PRA Research at CRR

Presentation to Constellation Energy

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Maryland Nuclear Engineering Research: PRA

- UMD’s Nuclear Engineering Program Started in Late 1950’s with a Research Reactor Still Operating and Many Nuclear Engineering Alums.
- Focus on PRA started in the early 1980’s: Longest and most comprehensive program in the U.S.
- My Presentation includes some recent focus in this area:

✓ Nuclear Site-level PRA analysis
✓ Physics of failure applications in PRA of advanced reactor involving passive systems and lack of reliability data
✓ Learning from past incidents and accidents in future advanced reactor design and operations.

PRA Experience at CRR

- UMD PRA research started in 1982
- Funded by NRC, DOE, EPRI, National Labs, Vendors and Utilities including Constellation (originally BG&E)
- Involved in the performance and review of several PRAs including the first PRA of Calvert Cliffs in early 1980’s under the NRC’s IREP studies. Others include: Seabrook1&2, Millstone-1, Crystal River, AP600 Review, AP1000 Review, NuScale, IPEEE reviews, IPE reviews, . . .
- Non-Nuclear PRAs (Space, Defense, Chemical Process and Transportation)
- Our research includes human reliability, probabilistic fracture mechanics, probabilistic thermal hydraulic analysis, multi-unit risk modeling, organizational risk models, external flood and earthquake modeling, uncertainty analysis in PRAs, precursor analysis, fire risk modeling, operator support systems, dynamic PRAs….
- Extensive Research. A partial list includes:

Examples of Specific Areas of Past Funded Research

Implications of a Multi-Unit Risk Modeling (PRA)
Integrated Uncertainty Analysis and Modeling (UM)
Framework development for a Bayesian model uncertainty for fire PRA (UM)
Probabilistic Fracture Mechanics (PFM) uncertainty characterization of reactor vessels under PTS regime with the procedure for implementation into the FAVOR code (UM)
Pressurized Thermal Shock (PTS)-Thermal Hydraulics (TH) uncertainty integration (UM)
PTS-TH uncertainty analysis of Oconee, Palisades, Beaver Valley, and Calvert Cliffs
Integrated TH uncertainty framework developments (UM)
Demonstration of Integrated TH uncertainty analysis for specific LOCA scenarios of the LOFT facility using RELAP (UM)
Fire risk models, verification, and validation, with model uncertainty (PRA/UMM)
Risk-Informed Applications (RI)
Risk ranking under uncertainty (UM)
Implications of using importance measures for safety-significance of SSCs (PRA)
Approaches to technology-neutral risk-informed regulation (RI)
Dynamic PRA methodology with applications to PTS (PRA)
The technical basis for using software engineering measures in software reliability prediction (PRA)
Probabilistic model development using CAROLFIRE and other test data to estimate fire-induced cable damage at nuclear power plants (PRA)
Development and demonstration of the use of Bayesian methods of inference in human reliability analysis (PRA)
Organized at least 15 workshops and symposia on PRA (W)

Key Areas of Research: Risk Frontiers

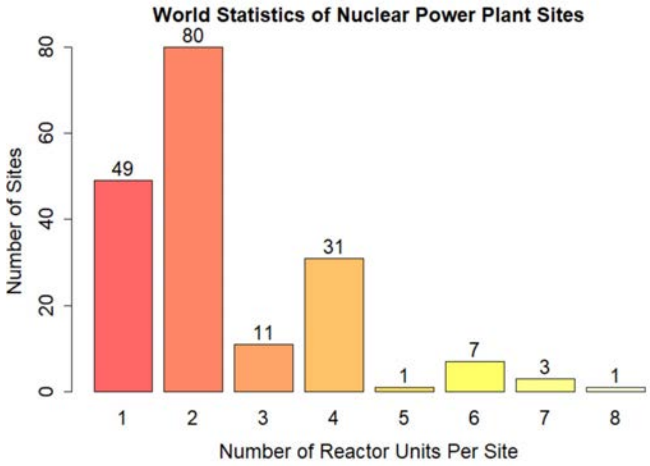
- Infrastructure Safety-Security-Resilience (SSR)
  - Integrity of Complex Nuclear Systems and Networks: Cyber-Human-Software-Physical (CHSP) Systems
  - Resilience of Highly Connected Infrastructure Networks: Electricity, Gas, and Water Pose Major Societal Risks Through Cyberspace Attacks
  - Societal Disruption, Health, Safety and Resilience Goals
- Life-Cycle Risks of Advanced Energy Systems
  - Renewable Systems (Building, Environmental, Internal and External)
  - Nuclear Energy (Fission and Fusion)
  - Climate Change Risks of Disruptions in Sustained Nuclear Plant Energy Supply
- Simulation-Based Dynamic Probabilistic Risk Assessment
  - High Power Computing Leading to Less Inductive Risk Models
  - More Deductive Computer-Assisted Risk Scenario Generation
  - Learning From Past Critical Events
  - AI-based Risk-Informed Decision Making

Critical Characteristics of Site-Level PRAs in NPPs

- SUPRA vs. MUPRA
- Intra- vs. Inter-dependencies
- Site vs. Multi unit
- Examples of Site-level Dependencies:
    - Proximity
    - Shared SSCs (e.g., shared batteries and diesel generators)
    - Common operation practices and shared control room
    - Procedural and other organizational similarities
- Current Major MUPTRA Activities: IAEA, U.S. EPRI, South Korea, Japan, Canada and France
- Some progress in site-risk PRAs since the Fukushima Daiichi accident, more room for research

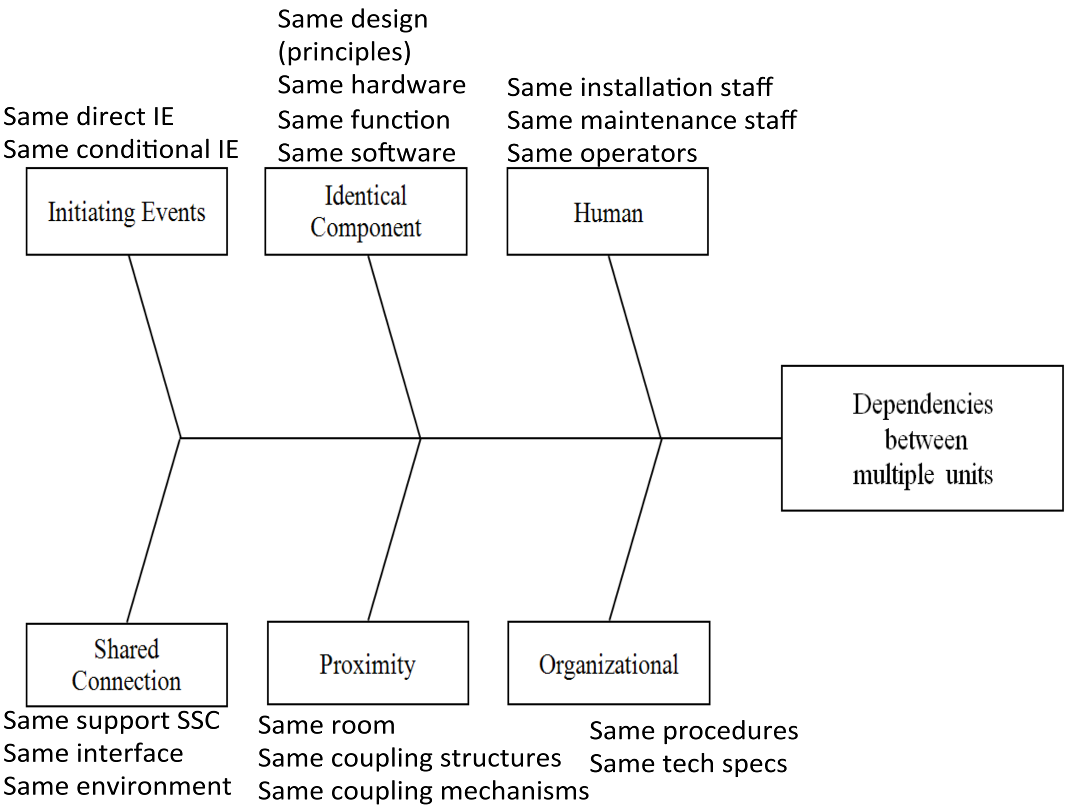
Why MUPRA is Important?

- 88.9% of the operating reactors are located on multi-unit sites
- 100% of SMRs and Advanced reactors will be on multi-unit sites.
- There are regional dependencies too: For example: Hope Creek & Salem; FitztPatrick and Nine Mile Point

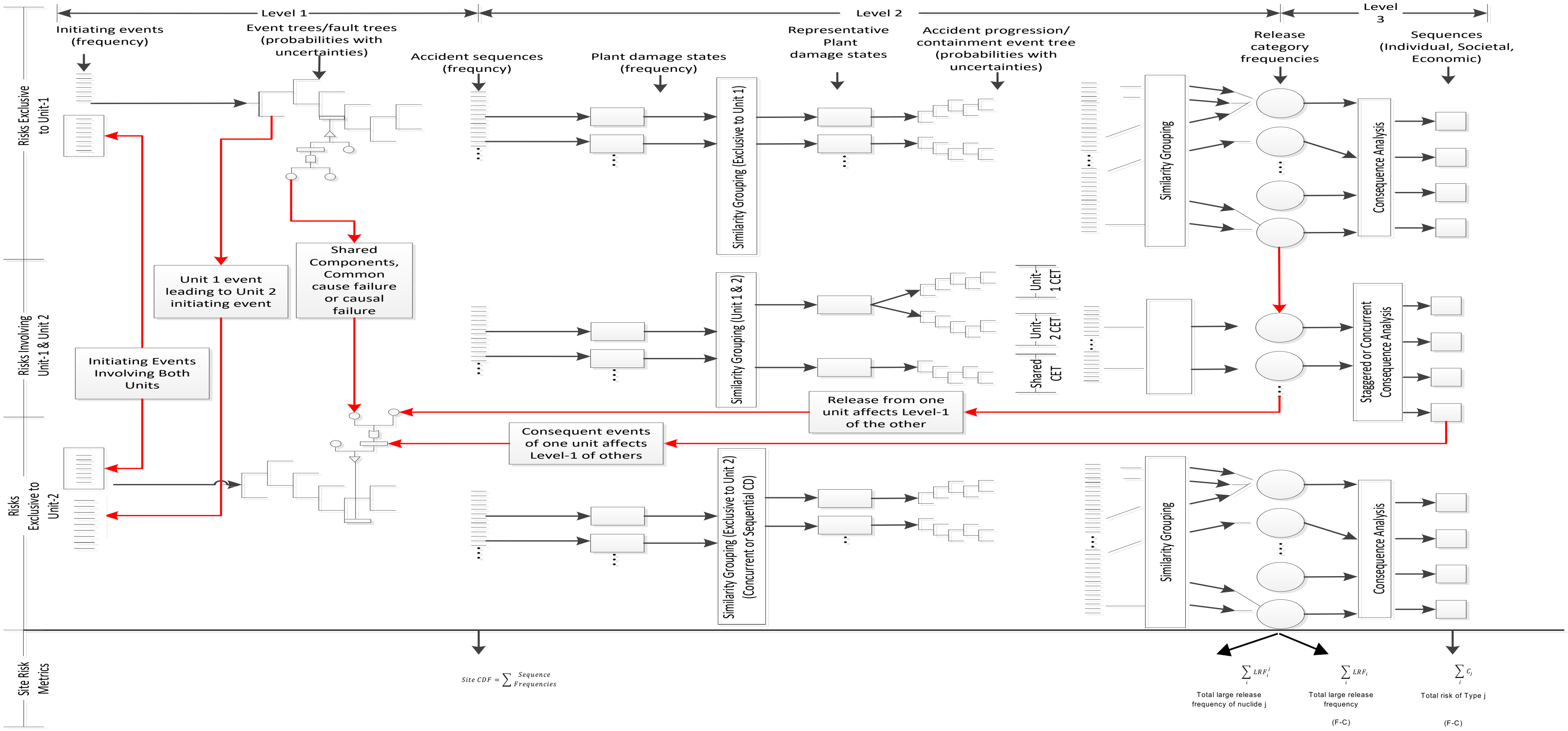


- Early considerations of MUPRA in U.S.:
  1. Indian Point & Seabrook PRAs (CCDP of 2nd Unit CD was 14%)
  2. Internal and Flood PRAs in Byron/Brainwood in 1990s showed 67% CCDPs
  3. SBO PRAs and some Seismic PRAs
- OECD/NEA CCF data Exchange: out of 192 CCFs, 87 involved multi-units (mostly attributed to design)
- External events: Seismic & Flood are critical contributors
- SMRs have harder multi-module dependencies than multiple Gen II/III units on a sites

Classes of Dependencies in Site-PRAs



An Overview of MUPRA



Level 1

Level 2

Level 3

Initiating events (frequency)

Event trees/fault trees (probabilities with uncertainties)

Accident sequences (frequncy)

Plant damage states (frequency)

Representative Plant damage states

Accident progression/ containment event tree (probabilities with uncertainties)

Release category frequencies

Sequences (Individual, Societal, Economic)

Risks Exclusive to Unit-1

Risks Involving Unit-1 & Unit 2

Risks Exclusive to Unit-2

Site Risk Metrics

Similarity Grouping (Exclusive to Unit 1)

Similarity Grouping (Unit 1 & 2)

Similarity Grouping (Exclusive to Unit 2) (Concurrent or Sequential CD)

Similarity Grouping

Consequence Analysis

Staggered or Concurrent Consequence Analysis

Unit-1 CET

Unit-2 CET

Shared CET

Unit 1 event leading to Unit 2 initiating event

Shared Components, Common cause failure or causal failure

Initiating Events Involving Both Units

Release from one unit affects Level-1 of the other

Consequent events of one unit affects Level-1 of others

$$Site\ CDF = \sum \frac{Sequence}{Frequencies}$$

$$\sum_i LRF_i^j$$

Total large release frequency of nuclide j

$$\sum_i LRF_i$$

Total large release frequency

(F-C)

$$\sum_j C_j$$

Total risk of Type j

(F-C)

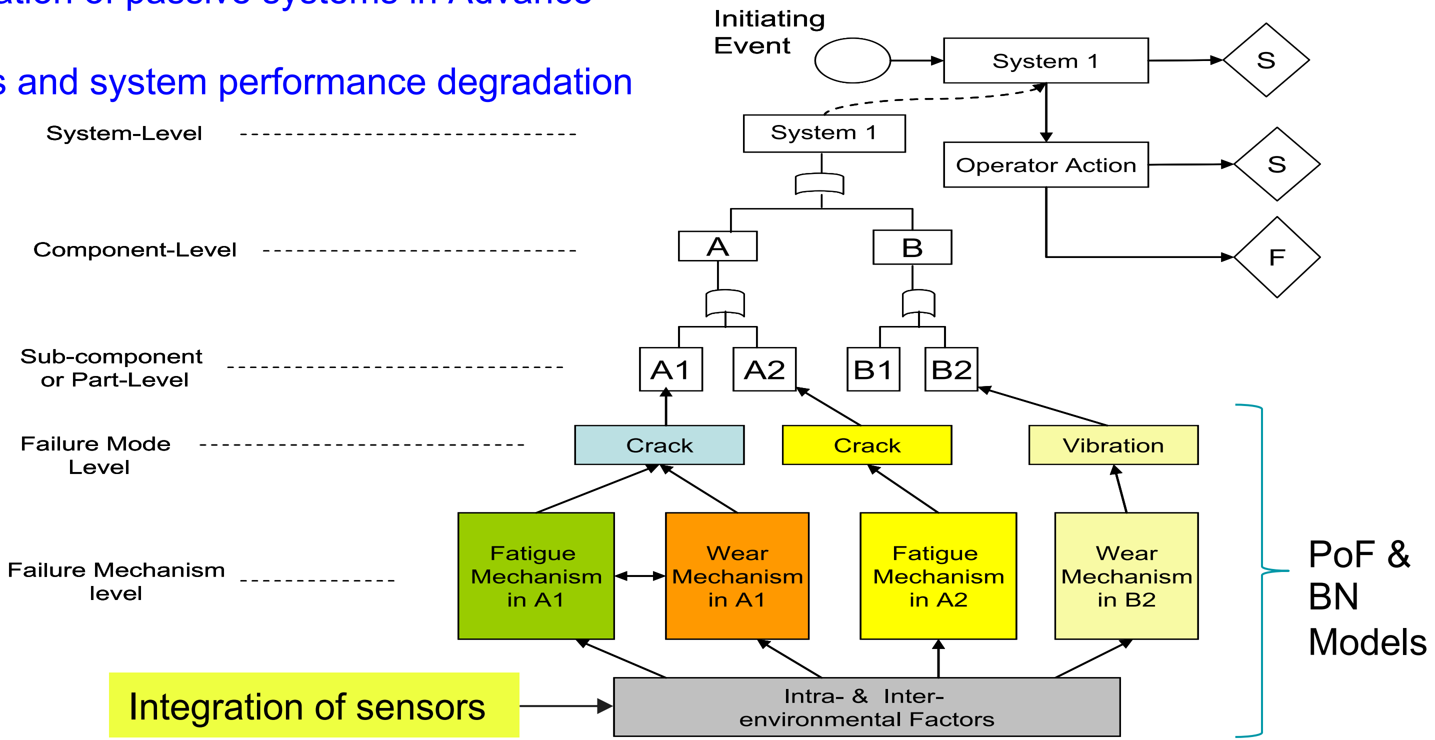
More Research Still Needed in MUPRA

- No universally acceptable treatment of internal, external, human, and organizational events exit
- Level-2 and Level-3 MUPRAs could play an important role in enhancing Defense in Depth implementation, but only limited work has been done
- Defining the three PRA levels in the context of MUPRA
- Modeling of human and organizational contributors including:
    - FLEX equipment
    - Site accessibility
    - HRA Dependencies
    - Emergency response measures
    - SAMGs in the context of multi-unit accidents
- Understanding cascading dependencies among heterogenous SSCs
- Site-based risk metrics are maturing but are not universally accepted
- Aggregation methods for site-level risks not well developed and understood
- More efficient tools to handle very large-scale models
- Dependent hazard frequency and SSC dependencies in external events particularly seismic and Flood
- SMR site risk models are primitive

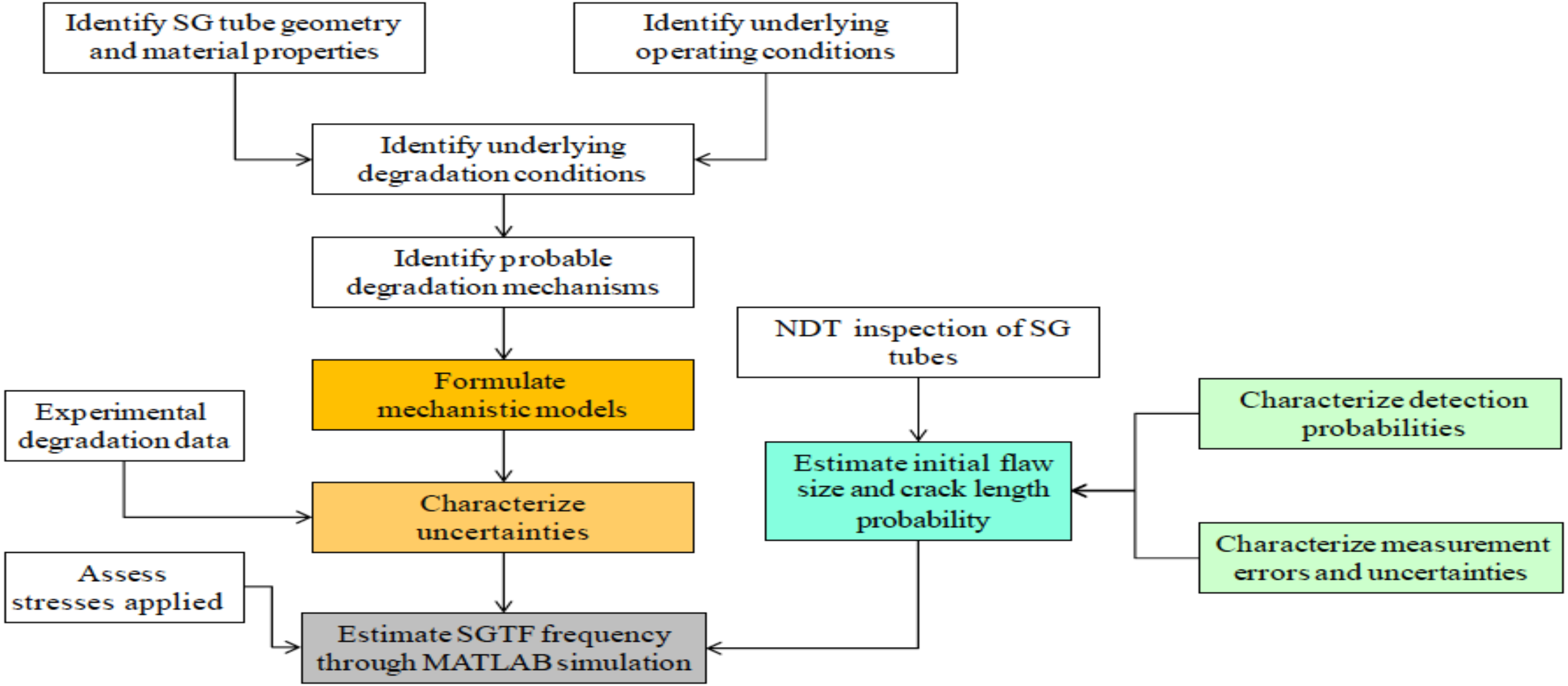
Physics of Failure Concepts in PRA

- Objectives:

1. Significant application of passive systems in Advance Reactor Designs.
2. Gradual materials and system performance degradation



PoF Models for New Systems with No Prior Operating Experience



Identify SG tube geometry and material properties

Identify underlying operating conditions

Identify underlying degradation conditions

Identify probable degradation mechanisms

Formulate mechanistic models

Experimental degradation data

Characterize uncertainties

Assess stresses applied

Estimate SGTF frequency through MATLAB simulation

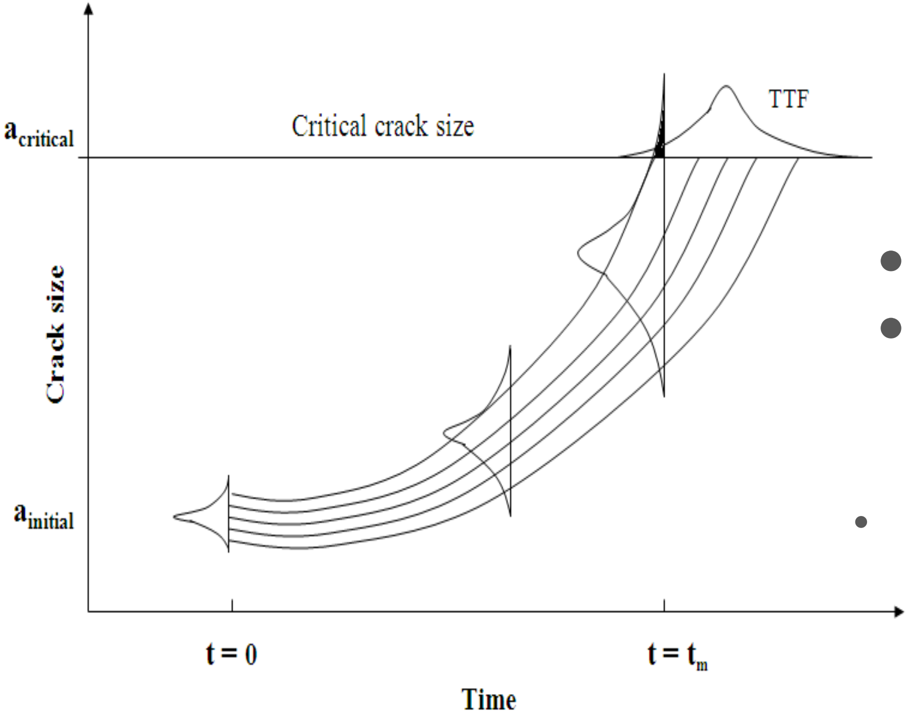
NDT inspection of SG tubes

Estimate initial flaw size and crack length probability

Characterize detection probabilities

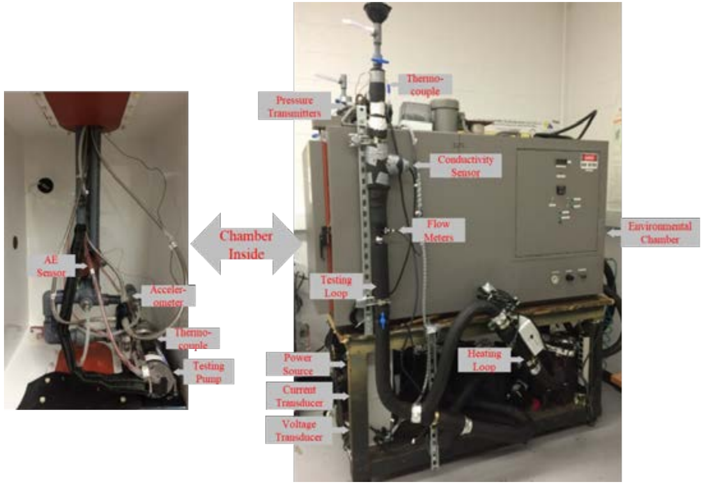
Characterize measurement errors and uncertainties

Forms of PoF Models



- *PoF is a regression-based mathematical model of failure, developed based on the empirical science of failure mechanisms such as fatigue, fracture, wear, and corrosion.*
- *PoF is of the form:*
- *Damage (of life)*$=\boldsymbol{f}(\boldsymbol{stress\ variables}, \boldsymbol{geometry}, \boldsymbol{envirnmental\ variables}, \boldsymbol{model\ parameters})$
- *When model error, parameter uncertainties in the mathematical PoF model are also estimated, the model is called Probabilistic PoF (PPoF)*

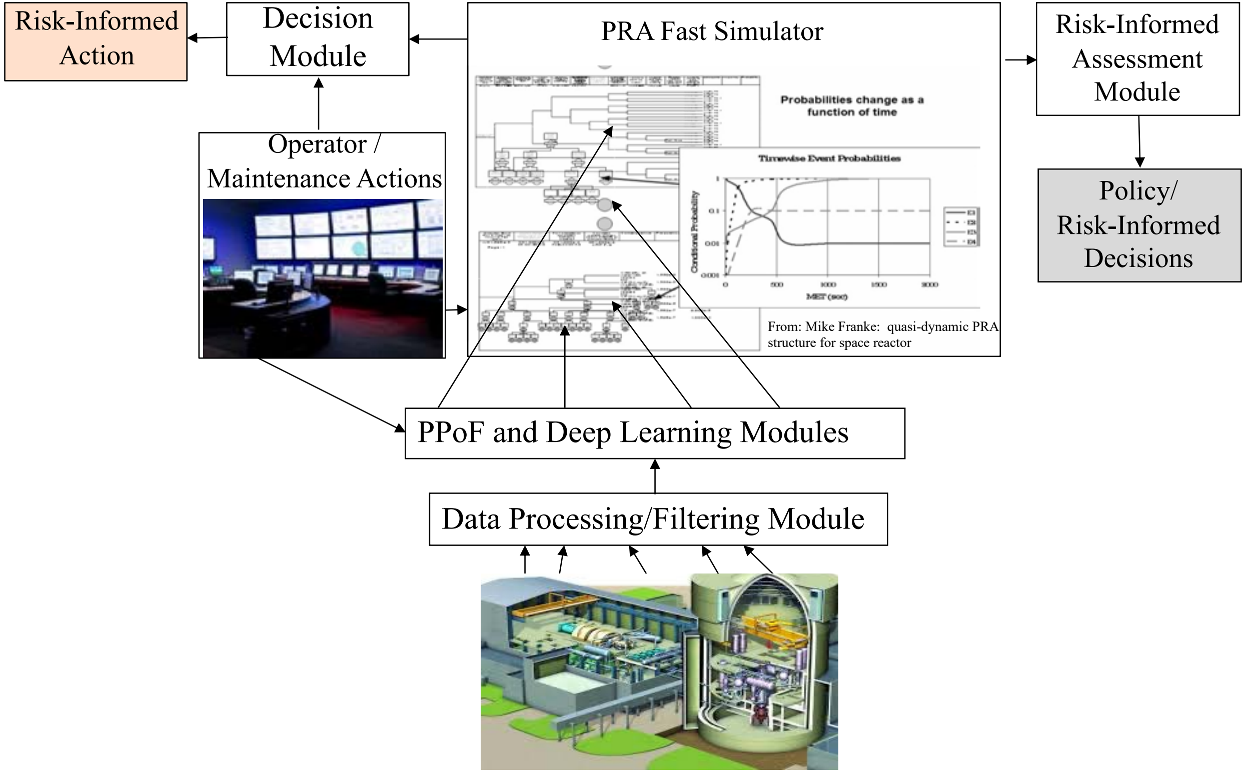
Experimental Setup & Failure Analysis



- Process Monitoring: flow Rate, differential pressure, electric current, and electric voltage
- Vibration Monitoring: three single-axis accelerometers
- AE Monitoring: three AE sensors located at suction, bearing and motor.

	Pump 1	Pump 2	Pump 3
Duration Until Failure	1954 hours	5103 hours	4654 hours
Failure Mode	Seal fracture	Shaft Corrosion	Leak
Failure Mechanism	Fatigue	Fretting corrosion	Pitting Corrosion
Failure Cause	Excessive fluid pressure on seal	Fretting corrosion in the contact surface	Pitting corrosion in the contact surface

Opportunities to Integrate ML with PRA



Risk-Informed Action

Decision Module

PRA Fast Simulator

Risk-Informed Assessment Module

Operator / Maintenance Actions

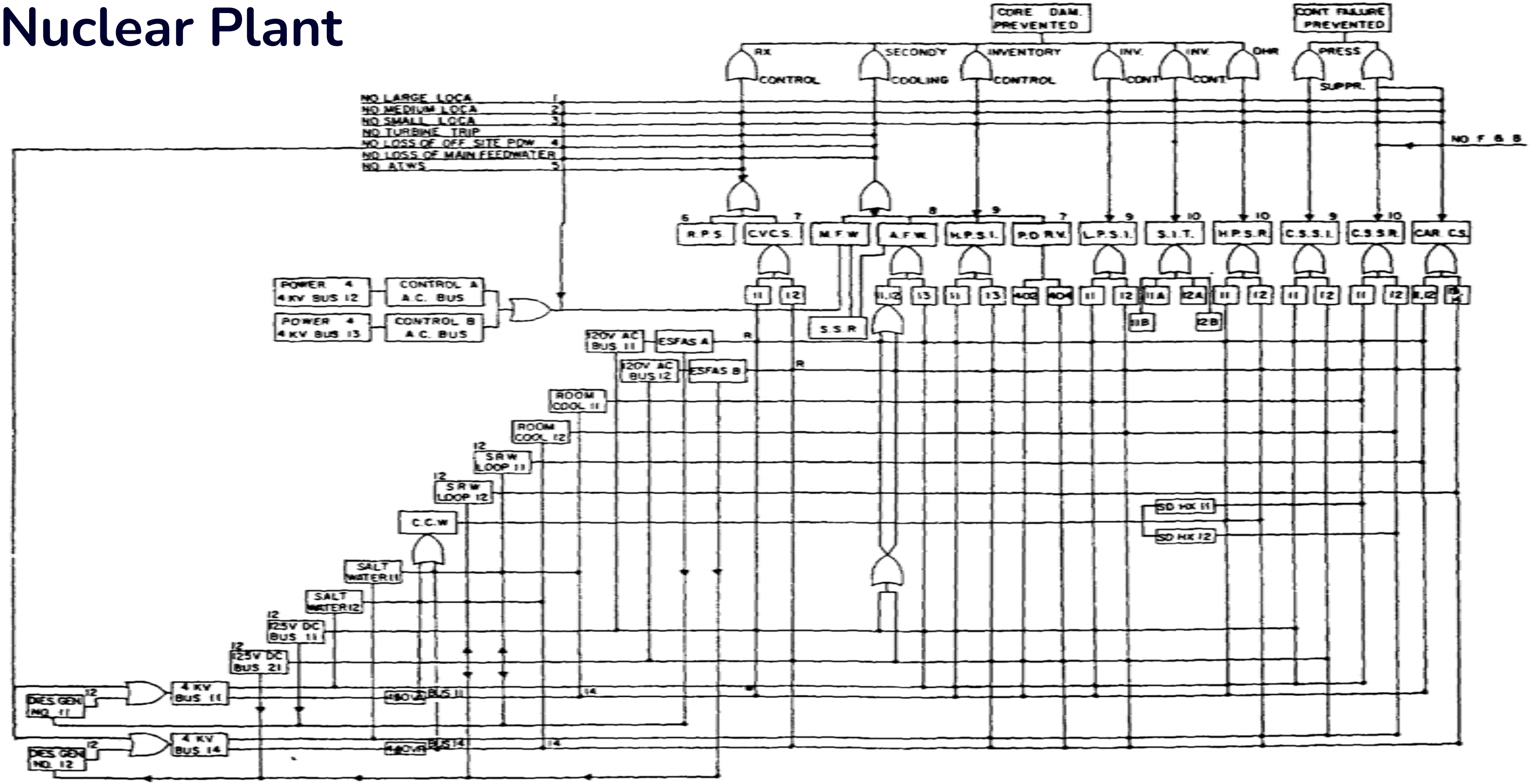
Policy/ Risk-Informed Decisions

PPoF and Deep Learning Modules

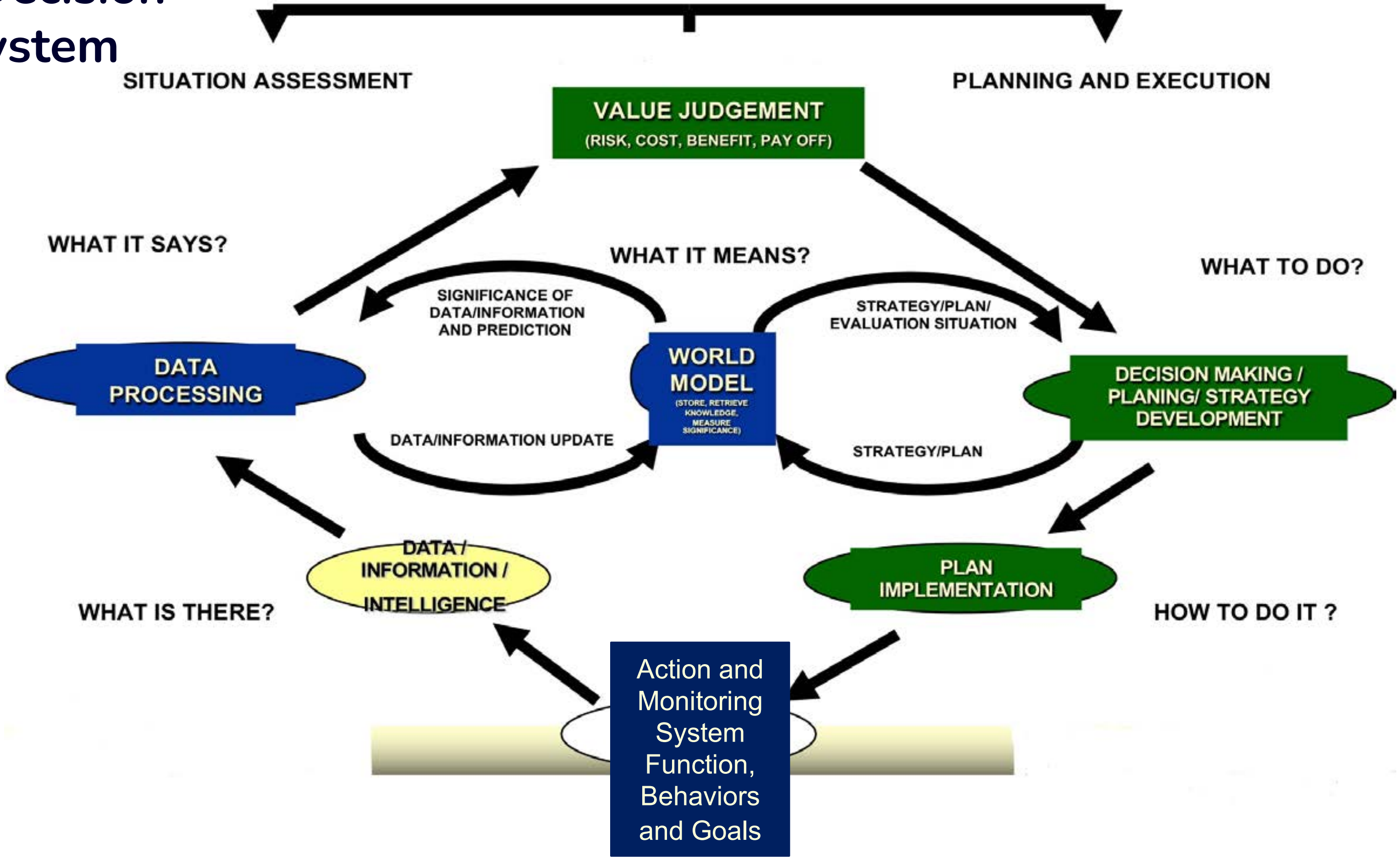
Data Processing/Filtering Module

From: Mike Franke: quasi-dynamic PRA structure for space reactor

Simplified Logic (Goal Tree) Models for Operator Advisory Nuclear Plant



Operator Decision Support System



SITUATION ASSESSMENT

PLANNING AND EXECUTION

VALUE JUDGEMENT
(RISK, COST, BENEFIT, PAY OFF)

WHAT IT SAYS?

WHAT IT MEANS?

WHAT TO DO?

SIGNIFICANCE OF DATA/INFORMATION AND PREDICTION

STRATEGY/PLAN/ EVALUATION SITUATION

DATA PROCESSING

WORLD MODEL
(STORE, RETRIEVE KNOWLEDGE, MEASURE SIGNIFICANCE)

DECISION MAKING / PLANING/ STRATEGY DEVELOPMENT

DATA/INFORMATION UPDATE

STRATEGY/PLAN

DATA / INFORMATION / INTELLIGENCE

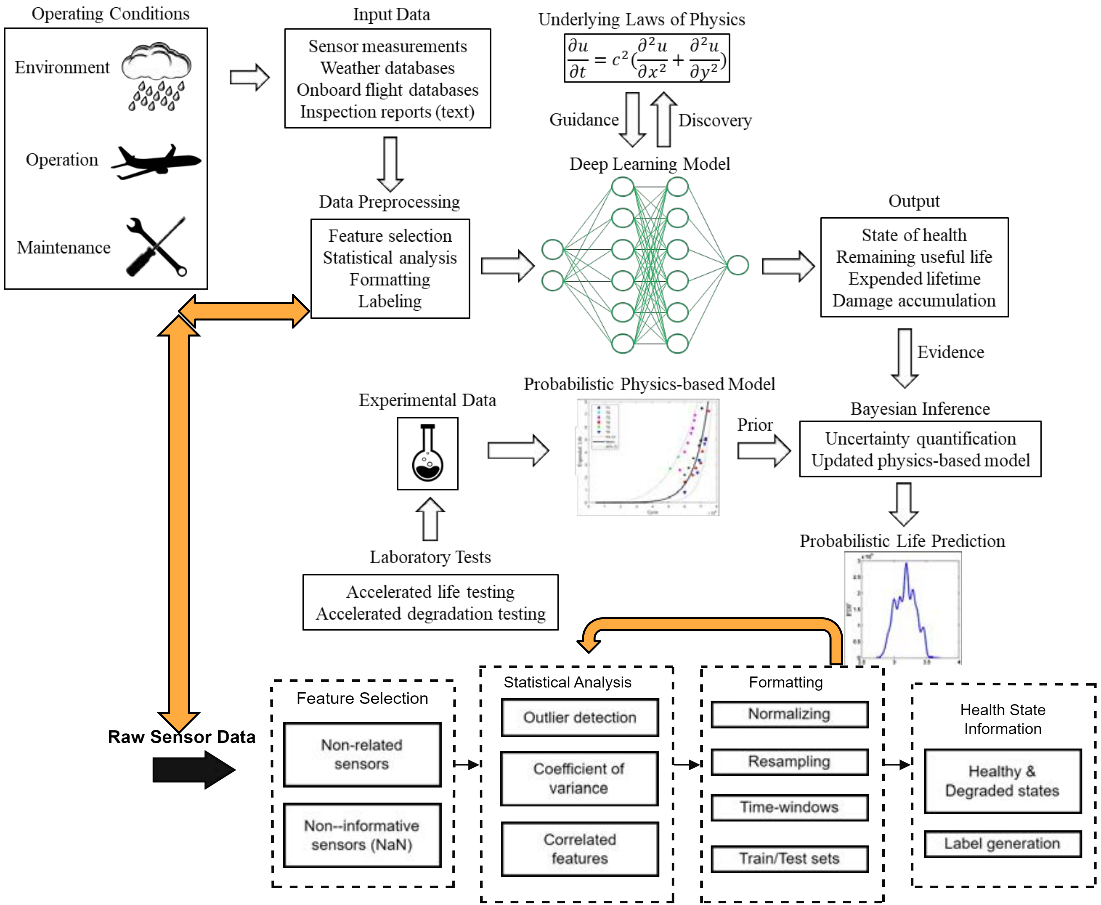
PLAN IMPLEMENTATION

WHAT IS THERE?

HOW TO DO IT ?

Action and Monitoring System Function, Behaviors and Goals

Hybrid Deep-Learning Physics Discovery & Physics of Failure Model



Operating Conditions

Environment

Operation

Maintenance

Input Data

Sensor measurements
Weather databases
Onboard flight databases
Inspection reports (text)

Data Preprocessing

Feature selection
Statistical analysis
Formatting
Labeling

Underlying Laws of Physics

$$\frac{\partial u}{\partial t} = c^2\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right)$$

Guidance

Discovery

Deep Learning Model

Output

State of health
Remaining useful life
Expended lifetime
Damage accumulation

Evidence

Experimental Data

Laboratory Tests

Accelerated life testing
Accelerated degradation testing

Probabilistic Physics-based Model

Prior

Bayesian Inference

Uncertainty quantification
Updated physics-based model

Probabilistic Life Prediction

Raw Sensor Data

Feature Selection

- Non-related sensors
- Non--informative sensors (NaN)

Statistical Analysis

- Outlier detection
- Coefficient of variance
- Correlated features

Formatting

- Normalizing
- Resampling
- Time-windows
- Train/Test sets

Health State Information

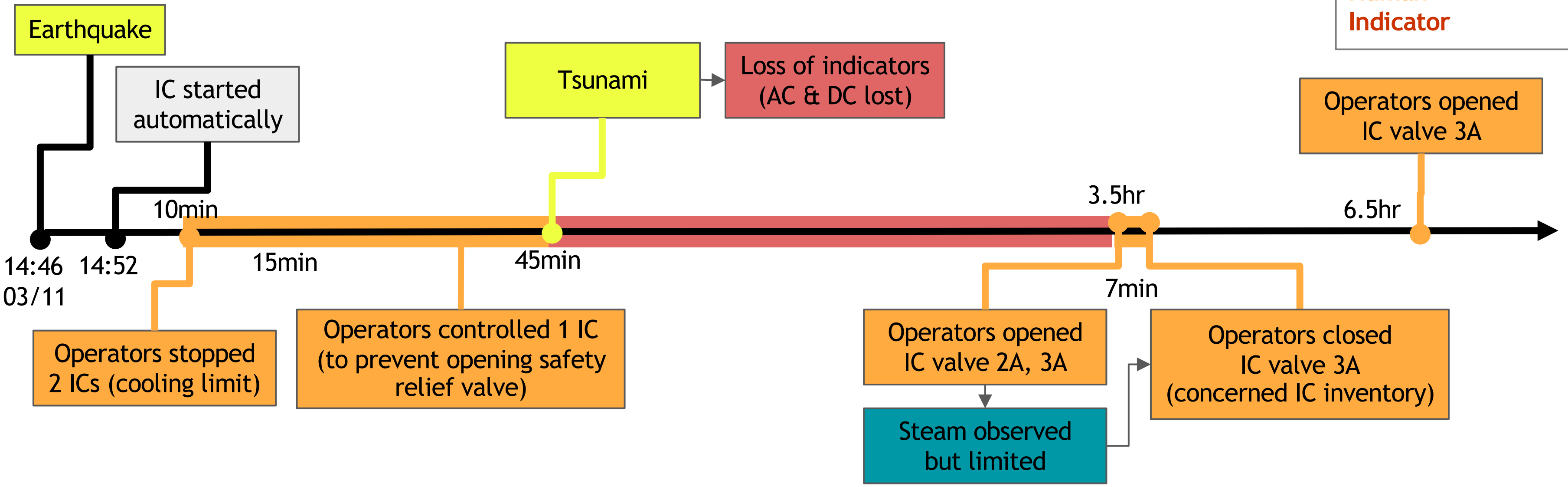
- Healthy & Degraded states
- Label generation

Learning From Actual Events

- Current approaches for risk-informed decision making for new and advanced reactors build on approaches developed for a stable fleet of operating reactors
- Deep learning, automatic text, voice and image indexing, generative AI and other data mining tools for learning from the OpE (primarily nuclear incidents and some relevant non-nuclear) exist
- When mature, an AI-trained tool can provide timely, extensive as well as effective support to the development of advanced PRAs.
- Given the ambitious schedules for SMRs and advanced reactors, a pilot study would be useful in the near term.

Learning From Actual Events (Cont.)

Plant condition
SSC
External environment
Human
Indicator



Earthquake

IC started automatically

Tsunami

Loss of indicators (AC & DC lost)

Operators opened IC valve 3A

10min

3.5hr

6.5hr

14:46
03/11

14:52

15min

45min

7min

Operators stopped 2 ICs (cooling limit)

Operators controlled 1 IC (to prevent opening safety relief valve)

Operators opened IC valve 2A, 3A

Steam observed but limited

Operators closed IC valve 3A (concerned IC inventory)

Mitigation actions during loss of indicators

- Connecting diesel-driven fire pump
- Evacuation order for residents within 2km
- Reactor water level was above TAF when the indicator was available

Key events

- 1 IC system was manually controlled before tsunami
- Operators were unaware of IC status during loss of indicators
- Operators stopped IC worrying about inventory
- Operators tried to check the status of IC

Conclusions

- PRA models stands on a strong philosophical foundation
- PRA Modeling has served well and can naturally be extended to work with modern ML approached for decision making
- The full potential of the PRA concepts are yet to be realized
- Collaboration and exchange of ideas will be critical for further expansion

Our alumni are making impact

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- Australian Government Defence
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- Department of Defense United States of America
- Naval Air Systems Command
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