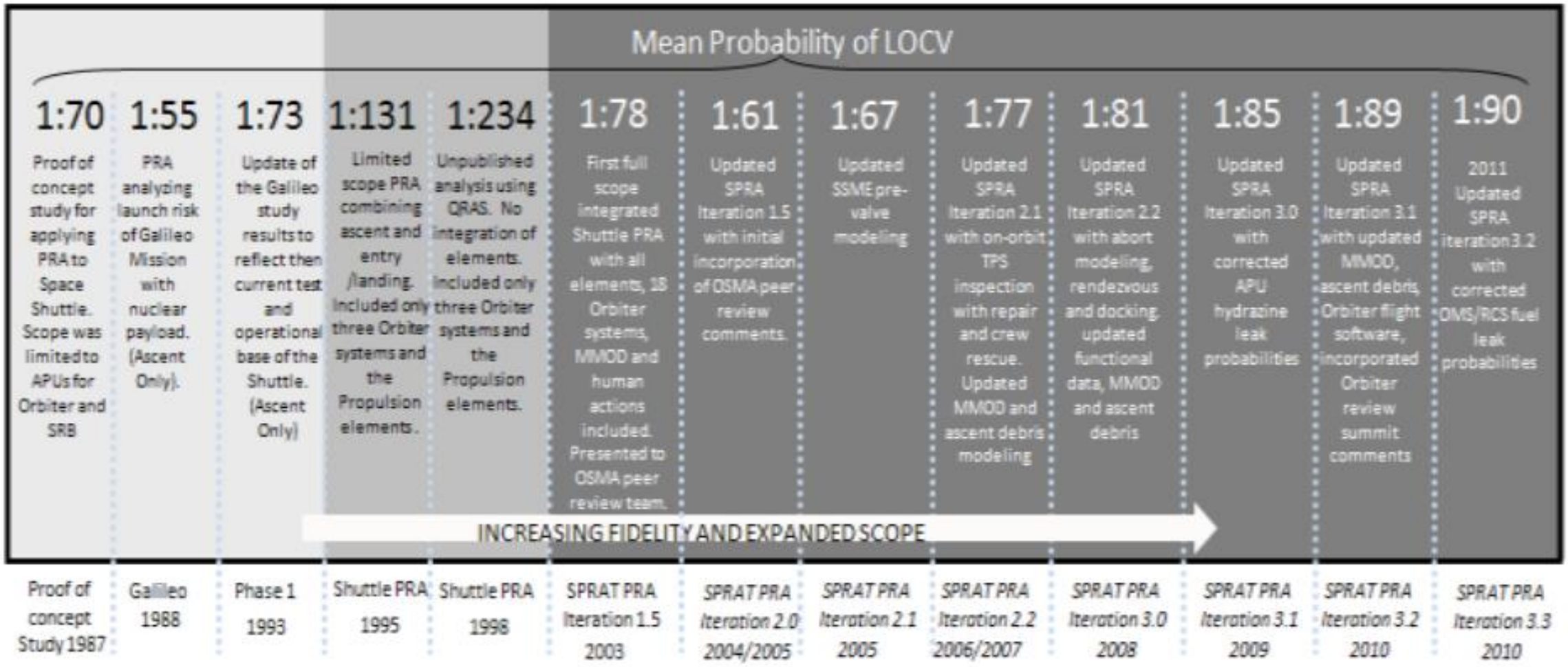
Nuclear PRA

- Components of the modern PRA begin to take shape:
- 1983; Human Reliability Analysis published in NUREG-1278, developed the THERP (Technique for Human Error Rate Prediction) Approach
- First Modern PRA, NUREG-1150/4550 (1990).
  - Summarized risks from severe accidents in five commercial nuclear power plants in the United States.
    - Estimated frequencies of core damage accidents from internally initiated accidents and externally initiated accidents for two of the plants;
    - Performance of containment structures under severe accident loadings;
    - Potential magnitude of radionuclide releases and offsite consequences of such accidents;
    - The overall risk (the product of accident frequencies and consequences)
    - Lot more detail for the T-H success criteria, HRA, and consequence analysis.

History of PRA at NASA

- Following the Challenger accident in 1986, the Rogers Commission Report recommended that NASA use PRA to evaluate the Shuttle design and operation.
- NASA started by applying PRA to evaluate nuclear payload launches for ascent only. Later, a 1995 PRA was performed for ascent and descent operations with minimal in-space application.
- By 2001, the Shuttle Program sanctioned a full scope PRA that was interrupted by the Columbia accident.

LOCV Estimation 1987-2010



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THE PRESENT
USE CASES IN INDUSTRY

Probabilistic Risk Assessment Today

- PRA methodology has developed and evolved over the past 50 years, and has more merit as an effective technique to evaluate risk in a complex system.
- PRA has developed into a tool used in multiple industries
  - Nuclear
  - Human spaceflight
  - Oil, gas, Industrial and Chemical Facilities
  - Medical
  - Environmental protection

Nuclear

- By 1990, the NRC required every US nuclear power plant (more than 100) to perform an Individual Plant Examination (IPE), which was accomplished using PRA.
- Internal Events Models, Seismic PRA, Fire PRA
- NUREG/CR-6928; Failure Rate data for the industry updated every few years by NRC and Idaho National Lab (INL).
- Level 1, 2, and 3 Models
  - Level 1: Provides first measure of risk (Core Damage Frequency), models a plant's response to an event that challenges plant operation. The frequency for each core damage accident sequence is estimated, and the frequencies for all core damage sequences are summed to calculate the total core damage frequency.
  - Level 2: Plant's response to Level 1 accident sequences, otherwise called a severe accident sequence. A Level 2 PRA analyzes the progression of an accident by considering how the containment structures and systems respond to the accident, which varies based on the initial status of the structure or system and its ability to withstand the harsh accident environment.
  - Level 3: *Consequence Analysis*; Estimates the consequences in terms of injury to the public and damage to the environment, and is based on the characteristics of the radioactivity release calculated in the Level 2.

Nuclear (Cont)

Risk-Informed Activities/Regulations –

"The increased use of Probabilistic Risk Assessments (PRAs) in the NRC's regulatory decision-making process requires increased confidence that the completeness, correctness, accuracy, and fidelity of the technical contents of a PRA are sufficient for its intended use, also referred to as the acceptability of the PRA" – USNRC

- RG 1.174 – "An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions On Plant Specific Changes to the Licensing Basis"
- RG 1.175 – Risk Informed Inservice Testing
- RG 1.177 – Risk Informed Technical Specifications
- RG 1.201 – Risk Informed Categorization and Treatment of SSCs
- RG 1.205 – Risk Informed Performance-Based Fire Protection

NASA/Human Spaceflight

- International Space Station PRA started in 1999. It includes hardware, medical, micro meteroid and orbital debris (MMOD). A fire assessment was added in 2011.
  - PRA Analysis enables the ISS Program to identify categories of risk and mitigate potential sources based on their risk contribution.
- Artemis Campaign Cross Program PRA (Orion, Space Launch System, Gateway, Exploration Ground Systems, HLS) used to capture overall risk associated with each Artemis mission.
  - Since 2014, the NASA Administrator has established an agency LOC threshold of 1 in 75 for cis-lunar missions.
  - Also used to establish Technical Performance Measures, which inform program managers a monitored risk is approaching an allocated threshold requirement (e.g., 1 in 300 for Ascent risk).
- “Preliminary PRA” is also used to evaluate design trades and architecture options (Thermal Control System single loop vs dual loop).

Medical/Oil-Gas

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Medical

- Socio-technical probabilistic risk assessment (ST-PRA) is a tool that incorporates risk estimates from the literature and uses experiential estimates from health care providers to estimate risks in rare health care outcomes.
- Examines single point failures and failure combinations, thereby allowing investigators to design interventions to reduce risks associated with the performance of process steps in a health care procedure.
- Aimed at improving patient safety.

Oil-Gas

- On offshore platforms, one of the primary reasons for hydrocarbon releases is the combination of process upsets and human errors.
- PRA is used to relate system reliability with the Human Reliability Analysis (HRA) to quantity the risks and impacts of fire, explosions, and hydrocarbon releases on offshore facilities.
- HAZOPs (Hazard and Operability Study) technique most often used to support risk studies in Oil-Gas.

Environmental Protection

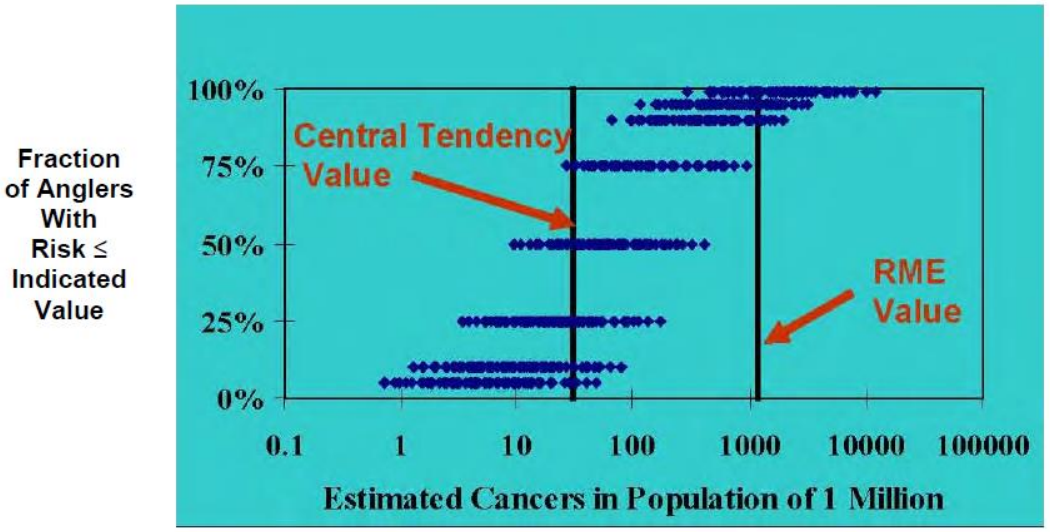

Figure A-1. Monte Carlo Cancer Summary Based on a One-Dimensional Probabilistic Risk Analysis of Exposure to Polychlorinated Biphenyls. The estimated cancer rate was calculated based on the consumption of fish from a contaminated sediment site. Source: USEPA 2000b.

- PRA of Exposure to Polychlorinated Biphenyls (PCB) via Consumption of Fish From a Contaminated Sediment Site.
  - PCBs used as a fire preventative and insulator.
  - Banned for use by the EPA in 1977.
  - During the 30yrs prior, estimated that 1.3million pounds were dumped into the Hudson River.
- A deterministic approach informed that consumption of recreationally caught fish provided the highest exposure among relevant exposure pathways, which resulted in cancer risks and noncancer health hazards that exceeded regulatory benchmarks.
- Conducted a PRA characterize the variability in risks associated with the fish consumption exposure pathway.
- PRA concluded that while the central tendency values agreed, the RME (reasonable maximum exposure) that was determined fell outside the 95th percentile.

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THE FUTURE

Advanced Nuclear Technologies

- PRA helps informed new designs to a greater extent than existing reactors and plants.
- Small Modular Reactors
  - GE-Hitachi BWRX-300
- Sodium-Cooled Fast Reactors
  - Natrium™ – a TerraPower & GE Hitachi technology
- Passively Safe Designs, Smaller Nuclear Footprints
- Just as probabilistic risk assessment (PRA) is a key activity in assuring the safety of nuclear power plants, generation risk assessment (GRA) is a key activity in assuring productivity and profitability as plants worldwide become more competitive.
  - Includes economic risk modeling.

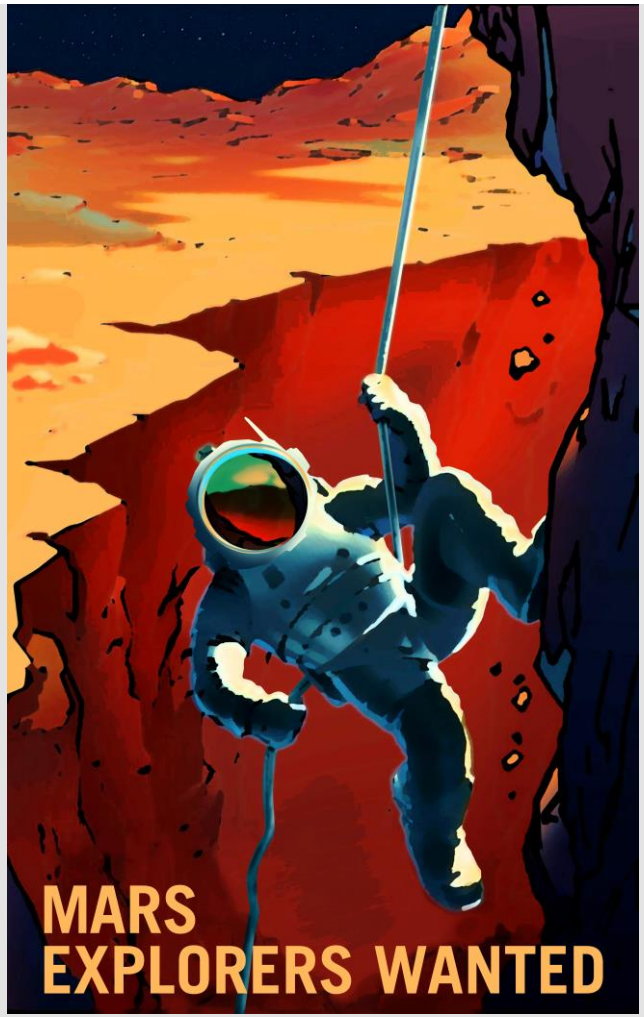
Nuclear Design and Licensing

- Industry is transitioning away from using PRA to “confirm” a plant risk is low enough, with recommendations to lower operational risk.
- PRA more involved in the design process than for older generation nuclear plants, resulting in reactors that are a much safer than previsions designs.
- Risk-Informed Design and Licensing
- Licensing Modernization Project (NEI-18-04); led by Southern Company, coordinated by the Nuclear Energy Institute (NEI), and cost-shared by the U.S. Department of Energy (DOE).
    - Focuses on identifying licensing basis events; classifying and establishing performance criteria for structures, systems, and components; and evaluating defense in depth for advanced reactor designs.

Lunar Exploration

- NASA's Human Exploration architecture includes an Artemis Base Camp at the South Pole of the Moon.
- Will consist of a combination of surface habitats, mobile platforms, and cargo landers.
- # of launches, launch vehicles types, staging orbits, and different mission profiles will all factor into risk acceptance.
- In a high-risk mission (Humans to Mars) PRA provides insight to whole mission risks and will be one of the tools used by NASA to understand key drivers of LOC and LOM risk and to influence the evolving architecture to mitigate the risks.

RAMS XIII – Probabilistic Risk Assessment of a Sustained Lunar Presence; Meshell



Machine Learning/Artificial Intelligence

- Substantial developments in machine learning techniques, enhancements in computer performance, and better data col-lection processes have led to an increased desire and ability to use machine learning methods for risk quantification.
- PRA traditionally has incorporated expert elicitation and heuristics; both are subjective and susceptible to bias.
- Processes have been proposed for developing natural language-based probabilistic risk assessment models, applying deep learning algorithms to emulate experts' quantified risk estimates. This allows the risk analyst to obtain an a-priori risk assessment when there is limited information in the form of text and numeric data.

Other Industries

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Several Articles Since 2021:

Medical methodology

- "PRA: The keystone for the future of toxicology" - Center for Alternatives to Animal Testing (CAAT), Johns Hopkins University
  - Potential benefits of probabilistic methods and Bayesian approaches in providing more realistic assessments of uncertainty, reducing conservative safety margins, and supporting evidence integration, ultimately leading to the development of a new toxicology paradigm.

Environmental Studies

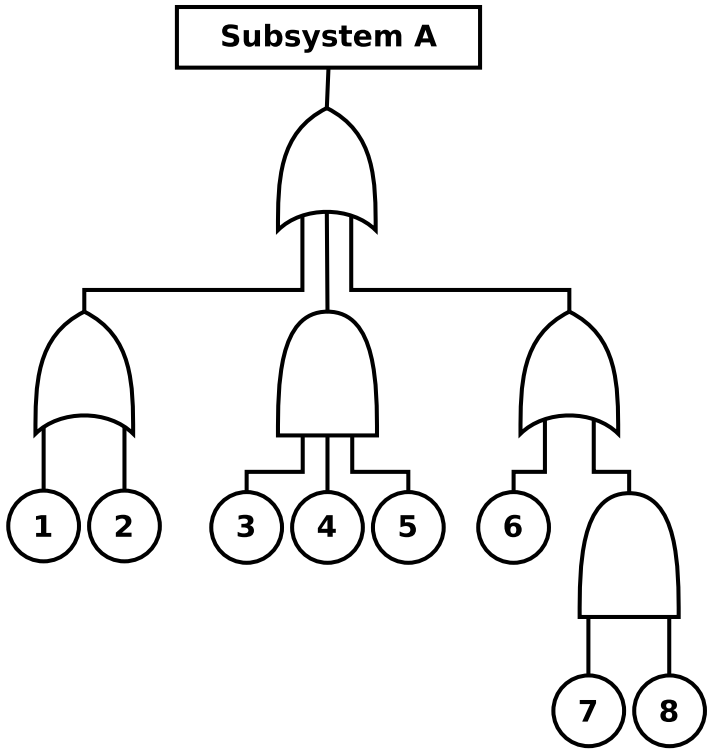
- "Probabilistic Risk Assessment of pesticides under future agricultural and climate scenarios using a Bayesian network" - Norwegian Institute for Water Research
  - The probabilistic risk assessment methodology, as implemented through the Bayesian network model, provided a more comprehensive and probabilistic approach to assess and visualize the environmental risks associated with pesticide exposure, considering uncertainties and various scenarios, including those related to climate change and pesticide application rates.
- "Risk and loss assessment for wildfires" – US Forest Service
  - Proposes a conceptual probabilistic wildfire risk assessment framework that accounts for uncertainties and models the dynamic risks associated with wildfires. This framework aims to assess various types of losses (physical, social, economic, environmental, and health) and emphasizes the need for an analytical-deliberative process involving stakeholders to make effective decisions related to risk reduction investments in wildfire-prone areas.

07

SUMMARY

Summary

- As we approach a new era defined by emerging technologies our comprehension of PRA's past and present equips us to effectively navigate the future of risk assessment and management.
- The future of the practice is not only tied to technical advancements, but also in recognition of its applicability in the evaluation of complex systems (ecosystems, medical processes, etc.).
- Risk-Informed licensing and decision making will be a driving force and affect how work is performed. Engineers and Decision Makers will only benefit from having a cursory knowledge of risk concepts.

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References/Links

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- Risk Assessment in Regulation – USNRC
- Advances in the Prevention and Control of HAIs – AHRQ
- Marx DA, Slonim AD; Assessing patient safety risk before the injury occurs: an introduction to sociotechnical probabilistic risk modelling in health care; BMJ Quality & Safety 2003;12:ii33-ii38.
- PRA Procedures Guide for Offshore Applications (Draft) – BSEE
- Probabilistic risk assessment of offshore installation hydrocarbon releases leading to fire and explosion, incorporating system and human reliability analysis; Rozuhan, Muhammad, Niazi – Link
- EPA White Paper - PRA