Risk-Informed Applications and Science – Past, Present, & Future

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www.inl.gov

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Abstract

- The Idaho National Laboratory is creating the next-generation reliability- and risk-assessment methods and tools that support risk-informed decision-making by combining physics-based models with probabilistic quantification approaches. Integrating these two worlds of physics and probability using a simulation framework leads us to predictions based upon an approach called "computational risk assessment" which will serve as the technical basis for the future of reliability and risk approaches. The driving factors for this new approach includes: temporal (timing issues), spatial (location issues), mechanistic (physics issues), and topological (complexity issues). By combining phenomenology directly with stochastic quantification, we can perform advanced uncertainty analysis directly on both parameters and models. In addition, new tools allow for the creation of reduced order models that mimic high-fidelity engineering models while still permitting the realization of thousands of simulation iterations in short run-times on current workstation-class computers. While these advanced methods and tools can provide increased realism in our engineering safety and risk approaches, their greater benefit is to provide a risk-informed engineering framework for design and operation.
- This talk will briefly review the history of risk assessment and risk-informed applications, describe some of the current research and development found at the Idaho National Laboratory, and discuss potential future applications and approaches for advanced methods and tools.

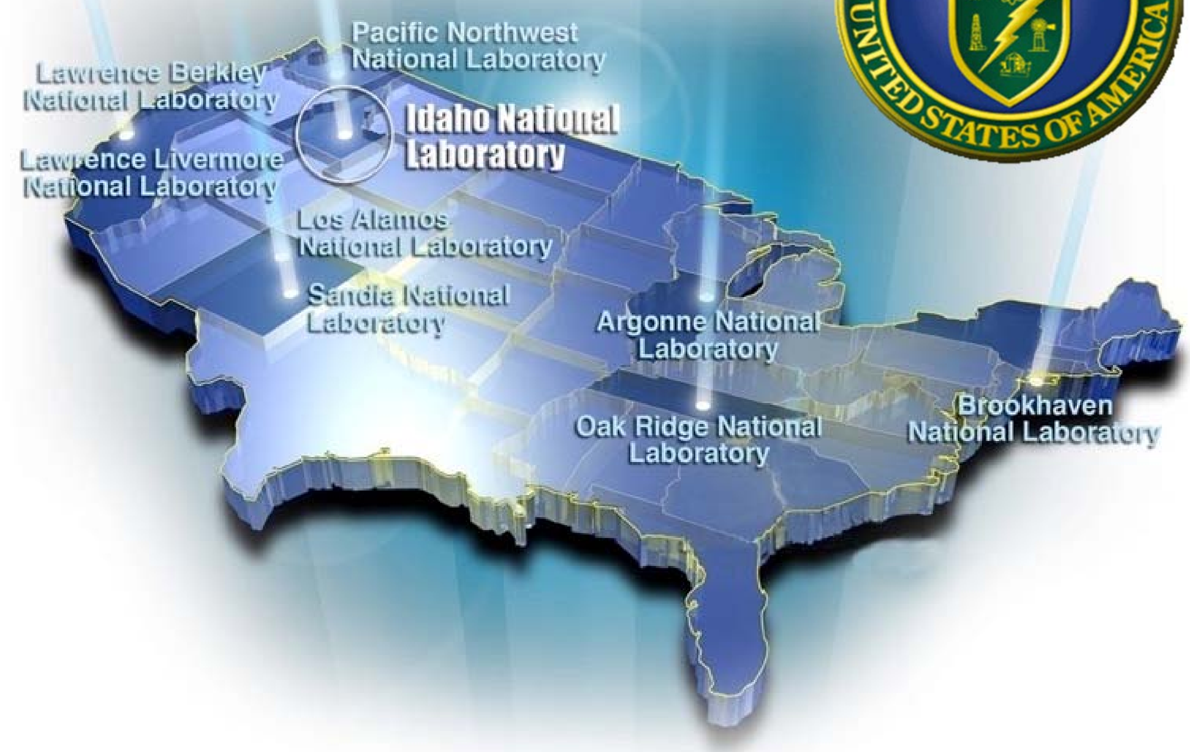
Outline of my talk today

- Background
- A brief history of regulatory risk assessment and applications
- Risk-informed (RI) activities in the U.S.
- Current RI research and development
- Potential future activities

Background

Idaho National Laboratory

- One of nine large DOE multi-program Labs
- DOE's Lead Lab for Nuclear Energy



Idaho National Laboratory – The Nation's Leading Nuclear Energy Laboratory

- 890 square miles
- 579 buildings
- 52 total reactors
- 3 operating reactors
- 2 spent fuel pools

- Loss-of-Fluid Test Reactor (LOFT)

- Experimental Breeder Reactor I (EBR-I)

Idaho National Laboratory

Our Vision:

Change the world's energy future by advancing nuclear

Our Mission:

Enable nuclear energy expansion through innovation

Our priorities:

- Continued operation of existing fleet
- Replacement and expansion of existing fleet
- Management and disposition of spent fuel

Idaho National Laboratory Initiatives

Address grand challenges and advance energy and security goals for the nation

Nuclear Reactor Sustainment and Expanded Deployment

Integrated Fuel Cycle Solutions

Advanced Materials and Manufacturing for Extreme Enviroments

Integrated Energy Systems

Secure and Resilient Cyber-Physical Systems

Idaho National Laboratory

Nuclear Research and Development Team at Idaho National Lab

1400 staff working to revive, revitalize, and expand nuclear energy, enabled by unique research facilities, infrastructure & capabilities

Nuclear Science & Technology

Change the world's energy future by advancing nuclear energy.

- Nuclear fuels and materials
- Nuclear systems design and analysis
- Fuel cycle science and technology
- Nuclear safety and regulatory research
- Advanced Scientific Computing

398 Employees
- 149 Ph.D.
- 90 Master
- 94 Bachelor
- 4 Associates
- 13 Postdocs

Materials & Fuels Complex

Experiments and engineering that drive the world's nuclear energy future.

- Transient testing
- Space nuclear power and isotope technologies
- Analytical laboratories
- Fuel Fabrication
- Post-irradiation examination
- Advanced characterization

614 Employees
- 39 Ph.D.
- 65 Master
- 187 Bachelor
- 84 Associates

Advanced Test Reactor

Provide unique irradiation capabilities for nuclear technology research and development.

Steady-state neutron irradiation of materials and fuels

- Naval Nuclear Propulsion Program
- Industry
- National laboratories and universities

388 Employees
- 2 Ph.D.
- 36 Master
- 121 Bachelor
- 43 Associates

19-50373

Unique Research Facilities and Infrastructure/Foundational Enablers

Nuclear Science & Technology

NS&T Associate Lab Director
John Wagner

NS&T Chief Scientist
Jess Gehin

GAIN
John Jackson,
Acting Director

Naval Reactors
Casey Stengel

NS&T Chief Operations Officer
Pete Wells

Integrated Fuel Cycle Solutions
Monica Regalbuto

International Programs
Bonnie Hong

Strategic Planning
Steve Aumeier

NE Senior Technical Advisor
Jon Carmack

National Reactor Innovation Center (NRIC)
Ashley Finan

C100
Reactor Systems Design & Analysis
Youssef Ballout, Director

C200
Nuclear Safety & Regulatory Research
Curtis Smith, Director

C400
Fuel Cycle Science and Technology
Michael Norato, Director

C500
Advanced Scientific Computing
Eric Whiting, Director

C600
Nuclear Fuels & Materials
Steven Hayes, Director

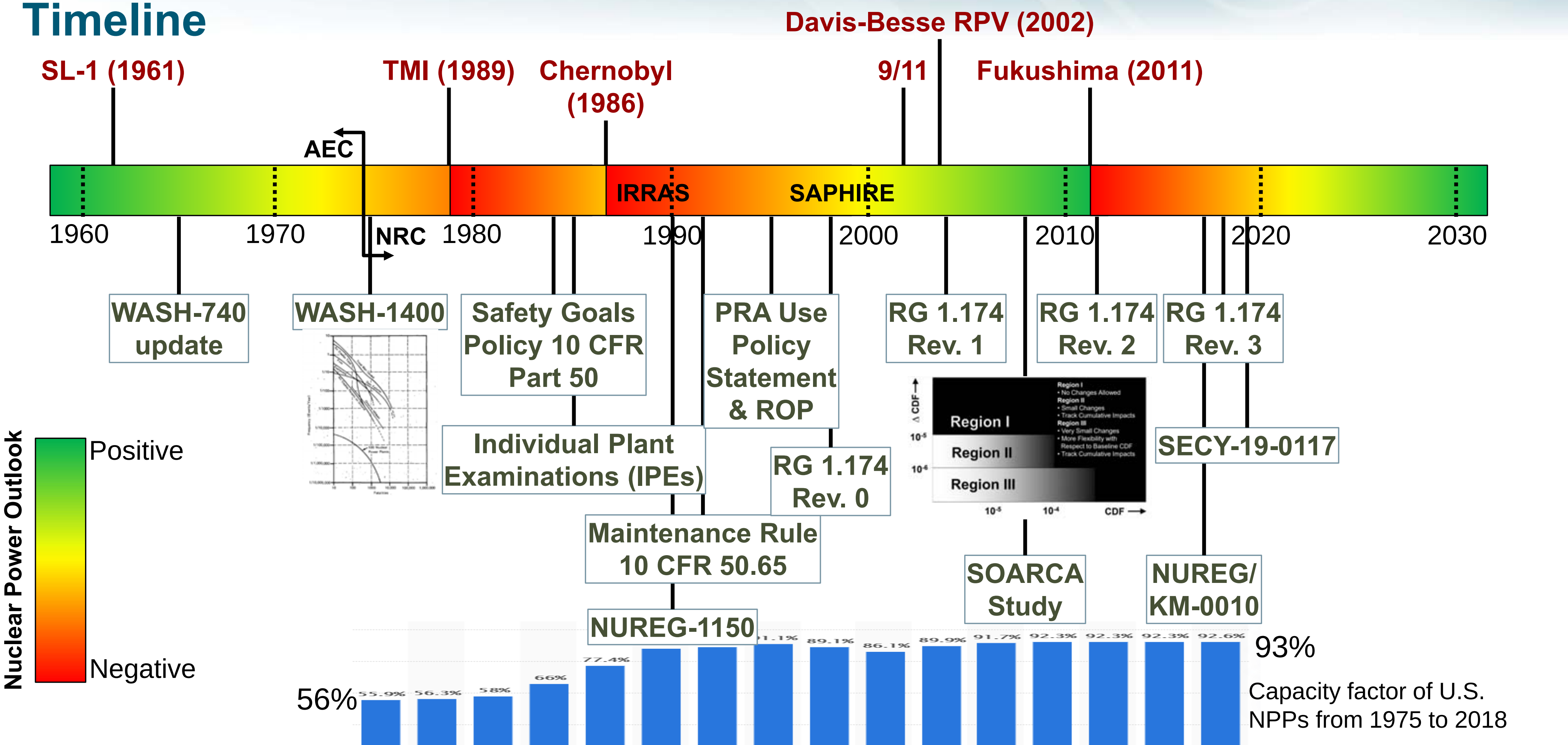
Nuclear Safety and Regulatory Research Division

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

- **A Division in Nuclear Science and Technology**
- **Four Departments**
  - Regulatory Support
  - Probabilistic Methods and Tools
  - Human Factors and Reliability
  - Instrumentation & Controls and Data Sciences
- **Three Major Programs**
  - Light Water Reactor Sustainability
  - Nuclear Energy Enabling Technologies
  - US Nuclear Regulatory Commission Support

U.S. Regulatory History of RI Activities

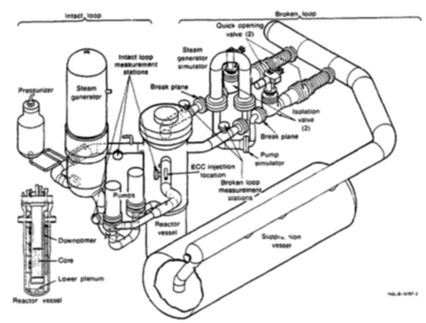
Timeline



https://www.statista.com/statistics/191201/capacity-factor-of-nuclear-power-plants-in-the-us-since-1975/

INL 40+ Year Risk Analysis and Tool Development History

- **INL in 1970s with reactor testing and code development → Initial versions of RELAP**
  - Semiscale and Loss-of-flow Test (LOFT) facility experiments supported code development
- **In the 1980s, 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
  - Further development of the RELAP series



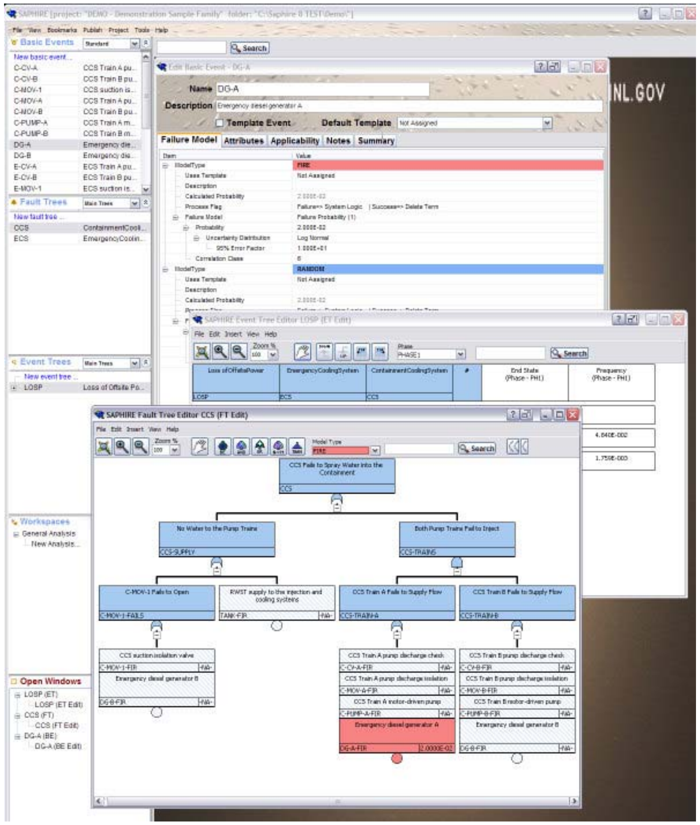
- **In the 1990s-2000s application development increased**
  - RI decision making
    - Significance Determination Process Module
  - Refinement of tools such as SAPHIRE and RELAP
  - Applications outside of nuclear (e.g., NASA)
- **Currently, research into advanced methods and tools for PRA**
  - RAVEN and EMRALD for dynamic risk assessment
  - HUNTER for dynamic human reliability assessment

General Focus of Division NRC Support

- **Risk modeling → Standardized Plant Analysis Risk (SPAR) models**
- **Risk tools → Systems Analysis Program for Hands-On Integrated Reliability Evaluation (SAPHIRE; currently planning for Version 9, Cloud SAPHIRE)**
- **Data collection/analysis**
  - A large activity including diverse information collection and processing
  - Computational support and industry trends analysis
- **Training for risk-informed activities (1981 – present)**
  - P-102 Bayesian Inference in Risk Assessment; P-105 PRA Basics for Regulatory Applications; P-108 Fire Protection SDP; P-109 Assessing the Adequacy of Models for Risk-Informed Decisions; P-201 SAPHIRE Basics; P-203 Human Reliability Assessment; P-401 Overview to Risk Assessment for Materials Safety and Waste Management; P-501 Advanced Risk Assessment Topics
- **Human factors (HF) and human reliability analysis (HRA) applications**
  - HRA for the SPAR models → SPAR-H
  - Scenario Authoring, Characterization and Debriefing Application (SACADA)

Overview of SAPHIRE

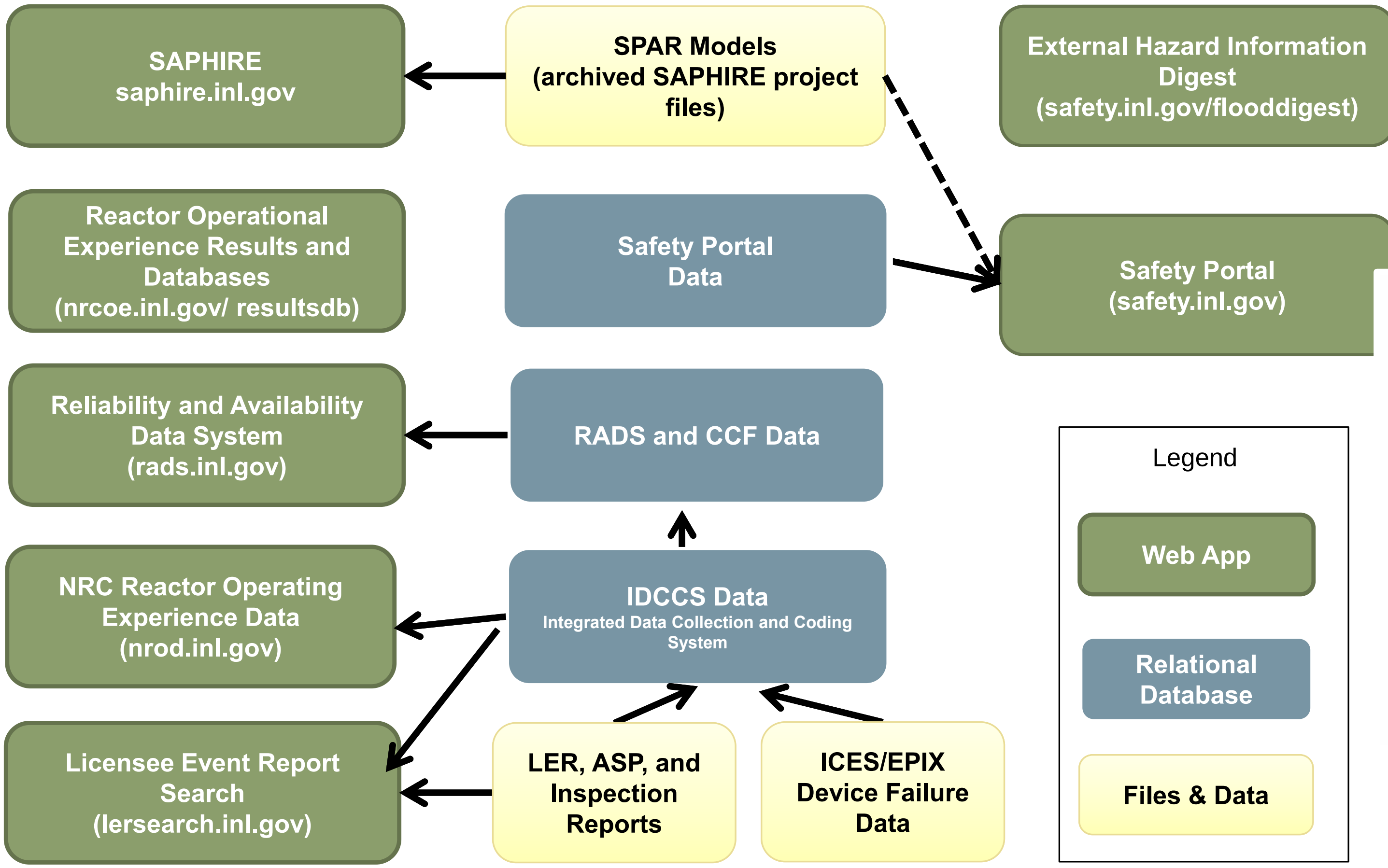
- **1987 Version 1 called IRRAS introduced innovative way to draw, edit, and analyze graphical fault trees**
- **1989 Version 2 released incorporating the ability to draw, edit, and analyze graphical event trees**
- **1990 Analysis improvements to IRRAS led to the release of Version 4 and formation of the IRRAS Users Group**
- **1992 Creation of 32-bit IRRAS, Version 5, resulted in an order-of-magnitude decrease in analysis time**
- **1997 SAPHIRE for Windows released → Current Version 8**
- **Built in features include**
  - Generation, display, and storage of “cut sets” (ways to get to core damage)
  - Graphical editors (fault & event tree) and database editors
  - Uncertainty analysis
  - Data input/output via ASCII text files (MAR-D)
  - Special analysis features (e.g., seismic, fire)
  - Dual language support

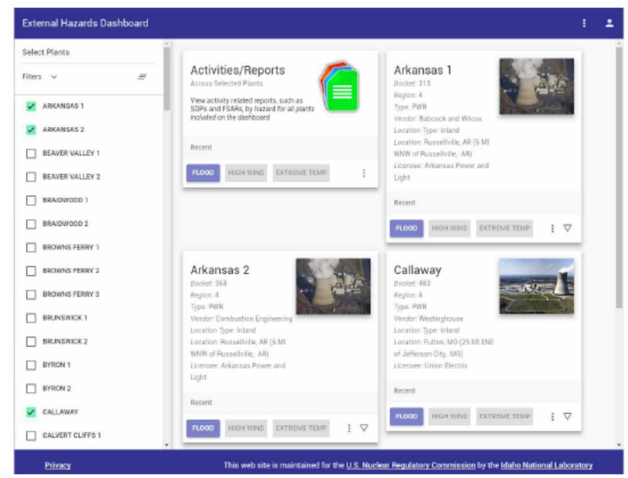


Data Collection and Analysis (since late 1980s)

- **Nuclear Materials Events Database – Non-reactor nuclear materials event data collection and coding**
- **Industry Trending Program – Tracks and trends performance indicators for health of nuclear industry**
- **Reactor Operating Experience Data**
  - Licensee Event Reports (LERs), Event Notifications (ENs), Equipment Performance and Information Exchange (EPIX) system data, etc., collected and coded
  - Supports PRA data, system reliability trending and special reliability studies
- **Computational Support for Risk Applications – Develop data for PRA and risk/reliability trending**
- **Risk Application Special Studies – Conducts special evaluations of possible adverse trends and emerging risk and reliability issues**
- **INL provides the latest risk and reliability parameters for all risk models used in risk-informed Reactor Oversight Program (ROP)**

NRC-Related Information at INL





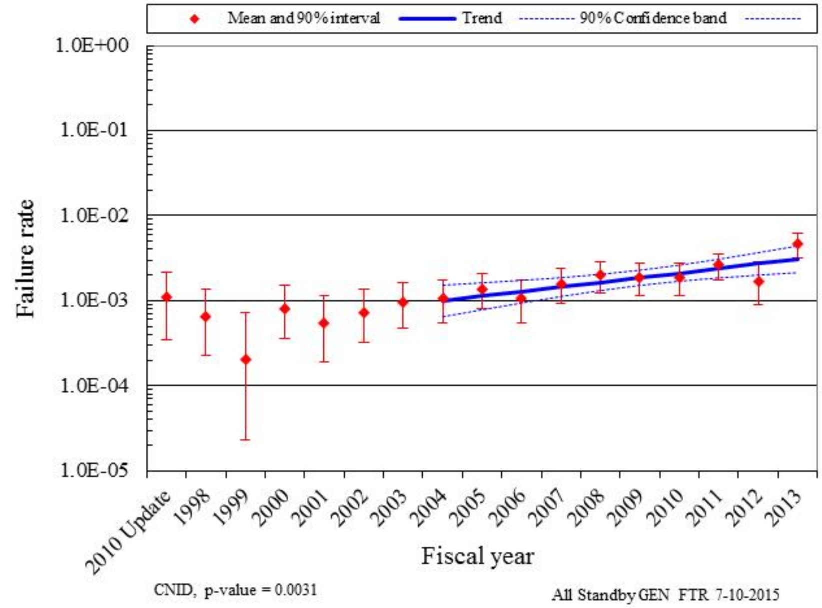
Example of Flood Digest Page

Example of Data Analysis Results

	Initiating Event	Description	DataSource	Data: Number of Events	Data: Critical Years (rcry)
TRANSIENTS	Loss of Feedwater				
	IE-LOMFW	Loss of Main Feedwater	IEDB	113	1638.768
	General Transients				
	IE-TRANS (BWR)	General Transient (BWR)	IEDB	332	437.264
	IE-TRANS (PWR)	General Transient (PWR)	IEDB	553	803.884
	Loss of Condenser Heat Sink				
	IE-LOCHS (BWR)	Loss of Condenser Heat Sink (BWR)	IEDB	65	465.633
	IE-LOCHS (PWR)	Loss of Condenser Heat Sink (PWR)	IEDB	57	
HEAT SINK	Loss of Support Systems				
	Loss of Cooling Water				
	IE-LOSWS	Loss of Service Water System	IEDB	0	
	IE-PLOSWS	Partial Loss of Service Water System	IEDB	3	
	IE-LOCCW	Loss of Component Cooling Water	IEDB	0	
	IE-PLOCCW	Partial Loss of Component Cooling Water	IEDB	4	
LOIA	Loss of Instrument Air				
	IE-LOIA (BWR)	Loss of Instrument Air (BWR)	IEDB	4	
	IE-LOIA (PWR)	Loss of Instrument Air (PWR)	IEDB	7	
	Loss of Electrical Bus				
	IE-LOAC	Loss of AC Bus	IEDB	11	
	IE-LOAC 4160V	Loss of 4160V AC Bus	IEDB	7	
	IE-LOAC LOWV	Loss of Low Voltage AC Bus	IEDB	4	

SPAR Model Data (NUREG/CR-6928) Updates

Emergency Diesel Generator Failure Rate Trend



http://nrcoe.inl.gov/resultsdb/

PRA Methods, Models and Applications

- **Standardized Plant Analysis Risk (SPAR) Models (1992 – present)**
  - Covers all US operating reactors
  - Advanced reactors such as AP-1000, GE ABWR, Toshiba ABWR
  - US APWR
  - Level 1 PRA
    - Full-Power
    - Shutdown
    - External Events
  - Level 2 – Peach Bottom
  - Level 3 – Vogtle 1 & 2 Site
- **Evaluation of License Amendment Requests (LARs)**
- **INL is the leading provider of risk assessment and risk management services for the NRC**
  - We are developing new capabilities and methods to incorporate in our risk activities in support of risk-informed regulation and reactor oversight.

Risk-Informing the Decision-making Process such as the Reactor Oversight Process

PRA Methods & Applications

- Risk Models Development
- Advanced Methods Development (PRA/HRA)
- Advanced Reactor Design Analysis
- Event Assessment

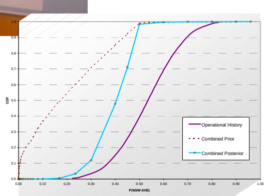
Figure 7. General Event Information.

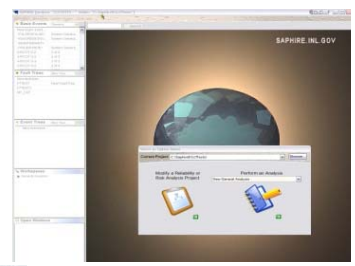
Risk Training

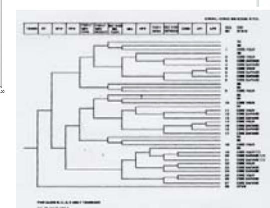
- PRA Basics
- Advanced Topics (HRA, CCF)
- Event Assessment
- Risk Tools
- Uncertainty

Data & Tools

- Operational Events
- Trends and Metrics
- Databases
- Risk Tools and Methods
- Statistical Analysis







Current RI Research and Development

Why do we need to advance/improve reliability and safety analysis?

- **Recent nuclear power challenges have been mostly on economics and safety**
  - Need to treat safety as an asset with strong ties to economics in order to demonstrate the economic benefits
    - Improvements to operation (focus on risk-important issues)
    - Reduction of conservatisms
- **Provide cost-beneficial approaches to safety by using modern methods, tools, and data in new ways**
  - Develop more-predictive tools & apply multiple-physics/time
  - Facilitate ease of use for more efficient risk-analysis processes
  - Support faster training
- **We want the next generation of scientists/engineers to use these new approaches in order to attract talent**

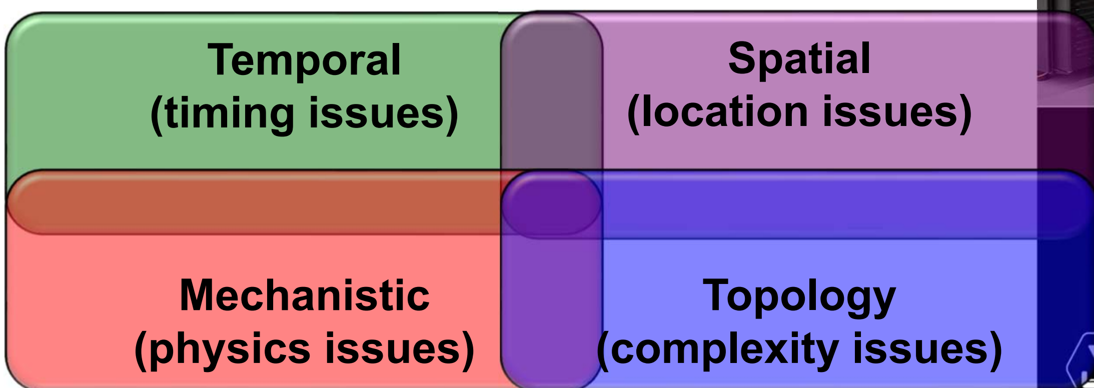
Computational Risk Assessment (CRA)

- **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

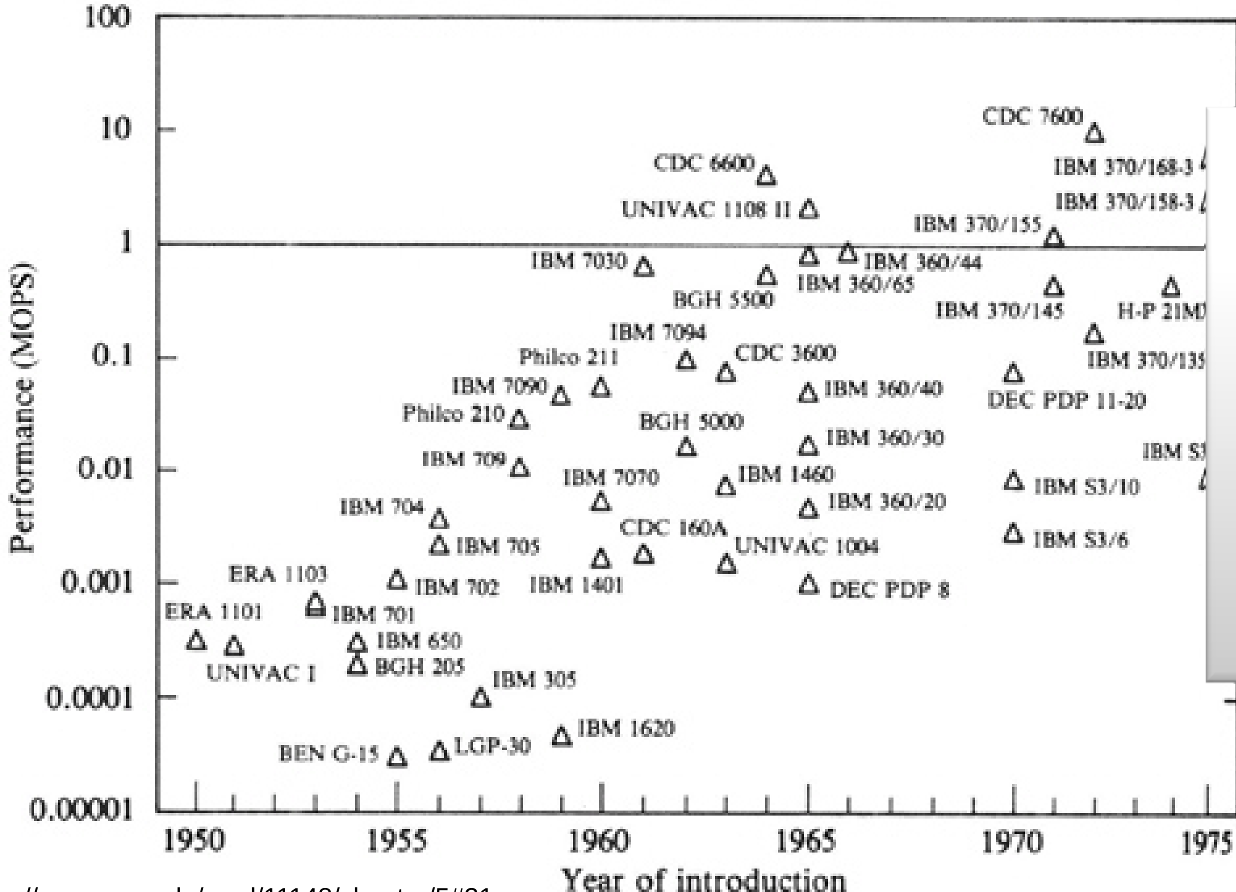
Integrating the worlds of physics and probability leads us to predictions based upon an approach called "computational risk assessment"

CRA driving factors

- **Computers are improving**
- **Software is improving**
  - And much of it is free
- **Analysis characteristics including**



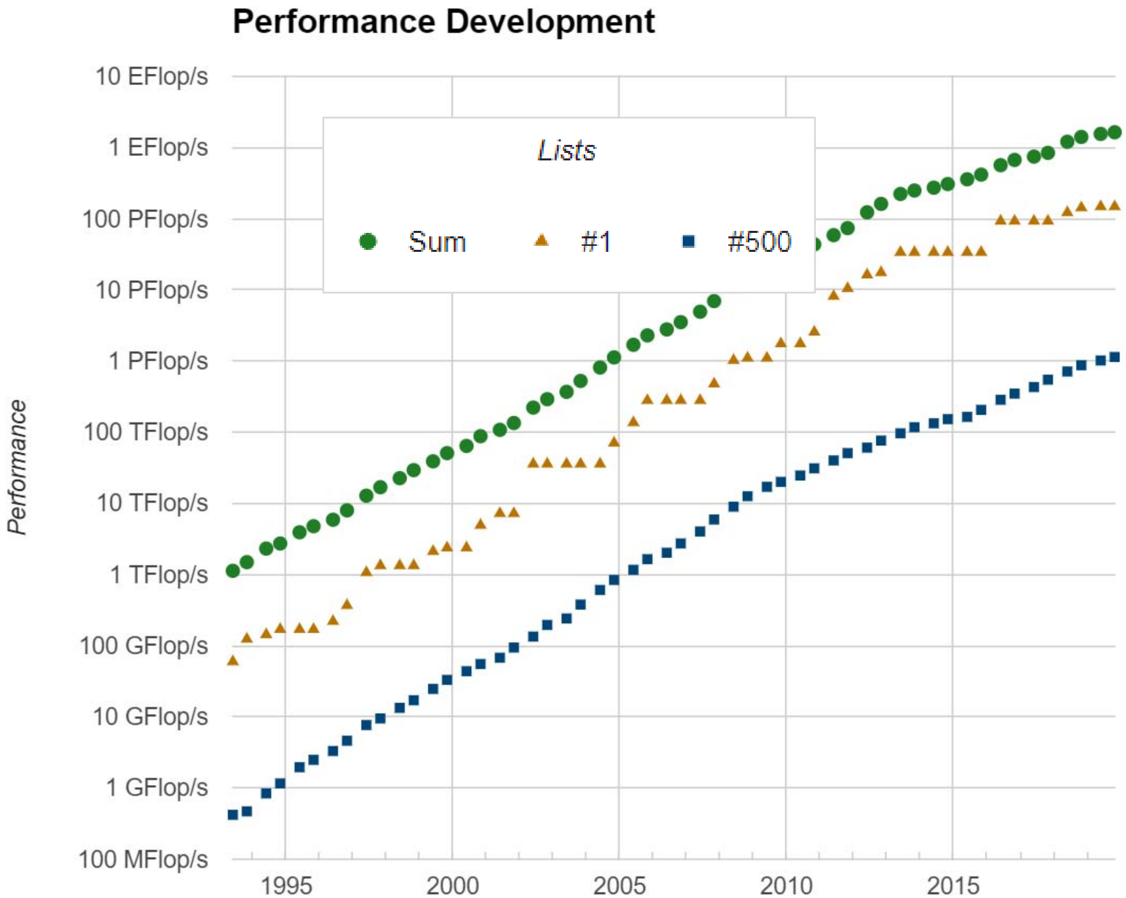
Computational performance @ dawn of risk and reliability analysis



MOPS = millions of operations per second

https://www.nap.edu/read/11148/chapter/5#31

Computational performance over time has steadily increased



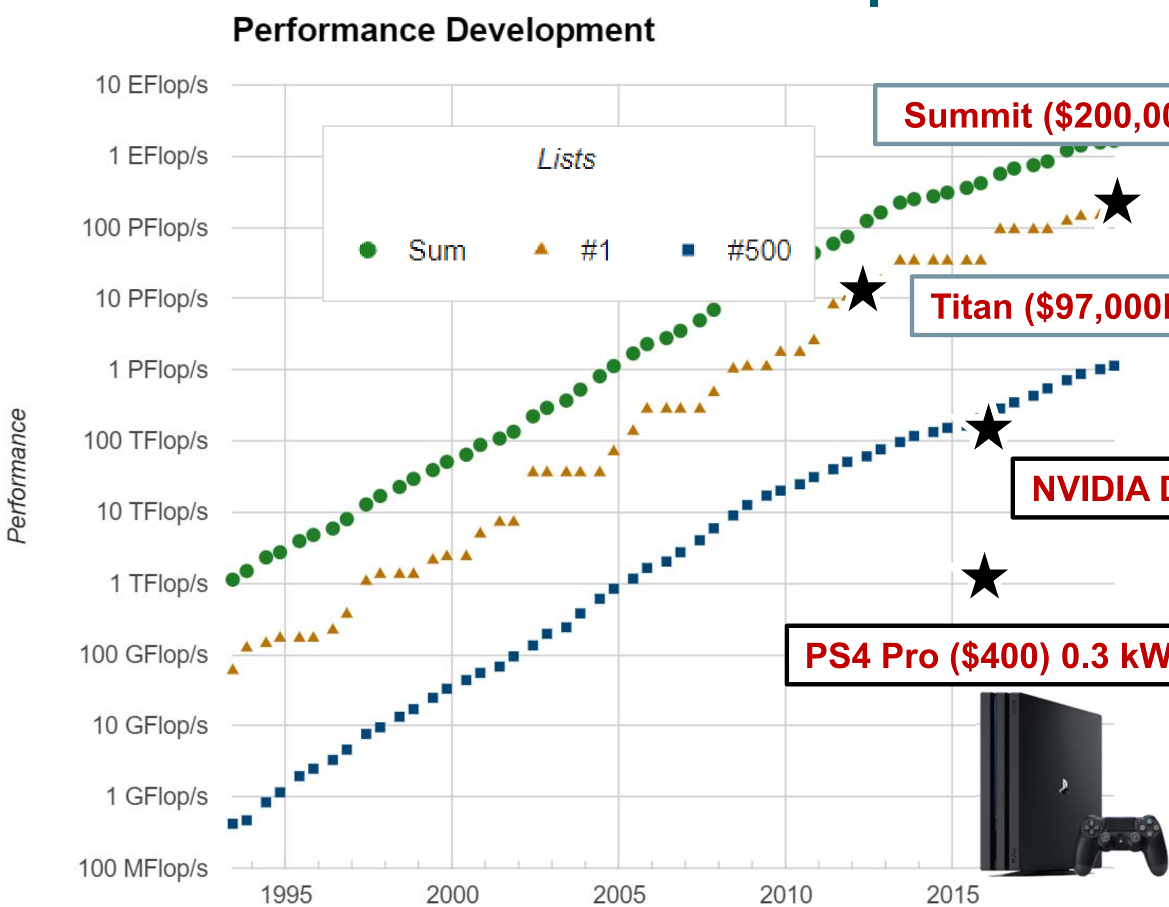
Notes:

1 EFlop/s = one exaFLOPS, or a billion billion calculations per second (10^{18})

1 MOPS does not even appear on this plot.

https://www.top500.org/statistics/perfdevel/

But how available is this "computational performance?"



Summit ($200,000K) 10,096 kW

Titan ($97,000K) 8,200 kW

NVIDIA DGX-1 ($130K) 3.2 kW

PS4 Pro ($400) 0.3 kW

https://www.top500.org/statistics/perfdevel/

Assessment is the predictive process that informs decision makers about outcomes

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

Risk represents a measured impact to safety

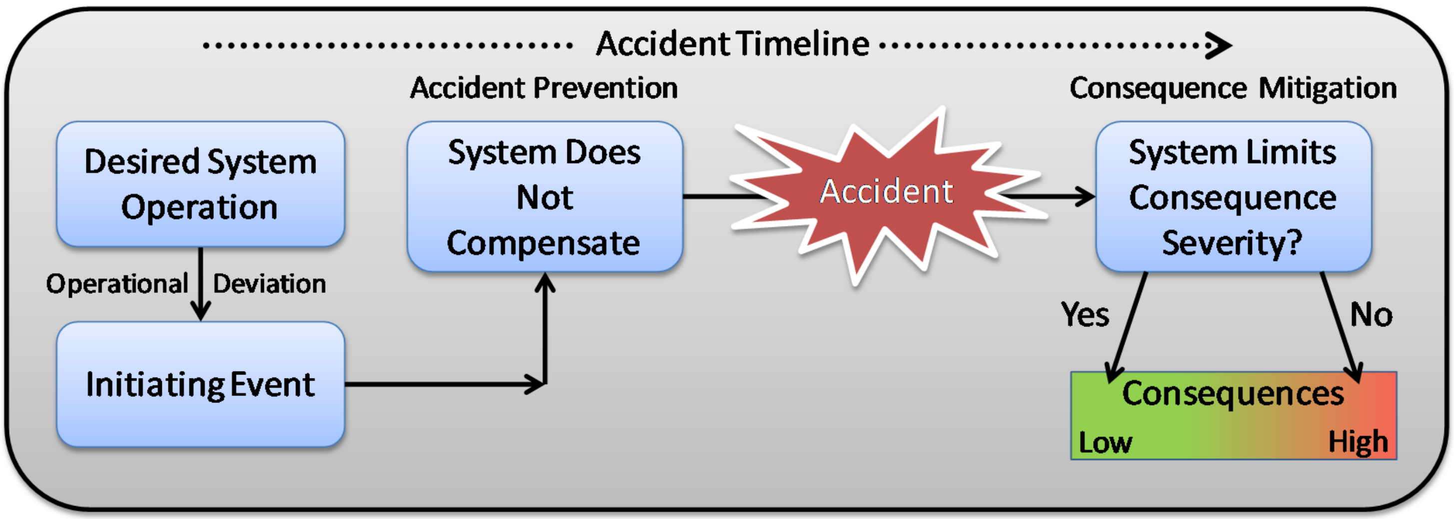
CRA → science-driven way to make things *safer*

Risk represents a performance shortfall

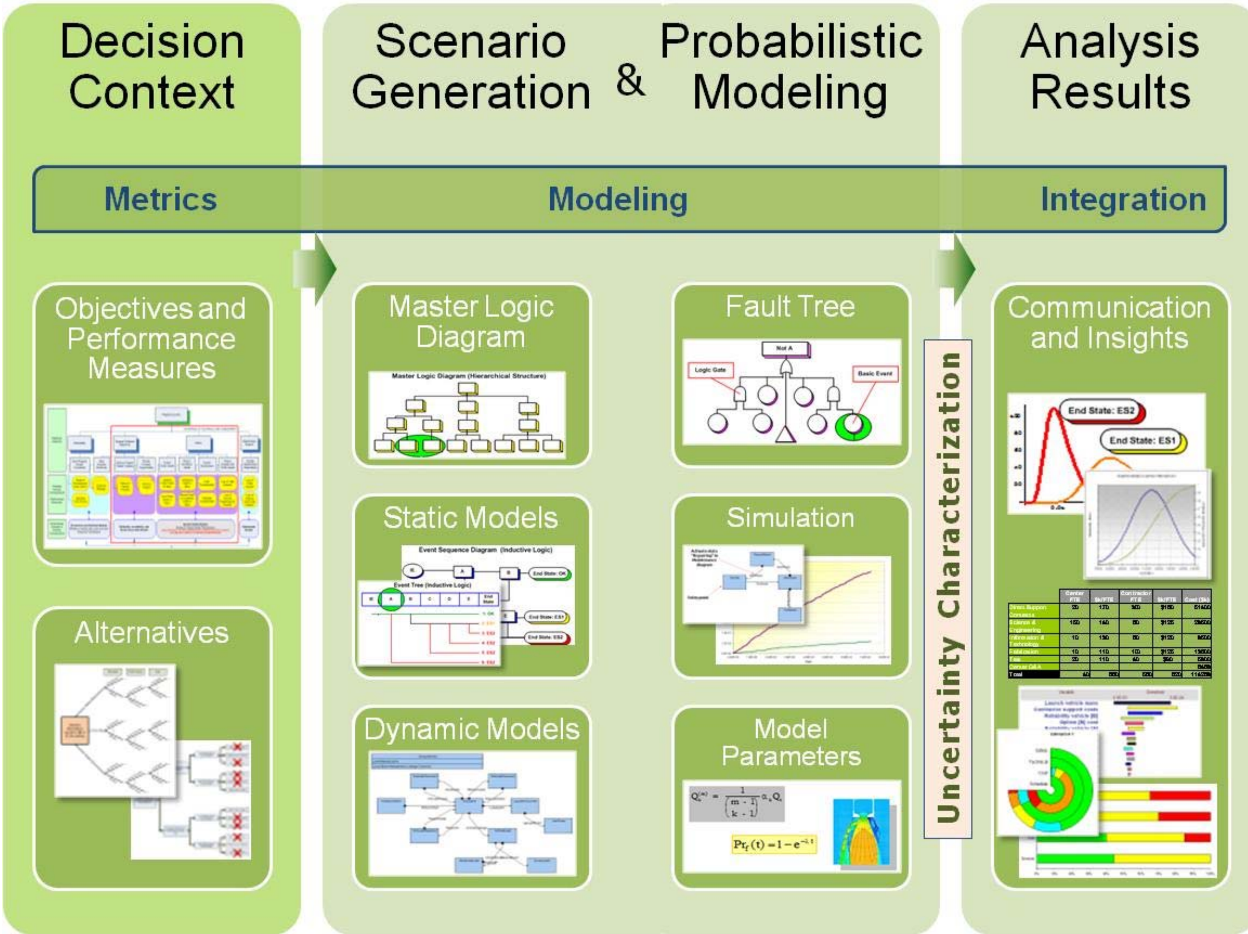
CRA → science-driven way to make things *better*

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



PRA Methodology



Proven approach to risk is used in CRA

Risk is still defined by the scenarios that may be realized leading to outcomes of interest

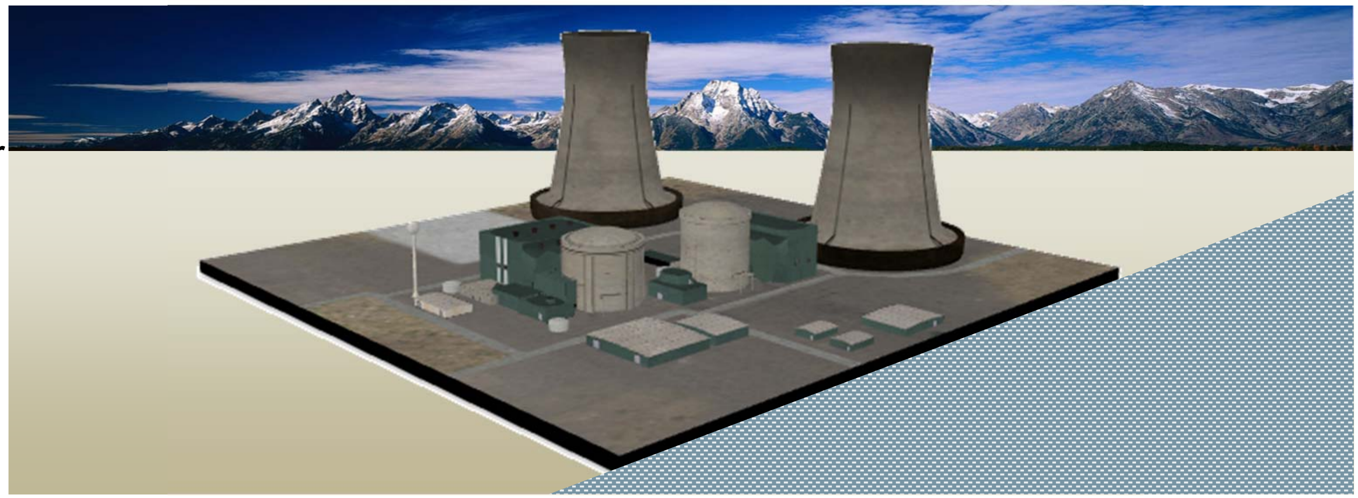
We just have a different way of getting those scenarios

We let the computer figure out the scenarios

Risk Analysis Steps for Scenario Generation

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

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



Computational Layers Used for the Analysis

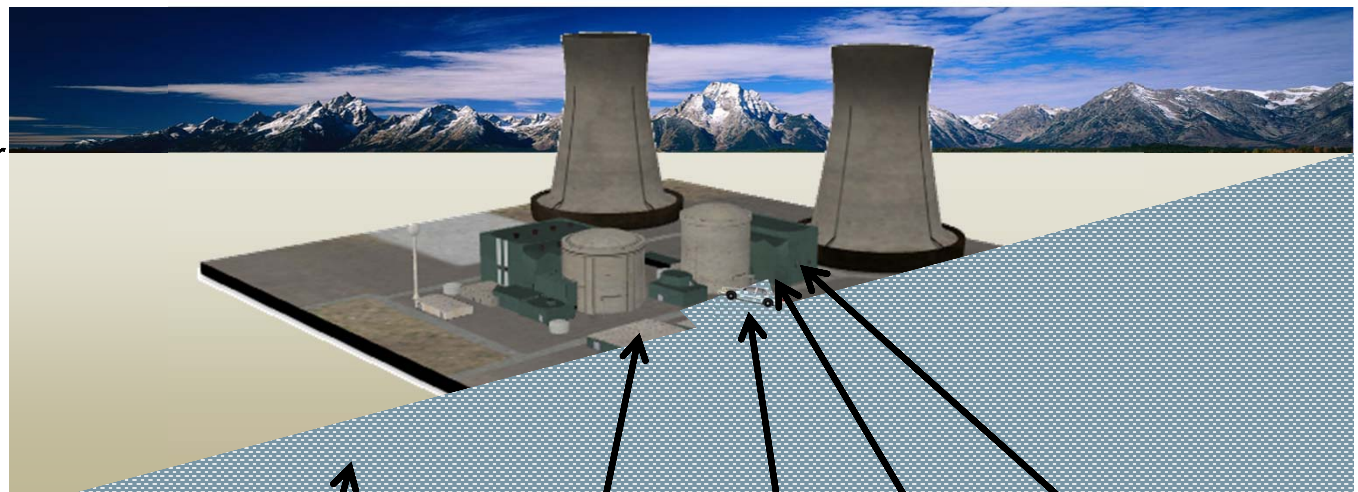
- Probabilistic events — **These tend to be stochastic models (but could be load/capacity)**
- Seismic
- Flooding
- . . .
- Thermal-hydraulics

These tend to be physics models

Risk Analysis Steps for Scenario Generation

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

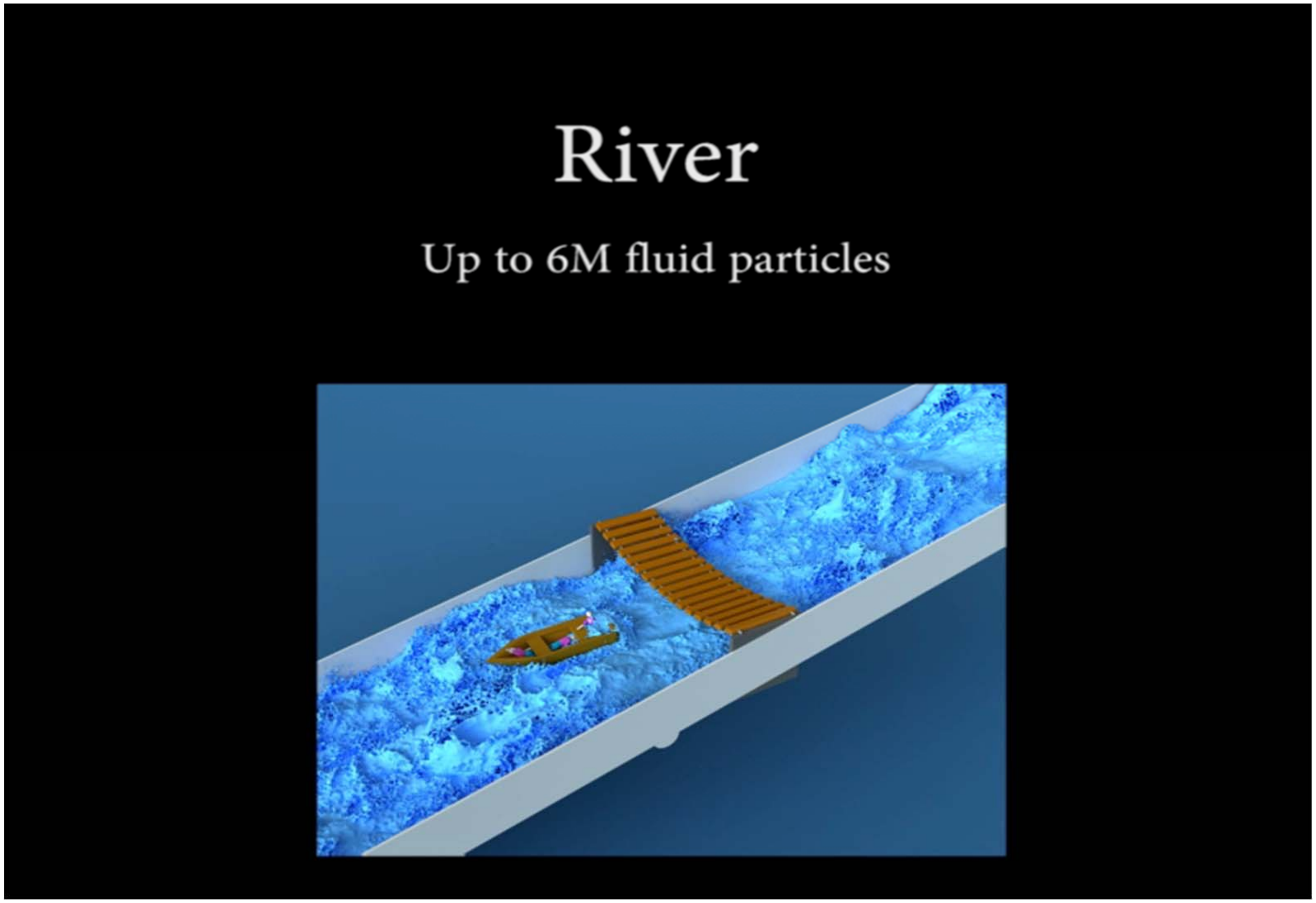
3D Models for the Facility including Systems, Structures, & Component (SSC)



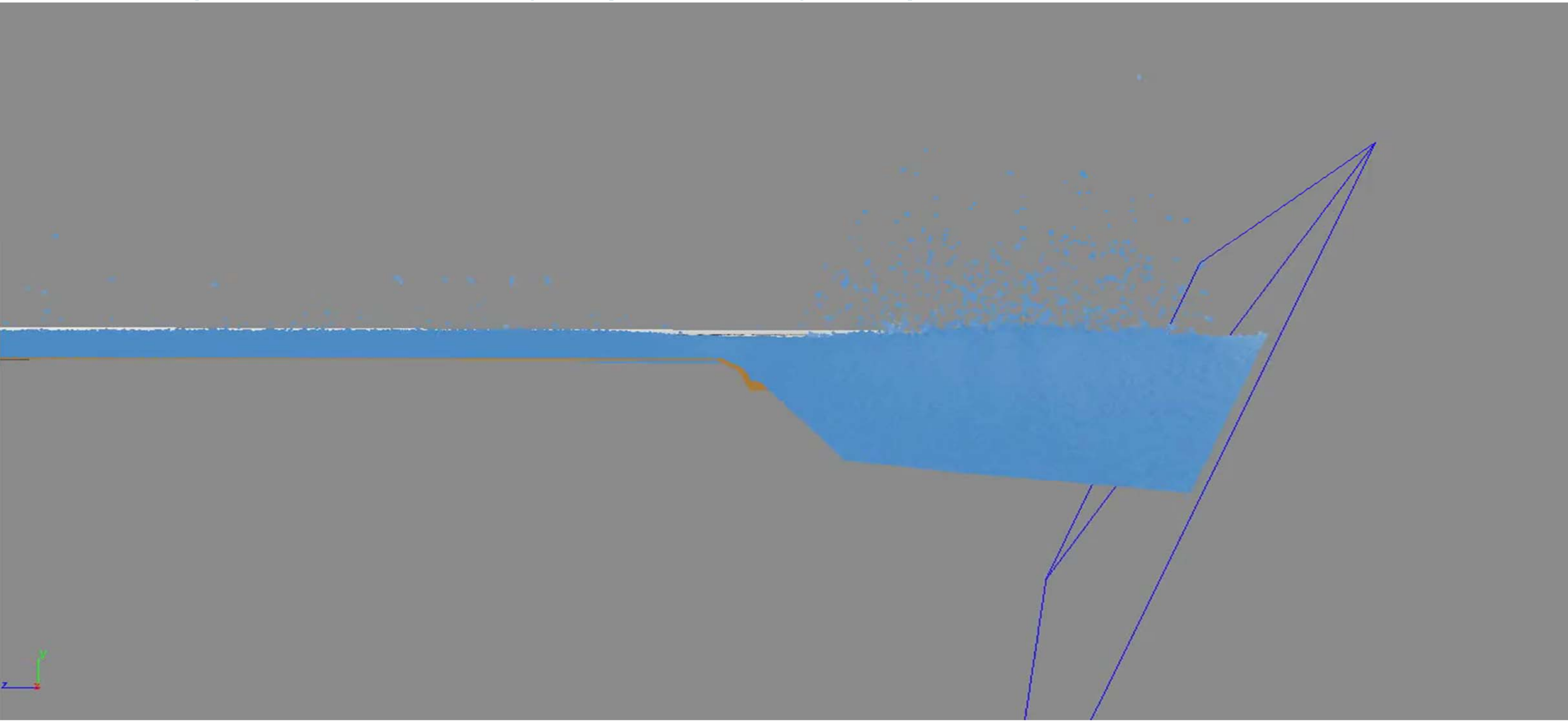
Computational Layers Used for the Analysis

- Probabilistic events
- Seismic
- Flooding: Hazard Freq. | Static/Dynamic Loads | Debris | Water Migration | Fragilities
- . . .
- Thermal-hydraulics

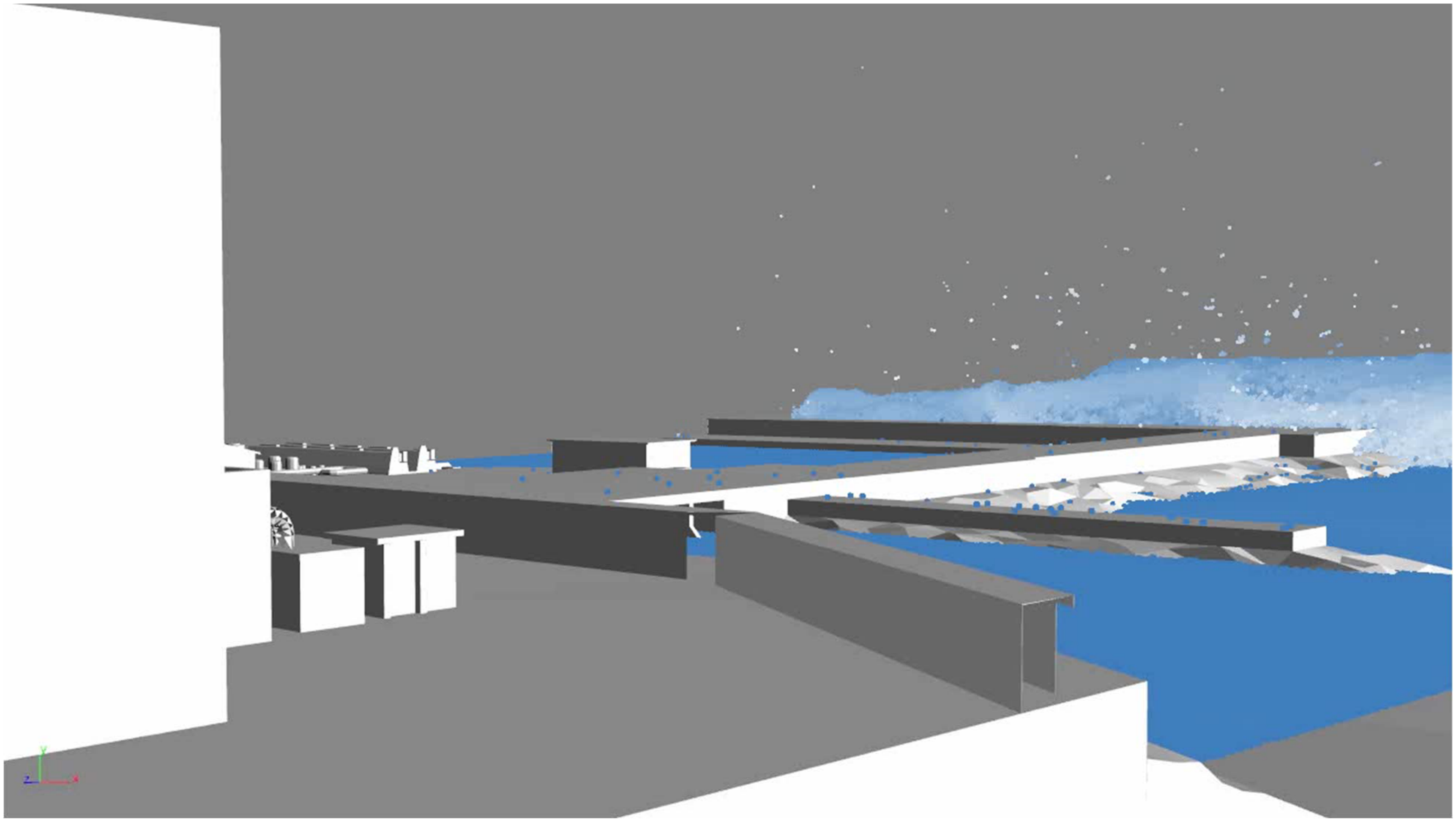
Example of a fluid solver (physics representation)



Making a wave CRA style (water physics)



Physics (water) + facility model + probabilistic failures = CRA



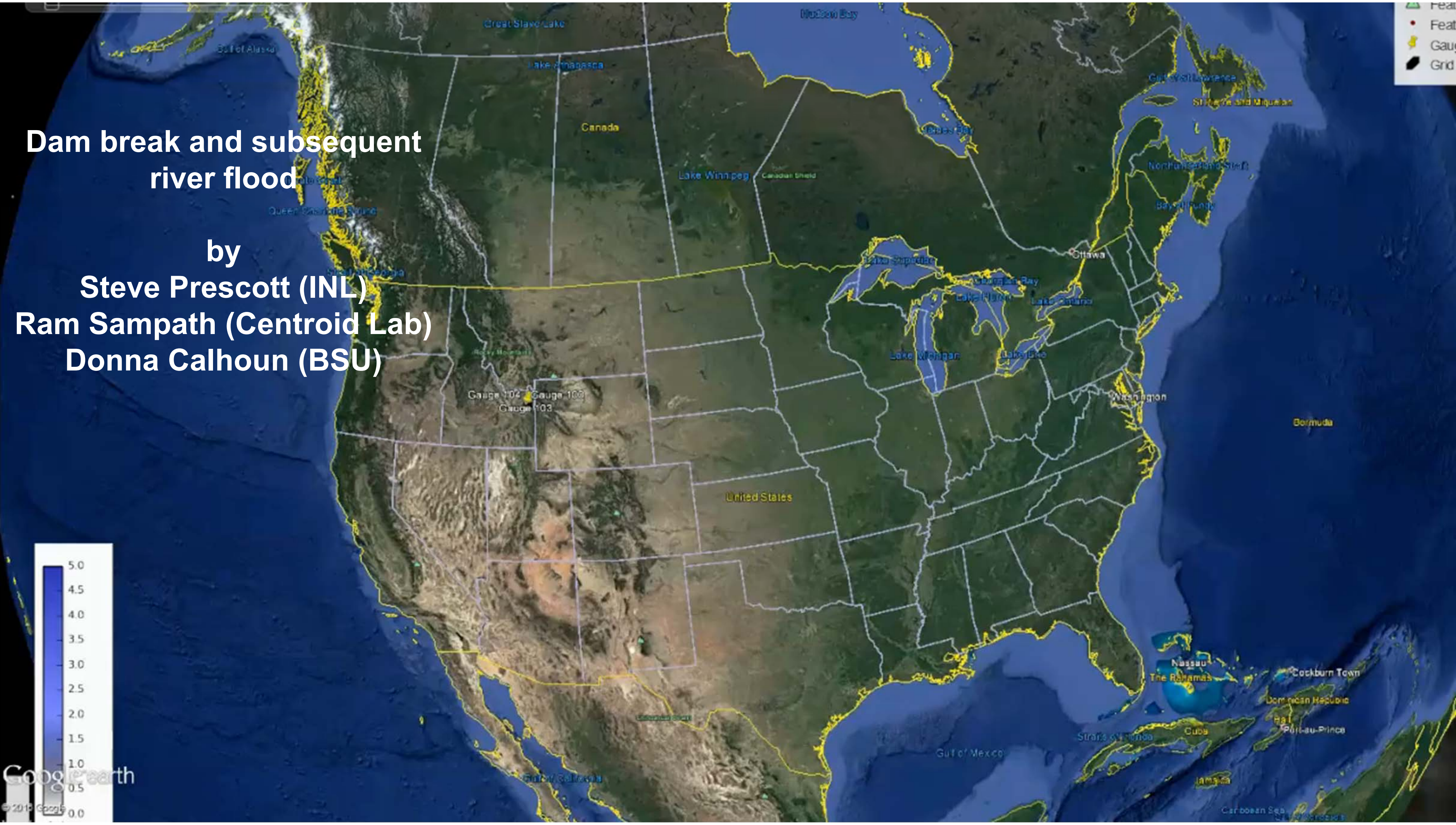
Dam break and subsequent river flood

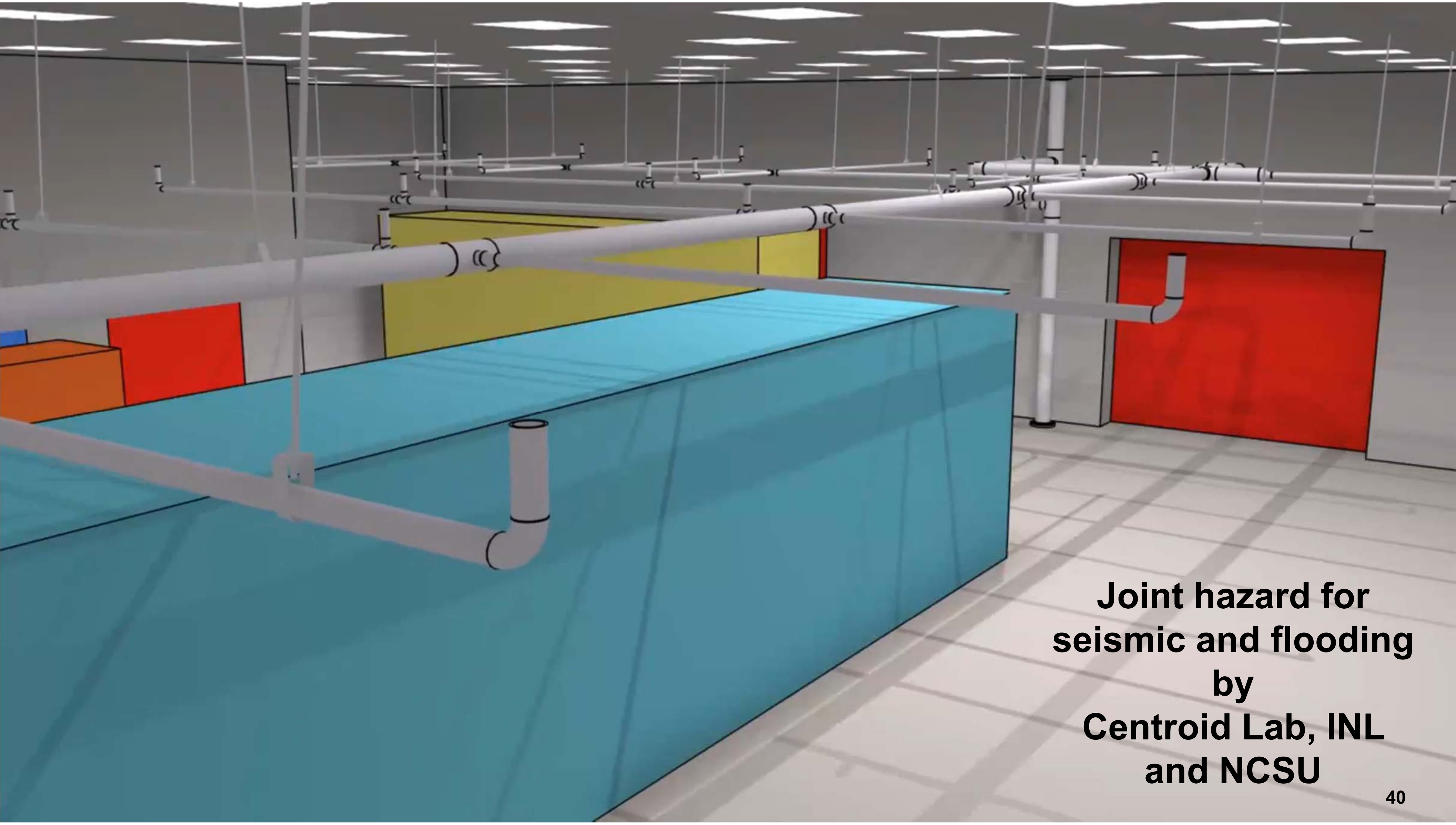
by

Steve Prescott (INL)

Ram Sampath (Centroid Lab)

Donna Calhoun (BSU)





Joint hazard for seismic and flooding by Centroid Lab, INL and NCSU

Example of Current R&D in DOE Light Water Reactor Sustainability

- **Risk-Informed Systems Analysis Pathway**
- **Pilot Projects**
  - Enhanced Resilient Plant Systems
  - Enhanced Operation Strategies for System Components
  - Plant Health Management
  - Risk-Informed Asset Management
  - Enhanced Fire Probabilistic Risk Assessment (PRA)
  - Digital Instrumentation and Control (I&C) Risk Assessment
  - Plant Reload Process Optimization
  - Verification and Validation of Tools

Enhanced Resilient Plant Concepts

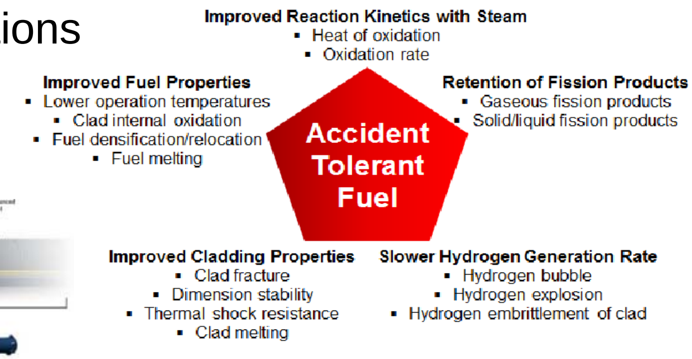
Cost and Risk Categorization Applications

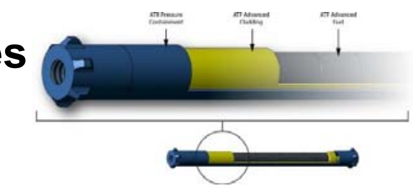
Margin Recovery and Operating Cost Reduction

Enhanced Resilient Plant Systems

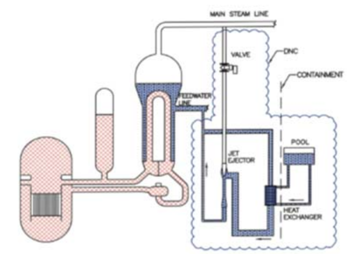
Enhanced Resilient Plant (ERP) Systems

- **ERP: An enhanced resilient plant can better cope with both internal and external events, with advanced nuclear technologies (e.g., ATF, FLEX, Passive Cooling), and keep the plant operating safely, efficiently and economically**
- **ATF: Accident Tolerant Fuel**
  - Improved fuel and cladding properties, fuel cladding interactions
  - Improved clad reaction with steam
  - Slower hydrogen generation rate
  - Better fission product retention



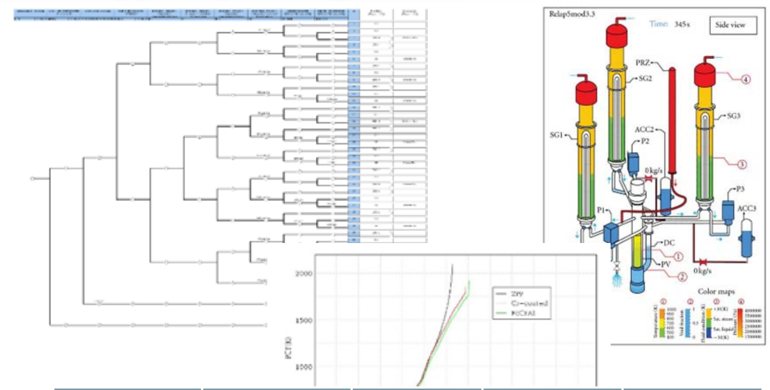


- **FLEX: Diverse and Flexible Coping Strategies**
  - AC Power / DC Power
  - Reactor Coolant System (RCS) Makeup
  - Secondary Cooling
  - Spent Fuel Pool (SFP) Cooling
- **Passive Cooling System**
- **Dynamic Natural Convection (DNC) system**



Enhanced Resilient Plant Activities

- **Risk-Informed ATF Analysis with SAPHIRE PRA & RELAP5-3D Model for a Generic Westinghouse 3-Loop PWR**
- **Industry Engagement on ATF/FLEX Collaboration**
- **ERP Workshop in July 2019 Hosted by INL**
  - NEI, EPRI, PWROG, Jensen Hughes, DYNAC
  - Southern, Xcel, Framatome
  - MIT, RPI, UW, TAMU, UM
  - INL, SNL, NRC, NCSU
  - South Korea, Zachary
- **ATF Analysis Benchmarking – RELAP5-3D & MELCOR**
- **FLEX Risk and Benefit Analysis**
  - FLEX PRA Modeling and Risk Impact Analysis
  - FLEX HRA Investigation
  - FLEX Significance Determination Process



LOOP ET	CDF No FLEX	CDF with FLEX	ΔCDF	ΔCDF%
LOOPGR	1.07E-06	8.12E-07	-2.55E-07	-23.9%
LOOPPC	6.21E-08	5.19E-08	-1.02E-08	-16.4%
LOOPSC	4.57E-07	3.58E-07	-9.85E-08	-21.6%
LOOPWR	6.89E-07	4.60E-07	-2.29E-07	-33.2%
LOOP Total	2.28E-06	1.68E-06	-5.93E-07	-26.1%

	SDP Color	Without FLEX	With FLEX	Delta	Benefits
t(ICCDP=1E-6), day	White	7	10	3	$$
t(ICCDP=1E-5), day	Yellow	66	96	30	$$$

Plant Health Management

Plant Health Management (PHM)

- **Mission**
  - Develop a RI Plant System Health (RI-PSH) program
- **Goals**
  - Leverage advances in technology to reduce costs and maintain / improve system performance
  - Expected links and efficiencies with approaches applied to asset management use case
- **Expected Outcomes**
  - Improve efforts to manage equipment reliability
  - Provide real time safety and economical risks associated to plant equipment
  - Optimize maintenance strategies

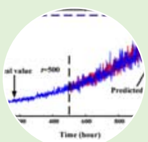
Risk Informed Plant System Health

- **Continuous integration of:**
  - Plant health data (e.g., failure data, maintenance report)
  - System, structure, and component economic data
    - Maintenance cost
    - Replacement cost
    - Consequence of SSC failure

- **Provide real time risk information**
  - Safety: CDF, LERF
  - Economic: Loss of MWe
  - Regulatory: Significance Determination Process (SDP), Mitigating System Performance Index (MSPI)
- **Update plant operations**
  - Preventive maintenance schedule
  - Surveillance frequency
  - Replacement date
  - Procurement scheduling

Equipment reliability and maintenance data

Equipment performance monitoring data



Predictive and diagnostic data

Data analysis

Reliability assessment

Plant risk and safety assessments

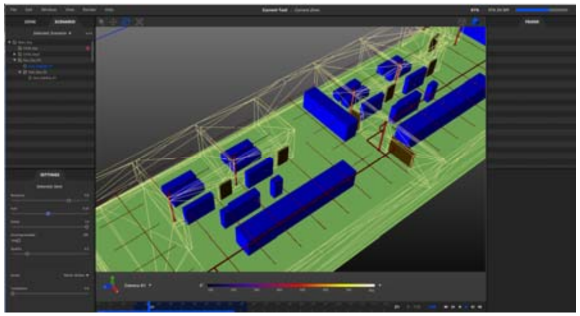
Plant performance and economic assessments

Decision support

Enhanced Fire Probabilistic Risk Assessment

Enhanced Fire PRA

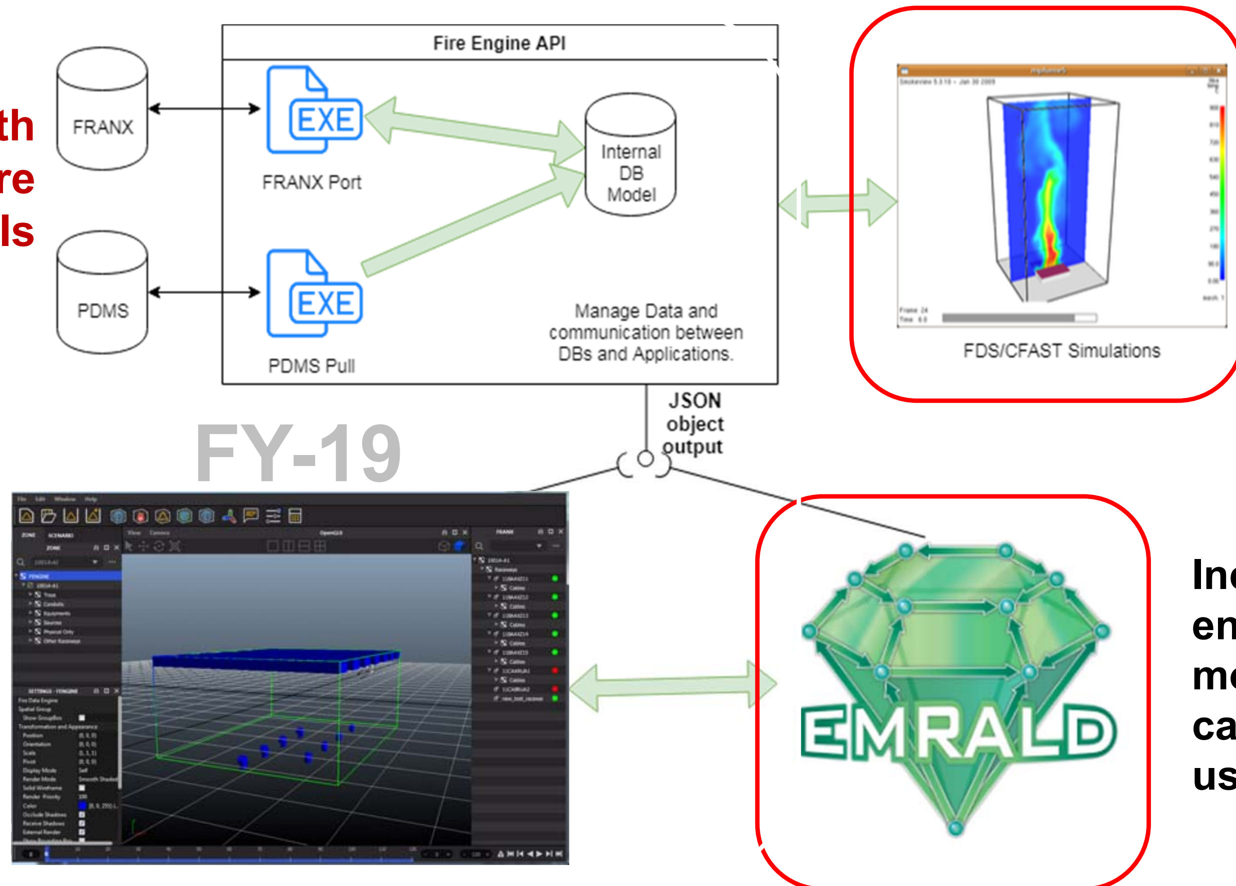
- **Goal – Reduce utility cost associated with plant fire risk analysis**
  - Significant reduction of fire model analysis cost in day-to-day operations
  - Minimize conservatisms that may exist while simplifying industry fire analysis
  - Develop methods to capture operator actions and time-dependent procedures
- **Purpose**
  - Support implement NUREG-6850 (EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities) and meet NFPA 805 standards
- **Objectives**
  - Leverage tools to develop a visualization combining existing Fire PRA models with 3D spatial information
  - Develop a framework for dynamic analysis of key fire PRA scenarios to reduce conservatism
- **Near-term activities**
  - Simplify scenario creation through simulation & automation
  - Model real plant scenario & conservatism reductions
  - Path for initial industry use



Developmental Fire PRA Interface

Simulations & Enhanced Analysis

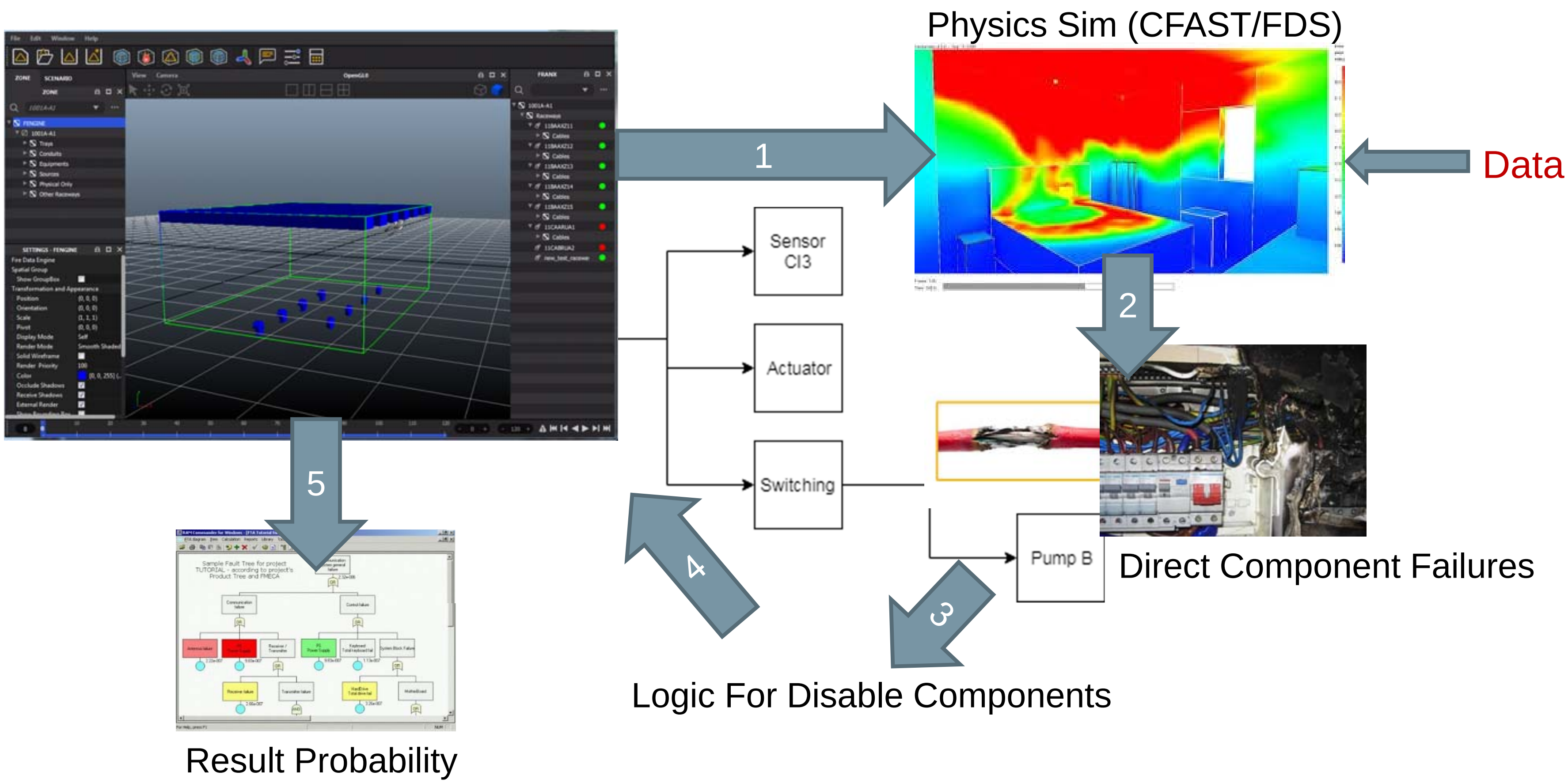
Couple with industry fire simulation tools



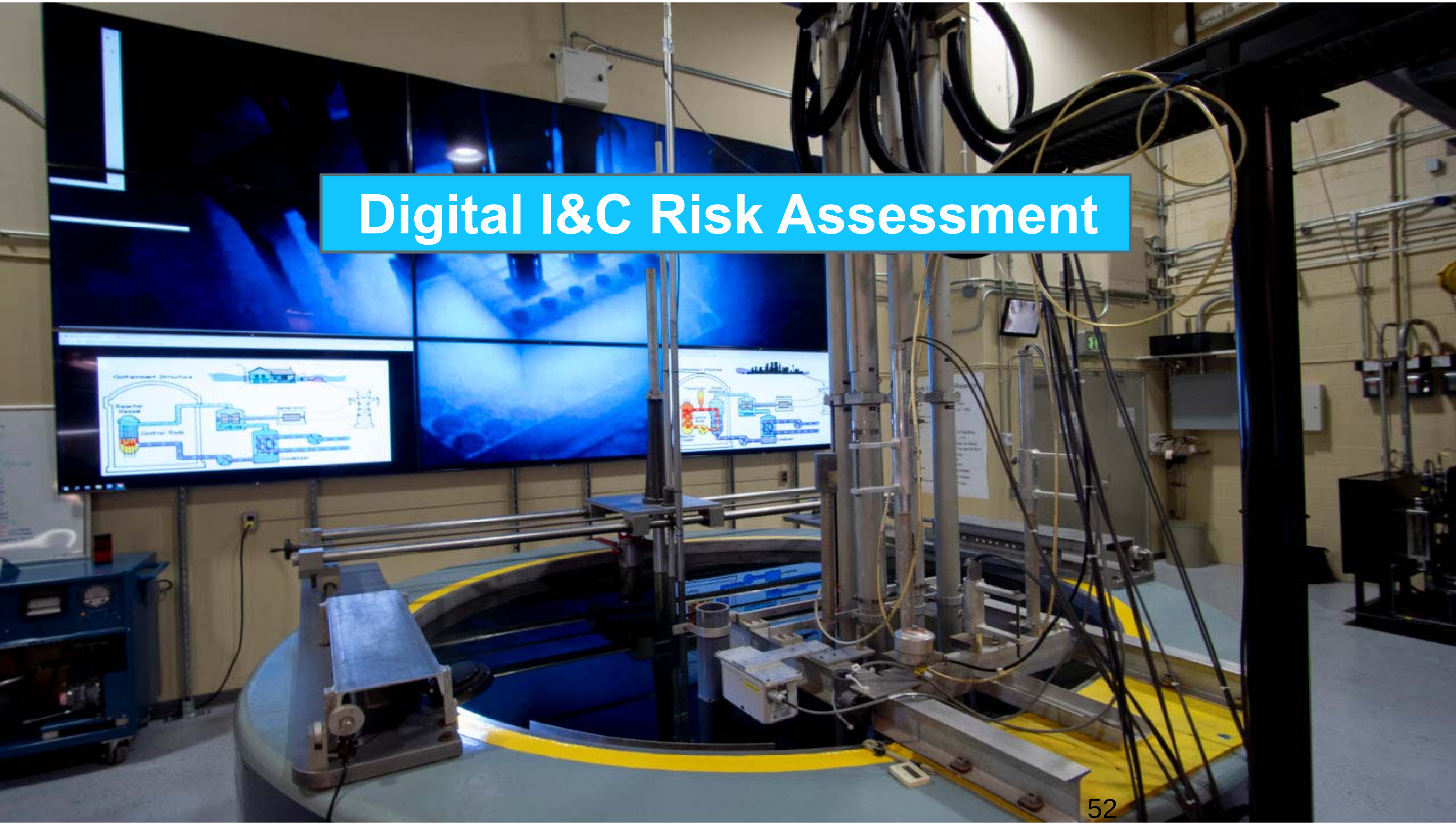
Incorporate enhanced fire modeling capabilities using RISA tools

Fire Risk Investigation in 3D (FRI3D)

Scenario Generation from Simulation



Digital I&C Risk Assessment

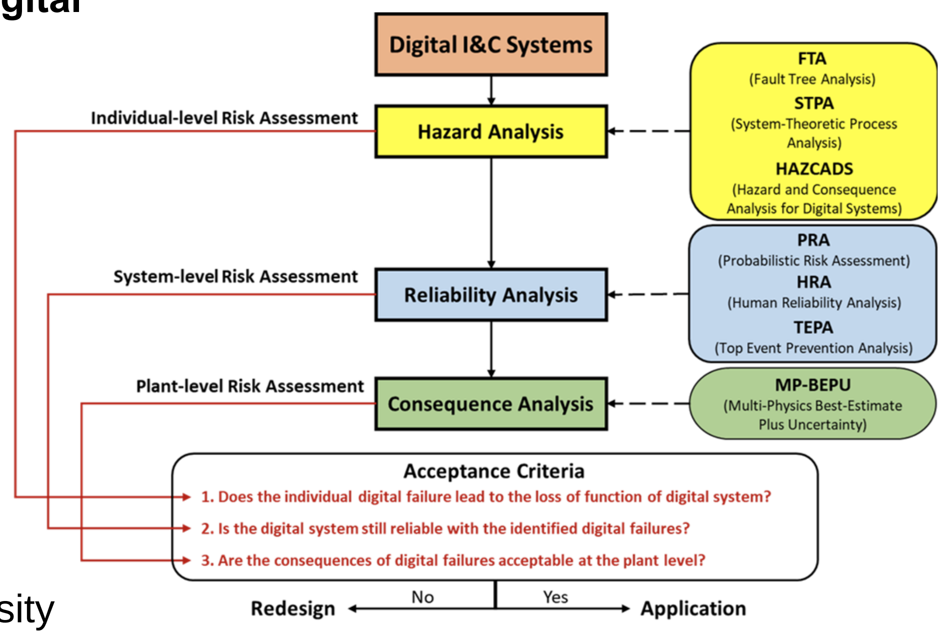


Digital I&C Risk Assessment

- **Goal**
  - Develop risk assessment methodology to support transition from analog to digital I&C technologies for nuclear industry
  - Assure the long-term safety and reliability of vital engineered systems
  - Reduce uncertainty in costs & time and support integration of digital systems in the plant
- **Objectives**
  - Define a risk-informed analysis process for digital I&C upgrade
    - Example systems
      - Reactor trip system (RTS)
      - Engineered safety feature actuation system (ESFAS)
  - Support development and deployment of digital I&C technologies
  - Apply risk-informed approaches of (non-)safety related digital I&C licensing
- **Near-term activities**
  - Develop a risk assessment strategy for digital I&C upgrades using current digital technology information
    - Reliability studies of digital reactor protection system for a conceptual digital design
  - Apply risk-informed tools to address common cause failure for digital I&C technology

Digital I&C Risk Assessment Activities

- **Developed integrated Risk Assessment process for Digital Instrumentation & Control systems of nuclear power plants**
  – System-theoretic hazard analysis
  – Integrated reliability analysis
- **INL Report**
  – INL/EXT-19-55219, An Integrated Risk Assessment Process for Digital Instrumentation and Control Upgrades of Nuclear Power Plants, August 2019
- **Conducting integrated reliability analysis for digital designs**
  – Providing technical basis (models and methods) for cyber security analysis of digital I&C systems
  – Providing risk insights to defense-in-depth and diversity applications of digital I&C system designs
    - Identify crucial software common-cause failures and their triggers
    - Quantitatively evaluate (risk, safety, cost) benefits



Verification and Validation of Tools

RISA Pathway Toolkit Deployment Plan

- **Deployment of risk-informed tools to industry is key for RISA Pathway**
- **Pilot project is way to perform demonstration of selected tool**
- **Tools should have highest technical maturity as possible**
  - Technology Readiness Level (TRL) higher than 5 at least (among 1-9)
- **Performs Technical Maturity Assessment (TRA)**
  - Assess V&V status
  - Define requirements and importance level to be used in RISA Pathway
  - Suggest Technology Maturity Level (TRL)
  - Identify technical gaps
  - Propose additional development and upgrades

Notional 5-year RISA Toolkit deployment Plan

Year 1
- Preliminary study on selected pilot demonstrations
- Create RISA-industry working group

Year 2
- Perform full scale pilot demonstrations
- RISA Toolkit validation and verification

Year 3
- Continue full scale pilot demonstrations and validations
- Initiation of RISA Pathway industry deployment

Year 4
- Finalize full scale pilot demonstration and validations

Year 5
- RISA Toolkit deployment
- RISA Pathway technology transfer to industry

Technical Maturity Assessment Requirements as RISA Toolkit

- **14 requirements to evaluate technical maturity in three areas**

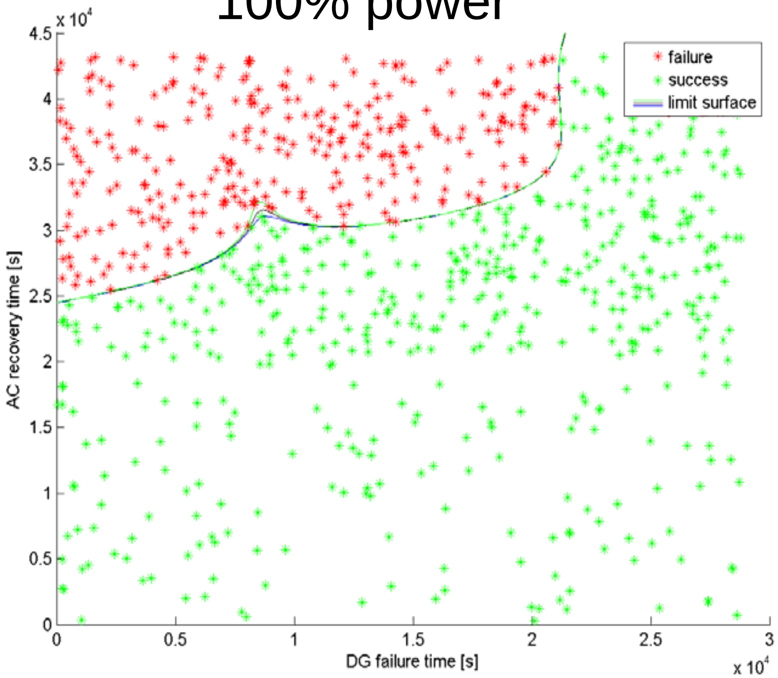
Fundamentals	Software	Support
• Highest development level (> TRL 5 desired) • Use of proven technology for existing NPPs • PRA capability / coupling applicability	• System requirements (various OS) • Easy installation • Graphic user interface (GUI) • Version control • V&V history	• Documentation • QA program • Web page • User feedback • Training program • License control


Additional RI Research

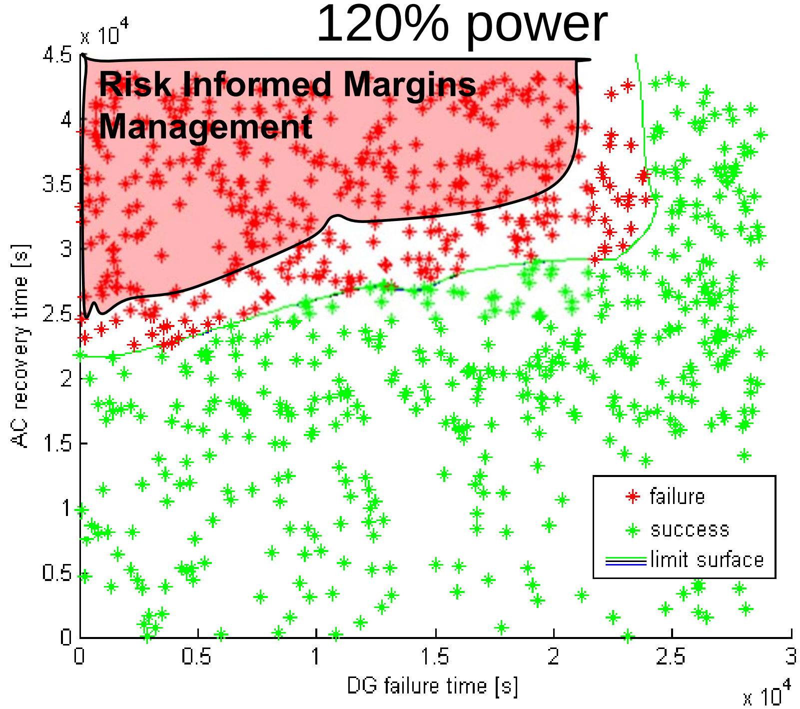
BWR Power-Uprate with Station Blackout Test Case Results

- **Limit surface: boundaries in input space between failure & success**
  - Diesel Generator failure time versus AC power recovery time
- **Other "surfaces" evaluated for RI margins management**

100% power

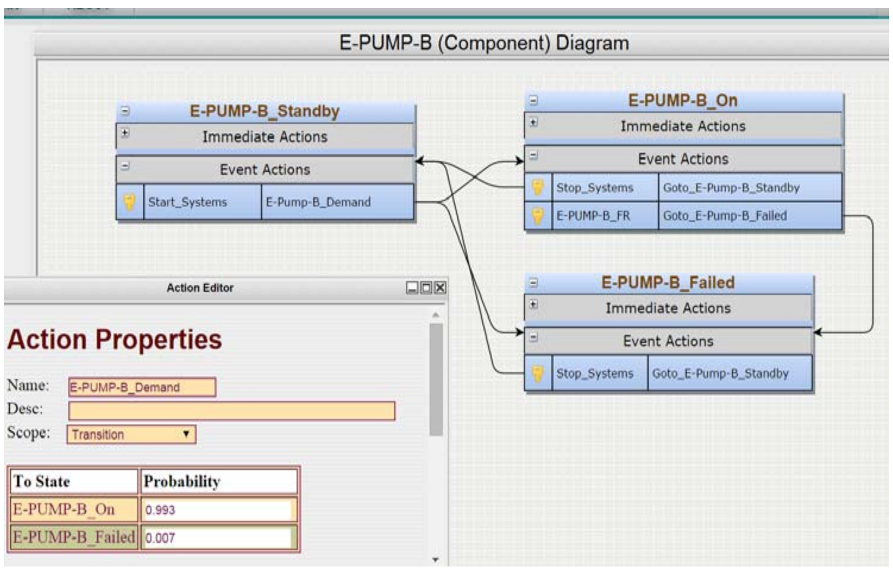


120% power

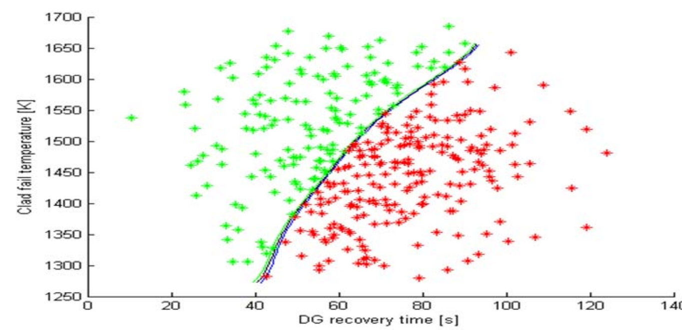


Next-Generation Risk Analysis Tools

- **Event Model Risk Assessment using Linked Diagrams → EMRALD**
- **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**

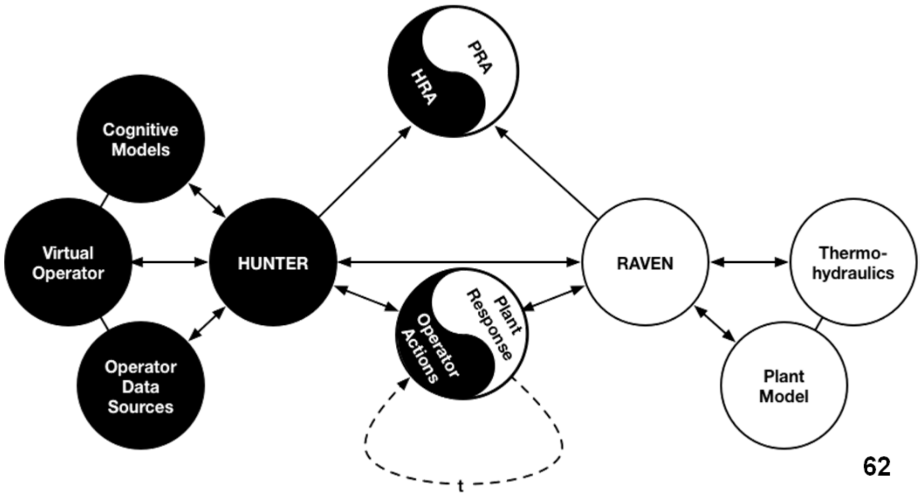


Human Systems Simulation Laboratory (HSSL)

- **A reconfigurable, full-scale, full-scope research simulator**
  - 15 bays with 3 large screens on each bay
- **Full-scale, full-scope simulator model that includes all functions found in a control room (capable of modeling normal and abnormal plant operations)**
- **Reconfigurable**
  - Mimics both analog and digital systems and controls virtually
  - Multiple control room configurations possible for both PWRs and BWRs
- **Suite of human performance and risk measurement tools for operator-in-the-loop studies**

HUNTER Human Reliability Analysis Research

- **HUNTER: Human Unimodels for Nuclear Technology to Enhance Reliability**
  - Take static HRA approach and make it dynamic
    - Much of work centers on SPAR-H, a simplified method quantified by assigning weights to performance shaping factors (PSFs)
    - Static HRA is analyzed at the Human Failure Event (HFE) level
  - Couple dynamic information from scenario simulation to human model
  - Determine way to quantify Human Error Probability (HEP)
    - Dynamic HRA to auto-quantify based on available plant states and other contextual factors
    - Can iterate (e.g., Monte Carlo simulation)



Recap → "why are we performing CRA?"

- **Insights into risks of interest → RI decisions**
- **Validity of the decisions predictions we are making**
  - Did we capture timing, spatial interactions, physical phenomena, and complexity of the problem adequately?
  - How do we know to the degree of "validity?"
- **In many ways, creating the CRA model is more straightforward than legacy approaches**
  - Describe how things work rather than creating a Boolean representation of how things fail
- **Allows for different (better?) set of assumptions**
- **"Data" for Machine Learning?**

Potential Future RI Activities

What is Machine Learning/Artificial Intelligence (ML/AI)?

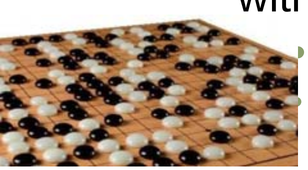
- **From Wikipedia**
- **Artificial intelligence (AI) is intelligence demonstrated by machines**
  - Study of "intelligent agents": any device that perceives its environment and takes actions that maximize its chance of successfully achieving its goals
  - Machines that mimic "cognitive" functions that humans associate with the human mind, such as "learning" and "problem solving"
- **Machine learning (ML) is the scientific study of algorithms and statistical models that to perform a specific task without using explicit instructions, relying on patterns and inference instead**
  - Subset of artificial intelligence
  - Builds a mathematical model based on sample data ("training data“) to make predictions or decisions without being explicitly programmed to perform the task
  - Closely related to computational statistics, which focuses on making predictions using computers

Examples of current ML and AI applications

- **Symbolic reasoning to differentiate & integrate math expressions**
  - Neural network used 80 million examples of first- and second-order differential equations and 20 million examples of expressions integrated by parts
  - How well does it work?
    - Significantly outperforms Mathematica (on integration, close to 100% accuracy)
      - Mathematica barely reaches 85%, Maple and Matlab perform less well
      - In many cases, conventional solvers unable to find a solution in 30 seconds
      - The neural net takes about a second to find its solutions
  - https://www.technologyreview.com/s/614929/facebook-has-a-neural-network-that-can-do-advanced-math/

$$y' = \frac{16x^3 - 42x^2 + 2x}{(-16x^8 + 112x^7 - 204x^6 + 28x^5 - x^4 + 1)^{1/2}}$$

- **AlphaGo and AlphaGo Zero to play Go**
  - AlphaGo defeated 18-time world champion Lee Sedol 4 games to 1
    - Used game tree search, neural network trained on expert human games, second neural network for board positions, and additional Monte Carlo rules
  - AlphaGo Zero used same tree search algorithm, but then single neural network trained without any human games
    - AlphaGo Zero defeated AlphaGo 100 games to 0
    - https://medium.com/ww-engineering/alphago-zero-a-brief-summary-dcff16ba3064



Potential Future RI Applications

- **CRA to produce "data" for ML**
- **Digital twin**
- **Digital regulator**
- **System abstraction**
- **RI construction**
- **Autonomous operation**
- **RI design**

Discussion of Future Applications (1 of 2)

- **CRA to produce "data" for ML**
  - ML requires training data – however risk and reliability applications have a small set of "failure" data
  - Advanced computational methodologies (e.g., CRA) can be used to produce very large set of synthetic data
    - Use this data to train ML models
- **Digital twin**
  - Advance applications such as CRA and autonomous control requires virtual representation of complex systems
  - "Operating" these facilities complete with potential hazards provides robust understanding
- **Digital regulator**
  - Agent-based systems can be created to accomplish difficult real-world tasks such as oversight of construction and operations
  - CRA combined with real-world sensors can facilitate next-generation of regulation
    - Technology to keep a digital presence in complex systems to enable real-time independent oversight

Discussion of Future Applications (2 of 2)

- **System abstraction**
  - Ability to describe systems using an integrated approach is vital to cost-effective analysis
  - SysML is an open modeling language being increasing used for engineering applications
    - Standard that can describe system specifications (e.g., what is a system), containing details of system geometry, material properties, dependencies, & operational rules
- **RI construction**
  - Tailor construction (e.g., 3D printing) of complex systems to focus on facility characteristics that minimize hazards and construction costs
- **Autonomous operation**
  - To lower the cost of complex systems, AI will need to combine sensing, computational engineering, and advanced algorithms to achieve heightened state-space awareness
  - These AI strategies will provide economical, resilient operations
- **RI design**
  - Develop risk analysis to focus on community infrastructures, with special emphases on the impacts of changing climate
  - For example, make systems and components more resilient to flood hazards

Conclusions

- **The Idaho National Laboratory, through a variety of projects, is demonstrating a next-generation uncertainty and risk-assessment approach that supports decision-making**

- **Combines mechanistic physics-based models with probabilistic analysis (CRA)**

  - **Uncertainty analysis can be built upon and supported for next-generation methods and tools**

    - **Provides an opportunity to greatly enhance the realism in our risk models**

      - **Also provides solutions to many of the vexing issues found in PRA**

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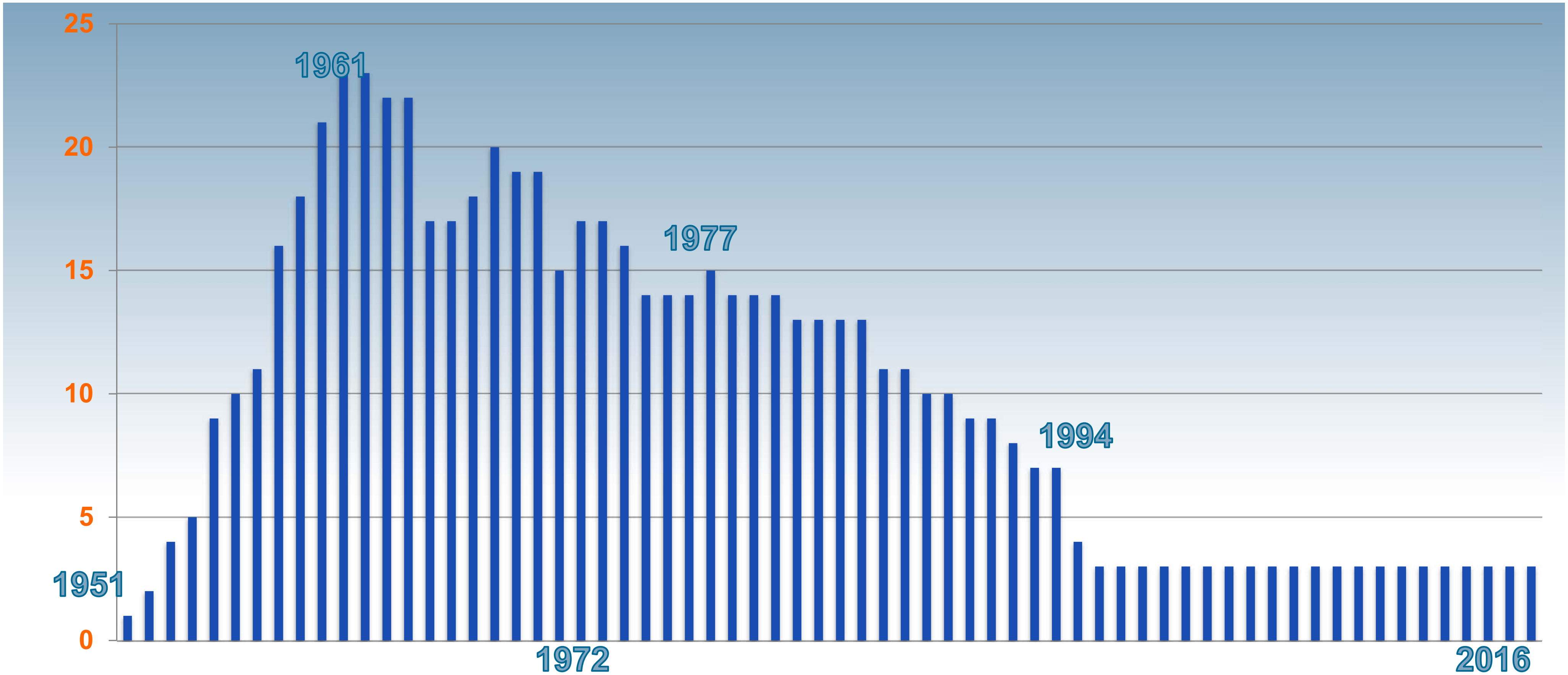
Thank you!

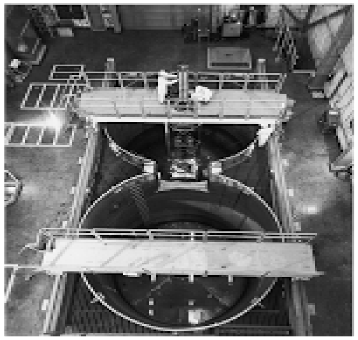
Idaho National Laboratory

INL's Operating Reactors by Year

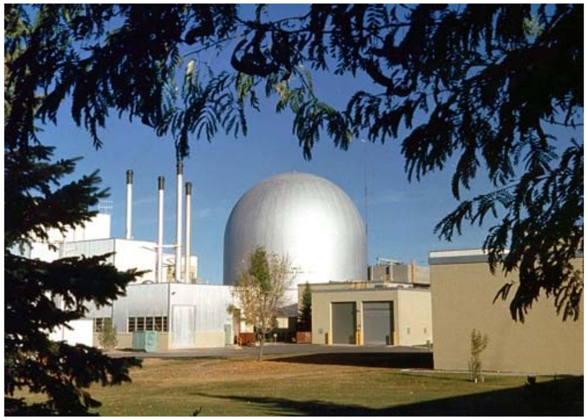


Safety Testing, Including Transients


Loss Of Fluid Test Facility (LOFT)


Special Power Excursion Reactor Tests I though IV (SPERT)

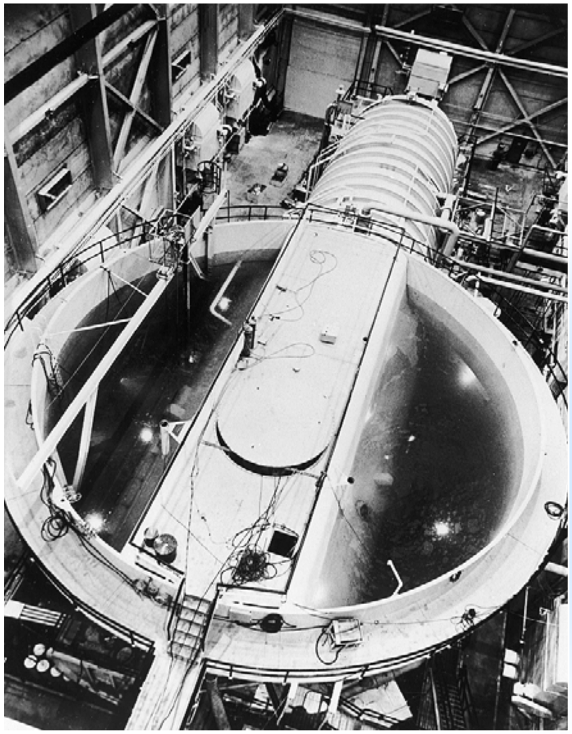

Transient Reactor Test Facility (TREAT)


Experimental Breeder Reactor-II (EBR-II)

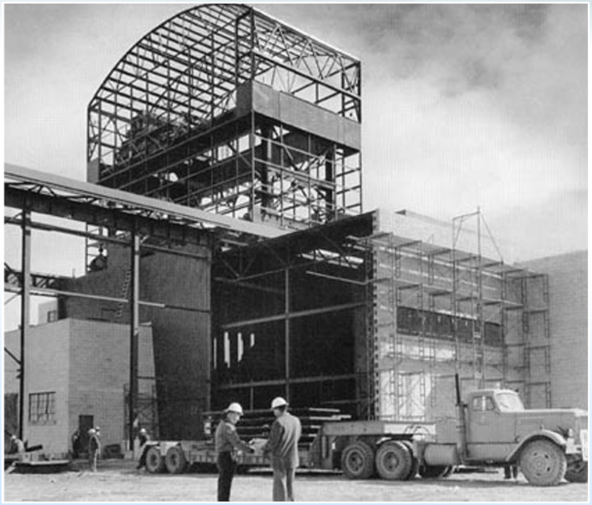

Boiling Water Reactor Experiment-I (BORAX-I)


Power Burst Facility (PBF)

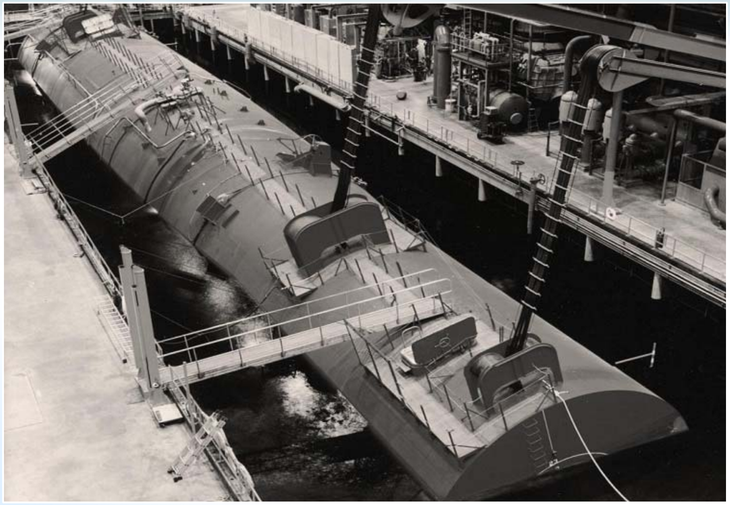
Marine Propulsion



S1W aka STR



A1W

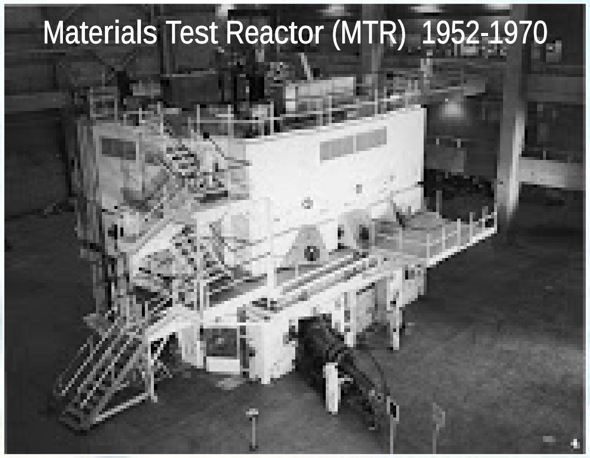


S5G

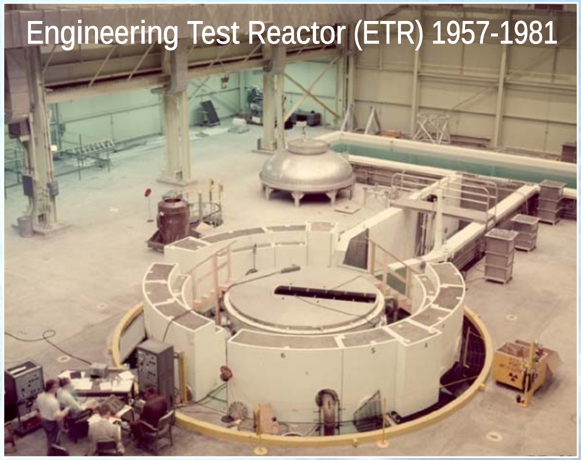
Nautilus Prototype

High Temperature Marine Propulsion Reactor 630A (civil)

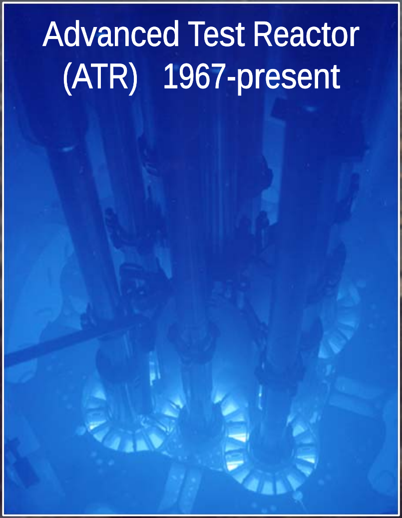
Reactors for Testing Fuels and Materials



Materials Test Reactor (MTR) 1952-1970



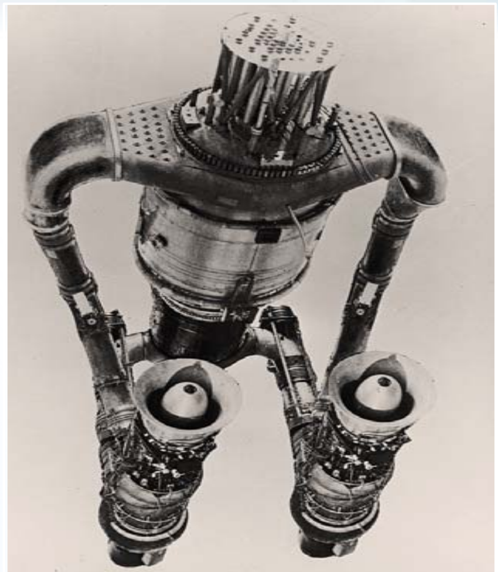
Engineering Test Reactor (ETR) 1957-1981

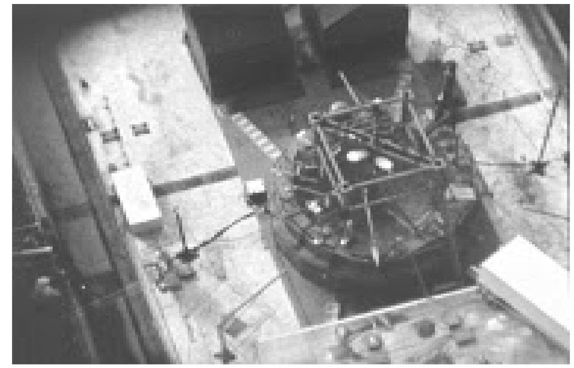


Advanced Test Reactor (ATR) 1967-present

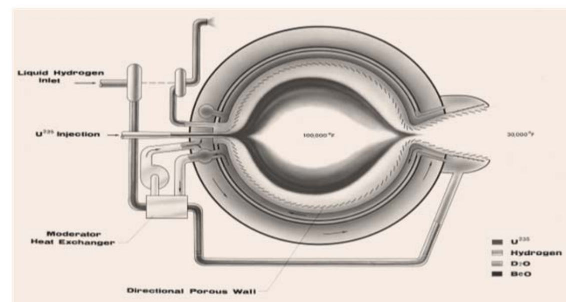
Air and Space Propulsion

Aircraft Nuclear Propulsion HTRE units on public display at Historic EBR-1 site





SNAP 10A (1964-1966)



Spherical Cavity Reactor Critical Experiment 1972-73