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Safety and Risk Assessment for Small Modular Reactors

April 2024

Changing the World's Energy Future

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Idaho National Laboratory

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Safety and Risk Assessment for Small Modular Reactors

“Risk” tends to be used to describe one of two contexts

Risk represents a measured impact to safety

Risk Analysis → science-driven way to make things *safer*

PRA

Uncertainty Quantification

Risk represents a performance shortfall

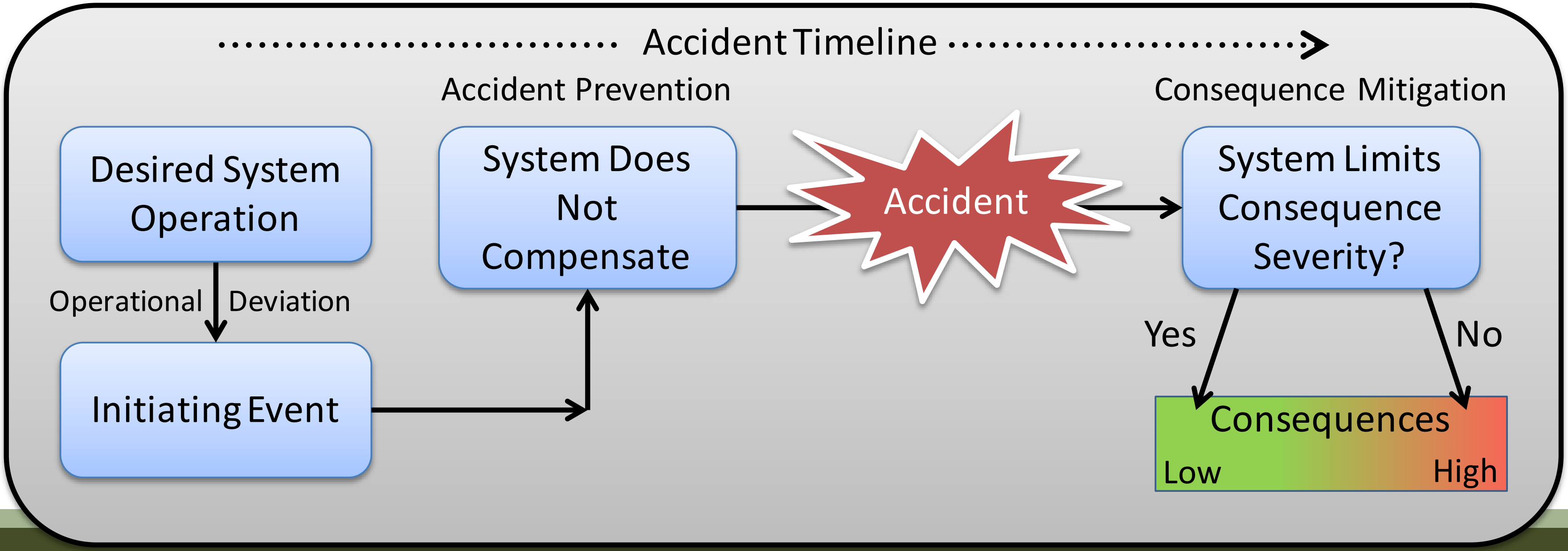
Risk Analysis → science-driven way to make things *better*

Risk analysis is made up of several elements

- **Arises from a "Danger" or "Hazard" – associated with undesired event**
  - Tied to the idea of a scenario
- **Three questions which are commonly referred to as the risk triplet**
  - What can go wrong?
    - (accident scenario)
  - How likely is it to occur?
    - (frequency, probability)
  - What will be the outcome?
    - (consequences)
- **A fourth question, reflecting the importance of uncertainty, has also been addressed in recent PRAs**
  - How confident are we in our answers to these three questions?

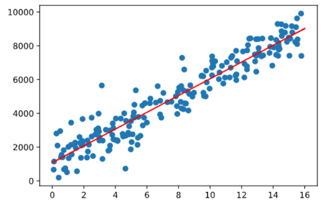
The Concept of a Scenario

- **Scenario modeling**
  - For each hazard, identify an initiating event and necessary enabling conditions that result in undesired consequences
- **Enabling conditions often involve failure to recognize a hazard or failure to implement controls such as protective barriers or safety subsystems**
- **Accident scenario is the sequence of events comprised of:**
  - Initiating event + enabling conditions + events that lead to adverse consequences

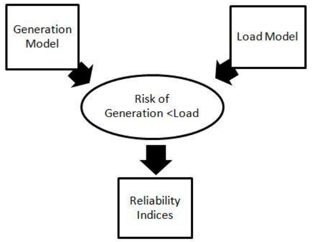


Risk and Reliability

- **Risk investigates performance shortfalls for a “system”**
  - Reliability is a part of the models that form a risk analysis
- **Two different types of reliability approaches**
  - Statistical modeling
    - Consists of distributions, data, and probabilistic models
    - Traditional methods well established (both classical statistics and Bayesian)
    - Machine learning methods are become more understood and applied
      - However, an underlying challenge is the lack of reliability, operational, and maintenance data to support ML

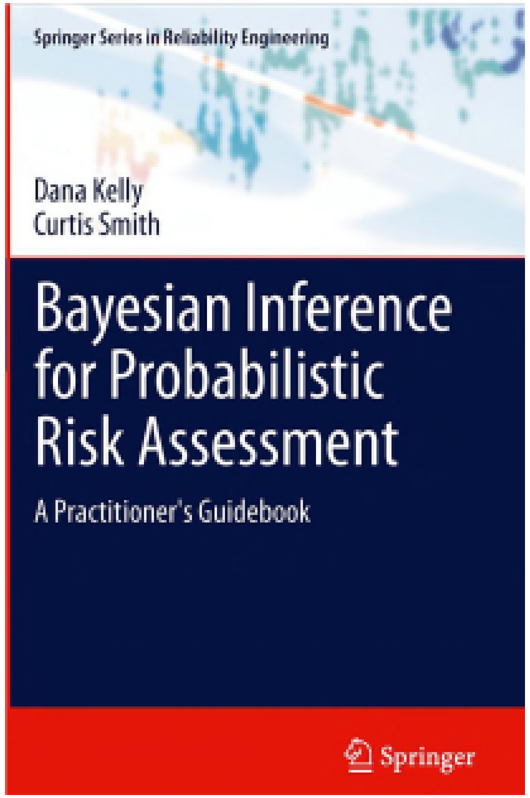


  - Physics-based causal modeling
    - Load-Capacity models have a long history, but are not as widely used as statistical models
      - Relies on engineering physics models, thus fits well into Computational Risk Assessment
    - Machine learning models are a research topic



Bayesian Inference for Parameters

- **INL teaches the NRC Bayesian probability courses (Basics and Advanced)**
- **Textbook used for P502 is "Bayesian Inference for PRA"**
- **Topics addressed include**
  - Bayesian networks
  - Models for recovery and repair
  - Models for population variability
  - Uncertain or fuzzy data
  - Time trends
  - Mixture priors
  - Model checking
- **Bayesian approach is used to**
  - Determine distribution of parameter values
  - Describe our state-of-knowledge for parameters

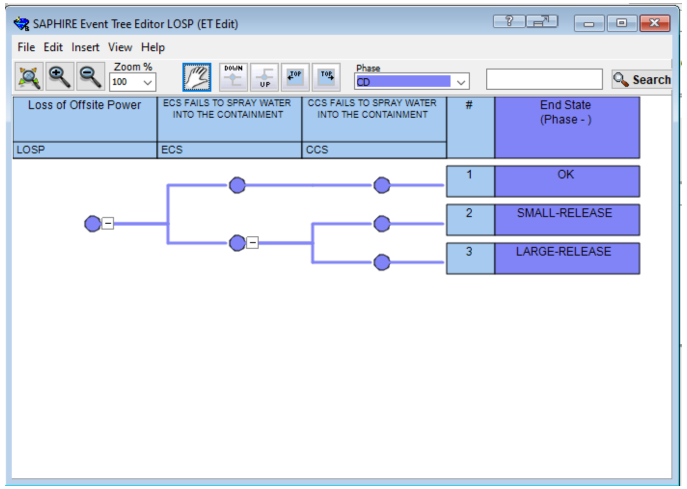


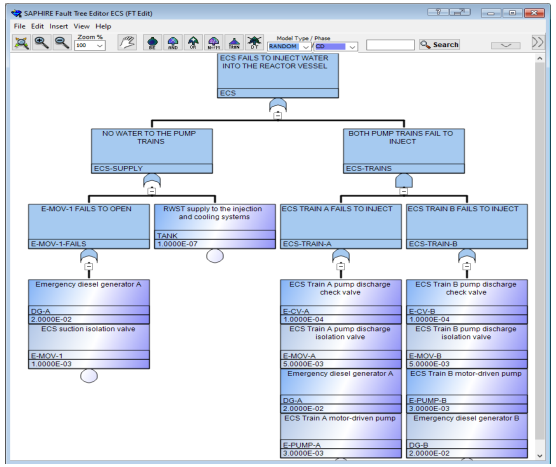
INL 40+ Year PRA and Tool Development History

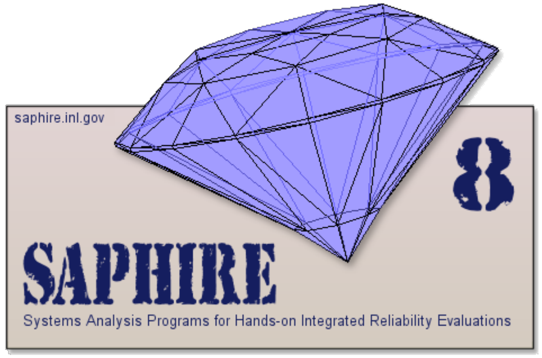
- **In the 1980s, following WASH-1400, more focus on probabilistic risk assessment (PRA)**
  - Development of the SAPHIRE code in mid 1980s
  - Regulatory applications
  - Data analysis for the NRC
  - PRA training
  - Human reliability modeling
- **In the 1990s-2000s application development increased**
  - Risk-informed decision making
    - Significance Determination Process Module
  - Refinement of tools such as SAPHIRE and RELAP
- **Currently, research into advanced methods and tools for PRA**
  - RAVEN and EMRALD for dynamic risk assessment
  - HUNTER for dynamic human reliability assessment

SAPHIRE - Risk Analysis Tool

- **SAPHIRE - Systems Analysis Programs for Hands-on Integrated Reliability Evaluation**
- **Recent Article about SAPHIRE and its use by the Nuclear Regulatory Commission (NRC) - https://inl.gov/nuclear-energy/watching-trends-how-inl-helps-the-nrc-model-risk-and-reliability/**
- **SAPHIRE is used to create Probabilistic Risk Analysis models and is updated to reflect current computer science practices**
  - Is used by the NRC and other industries, like aerospace, to manage risk
- **Website: https://saphire.inl.gov/**



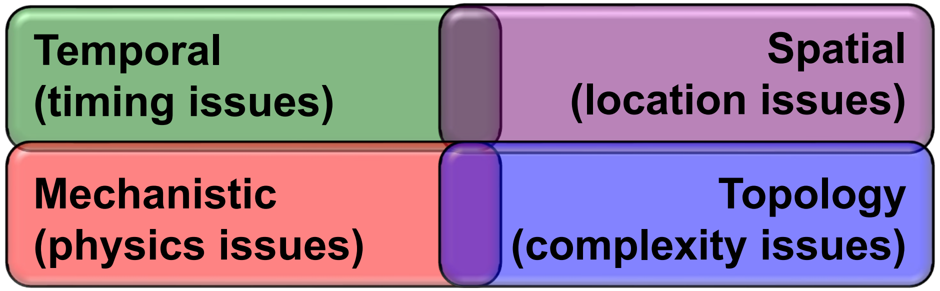




Computational Risk Assessment (CRA)

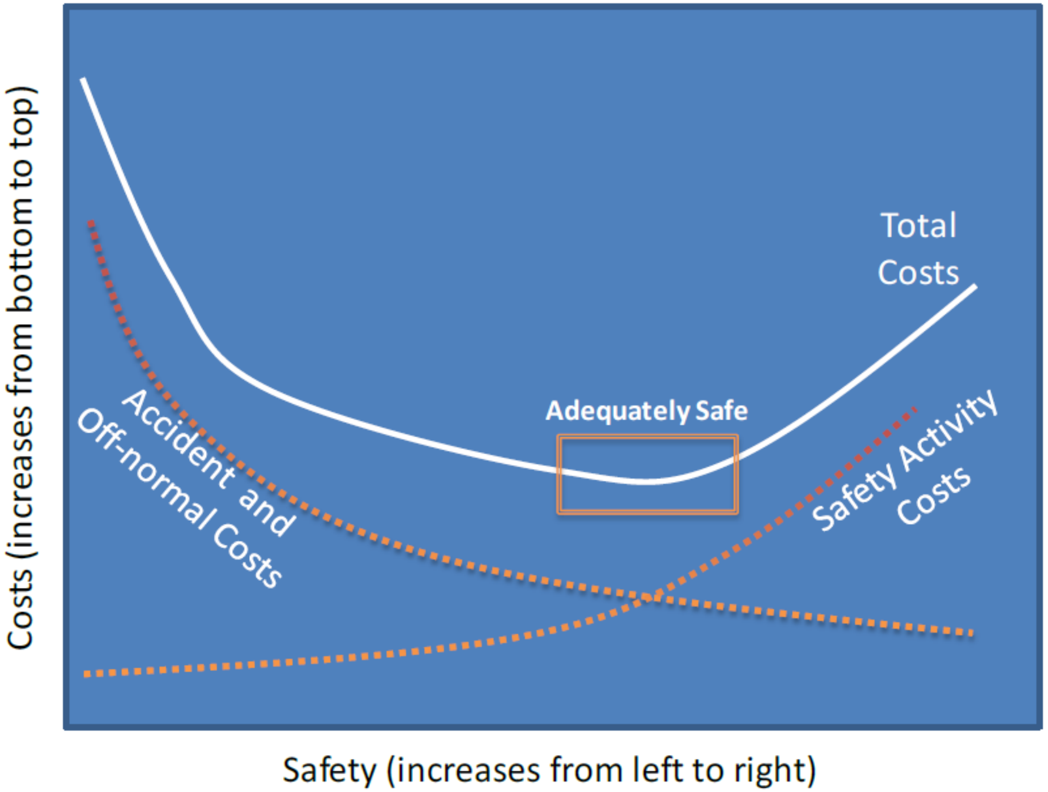
- **Computational Risk Assessment is a focus of current research and development**
- **CRA is a combination of**
  - Probabilistic (i.e., dynamic) scenario creation where scenarios unfold and are not defined a priori
  - Mechanistic analysis representing physics of the unfolding scenarios
- **CRA relies on the availability of computational tools**
  - Processors (hardware)
  - Methods (software)
- **CRA is not simply solving traditional PRA models faster or with higher precision**
  - It is a different way of thinking about the safety problem

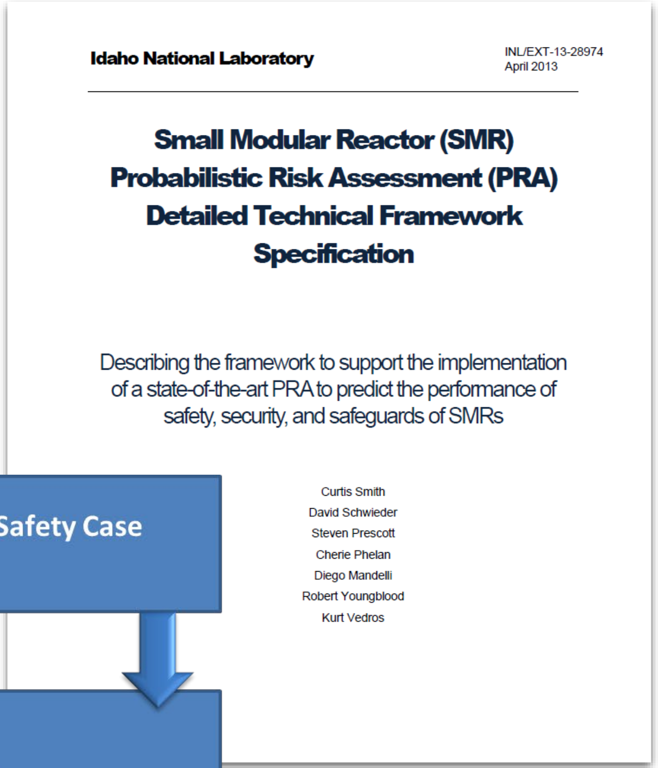
Integrating the worlds of physics and probability leads us to predictions based upon an approach called "computational risk assessment"



Genesis of CRA Started with a Focus on Small Modular Reactors

- **Desire to use computational methods to balance safety and costs**





Idaho National Laboratory

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Small Modular Reactor (SMR) Probabilistic Risk Assessment (PRA) Detailed Technical Framework Specification

Describing the framework to support the implementation of a state-of-the-art PRA to predict the performance of safety, security, and safeguards of SMRs

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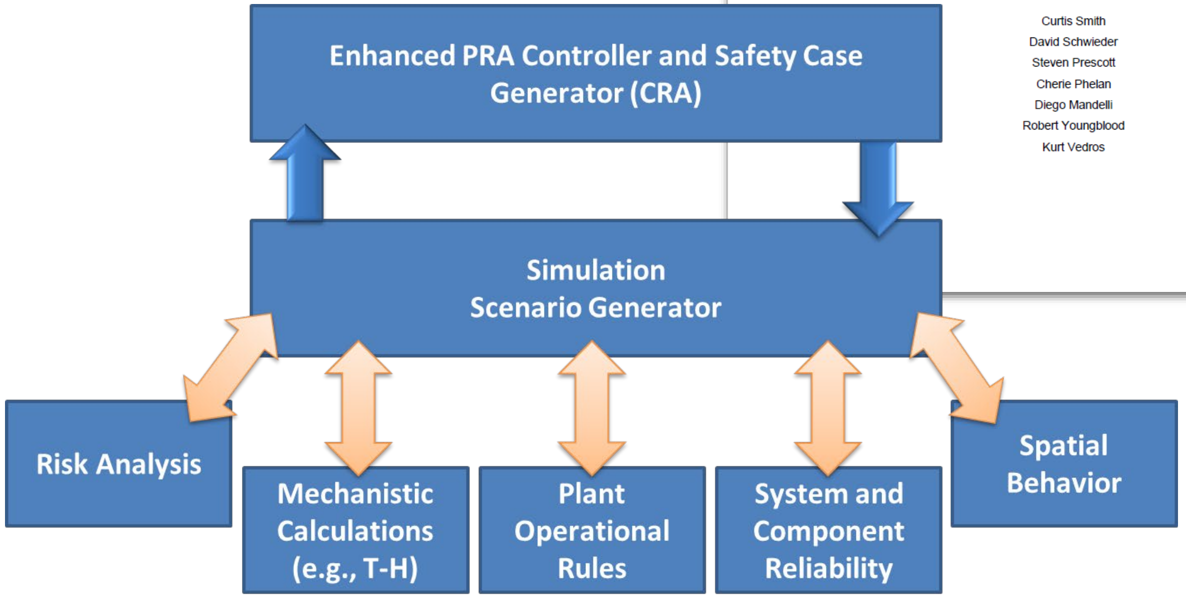
Diego Mandelli
Robert Youngblood
Kurt Vedros



Risk Analysis Steps for Scenario Generation

Enabling Conditions → Initiating Event → Plant SSC Response to Initiator → SSC Failures & Successes → Scenario Simulation

2D and 3D Models for the Facility including Systems, Structures, & Component (SSC)

Computational Layers Used for the Analysis

Probabilistic events **These are either statistical or causal models**

Seismic

Flooding

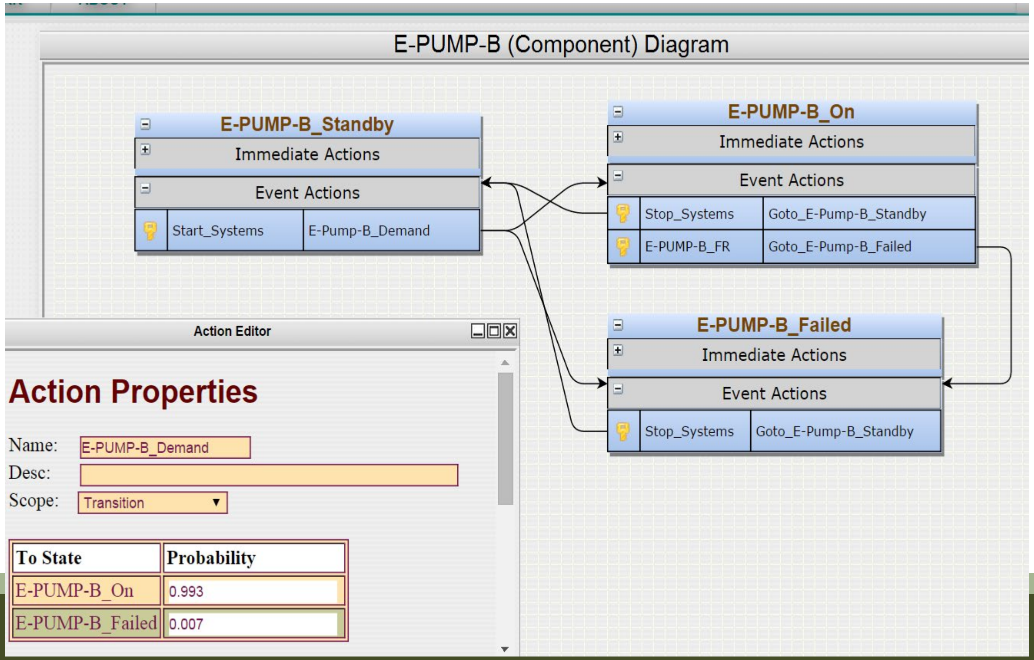
. . .

Thermal-hydraulics

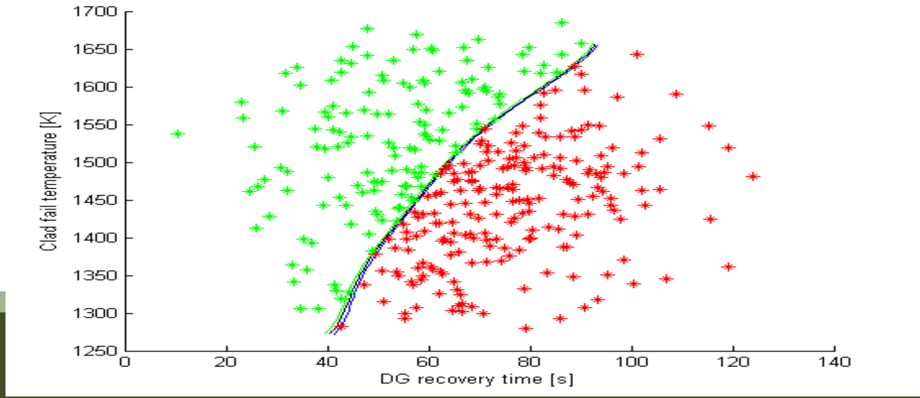
These tend to be physics/engineering models

Next-Generation Risk and Reliability Analysis Tools

- Event Model Risk Assessment using Linked Diagrams → EMRALD emrald.inl.gov
- Dynamic probabilistic risk assessment (PRA) model based on state-based simulation
- Graphical user interface to represent states and logic corresponding to traditional methods



- Risk Analysis in a Virtual Environment → RAVEN
  - raven.inl.gov
- High performance computing to provide advanced algorithms to analyze complex system
- Modular construction including
  - Job handing for analysis tasks
  - Sampling strategies for efficient simulation
  - Flexible model construct
    - Script-based models
    - Reduced order models (emulators)
    - External models



PRA is a part of Trust Engineering

- **Information includes uncertainty, we need to embrace this in our models**
- **And our systems need to be evaluated in potential challenging operating conditions**
  - These provide complex and rich boundary conditions for our models
- **As we design, build, and operate our future engineered systems, we will rely more and more on mod/sim and highly complicated models**
- **How will we trust what we are doing, how will others?**
- **By integrating our best practices and obtaining a detailed representation of our models, including risks, we can engineer trust in our practices and outcomes**

TRUST ENGINEERING

- **Includes incorporating practices such as**
  - Computational risk assessment
  - System safety case
  - Physics-informed models
  - Application of codes and standards
  - Reliability integrity management
  - PRA
  - Quality assurance
  - Data brokering and management

Nuclear Safety and Regulatory Research (NSRR) Division

Our goal is to ensure the nation's safe, competitive, and sustainable use of engineered systems

in many domains by applying our capabilities to impactful issues

in risk, reliability, and operational performance

- Six Departments
  - Mike Calley → Regulatory Support
  - Nancy Lybeck → Instrumentation, Controls & Data Science
  - Shawn St. Germain → Reliability, Risk, and Resilience Sciences
  - Ron Boring → Human Factors and Reliability
  - Lana Lawrence → Risk Phenomena Modeling
  - Katya Le Blanc (acting) → Automation, Instrumentation, and Controls
- Major Programs
  - Light Water Reactor Sustainability
  - US Nuclear Regulatory Commission Support