*PRA and Risk-Informed Decision Making at the NRC: Some Trends and Challenges**

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*The views expressed in this presentation are not necessarily those of the U.S. Nuclear Regulatory Commission

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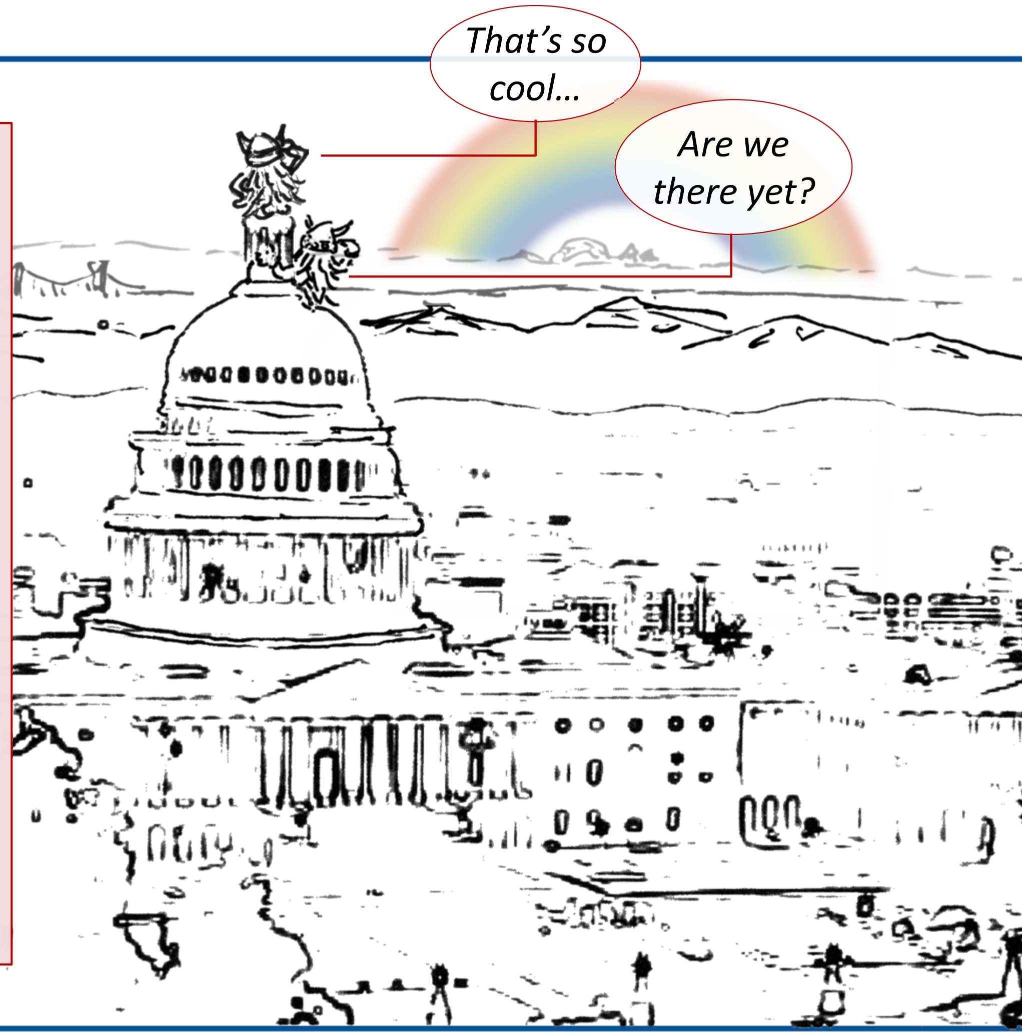
Outline

- A decision making challenge
- Use of risk information at NRC
- Some PRA technology challenges (audience participation)
- Closing thoughts
- Additional material



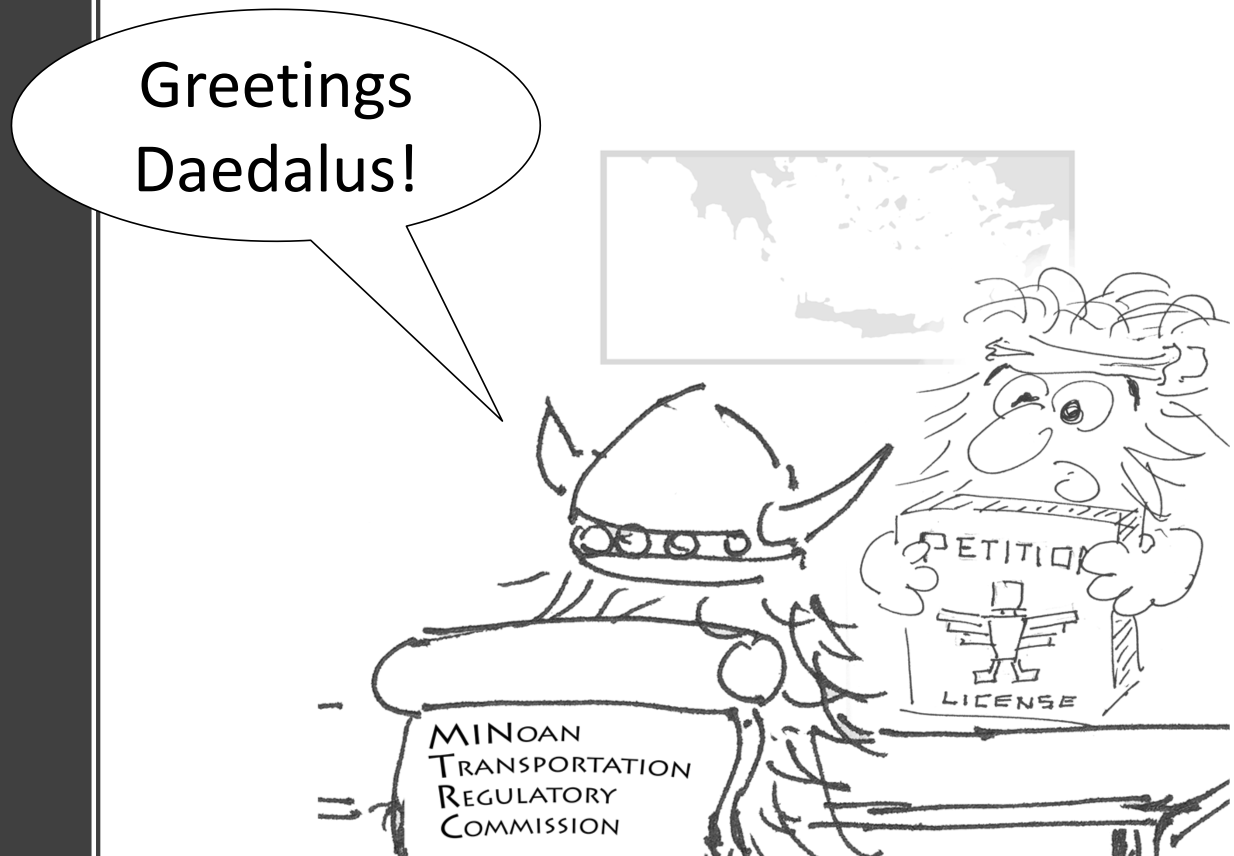
Acknowledgments

I would like to thank many colleagues (especially Jing Xing, James Chang, Susan Cooper, Keith Compton, Tina Ghosh, Chris Hunter, Shivani Mehta, Stacey Rosenberg, Tom Wellock, Sunil Weerakkody, John Garrick, and Andreas Bye) for their assistance and discussions in developing material for this presentation. I would also like to thank Jorge Luis Hernandez and Shahen Poghosyan (IAEA) for organizing a recent international workshop that provided current perspectives on a number of key topics. Any errors or changes in emphasis in material are my own.

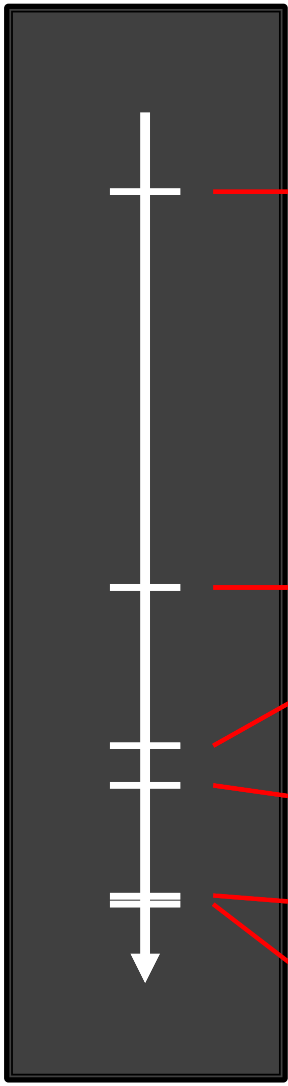
Just for fun…

DAEDALUS, ICARUS, AND RISK-INFORMED REGULATORY DECISION MAKING

3000+ Years Ago…



MinTRC Chronology



Y-450: Thera explosion, earthquake, giant waves

Y-200: Earthquake, conquest

Y-100: Minoan Transportation Development Agency (MinTDA)

Y-75: MinTDA => Minoan Ministry of Transportation (MinMoT)
Minoan Transportation Regulatory Commission (MinTRC)

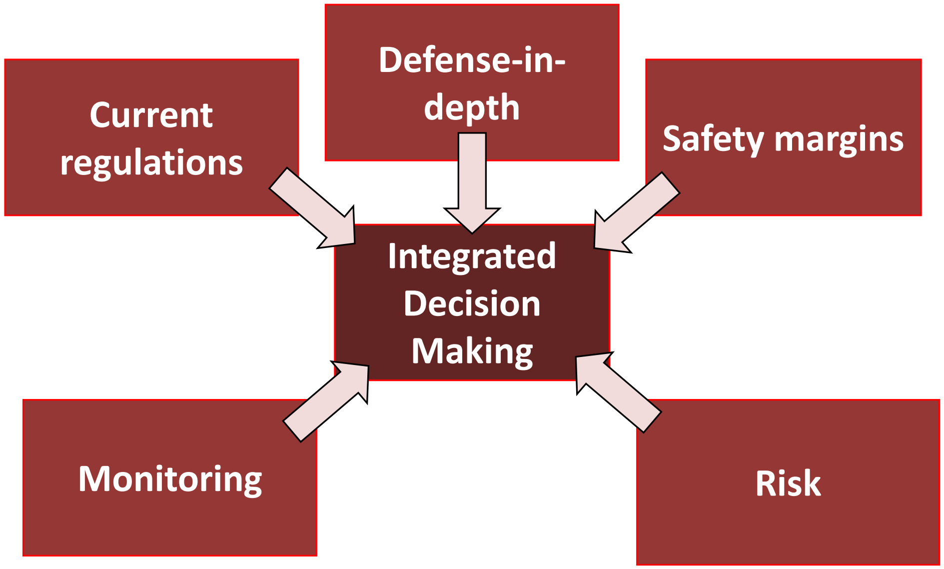
Y-5: Developer complaints to King Minos (“impediments to innovation”)

Today

Daedalus’ Proposal

- Design concept: human-powered wings (imitate birds)
- Construction: feathers attached by wax and thread/twine, assembly bent into slight curve
- Procedures: oral
  - Don’t fly too high (“scorching”) or too low (damp feathers)
  - Stick together; don’t navigate by stars or constellations
- Testing:
  - Demonstration of principle
  - Two-person flight north

A Risk-Informed Decision Making Problem…



- Current regulations: none applicable
- Defense-in-depth: none
- Safety margins: unknown, heavy reliance on Daedalus' skill
- Risk assessment: possible scenarios recognized but incomplete (see next)
- Performance monitoring: possible

Risk Assessment Concerns

- Completeness of risk metrics
- Correctness of models for identified scenarios
- Other possible scenarios
- Peer review

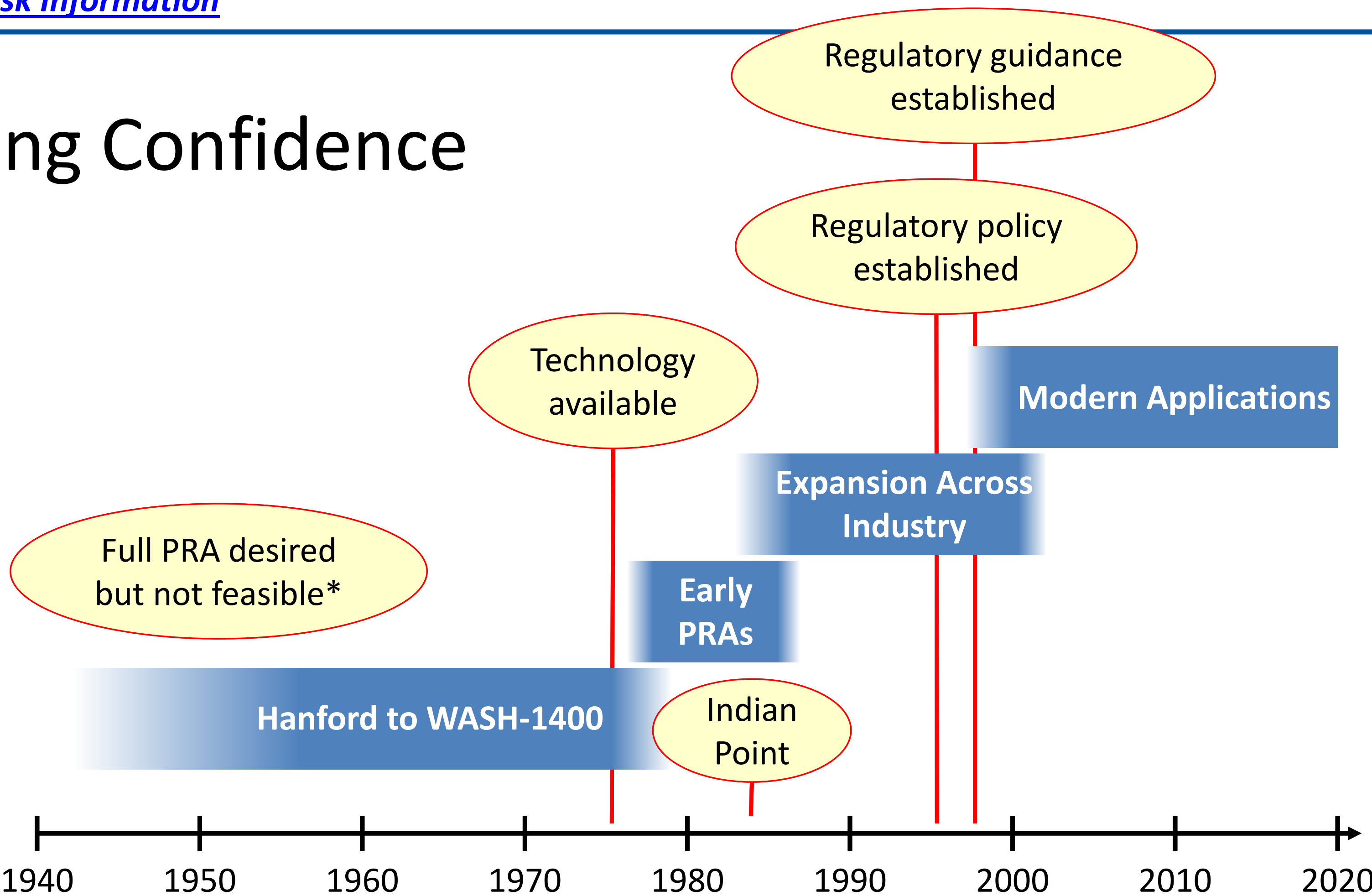
"It is of the highest importance in the art of ~~detection~~ decision making to be able to recognize, out of a number of facts, which are incidental and which vital. Otherwise your energy and attention must be dissipated instead of concentrated."

- *With apologies to Sherlock Holmes*

(The Hound of the Baskervilles)

NRC USE OF RISK INFORMATION

Building Confidence



*See T.R. Wellock, "A figure of merit: quantifying the probability of a nuclear reactor accident," *Technology and Culture*, **58**, No. 3, 678-721, July 2017.

Triplet Definition of Risk (Kaplan and Garrick, 1981)*

Risk ≡ $\{s_i, C_i, p_i\}$

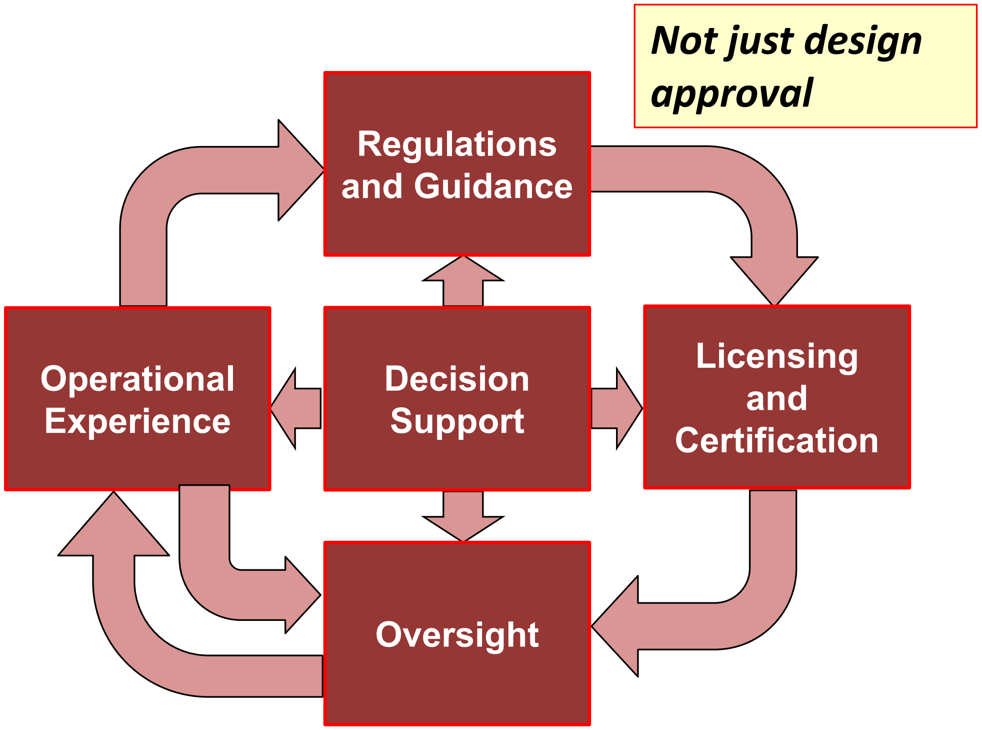
- **What can go wrong?**
- **What are the consequences?**
- **How likely is it?**

Features

- Vector, not scalar
- Qualitative and quantitative
- Differences across accident spectrum

*Adopted by NRC. See:
- "White Paper on Risk-Informed and Performance-Based Regulation (Revised)," SRM to SECY-98-144, March 1, 1999
- "Glossary of Risk-Related Terms in Support of Risk-Informed Decisionmaking," NUREG-2122, May 2013
- "Probabilistic Risk Assessment and Regulatory Decisionmaking: Some Frequently Asked Questions," NUREG-2201, September 2016

NRC Uses of Risk Information

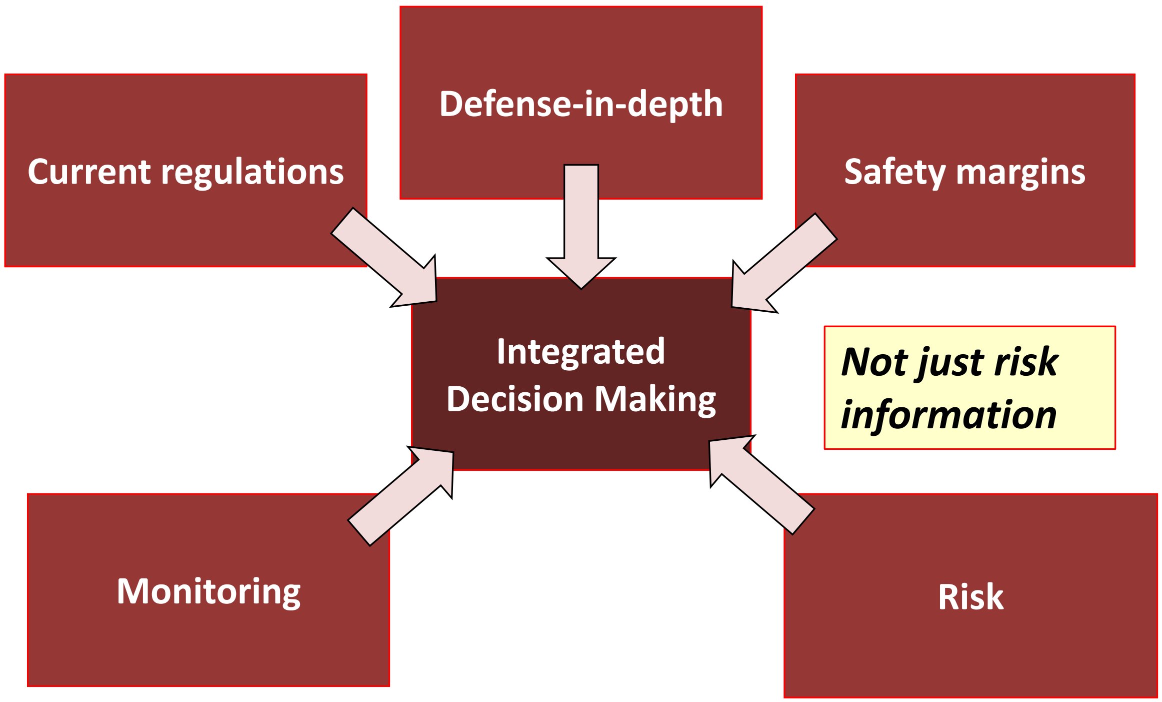


PRA Policy Statement (1995)

- Increase use of PRA technology in all regulatory matters
  - Consistent with PRA state-of-the-art
  - Complement deterministic approach, support defense-in-depth philosophy
- Benefits:
  (1) Considers broader set of potential challenges
  (2) Helps prioritize challenges
  (3) Considers broader set of defenses

U.S. Nuclear Regulatory Commission, "Use of Probabilistic Risk Assessment Methods in Nuclear Activities; Final Policy Statement," *Federal Register*, **60**, p. 42622 (60 FR 42622), August 16, 1995.

Risk-Informed Regulatory Decision Making (RIDM)

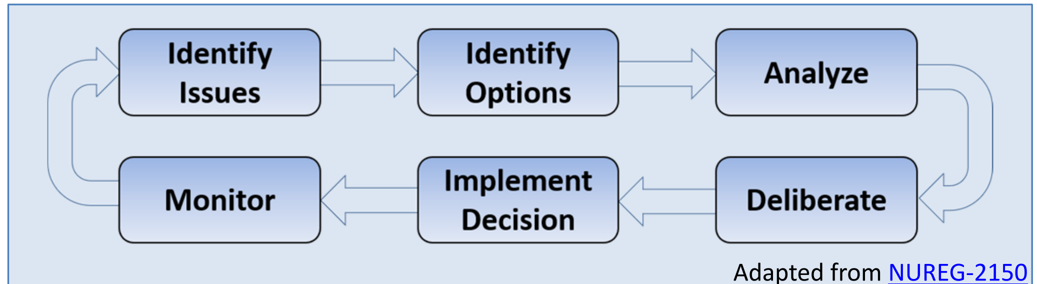


"…a **philosophy** whereby **risk insights are considered together with other factors** to establish requirements that **better focus licensee and regulatory attention** on design and operational issues **commensurate with their importance to public health and safety**." [Emphases added]

"White Paper on Risk-Informed and Performance-Based Regulation," SECY-98-144, January 22, 1998.

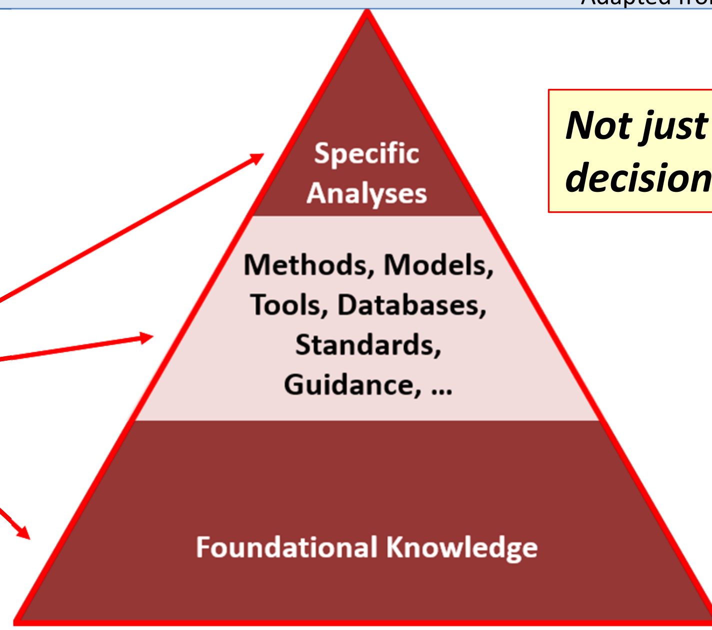
Adapted from: U.S. Nuclear Regulatory Commission, "An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis," *Regulatory Guide 1.174, Revision 3*, January 2018.

Multiple Products and Uses



Risk Information

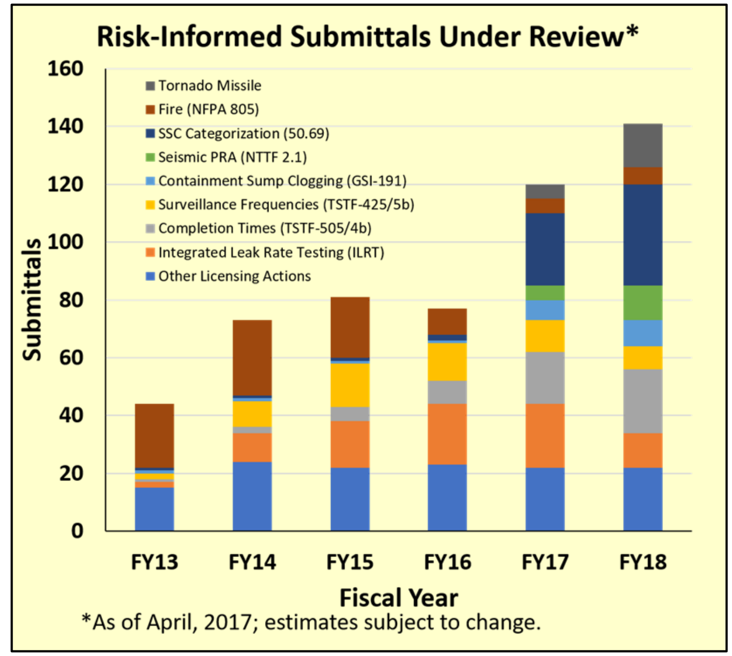
- Results
- Insights
- Explanations
- Uncertainties
- Qualifications



Not just immediate decision support

Some Trends

- Market forces
  - Increased number of applications
  - Increased credit for capabilities (e.g., FLEX)
  - Greater role in design (e.g., LMP)
- Novel designs, technologies, and operational concepts
- Improving analysis capabilities
  - Computational resources
  - Smart technologies (e.g., content analytics)
- Changing workforce (KSAs, preferences)



Challenge to NRC:
Be Ready!

"…it is incumbent upon the new industry and the Government to make every effort to recognize every possible event or series of events which could result in the release of unsafe amounts of radioactive material to the surroundings and to take all steps necessary to reduce to a reasonable minimum the probability that such events will occur in a manner causing serious overexposure to the public."

W. F. Libby (Acting Chairman, AEC) – March 14, 1956 response to Senator Hickenlooper
[from D. Okrent, *Reactor Safety*, U. Wisconsin Press, 1981]

Audience Participation

SOME PRA TECHNOLOGY CHALLENGES*

* In this presentation "Technology" = {methods, models, tools, data}

Identifying Challenges: Many Perspectives

Fukushima Review*

- PRA scope (2)
- Feedback loops (1)
- "Game over" modeling and intentional conservatisms (4)
- Long duration scenarios (3)
- External hazards analysis (12)
- Human reliability analysis (HRA) (5)
- Representation of uncertainty in phenomenological codes (1)
- Searching (vs. screening) (5)

IAEA Technical Meeting**

- Dynamic PSA (7)
- Combinations of hazards (3)
- Portable equipment (4)
- Use of PSA in development of SAMGs (6)
- Level 3 PSA (4)
- Software reliability and modelling (4)
- Incorporation of ageing aspects (5)

Uncertainty Typology***

- Parameter uncertainty (3)
- Model uncertainty (6)
- Completeness uncertainty (8)

\+ Internal risk communication (9)

*N. Siu, et al., "PSA technology challenges revealed by the Great East Japan Earthquake," *PSAM Topical Conference in Light of the Fukushima Dai-Ichi Accident*, Tokyo, Japan, April 15-17, 2013. [ML13038A203 (paper), ML13099A347 (presentation)]

***IAEA Technical Meeting on the Enhancement of Methods, Approaches and Tools for Development and Application of Probabilistic Safety Assessments*, September 29-October 2, 2020.

***M. Drouin, et al., "Guidance on the Treatment of Uncertainties Associated with PRAs in Risk-Informed Decisionmaking," *NUREG-1855, Rev. 1*, 2017.

Topics

Qualitative lessons from a PRA-oriented review

PRA TECHNOLOGY INSIGHTS FROM 3/11

PRA Technology Insights from 3/11*

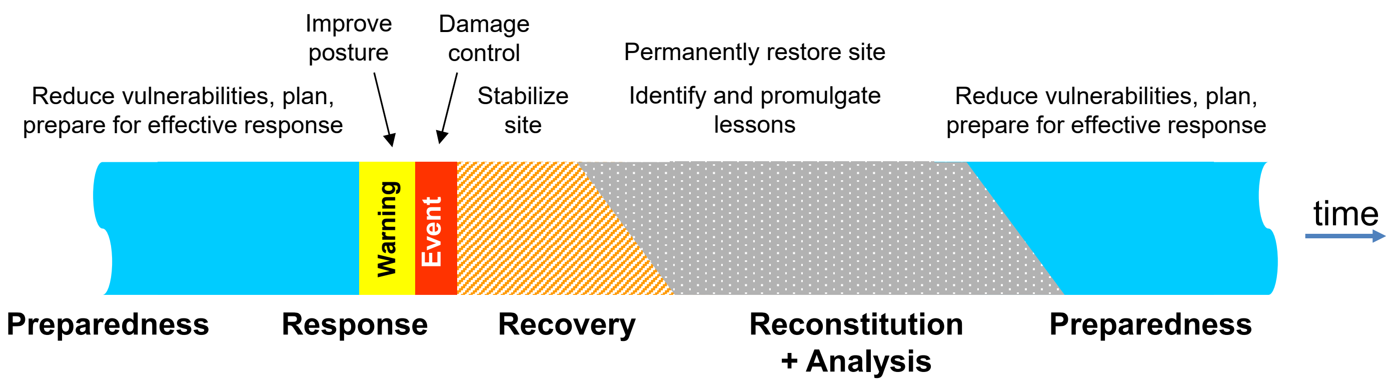
- Review: 2013, updated 2016
- Purpose: support ongoing activities (Level 3 PRA, R&D planning, international discussions)
- Scope: all affected plants
- Approach
  - Literature review
  - Event review
    - Timeline-based
    - PSA-topic based
- Results: PRA-technology "Reminders," "Challenges," and discussions of selected topics

*See:

1) N. Siu, et al., "PSA technology challenges revealed by the Great East Japan Earthquake," *PSAM Topical Conference in Light of the Fukushima Dai-Ichi Accident*, Tokyo, Japan, April 15-17, 2013. [ML13038A203 (paper), ML13099A347 (presentation)] (used for this presentation)
2) N. Siu, et al., "PSA technology reminders and challenges revealed by the Great East Japan Earthquake: 2016 update," *13th International Conference on Probabilistic Safety Assessment and Management (PSAM 13)*, Seoul, Korea, October 2-7, 2016. [ML16245A871 (paper), ML16270A522 (presentation)]

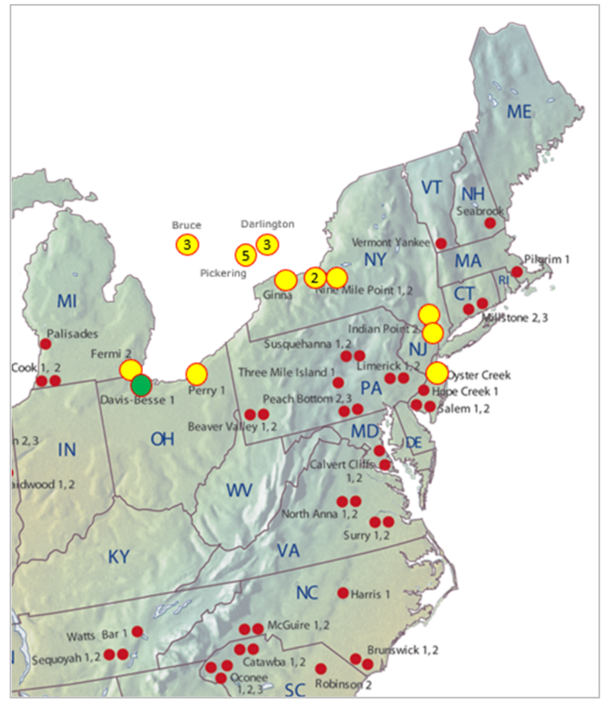
PRA Scope (1/2)

Dimension	Typical U.S. (c. 2011)	Observations (3/11/2011)
"Space"	- Single unit (reactor) - Frontline mitigating systems + support	- Multiple reactors, SFP; multiple sites - Additional systems (e.g., security access)
Time	- At power operation - Accident	- Shutdown operations (incl. testing) - Post-accident susceptibility
Organization	- Onsite staff	- Offsite involvement (directions, requests for information)



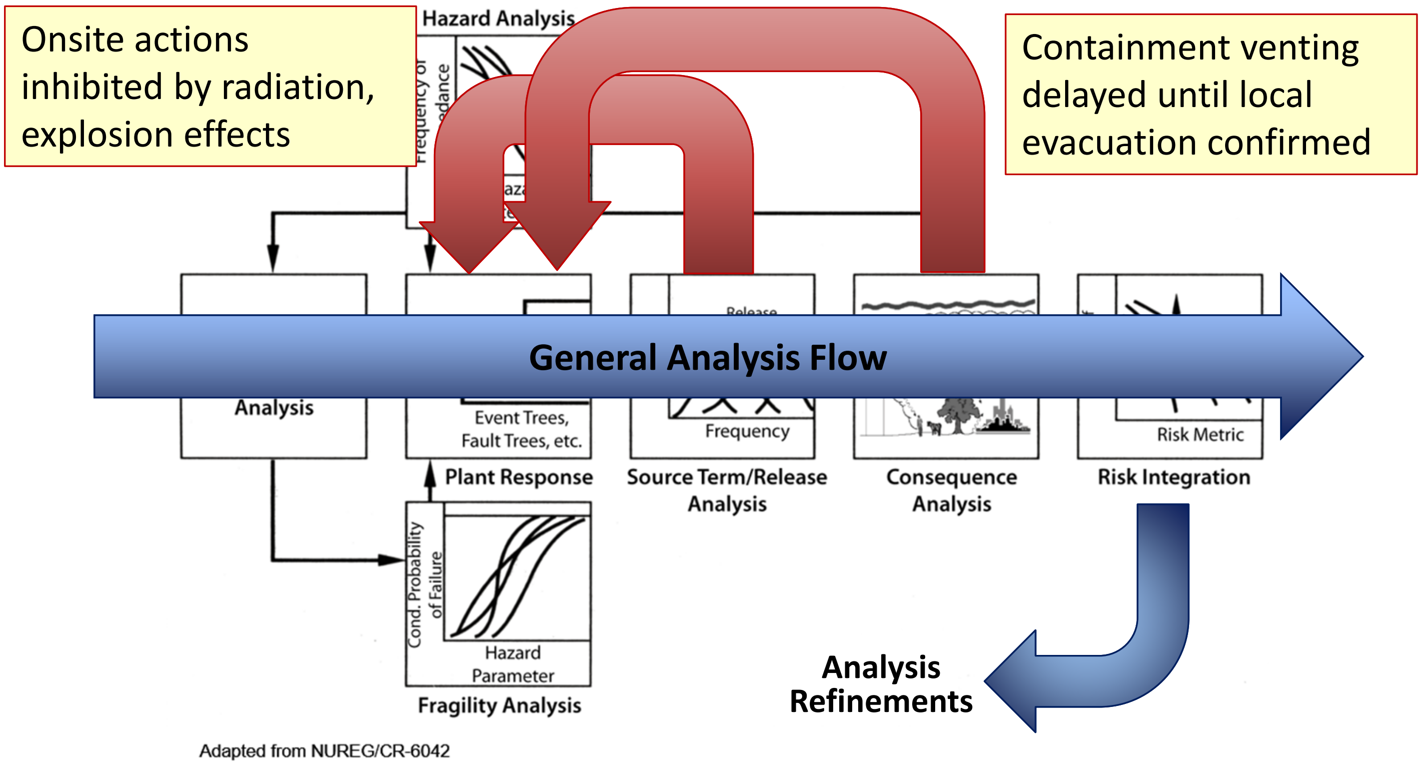
PRA Scope (2/2): Multi-Site Events

March 11, 2011



August 14, 2003

Feedback Loops (1/1)



"Game Over" Modeling (1/4)

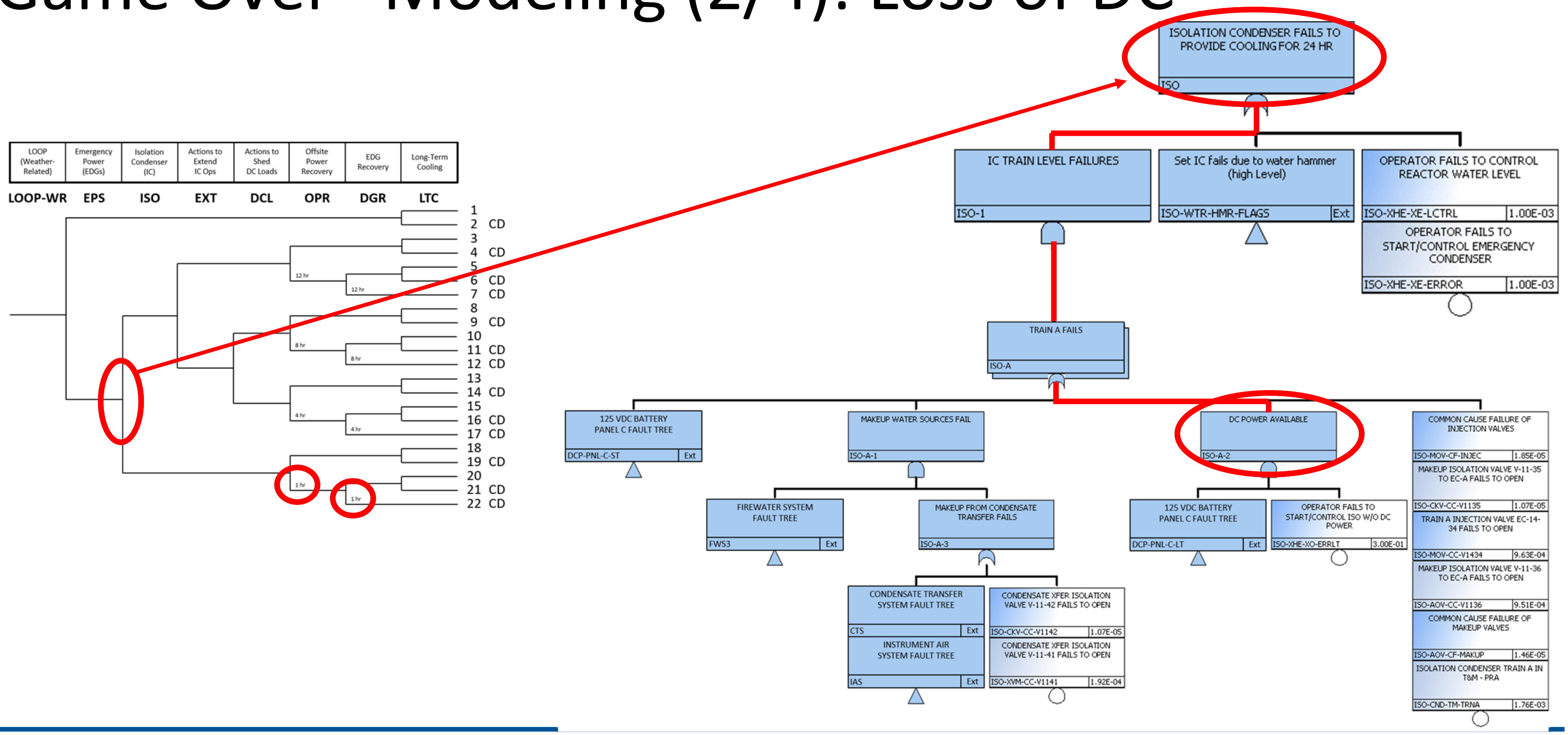
- Plant Level: Loss of AC and DC
  - Conventional PRA analysis: core damage (if AC power is not recovered)
  - Deterministic analysis: rapid onset of fuel damage
- System Level: Loss of DC
  - Isolation condenser, RCIC, and HPCI fail (unable to control)**

Plant	Core Damage Onset (hr)
Peach Bottom (NUREG/CR-7110)*	1.0
Fukushima Daiichi Unit 1	19
Fukushima Daiichi Unit 2	89
Fukushima Daiichi Unit 3	52

*Unmitigated short-term station blackout (STSBO). See N. Bixler, et al., "State-of-the-Art Reactor Consequence Analyses Project Volume 1: Peach Bottom Integrated Analysis," *NUREG/CR-7110, Rev. 1*, 2013.

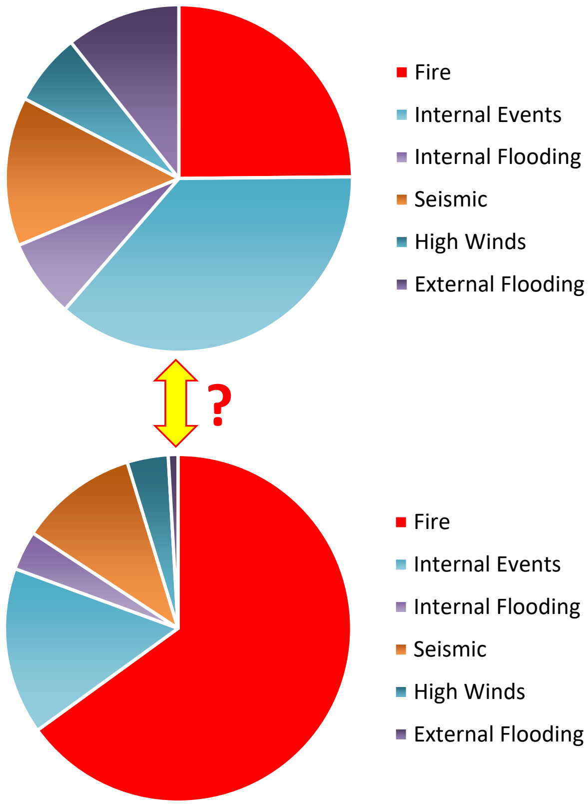
**DC power is used to operate a number of control valves. Uncontrolled RCIC and/or HPCI could lead to RPV overfill, water in the RCIC/HPCI steam line, and potential failure of the RCIC/HPCI turbine(s). During the accident, operators bypassed some flow through a mini-flow test line (which returns water to the Condensate Storage Tank) to reduce the possibility of RPV overfill.

“Game Over” Modeling (2/4): Loss of DC



Game Over Modeling (3/4): RIDM Implications

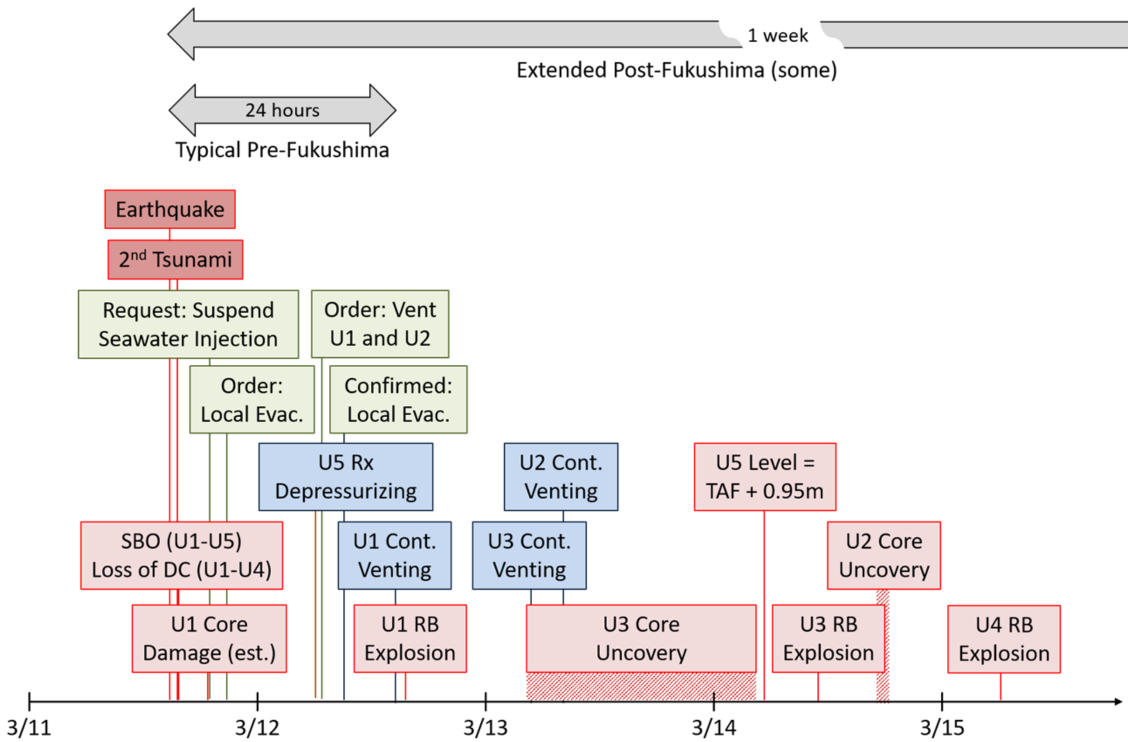
- Useful simplification for applications focused on total results
- Concerns
  - Potential overemphasis on scenarios that are actually not as important as others ("masking effect")
    - Training resources
    - Establishing expectations (bias)
  - Strong constraints on mitigation actions considered as viable, worth emphasizing (e.g., through procedures and training)
  - Loss of PRA model credibility to key stakeholders



Game Over Modeling (4/4): Other Notes

- Assuming immediate failures is not necessarily conservative – in reality, lacking omniscience, operators might spend time trying to implement a non-feasible path
- Other common "game over" modeling assumptions
  - Lack of credit for recovery or repair
  - Assumed loss of structure contents on "failure" of structure

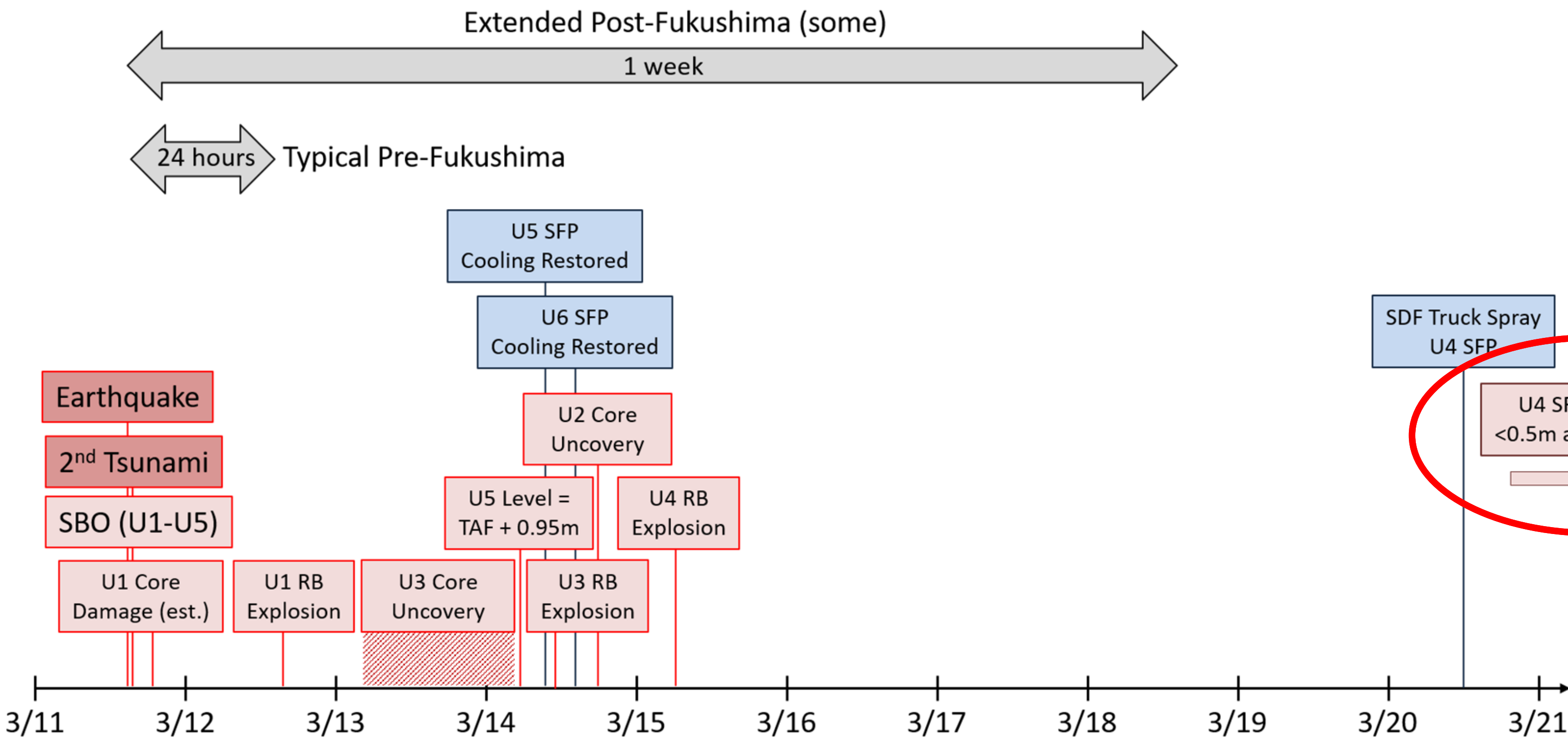
Long Duration Scenarios (1/3): Fukushima "Early"



Data from multiple sources, including:

1) International Atomic Energy Agency, "The Fukushima Daiichi Accident: Report by the IAEA Director General," *STI/PUB 1710*, Vienna, Austria, 2015.
2) Government of Japan, Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company, Interim Report. December 26, 2011.

Long Duration Scenarios (2/3): Fukushima "Late"



Data from multiple sources, including:

1) International Atomic Energy Agency, "The Fukushima Daiichi Accident: Report by the IAEA Director General," *STI/PUB 1710*, Vienna, Austria, 2015.
2) Government of Japan, Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company, Interim Report. December 26, 2011.

Long Duration Scenarios (3/3): Modeling Challenges

- Recovery and repair
  - Human reliability analysis (HRA)
  - Site and equipment conditions (debris, roads, tools, spares, housing, …)
- Non-binary behavior (e.g., intermittent and/or degraded performance)
- Offsite
  - Conditions (site access, demands on emergency services, …)
  - Organizational response

Yuriage – Before and After 3/11 Tsunami

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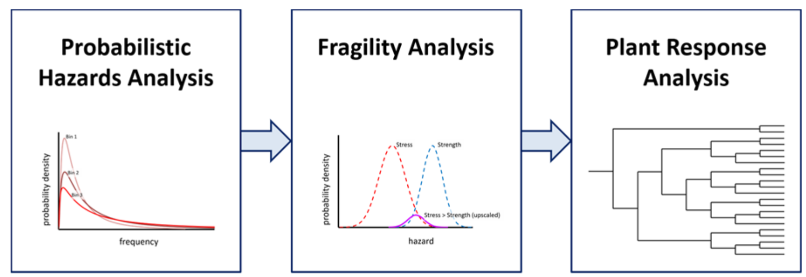
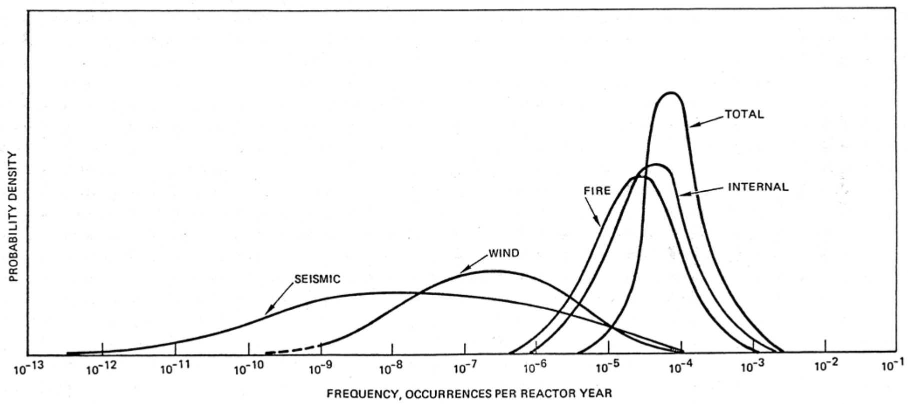
External Hazards Analysis (1/12)

- 3/11/2011: Seismically-induced loss of offsite power, tsunami-induced loss of all power and multiple severe accidents
- Long-standing general approach, e.g.,
  - Zion/Indian Point PRAs (1982)*
  - PRA Procedures Guide (1983)*
- Typical practice
  - General emphasis on internal events, earthquakes, internal fires and floods
  - "Other" external hazards (including external floods) sometimes dismissed (pre-3/11)
- **Typical results**
  - **Important or even dominant contributor to risk**
  - **Uncertainty driver: hazards analysis**

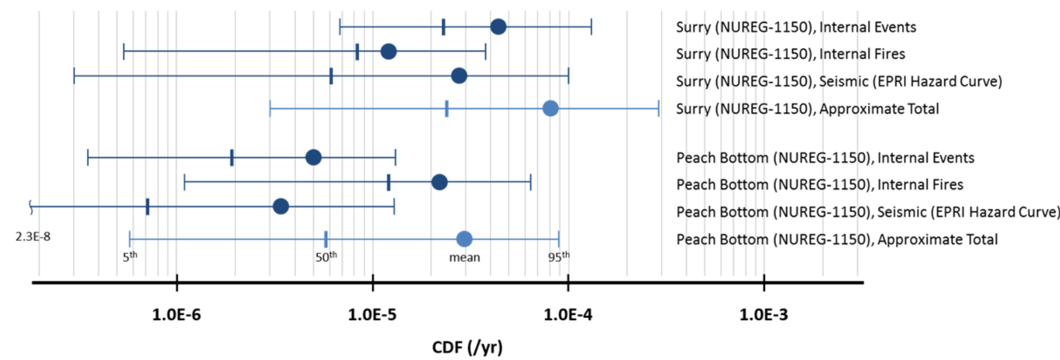


*See:
1) B.J. Garrick, "Lessons learned from 21 nuclear plant probabilistic risk assessments," *Nuclear Technology*, **84**, No. 3, 319–339(1989)
2) American Nuclear Society and the Institute of Electrical and Electronics Engineers, "PRA Procedures Guide," *NUREG/CR-2300*, 1983.

External Hazards Analysis (2/12): Past PRA Results



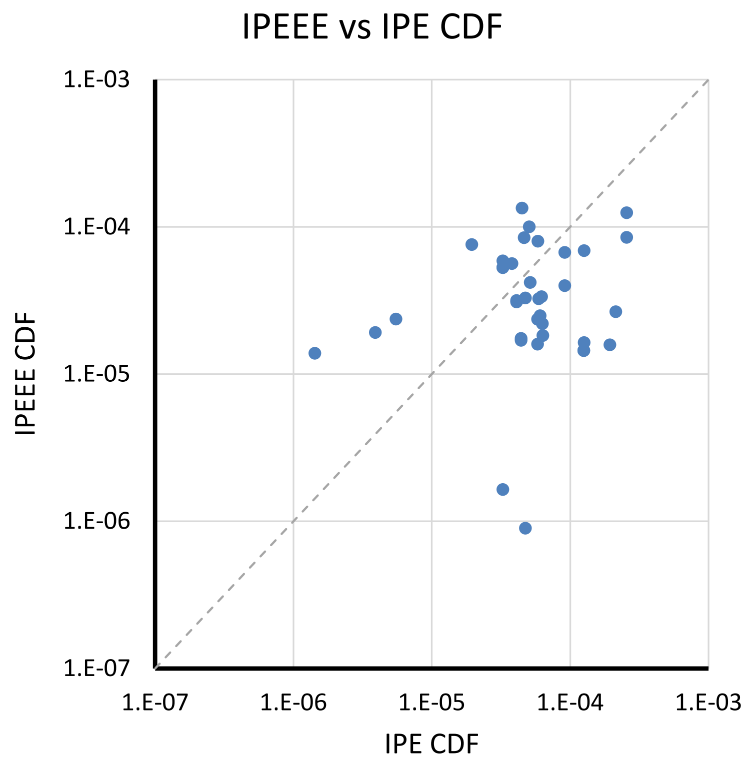
An early study (c. 1980)

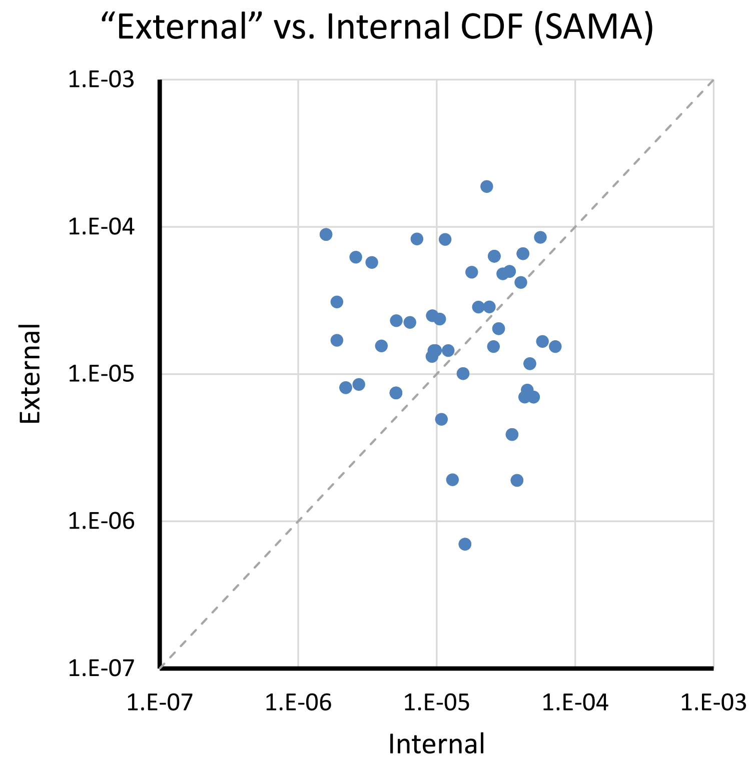


NUREG-1150 (1990)

Note: Orders-of-magnitude uncertainties

External Hazards Analysis (3/12): Past PRA Results





Note: "External" includes internal fires

External Hazards Analysis (4/12): A Fukushima Precursor

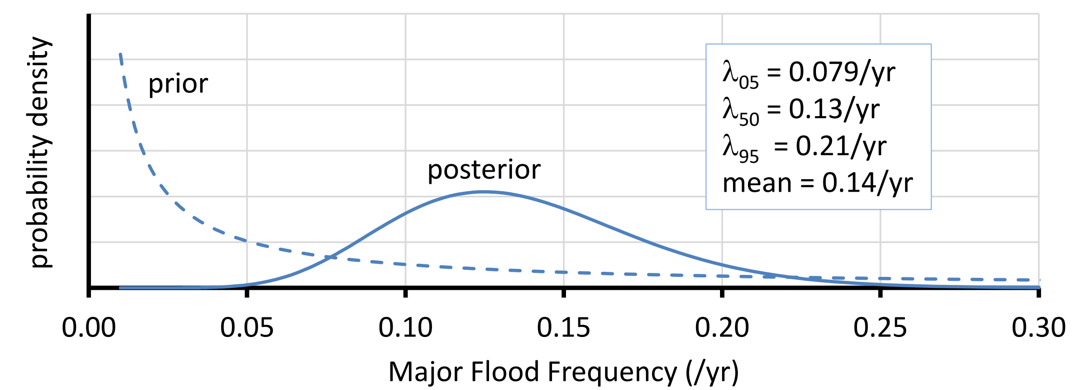
Le Blayais (December 27, 1999)

- Wind-driven waves + major storm surge
  - Overtop and sweep around dike, damage dike, flood site
  - Flood waters pass through penetrations, burst an internal fire door, and flood key areas
- System impacts
  - Loss of offsite power (LOOP) at Units 2 and 4
  - Unit 1 service water degraded
  - Units 1 and 2 low-head safety injection and containment spray pumps lost
  - Site access lost

E. de Fraguier, "*Lessons learned from 1999 Blayais flood: overview of EDF flood risk management plan,*" *NRC Regulatory Information Conference*, Rockville, MD, March 9-11, 2010.

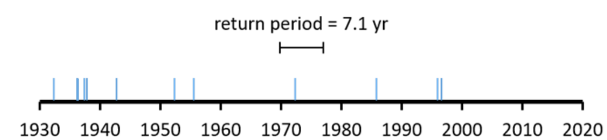
External Hazards Analysis (5/12): PFHA* Background

- Parameter of interest: frequency of major flooding (λ)
- Prior state-of-knowledge: minimal
- Evidence: 12 major floods over 1932-2019 (87 years)
- Bayes' Theorem: $$\pi_1(\lambda|r,T) = \frac{L(r,T|\lambda)\pi_0(\lambda)}{\int_0^\infty \underbrace{L(r,T|\lambda)}_{\text{Poisson}}\underbrace{\pi_0(\lambda)}_{\text{Non-informative}}d\lambda}$$
- Posterior state-of-knowledge:



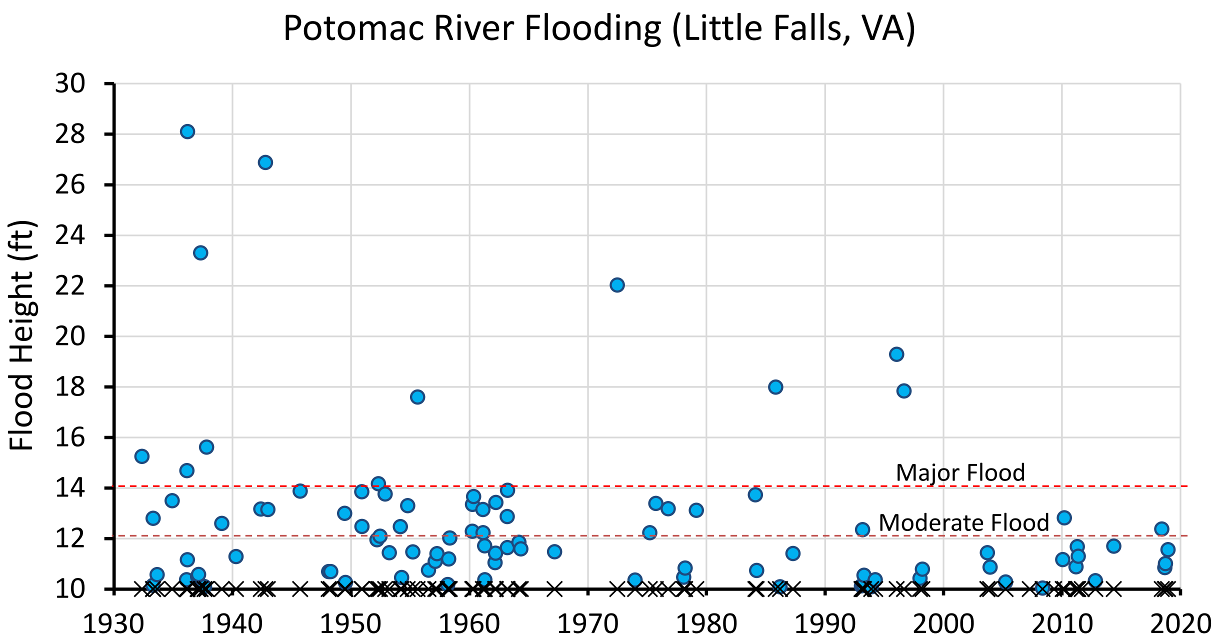
Potomac River (Little Falls, VA)*

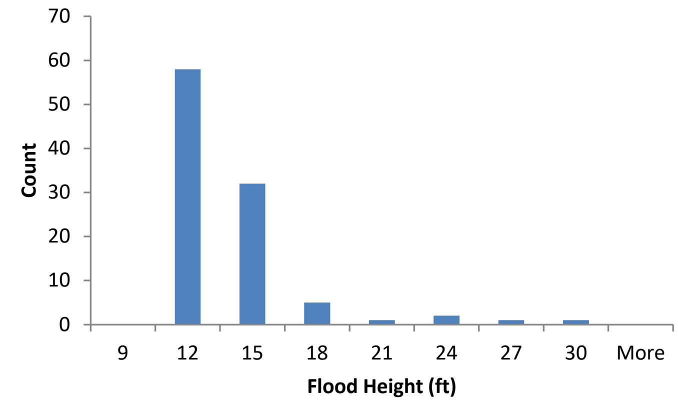
Date	Flood Height (ft)
5/14/1932	15.25
2/27/1936	14.69
3/19/1936	28.10
4/28/1937	23.30
10/30/1937	15.62
10/17/1942	26.88
4/29/1952	14.17
8/20/1955	17.60
6/24/1972	22.03
11/7/1985	17.99
1/21/1996	19.29
9/8/1996	17.84



*Notes:
1) PFHA = probabilistic flooding hazards analysis
2) Data from: https://water.weather.gov/ahps2/crests.php?wfo=lwx&gage=brkm2&crest_type=historic
3) "Major Flood:" height > 14 ft

External Hazards Analysis (6/12): PFHA Background

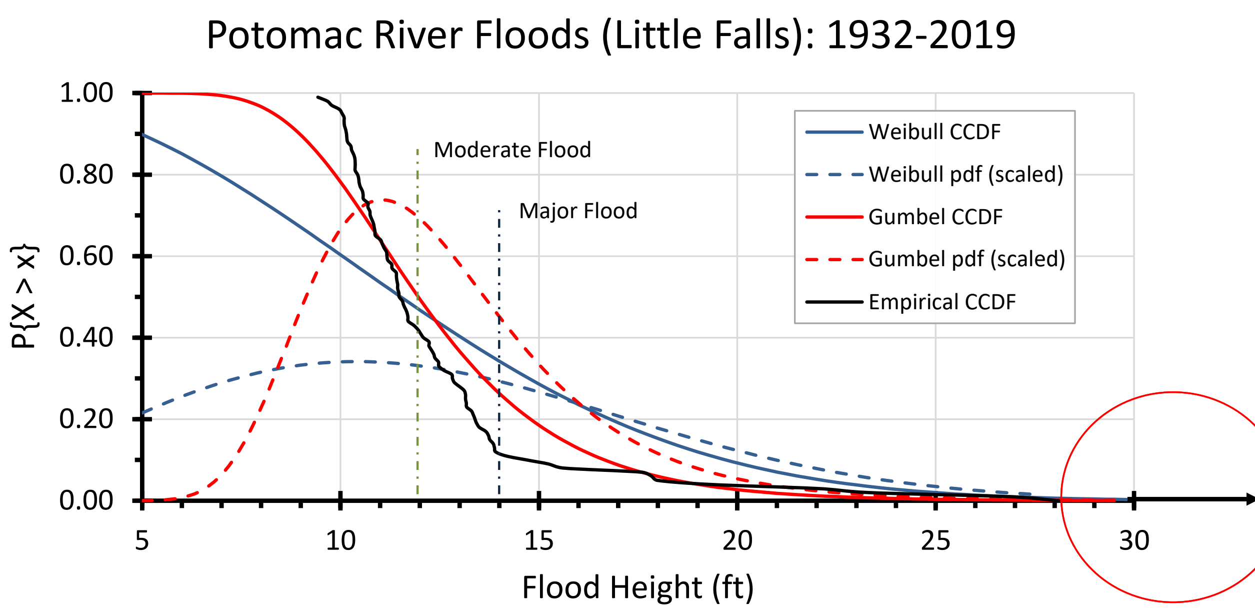




Notes:

1) Data from: https://water.weather.gov/ahps2/crests.php?wfo=lwx&gage=brkm2&crest_type=historic
2) "Major Flood:" height > 14 ft; "Moderate Flood:" 12 ft < height < 14 ft

External Hazards Analysis (7/12): PFHA Challenge



Beyond historical experience: how to estimate for RIDM?

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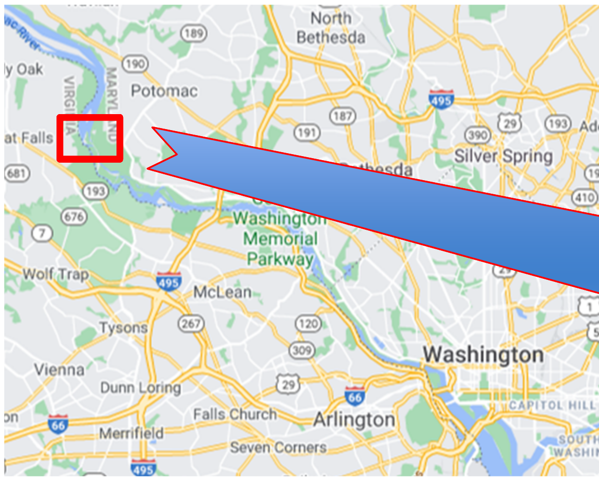
External Hazards (8/12): PFHA Challenge



External Hazards Analysis (9/12): PFHA Challenge

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External Hazards Analysis (10/12): Lessons from Some Other Flood-Related Operational Events*

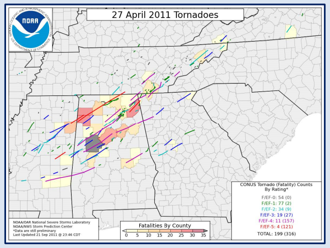
- Qualitative review of 5 floods and 5 storms
- Observations:

Confirmatory

- Multiple hazards
- Asymmetrical multi-unit impacts
- Less-than-extreme hazards
- Hazard persistence
- Failure of mitigation SSCs
- Failure of implicitly considered SSCs
- Warning times and precautionary measures
- HRA and emergency response complexities

Less discussed

- Multiple shocks
- Scenario dynamics
- Geographical extent and potential for multi-site impacts



*See: N. Siu, et al., “Qualitative PRA insights from operational events,” *14th International Conference on Probabilistic Safety Assessment and Management (PSAM 14)*, Los Angeles, CA, September 16-21, 2018. [paper (ML18135A109), presentation (ML18249A340)]

External Hazards Analysis (11/12): Lessons from Some Seismically-Initiated Operational Events*

- Qualitative review of 50 events
- Observations:
  - Reported PGAs << max values considered in recent PRAs
  - Other than offsite power, no direct damage to major mitigating systems due to ground motion; major effects due to induced hazards (fire, external flood)
  - Some reactor trips/safety system actuations for events with very low onsite PGAs
  - If one unit affected, typically all units onsite also affected
  - Some events affected multiple sites:
  - **Reactivity effects:**
    - **Flux-induced trips (Onagawa, 1993; North Anna, 2011)**
    - **Stuck control rod (Kashiwazaki-Kariwa, 2007)**

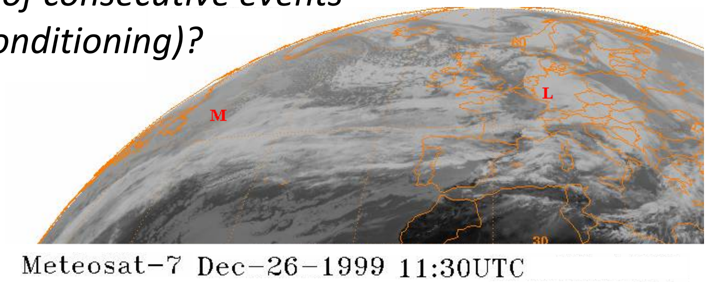
Impacts at Multiple Sites	# Events
Minimal response** or greater	10
Reactor trip	3
Serious challenge	1

*See: N. Siu, et al., "Qualitative PRA insights from seismic events," *25th Conference on Structural Mechanics in Reactor Technology (SMiRT-25)*, Charlotte, NC, August 4-9, 2019. [paper (ML19162A422), presentation (ML19210D835)]

External Hazards Analysis (12/12): Challenges

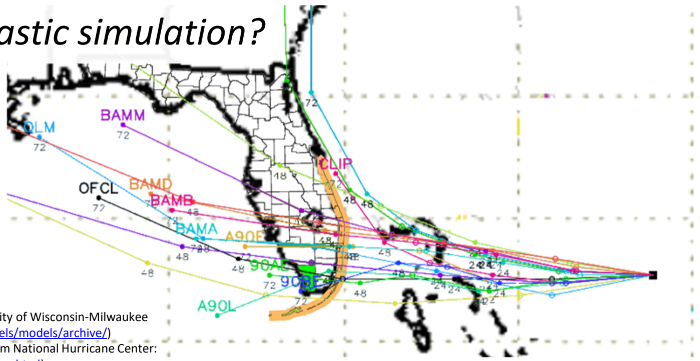
- Hazards analysis
  - Relevance of historical data
    - Natural trends
    - Man-made trends
  - Need for knowledgeable experts
  - Role of simulation
  - [Combination of hazards](#)
  - Technical cultures
    - What is the "hazard" (varying points of view)
    - Buy-in for risk assessment (especially rare events)
- Fragility analysis
  - Full range of hazards (dynamic loads, clogging, …)
- Plant response analysis
  - [Human reliability analysis (HRA)](#)
  - Dynamics

Treatment of consecutive events (and pre-conditioning)?



https://commons.wikimedia.org/wiki/File:Storms_Lothar_and_Martin_december_1999.png

Role of stochastic simulation?



Hurricane tracks adapted from University of Wisconsin-Milwaukee (https://web.uwm.edu/hurricane-models/models/archive/)
Emergency response based on data from National Hurricane Center: (https://www.nhc.noaa.gov/1992andrew.html)

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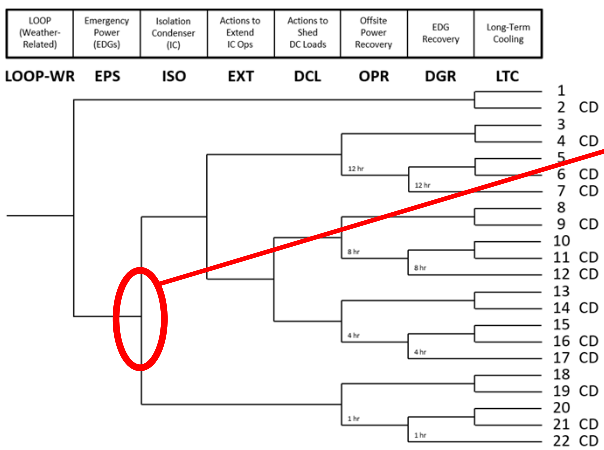
HRA (1/5): Observations from 3/11

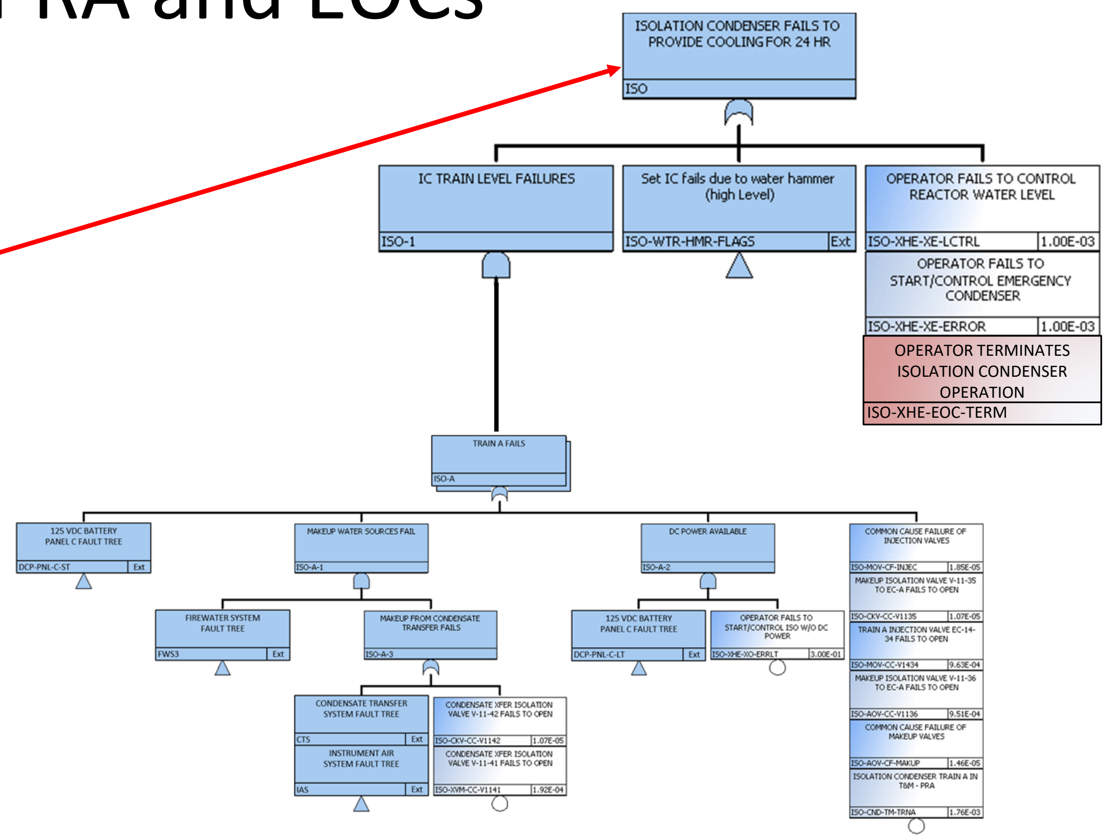
- "Error of commission" (isolation of 1F1 Isolation Condenser)
- Psychological impacts

See next slides

- External interventions in decision making
  - Seawater injection
  - Containment venting
- Uncertainty in plant conditions
  - Loss of instrumentation
  - Loss of access
  - Loss of communication systems => messengers (with associated delays for transit, reporting)
- Evolving conditions (radiation, explosions, evacuating staff and contractors) affecting recovery actions

HRA (2/5): Current PRA and EOCs

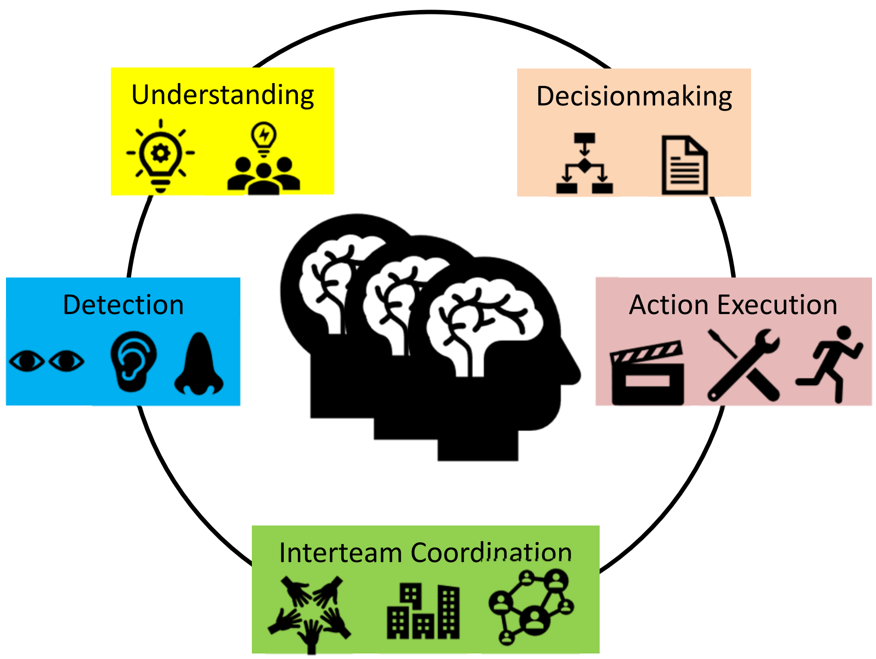




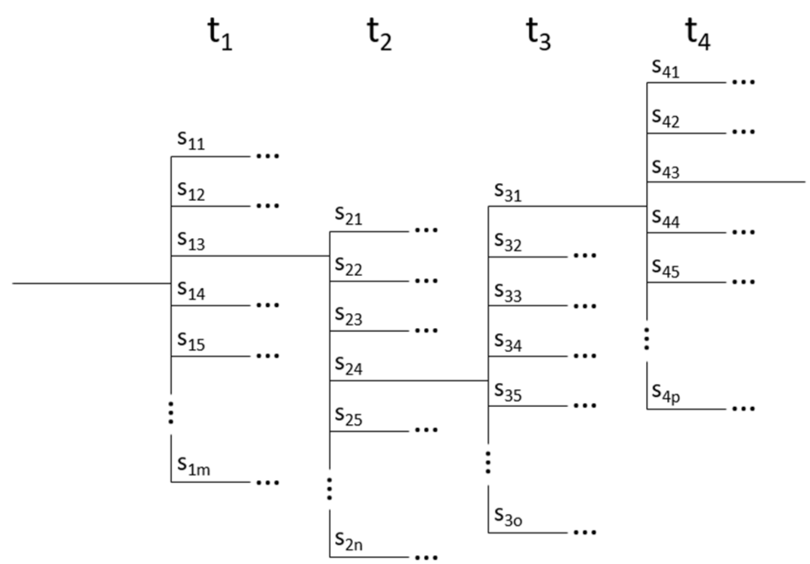
BUT WHY?

HRA (3/5): Adding EOCs

(1) Cognitive Basis



(2) Dynamic Context*



*Approaches to address context in a "classical" event tree/fault tree PRA framework include:

1) L. Podofillini, V.N. Dang, O. Nusbaumer, and D. Dres, "A pilot study for errors of commission for a boiling water reactor using the CESA method," *Reliability Engineering and System Safety*, **109**, 86-98 (January 2013).
2) C. Picoco and V. Rychkov, "Advanced thermal-hydraulic simulations for HRA," *IAEA Technical Meeting on Enhancement of Approaches and Tools for the Development and Application of Probabilistic Safety Assessments (Virtual)*, September 29-October 2, 2020.

HRA (4/5): The Human Dimension (3/11)

- Decision maker frustrations
  - Limitations of available accident management guidance
  - Offsite organizational interventions
- Staff stressors
  - Progressive loss of situation awareness and control
  - Onsite conditions (aftershocks, tsunami warnings, radiation, dark, debris, open manholes, …)
  - ERC conditions (food, sleep, sanitation, …)
  - Offsite conditions

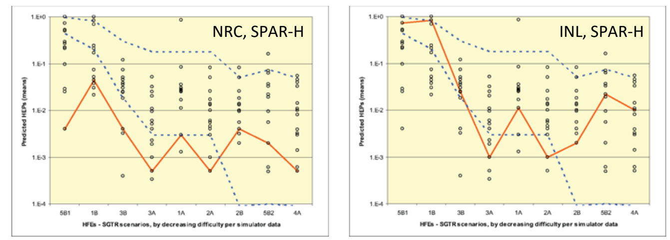
> "Yoshida was asked if he opened up the accident management manual and used it as a reference. He said he never referred to it or even opened it up.
>
> He explained how ineffective measures thought up by people beforehand can be."
>
> Yoshida also explained that nuclear plants in Japan were designed with priority placed on internal factors leading to malfunctions. He went on to explain that no thought was given to malfunctions occurring simultaneously at a number of plants due to external factors, such as tsunami, tornado, a plane crash or an act of terrorism."
>
> \- *The Yoshida Testimony* (2014)

"The Yoshida Testimony: The Fukushima nuclear accident as told by plant manager Masao Yoshida," *Asahi Shimbun*, 2014. (Available from: http://www.asahi.com/special/yoshida_report/en/)

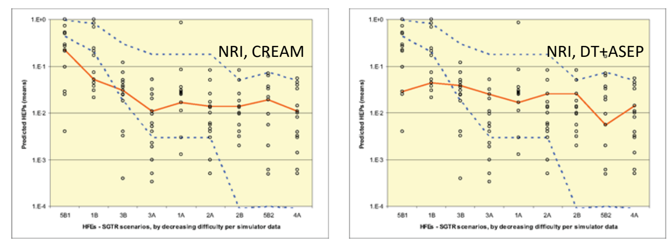
HRA (5/5): Beyond Fukushima

- Other analysis concerns
  - Need for improved qualitative analysis (“little stories”)
    - Basis for analysis assumptions
    - Qualitative dimension of “risk”: what can go wrong
  - Treatment of “new” situations
    - Ex-MCR (particularly portable equipment)
    - Level 2
    - Event and conditions assessment
  - Collection and use of empirical data

- Integrated Human Event Analysis System (IDHEAS)
- Scenario Authoring, Characterization, and Debriefing Application (SACADA)



Same method, different teams



Same team, different methods

A Bye, et al., “International HRA Empirical Study,” NUREG/IA-0216, 2011.

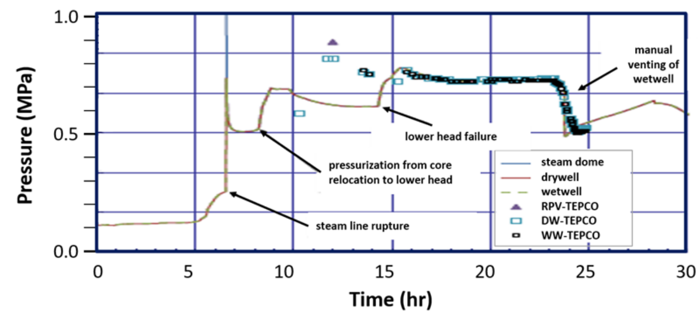
- A RIDM concern: recognition and treatment of model uncertainty – more benchmarks?

Some IDHEAS and SACADA references:
1) Y.J. Chang and J. Xing, “The general methodology of an Integrated Human Event Analysis System (IDHEAS) for human reliability analysis method development,” *13th International Conference on Probabilistic Safety Assessment and Management (PSAM 13)*, Seoul, Korea, October 2-7, 2016. (ML16298A411)
2) Y.J. Chang, et al., “The SACADA database for human reliability and human performance,” *Reliability Engineering & System Safety*, **125**, 117-133 (2014).

Representation of Uncertainties (1/1)

- Post-3/11 “Fukushima Forensic” study (SNL, ORNL):*
  - Reconstructs accident progression at Units 1-3 and Unit 4 SFP
  - Key challenge: accident data gaps and uncertainties
  - Demonstrates that current tools (MELCOR, TRACE) and modeling approaches can reproduce general trends, with good quantitative agreement in portions of the results
- Questions
  - How to incorporate findings into a PRA? Into RIDM?
  - How to represent and communicate analysis uncertainties?
- Challenges
  - Subject complexity
  - Multiple purposes
  - Personal and discipline viewpoints, sometimes strongly held

Additional discussion on parameter, model, and completeness uncertainty



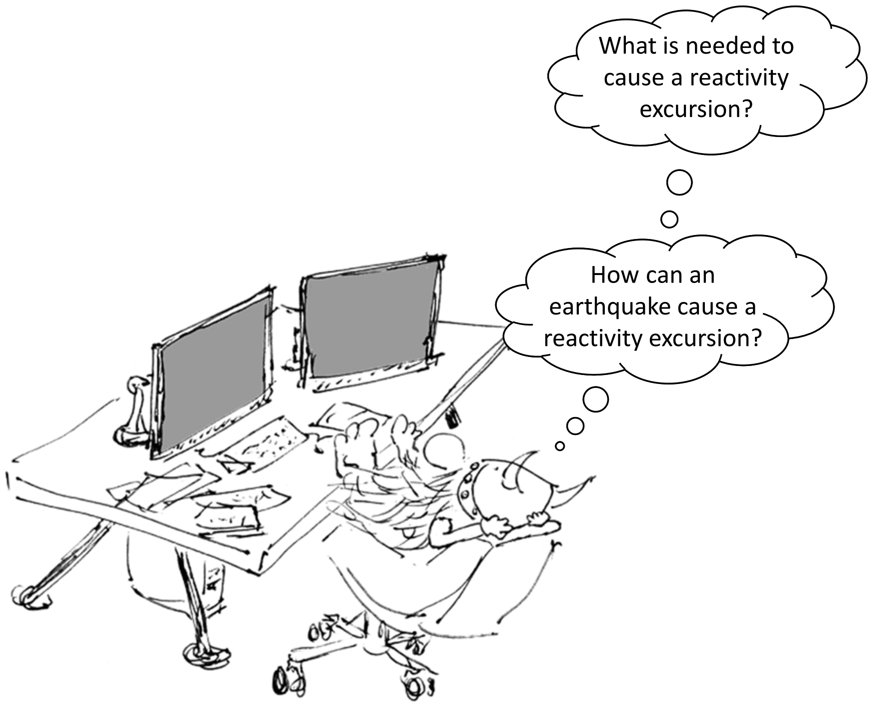
Uncertainty Frameworks and Typologies

- Subjective (“Bayesian”) vs. Objective (“frequentist”)
- Aleatory/Epistemic
- Parameter/Model/Completeness
- Probabilistic vs. Non-Probabilistic

*R. Gauntt, et al., “Fukushima Daiichi Accident Stuy (Status as of April 2012),” *SAND2012-6173*, Sandia National Laboratories, July 2012.

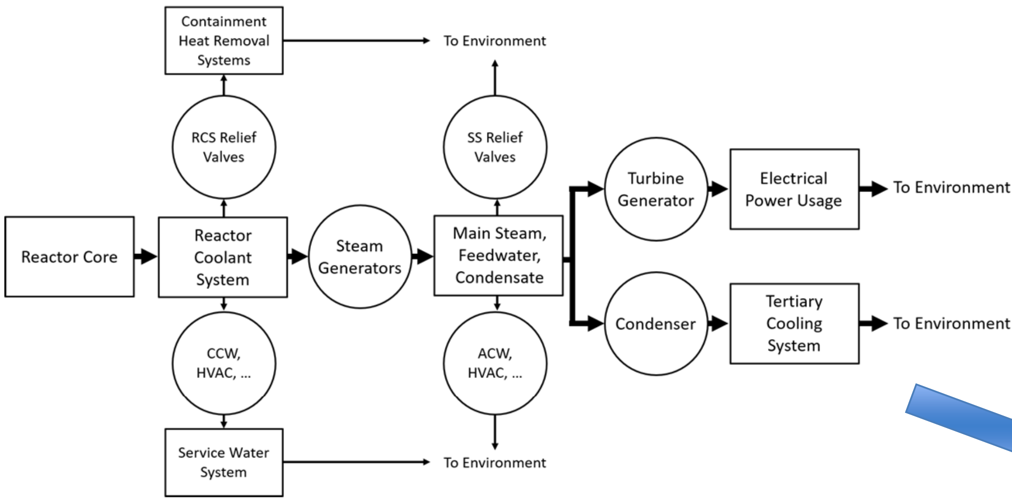
Searching (1/5): Active Supplement?

- Typical PRA approach for identifying external hazards: systematically generate possibilities, then screen
- Post-3/11 observations
  - IPEEE guidance* allowed screening of external floods based on deterministic, design-basis considerations
  - ASME/ANS PRA standard addenda (2009 and 2013) allowed similar screening
  - The Blayais flood (1999) can be viewed as a non-seismically induced precursor to the Fukushima Daiichi reactor accidents
- Active searches for hazards and hazard combinations ("red teaming") might support efficient identification
  - Logic-based approaches (e.g., Master Logic Diagram, Heat Balance Fault Tree, STAMP/STPA, …)
  - Functional classifications
  - Operational experience

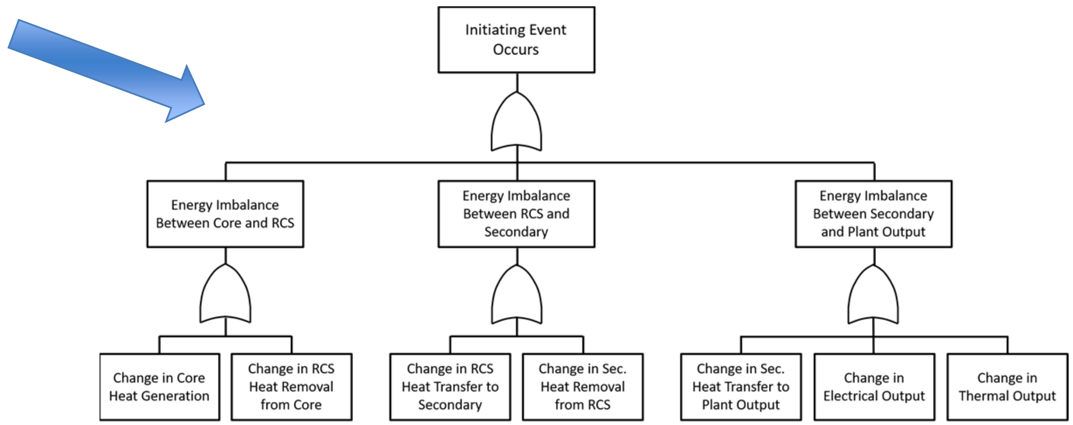


*U.S. Nuclear Regulatory Commission, "Procedural and Submittal Guidance for the Individual Plant Examination of External Events (IPEEE) for Severe Accident Vulnerabilities, Final Report," *NUREG-1407*, 1991.

Searching (2/5): Example Deductive Approach



"Heat Balance Fault Tree"



Searching (3/5): External Hazards Scenario-Based Classification Example

Hazardous Event/Condition

Events
- Storm
- Dam failure
- Earthquake

⋮

Conditions*
- High tide
- Low ambient temperature
- High ambient temperature
- Drought

⋮

*Conditions can contribute to the effect of hazardous events but are unlikely to trigger an initiating event by themselves

Hazardous Phenomena
(aka "hazard," "threat," "insult")
- Wetting
  - Flooding/immersion (e.g., storm surge + wind-driven waves, LIP)
  - Spray (conductive or not)
  - Dripping
- Wind loading
- Wind-driven missiles
- Waterborne debris
- Ice/Snow loading
- Lightning
- Extremely low temperatures
- Secondary ("domino effect") loadings (e.g., structural collapse)

Proximate Cause
- Loss of electrical integrity
- Loading
  - Dynamic
  - Static
  - Thermal
- Clogging
- Corrosion
- Displacement

SSC Failure Cause
- Physical damage
- Physical obstruction
- Beyond environmental qualifications
- Loss of motive power
- Incorrect signal

Hazardous Phenomena
(aka "hazard," "threat," "insult")
- Potentially hazardous conditions
  - Wind
  - Flooding
  - Missiles
  - Lightning
  - Low temperatures
  - Icing
  - Storm damage (structural integrity)
- Potentially job-affecting conditions (additional)
  - Reduced visibility
  - Storm effects (debris, loss of access, information system failures, etc., plus associated mitigation task demands)

Proximate Cause
- Inaccessible
- Inadequate time and/or resources
- Hazardous or challenging job conditions
- Information lacking or incorrect

Human Failure Event
- Infeasible
- Cognition error
  - Detection
  - Situation assessment
  - Decision making
- Execution error

Searching (4/5): Empirical Experience

Accidents

Year	Plant(s)	Precursor?
1979	TMI	Davis-Besse (1977)
1986	Chernobyl	Leningrad (1975)
2011	Fukushima	Blayais (1999)

Some Significant* U.S. Precursors

Year	Plant(s)	Notes
1975	Browns Ferry	Worst precursor Fire => loss of U1 ECCS
1978	Rancho Seco	Next worst precursor Human error (maintenance) => loss of NNI, LOFW
2002	Davis-Besse	Most recent significant precursor Multiple human/organizational faults => RPV head corrosion

*Per Accident Sequence Precursor (ASP) program

Searching (5/5): Other Interesting Events

Year	Plant(s)	Scenario Type	Notes
1957	Windscale 1 (UK)	Fire	Graphite fire in core, release to environment.
1975	Greifswald 1 (East Germany)	Fire	Power cable fire, loss of main feedwater, pressurizer safety valves fail to re-seat.
1977	Gundremmingen A (East Germany)	LOOP/LOCA	Partial loss of offsite power (LOOP) and subsequent loss of cooling accident (LOCA) with internal flooding.
1978	Beloyarsk 2 (Soviet Union)	Fire	Turbine Building fire spreads into Main Control Room, collapses Turbine Building roof.
1981	Hinkley Point A-1, A-2 (UK)	External Flood; LOOP (weather)	Severe weather LOOP and loss of ultimate heat sink (LOUHS).
1982	Armenia 1 (Soviet Union)	Fire	Fire-induced station blackout (SBO).
1989	Vandellos 1 (Spain)	Fire	Fire-induced internal flood.
1991	Chernobyl 2 (Soviet Union)	Fire	Fire-induced Turbine Building roof collapse.
1993	Narora 1 (India)	Fire	Fire-induced SBO.
1993	Onagawa 1 (Japan)	Reactivity Excursion	Seismically-induced reactivity excursion.
1999	Blayais 1, 2 (France)	External Flood	Severe weather LOOP and partial LOUHS.
2001	Maanshan 1 (Taiwan)	LOOP (Weather); Fire (HEAF)	Severe weather LOOP and subsequent SBO.
2003	Pickering 4-8; Darlington 1, 2, and 4; Bruce 3, 4, and 6 (Canada); Fermi 2 , Fitzpatrick, Ginna, Indian Point 2 and 3, Nine Mile Point 1 and 2, Oyster Creek, Perry (U.S.)	LOOP (weather)	Northeast Blackout.
2004	Madras 2 (India)	External Flood	Tsunami-induced LOUHS.
2009	Cruas 2-4 (France)	External Flood	LOUHS due to flood debris.
2011	Fukushima Dai-ichi 5-6, Fukushima Dai-ni 1-4, Onagawa 1-3, Tokai Dai-ni, Higashidori 1-2 (Japan)	External Flood	Earthquake- and tsunami-induced incidents (in addition to accidents at Fukushima Dai-ichi 1-3).

Topics

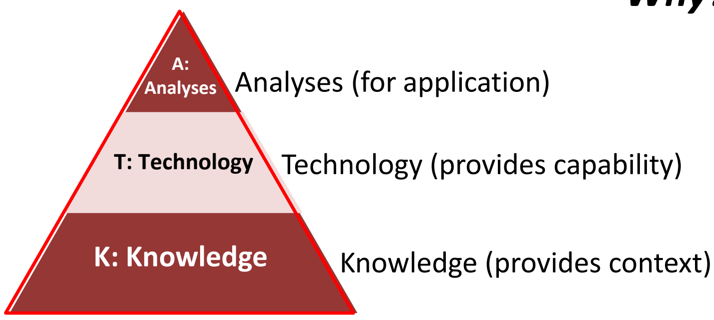
Perspectives on selected "advanced" PRA topics

IAEA TECHNICAL MEETING (TM) ON PSA TECHNOLOGY ENHANCEMENT: TOPICS

IAEA TM on PSA Technology Enhancement*

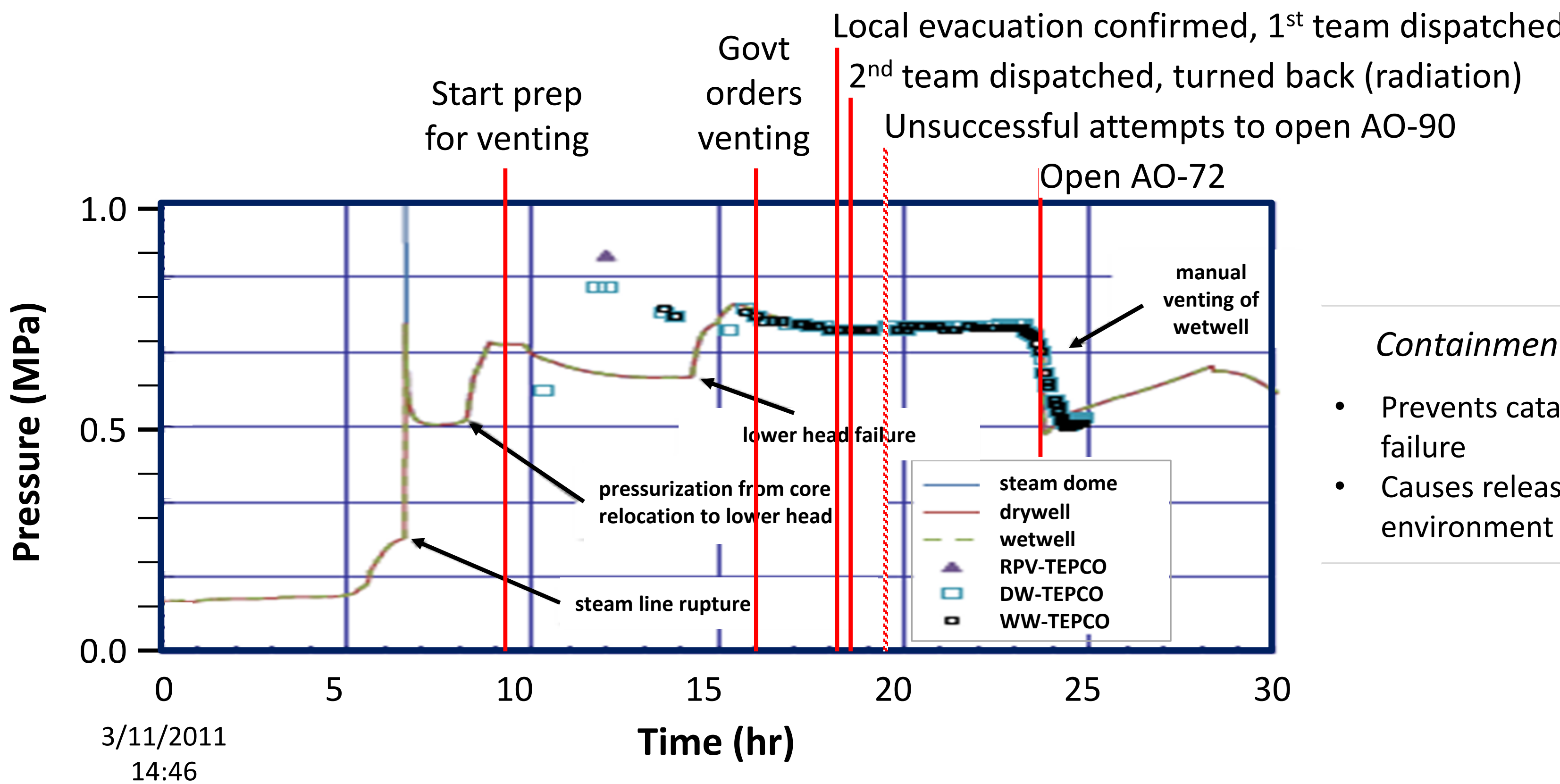
- Technical Meeting on the Enhancement of Methods, Approaches and Tools for Development and Application of Probabilistic Safety Assessments (virtual), September 29-October 2, 2020
- Objectives:
  - Discuss current status of and Member State experience with advanced PSA methods, approaches and applications
  - Update information on relevant topics in a draft technical report on advanced PSA approaches and applications.
- Highlighted topics (candidate areas for "enhancements"):
  - Dynamic PSA
  - Combinations of hazards
  - Portable equipment
  - Development of SAMGs
  - Level 3 PSA
  - Software reliability and modelling
  - Incorporation of ageing aspects

Why?



*Including state-of-practice as well as technology

Dynamic PRA (1/7): “Reality”

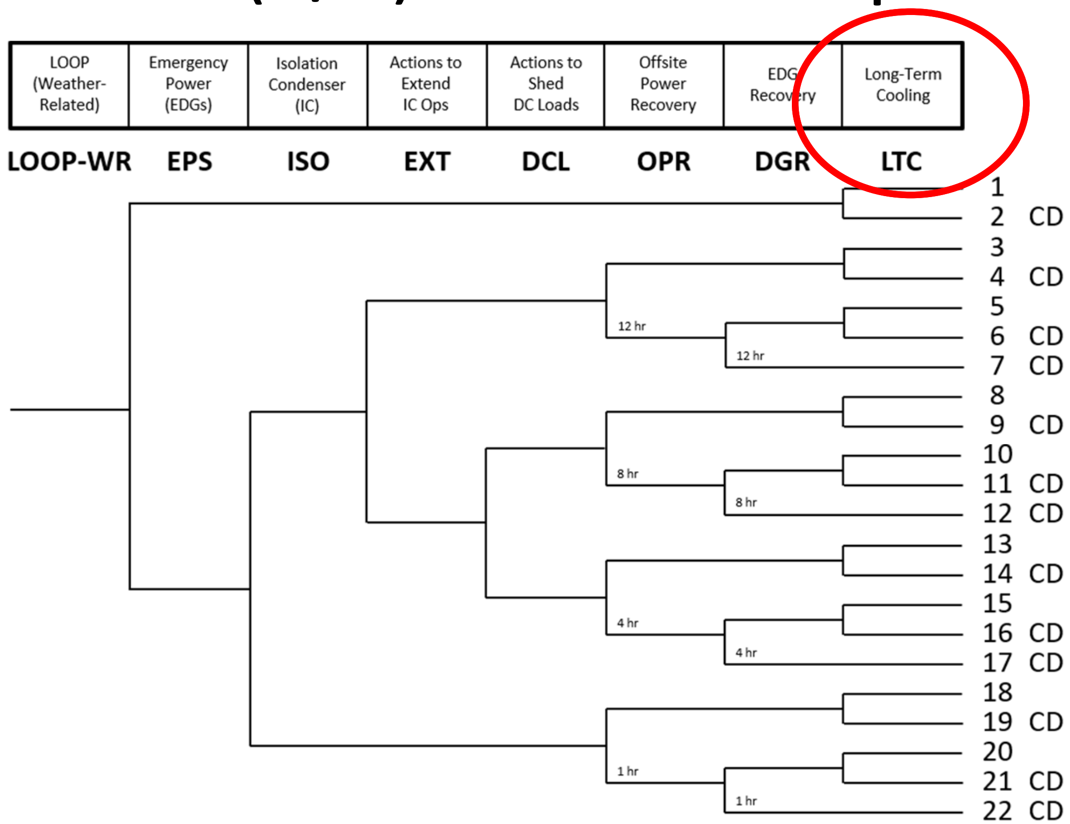


Containment Venting:

- Prevents catastrophic failure
- Causes release to environment

Adapted from: R. Gauntt, “Fukushima Daiichi Accident Study: MELCOR Analyses and Results,” *OECD/NEA Fukushima Accident Analysis Workshop*, Issy-les-Moulineaux, France, June 18-20, 2012.
See also R. Gauntt, et al., “MELCOR Simulations of the Severe Accident at the Fukushima 1F1 Reactor,” *ANS Winter Meeting and Nuclear Technology Expo*, San Diego, CA, November 11-15, 2012.

Dynamic PRA (2/7): Classical Representation



Dynamic PRA (3/7): Basics

- Risk ≡ {scenarios, consequences, likelihoods}
- PRA: likelihood expressed using probabilities
- "Dynamic PRA:"
  - **A simple view: PRA that explicitly models system dynamics ("what" not "how")**
  - Typically envisioned as a form of direct simulation but doesn't have to be
  - Not intended to address dynamically changing PRAs (e.g., risk monitors)

Dy•nam•ics, *n.* a branch of mechanics that deals with forces and their relation primarily to the motion but sometimes also to the equilibrium of bodies

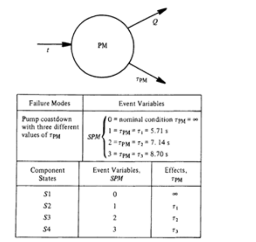
Typical Modeling Approaches
- State-transition ("cell-to-cell")
- Dynamic event trees
- Direct simulation

Related Names/Concepts
- Integrated Deterministic-Probabilistic Safety Assessment (IDPSA)
- Integrated Safety Assessment (ISA)
- Computational risk assessment (CRA)
- Integrated PRA (I-PRA)
- Simulation modeling (e.g., discrete event simulation)

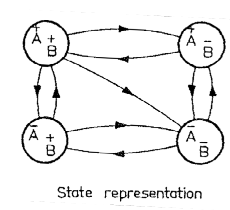
Dynamic PSA (4/7): Benefits of Enhancement

- Analyses (anticipated, potential)
  - Advanced reactor design approvals
  - Operating reactor risk-informed applications (e.g., FLEX, security)
  - External hazards scenarios (e.g., flooding)
  - Severe accidents
- Technology
  - Improved realism (fewer modelling approximations)
  - Reduced completeness uncertainties (e.g., EOCs, passive systems)
  - Improved synergy (other fields, educational trends)
- Knowledge
  - Improved risk insights (margins, contributors)

Long history (starting with fast rx)



A. Amendola and G. Reina, "Event Sequences and Consequence Spectrum: A Methodology for Probabilistic Transient Analysis," *Nuclear Technology*, **77**, 297-315(1981).



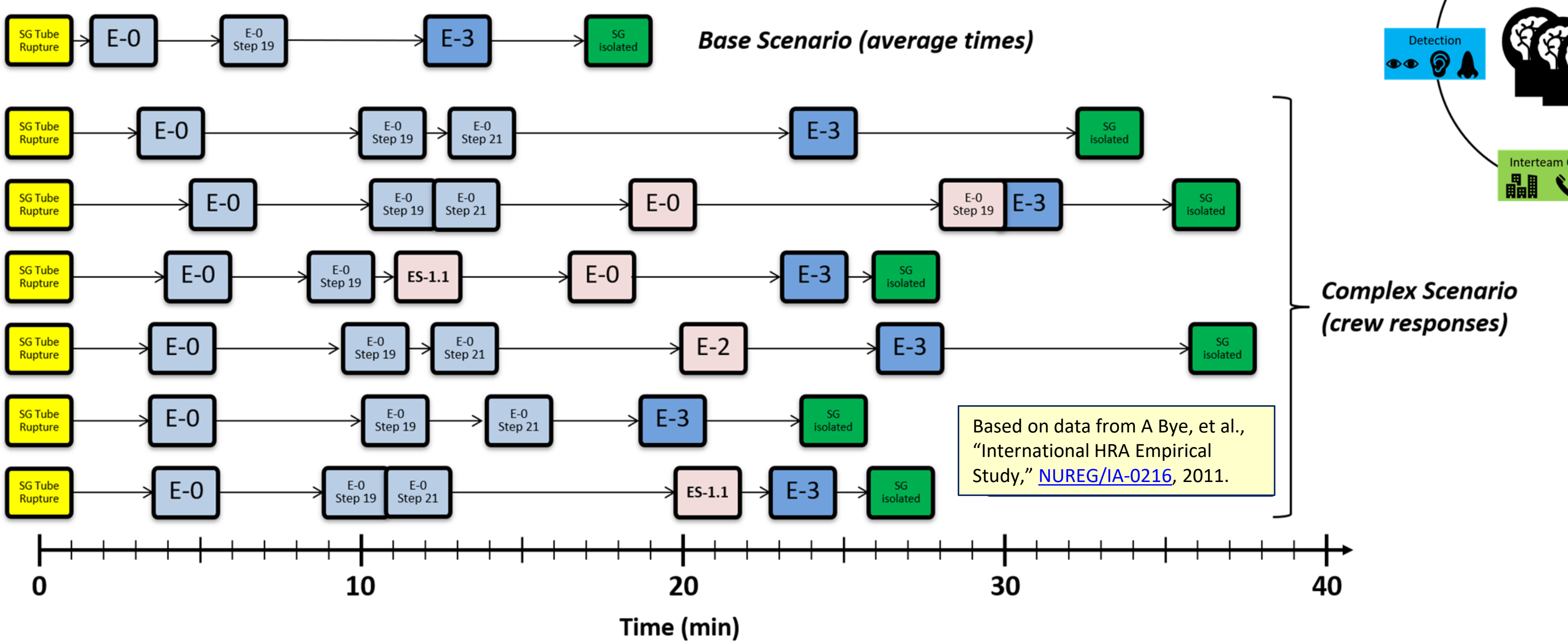
J.M. Lanore, et al, "Progress in Methodology for Probabilistic Assessment of Accidents: Timing of Accident Sequences," *ANS/ENS Intl Mtg Probabilistic Risk Assessment*, Port Chester, NY, 1981.

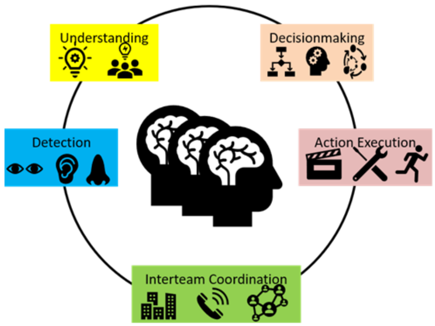
See also draft white paper (ML19066A390) and presentation from 2019 IAEA workshop (ML19248C656)

Dynamic PSA (5/7): Status and Technical Challenges

- Current status
  - U.S.: technology development, multiple demonstrations
  - International: some applications
- Technical Challenges
  - Phenomenological models (particularly operating crews)
  - Data
  - Computational requirements (for complex scenarios)
  - Treatment of uncertainties
  - Post-processing for insights

Dynamic PSA (6/7): Modeling Operating Crews



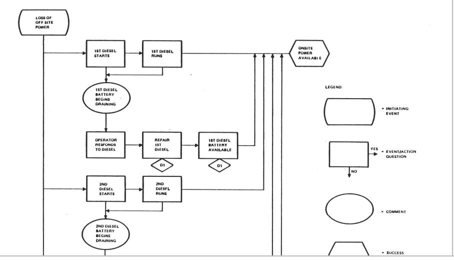


Based on data from A Bye, et al., "International HRA Empirical Study," NUREG/IA-0216, 2011.

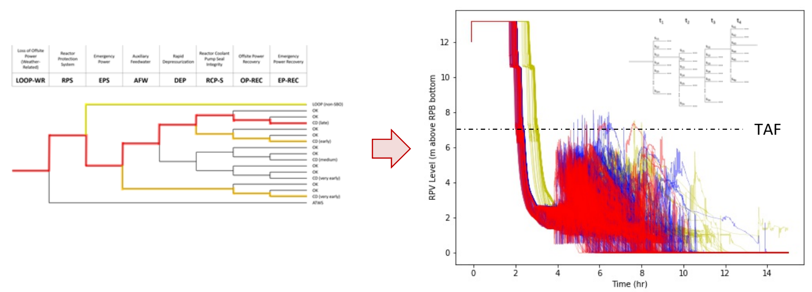
Dynamic PSA (7/7): Implementation Challenge

- **Challenge: transition from R&D to RIDM support**
  - **Conflicting goals: technology advancement vs. problem solving**
  - **Communication and perception**
  - **Investment requirements, cost/benefit**
  - **Cultural resistance**

Not always complicated



Computational capabilities + investments (e.g., DOE, TSOs, universities) => time to reap benefits?



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Combination of Hazards (1/3): Background

- Historical treatment
  - Hazards (earthquakes, fires, floods, high winds, aircraft crashes, offsite industrial accidents, …) typically treated one-at-a-time
  - Specific combinations (seismically-induced fires and floods) recognized and addressed in PRA guidance
- Increased interest in broader consideration following the Fukushima Daiichi reactor accidents (3/11/2011)

The Great Lisbon Earthquake (November 1, 1755)
https://commons.wikimedia.org/wiki/File:Lissabon-2.jpg

American Nuclear Society and the Institute of Electrical and Electronics Engineers, "PRA Procedures Guide," *NUREG/CR-2300*, 1983.
J.A. Lambright et al., "Fire Risk Scoping Study: Investigation of Nuclear Power Plant Fire Risk, Including Previously Unaddressed Issues, " NUREG/CR-5088, 1989.

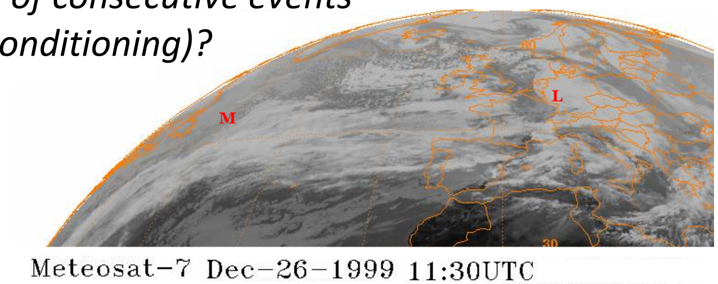
Combination of Hazards (2/3): Benefits of Enhancement

- Analyses (ongoing)
  - Current risk-informed applications (specific combinations)
- Technology
  - Improved realism (correlation of hazards)
  - Reduced completeness uncertainties
  - Improved synergy with natural hazards community
- Knowledge
  - Additional/improved insights

Combination of Hazards (3/3): Status and Challenges

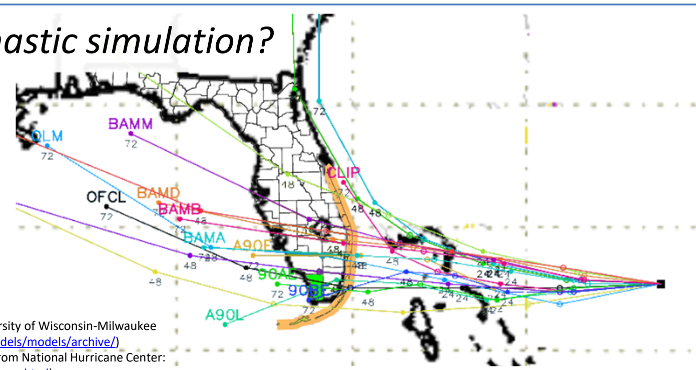
- Current status
  - U.S.: some methods developed and used, included in PRA standards and guidance
  - International: active development (focus on systematic, exhaustive approaches)
- Challenges
  - Efficient identification and prioritization
  - Data augmentation (simulation?)
  - Communication (discipline-specific frameworks – what is a “hazard”? Area of responsibility when performing analyses

Treatment of consecutive events (and pre-conditioning)?



https://commons.wikimedia.org/wiki/File:Storms_Lothar_and_Martin_december_1999.png

Role of stochastic simulation?



Hurricane tracks adapted from University of Wisconsin-Milwaukee (https://web.uwm.edu/hurricane-models/models/archive/)
Emergency response based on data from National Hurricane Center: (https://www.nhc.noaa.gov/1992andrew.html)

U.S.NRC United States Nuclear Regulatory Commission *Protecting People and the Environment*

Portable Equipment (1/4): Early Perspectives

- McCullough, Mills, and Teller (1955): nuclear "fire-fighters"
- Indian Point 3 PRA (1983): alternatives to fixed measures (e.g., core catcher, filtered/vented containment)
- IPE/IPEEE (1988-2002) plant improvements:
  - Portable pumps (e.g., isolation condenser makeup)
  - Portable generators (battery chargers)
  - Portable fans (room cooling, smoke removal)
- Severe accident management alternatives (SAMAs, 2002-2018) include similar ideas
- Reluctance to credit in PRA without incorporation in procedures and training

TABLE 1.6.2.2.1-13

INDIAN POINT 3 OFFSITE POWER RECOVERY ACTIONS

Recovery Action	Estimated Action Time*
Energize 6.9 kV buses 5 and 6 from Buchanan 13.8 kV supply (if available)	5 - 10 minutes
Reset transfer trips and sectionalizing relays to reenergize Buchanan 138 kV or 13.8 kV supply from an available feeder	10 - 20 minutes
Start gas turbine generator unit 1	30 - 60 minutes
Start gas turbine generator units at Buchanan substation	30 - 60 minutes
Repair at least one 138 kV or 13.8 kV feeder to the station	2 - 24 hours
Provide auxilary portable generation equipment to the station	24 - 72 hours

*This is not an estimate of total response time which depends upon the precise event scenario. Rather, it is an estimate of the time required to effect the given action once that action has been identified as appropriate (i.e., it is approximately equal to total response time minus recognition and evaluation time).

See also presentation from 2019 IAEA workshop (ML19248C655)

Portable Equipment (2/4): Some Pre-3/11 Events

- Major External Events
  - Hurricane Andrew/Turkey Point 3&4 (1992)
  - Winter Storm Martin/Blayais 1&2 (1999)

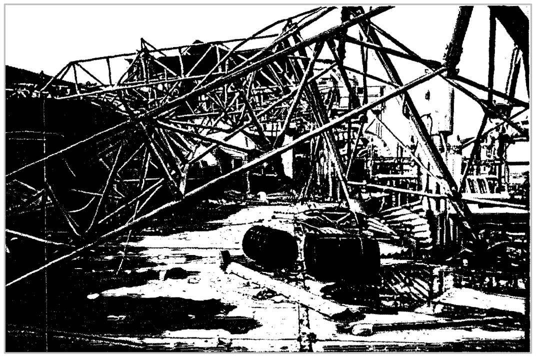
Onsite damage, loss of site access, offsite damage; portable fire pumps, debris removal

- Major Internal Fires
  - Greifswald 1 (1975)
  - Armenia 1&2 (1982)

Loss of power and control, smoke, explosions (A); temporary cables

- Lesser events
  - San Onofre 1 (1982): submersible pump for intake structure
  - Diablo Canyon (2000): generator for switchyard battery charger
- Non-Nuclear Events
  - Northridge Earthquake, M 6.7 (1994)
  - Kobe Earthquake, M 6.9 (1995)

Facility and infrastructure damage, fires, emergency service demands; portable generators, pre-planning, workarounds



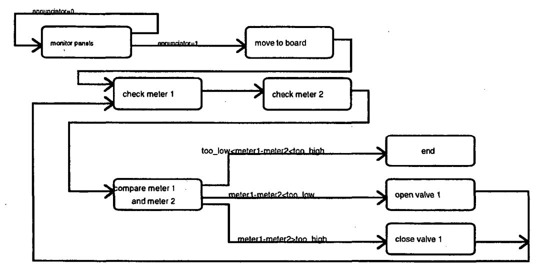
Turkey Point Turbine Deck

"Effect of Hurricane Andrew on the Turkey Point Nuclear Generating Station from August 20-30, 1992," *NUREG-1474*, March 1993 (ML063550235)

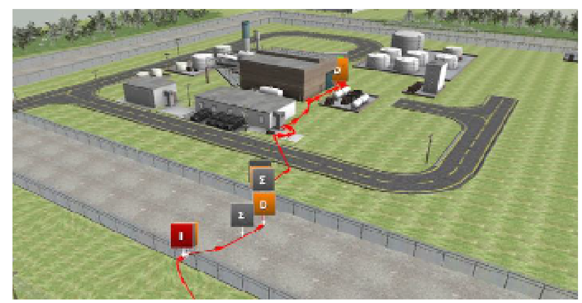
Portable Equipment (3/4): Benefits of Enhancement

- Analyses (ongoing)
  - U.S.: RIDM applications (FLEX, other non-safety related equipment)
  - International: PSA updates (PSR), EOP/SAMG improvement, margins assessments
- Technology
  - Improved HRA for ex-MCR activities (possibly including task-based simulation)
  - Improvements (practice, methods?) in constructing informed priors (potential)
- Knowledge
  - Improved insights

Task-Based Simulation: Old Idea, Recent Applications



M.T. Lawless, K.R. Laughery, and J.J. Persensky, "Using Micro Saint to Predict Performance in a Nuclear Power Plant Control Room: A Test of Validity and Feasibility," *NUREG/CR-6159*, 1995.



S. Fogarty, "Approaches and Tools to Quantifying Facility Security Risk," INMM Workshop on Risk-Informed Security , Stone Mountain, GA, February 11-12, 2014.

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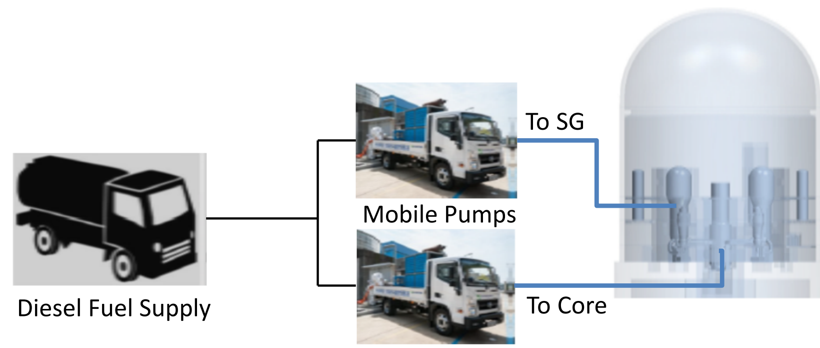
Portable Equipment (4/4): Status and Challenges

- Current status
  - Strong interest U.S. and abroad
  - Many applications (e.g., NOED, CRM, SDP, licensing actions, NTTF 2.1 seismic PRA)
  - Further applications being developed
  - Improved HRA demonstration (IDHEAS)
- Challenges
  - Reliability data (higher failure rates)
  - HRA (e.g., granularity/aggregation, quantification, credit for non-proceduralized actions)



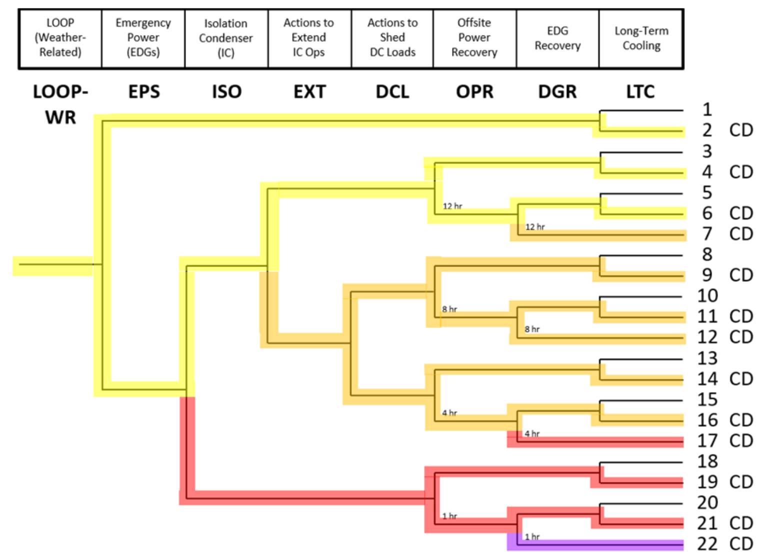
Adapted from T. Hong, "Application of Portable Equipment in PSA Model for WH-type Nuclear Power Plant," *IAEA Technical Meeting on the Enhancement of Methods, Approaches and Tools for Development and Application of Probabilistic Safety Assessments*, September 29-October 2, 2020.

Use of PSA in Development of SAMGs (1/6): Background

- SAMG/SAMGs = Severe Accident Management Guidance/Guidelines
- Severe Accident Policy Statement*
  - "[T]he commitment of utility management to the pursuit of excellence in risk management is of critical importance."
  - 1983 draft criticized for perceived over-reliance on PRA
- SECY 88-147: NRC plan for closing severe accident issues**
- NEI 91-04, Rev. 1 (1994): industry commitment to implement SAMGs; no NRC regulation***

"Severe Accident"

An accident more severe than design basis accidents; involves substantial damage to reactor core regardless of offsite consequences.*



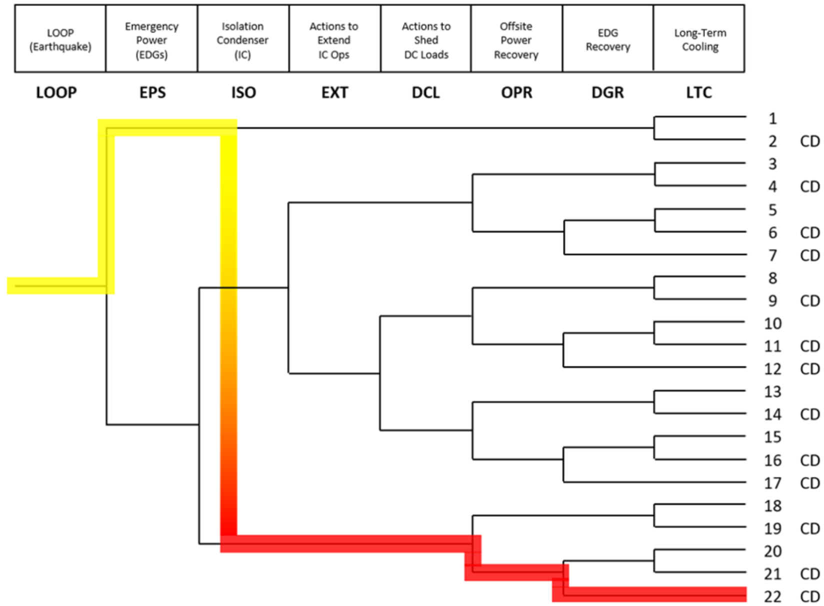
*U.S. Nuclear Regulatory Commission, "Policy Statement on Severe Reactor Accidents Regarding Future Designs and Existing Plants," 50 FR 3218, August 8, 1985.
**U.S. Nuclear Regulatory Commission, "Integration Plan for Closure of Severe Accident Issues," SECY 88-147, May 25, 1988.
***Nuclear Energy Institute, "Severe Accident Issue Closure Guidelines," NEI 91-04, Rev. 1, (formerly NUMARC 91-04), December 1994. (ML072850981)

Development of SAMGs (2/6): Responding *in extremis*

"**[Before TMI] core damage was 'never never land'…**"
- R. Bari[1]

"The NPS ERC [Emergency Response Center] received reports … that the nuclear reactors were successively losing their power supplies and Units 1, 2 and 4 in particular had lost all of their power sources. **Everyone at the NPS ERC was lost for words at the ongoing unpredicted and devastated state.**"
- Investigation Committee Interim Report[2]

"[Site Superintendent] Yoshida was asked if he opened up the accident management manual and used it as a reference. He said he never referred to it or even opened it up. **He explained how ineffective measures thought up by people beforehand can be.**"
- The Yoshida Testimony[3]



1) Plenary Panel: "Perspectives on Nuclear Safety Since the Three Mile Island Event," *ANS Intl Mtg Probabilistic Safety Assessment (PSA 2019)*, Charleston, SC, 2019.
2) Government of Japan, "Interim Report (Main Text)," *Government of Japan Investigation Committee on the Accident at Fukushima Nuclear Power Stations of Tokyo Electric Power Company)*, Tokyo, Japan, 2011.
3) "The Yoshida Testimony: The Fukushima nuclear accident as told by plant manager Masao Yoshida," *Asahi Shimbun*, 2014. (Available from: http://www.asahi.com/special/yoshida_report/en/)

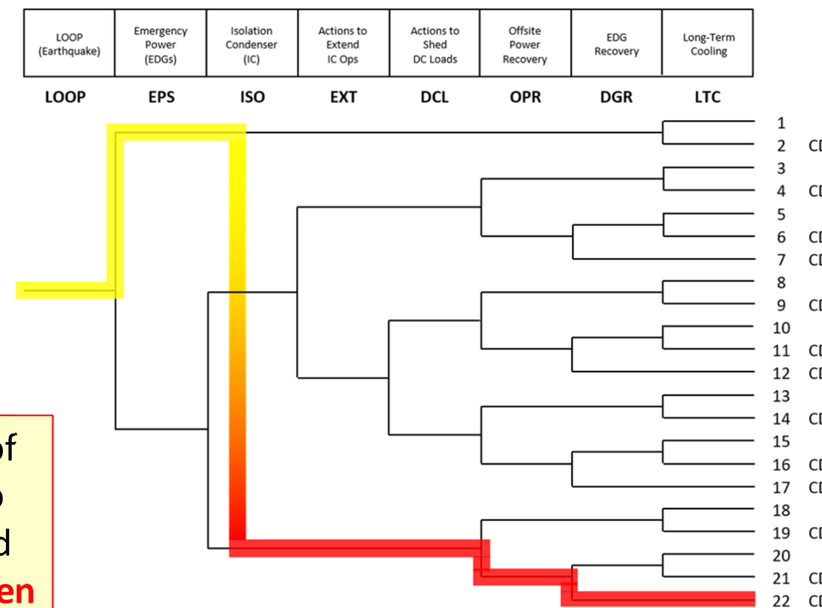
Development of SAMGs (3/6): Responding *in extremis*

"The Fukushima Daiichi accident extended over multiple days and imposed severe mental and physical fatigue on control room operators, field staff, and personnel in the plant's emergency response center. **Control room operators and field personnel were also exposed to physical stressors** (e.g., loss of lighting and high radiation) **as well as psychological stressors** associated with risk to their lives and those of their co-workers and families."

- National Research Council[1]

"we never had enough time, so the pump--the fire engine--ran out of fuel, and it could no longer pump water in when it was time to do so when reactor pressure had fallen. That gave us another letdown, and we talked about sending (workers) to pump in (water). **That was when I thought we were coming to the end.**"

- M. Yoshida, The Yoshida Testimony[2]



1) National Research Council, *Lessons Learned from the Fukushima Nuclear Accident for Improving Safety of U.S. Nuclear Plants*, National Academies Press, Washington, DC, 2014.
2) "The Yoshida Testimony: The Fukushima nuclear accident as told by plant manager Masao Yoshida," *Asahi Shimbun*, 2014. (Available from: http://www.asahi.com/special/yoshida_report/en/)

Development of SAMGs (4/6): Forms and Implications

- Forms
  - Tactical direction (procedure-like)
  - Strategic guidance
- PRA considerations
  - Scenario development (e.g., RCS conditions, site conditions)
  - Instrumentation survivability, trustworthiness
  - Crew factors
    - PSFs/PIFs and effect on performance
      - Cognition, decision making
      - Execution, coordination
    - Crew-to-crew variability

Tactical

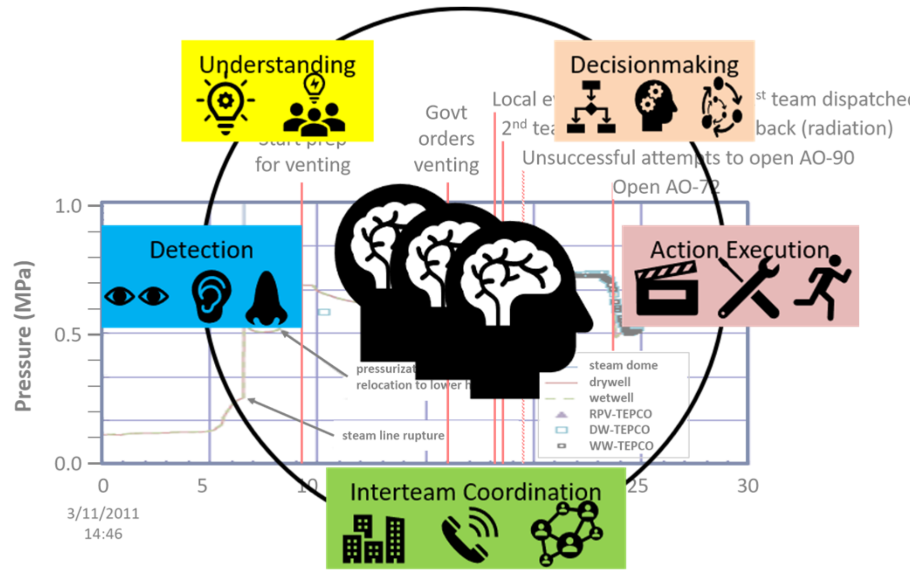
IF [condition(s)]
THEN [specific action(s)]

Strategic

- Identify available means to perform function (e.g., reducing containment release)
- Identify preferred strategy to perform function
  - Systems and lineups
  - Detection means for negative impacts
  - Limitations on uses of means
  - Special parameters to monitor
- Direct Control Room to implement strategy
- Verify strategy implementation
- Determine if challenge is being mitigated

Development of SAMGs (5/6): Benefits of Enhancement

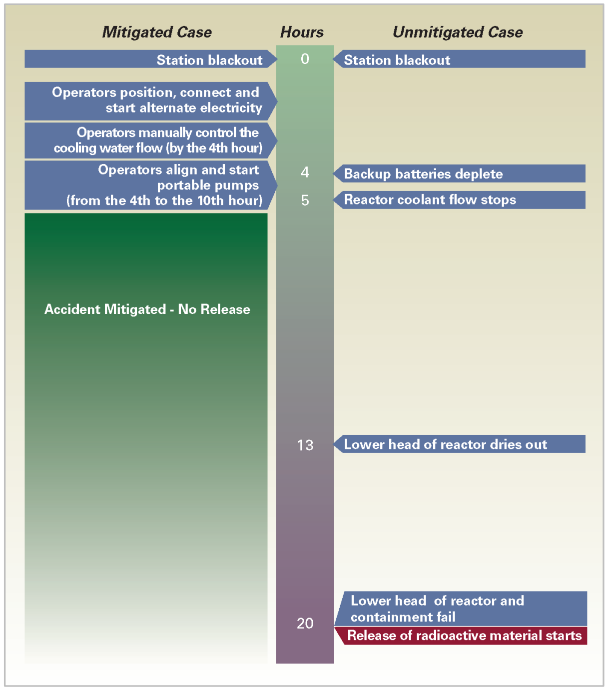
- Analyses
  - Improved SAMGs and implementation (e.g., new scenarios, prioritization for training)
- Technology
  - Improved HRA for post-core damage, guidance-oriented responses
  - Improved phenomenological models (e.g., for severe-accident induced cascading failures)
- Knowledge
  - Additional/improved insights (e.g., safety margins, priorities for severe accident R&D)
  - Improved realism => improved acceptance and appreciation of Level 2 PRA



Development of SAMGs (6/6): Status and Challenges

- Current status (use of PRA)
  - U.S.
    - SOARCA analyses of benefit
    - Some changes identified during FLEX implementation
  - International: widespread
- Challenges
  - Level 2 PRA uncertainties
    - HRA
    - Severe accident phenomenology
  - Scope: which scenarios/possibilities
  - Appropriate realism
    - Dependencies (e.g., multi-source)
    - Use of "Game Over" modeling
  - Low likelihood of event, incentives for full Level 2 PRA

SOARCA Assessment of "B.5.b" Measures



D. Collins, et al., "Modeling Potential Reactor Accident Consequences," *NUREG/BR-0359 Rev. 1*, 2012. (ML12347A049)

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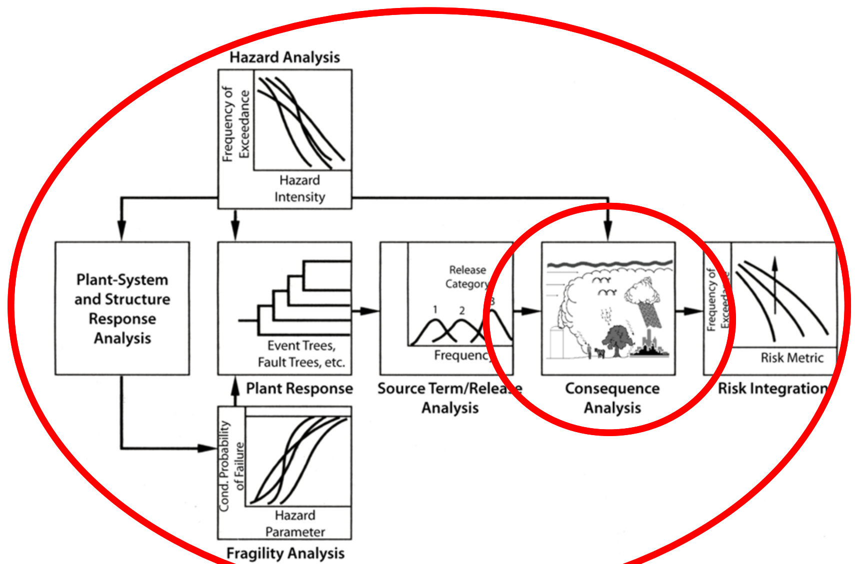
Level 3 PSA (1/4): Background

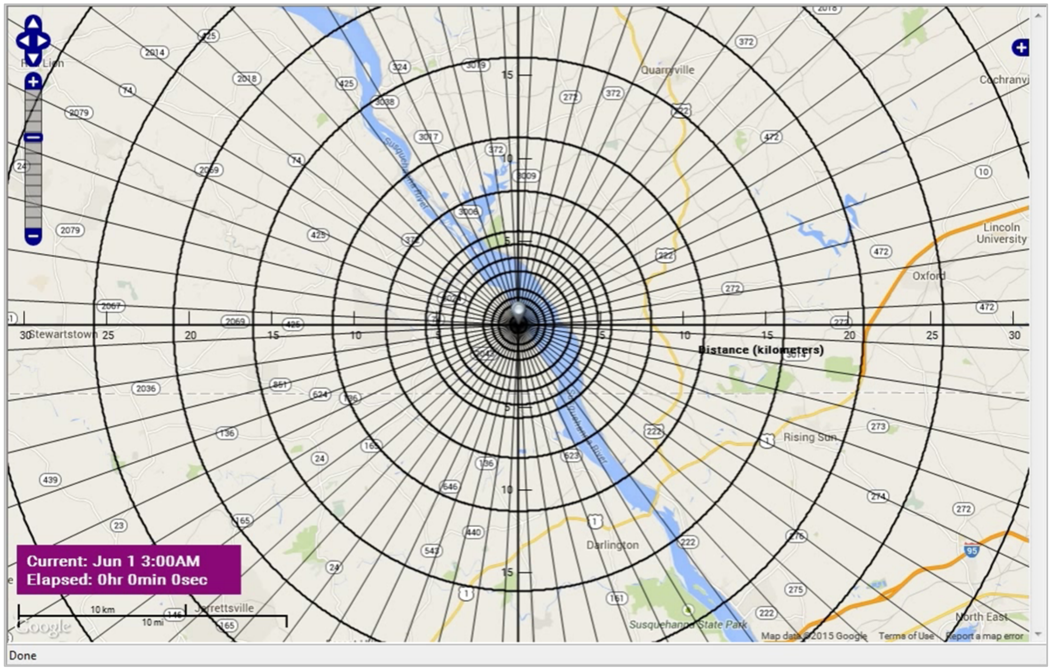
- Includes analysis of offsite consequences; some terminology ambiguity
  - Initiating event to offsite consequences
  - Release category to offsite consequences
- Scope of early PRAs
  - NRC: WASH-1400 (1975), NUREG-1150 (1990)
  - Industry: Oyster Creek (1979), Zion (1981), Indian Point (1982), Limerick (1982), Millstone (1983), Seabrook (1983), Oconee (1984)
- Vulnerability analyses (IPE, IPEEE) and later: focus on core damage and large early release



Adapted from NUREG/CR-6042

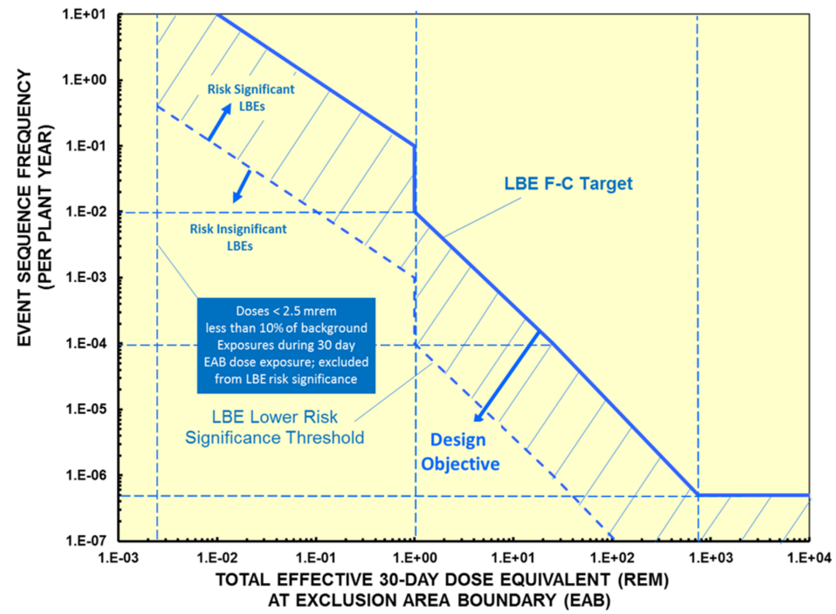
Level 3 PSA (2/4): Probabilistic Consequence Assessment

- Key elements
  - Weather and dispersion (atmospheric)
  - Response (sheltering, evacuation, interdiction)
  - Consequences
    - Dose (individual, societal)
    - Health effects (LNT, other)
    - Economic
- Tools
  - MACCS (U.S.)
  - COSYMA (EU)
  - PACE (UK)
  - OSCAR (Japan)
  - …



Level 3 PSA (3/4): Benefits of Enhancement

- Analyses
  - Demonstration of Licensing Modernization Program (LMP) for operating plants (pilot)
  - Regulatory analysis guidance revisions (potential)
  - Applications to Emergency Planning Zone (EPZ) sizing (potential)
- Technology
  - Developments in selected areas (e.g., multi-source PRA)
  - Assessment of impact of more detailed models (e.g., dispersion)
- Knowledge
  - Improved insights regarding safety margins
  - Improved insights for performing analyses (risk, feasibility of and benefits from future Level 3 studies)
  - Improved staff capabilities for performing and reviewing PRAs

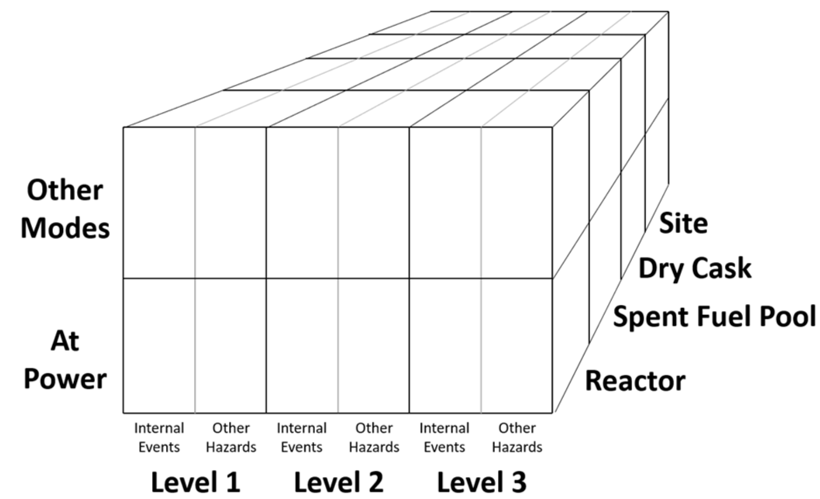


"Risk-Informed Performance-Based Technology-Inclusive Guidance for Non-Light Water Reactors," NEI 18-04, Rev. 1, August 29, 2019.

Level 3 PSA (4/4): Status and Challenges

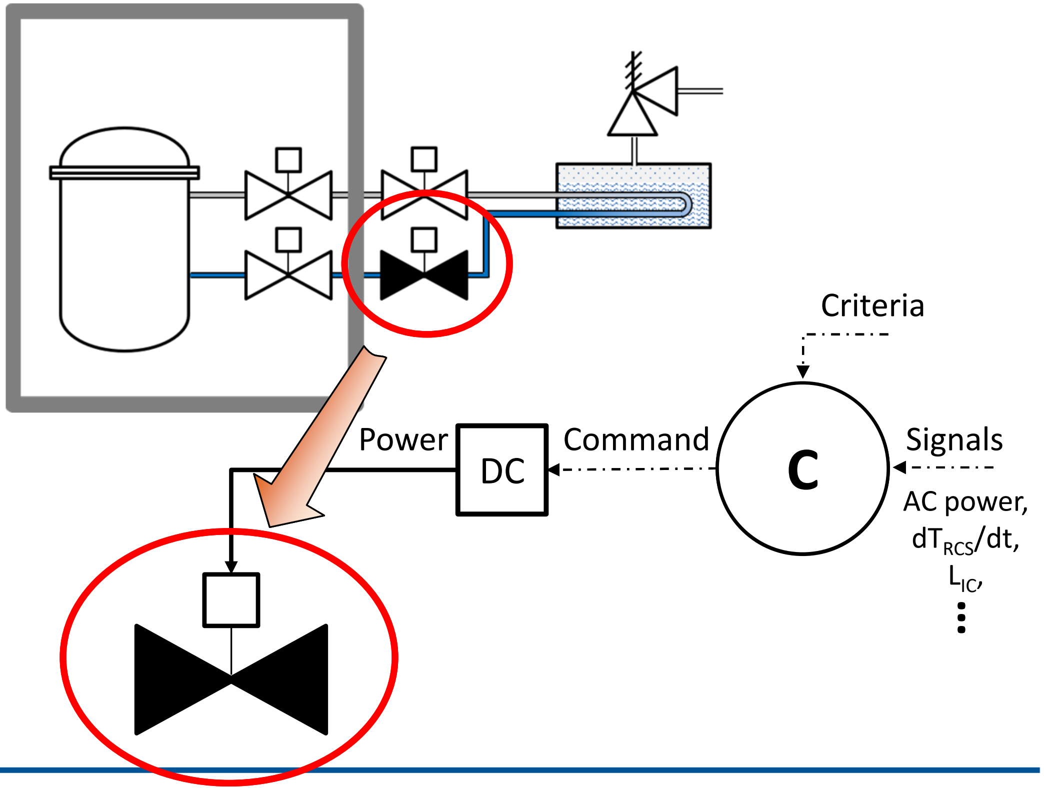
- Status
  - U.S.: reference plant state-of-practice study ongoing
  - International: some RIDM applications, e.g.,
    - Generic design assessments (UK)
    - Safety margins (Korea)
- Challenges
  - Technical
    - Current elements (dispersion, etc.)
    - Unaddressed elements (e.g., aquatic pathways, non-radiological consequences)
    - Uncertainties
  - Programmatic (scope and resources)

Level 3 PRA Project Scope



Software Reliability and Modeling (1/4): I&C Example

- Passive isolation condenser: flow (and cooling) controlled by opening/closing DC motor-operated isolation valve
- Possible control approaches
  - Analog (relays)
  - Digital
  - Manual (operators)
  - Combination
- Possible I&C failure modes include
  - Loss of signal(s)
  - Incorrect signal(s)
  - Incorrect (for situation) criteria
  - Incorrect decision (signal/criteria processing)
  - Incorrect command (decision implementation)



Software Reliability (2/4): Diversity and Commonality

- Diverse views
  - "Software doesn't fail randomly like hardware;" important software failures are due to erroneous/inadequate requirements => improper to model in classical PRA framework
  - Software is part of an overall "X-ware" system (hardware, software, "wetware") where similar arguments can be made about other system components => OK to model as a component at conventional PRA level of abstraction
- Diverse problems
  - Certification of I&C systems
  - Risk-informed plant design, operation, and oversight
- Common current view: Too many items to address deterministically => risk-informed approaches are needed

P{X|C,H}

subjective
proposition
conditions
knowledge

"[A]ll models are wrong, but some are useful."

\- G.E.P. Box

G.E.P. Box and N.R. Draper, *Empirical Model-Building and Response Surfaces*, John Wiley and Sons, 1987.

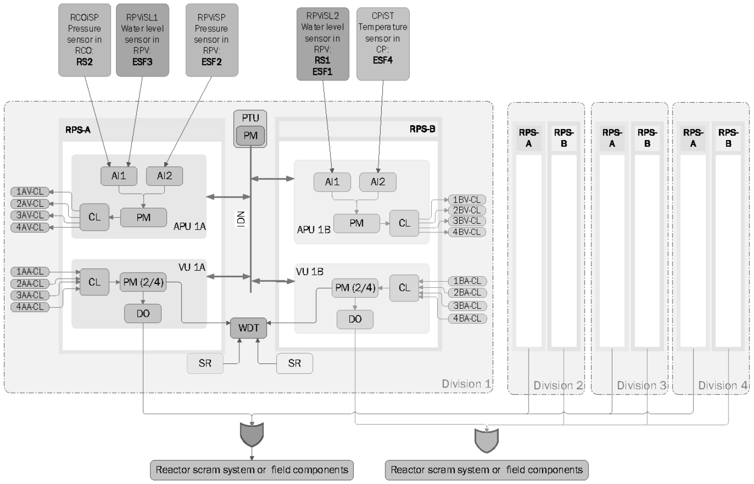
Software Reliability (3/4): Benefits of Enhancement

- Analyses
  - Licensing digital upgrades
  - Approving new designs
  - General risk-informed applications
- Technology
  - Improved hazard identification
  - Reduced completeness uncertainties
  - Improved synergy with I&C community
- Knowledge
  - Improved insights

Software Reliability (4/4): Status and Challenges

- Current status
  - Conventional fault tree analyses (AP600, Sizewell B, …)
  - U.S.: Technology development (e.g., integration of STAMP/STPA with conventional PRA)
  - International: multiple activities
    - Individual countries (e.g., Finland, France, Korea)
    - WGRISK benchmarking study (DIGMAP)
    - IAEA review
- Challenges*
  - Technical
    - Software CCF
    - Data
  - Implementation: standards and guidance
  - Cultural

WGRISK Benchmarking Study



M. Porthin, et al., "Comparative application of digital I&C modeling approaches for PSA," International Topical Meeting on Probabilistic Safety Assessment (PSA 2019), Charleston, SC, April 28-May 3, 2019.

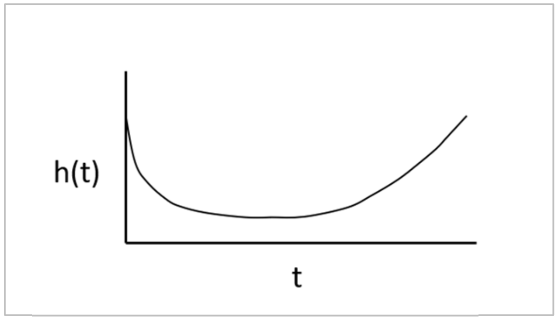
*See also S. Arndt, E. Thornsbury, and N. Siu, "What PRA needs from a digital systems analysis," 6th *International Conference on Probabilistic Safety Assessment and Management (PSAM 6)*, San Juan, Puerto Rico, June 23-28, 2002.

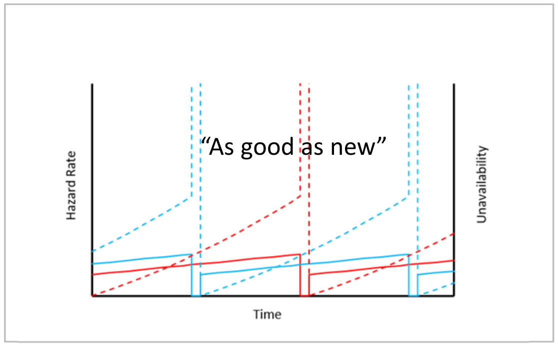
Incorporation of Ageing Effects (1/5): Background

- Conventional PRA models
  - Failures are “memoryless”
    - Fail on demand: Bernoulli process (binomial distribution)
    - Failure during operation: Poisson process (Poisson and exponential distributions)
  - Failure rates can be adjusted to reflect ageing
- More general model: time-dependent failure rates
  - Burn-in, steady-state, ageing (degradation) => “bathtub curve”

$$P\{T \leq t\} = 1 - exp\left(- \int_{0}^{T} h(t')dt' \right)$$

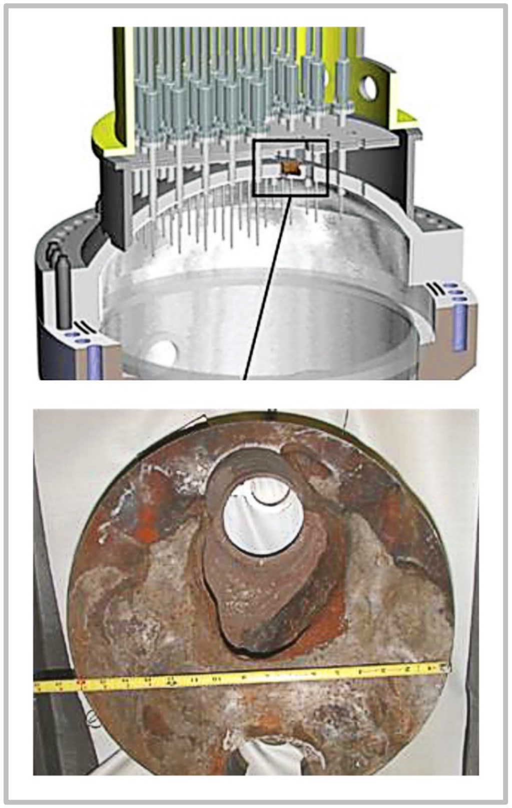
  - Different aging and repair/replacement for different SSCs => more complex model (“Renewal Theory”)





Ageing Effects (2/5): Experiences

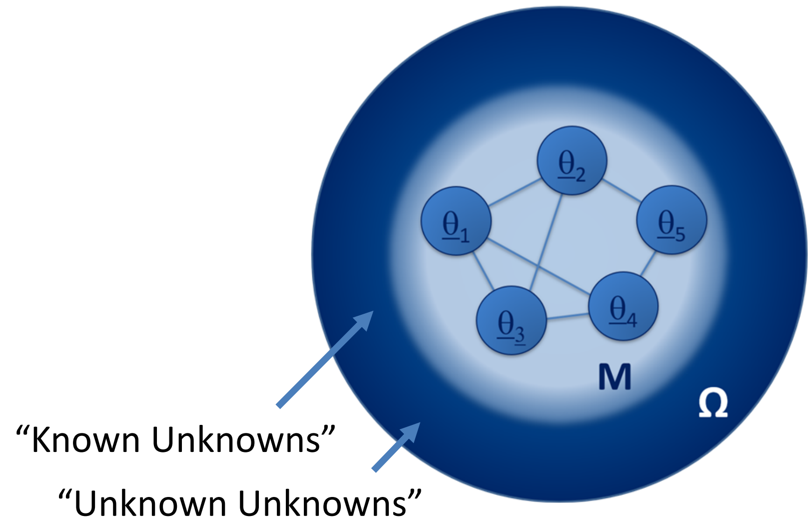
- Active components
  - Subject to testing and renewal
  - Large uncertainty bands
- Passive components
  - More difficult to inspect and renew
  - Subject to phenomena potentially amenable to mechanistic modeling and analysis
  - Famous example: Davis-Besse (2002)



Davis-Besse Reactor Pressure Vessel Head Degradation
Adapted from NUREG/BR-0353, Rev. 1

Ageing Effects (3/5): Modeling Approaches

- Statistical
  - Parametric models for failure rate (e.g., linear)
  - Quantification via operational experience data
  - Challenges
    - Data collection (current systems are insufficient)
    - Data characterization (failure? rectifiability?)
- Mechanistic
  - "First principles" causal models for SSCs
  - Challenges
    - Completeness (e.g., unexpected mechanisms, combinations and synergies; detection and response)
    - Treatment of uncertainties
    - Compatibility with conventional PRA framework



M ("Model of the World"): Scope, structure
θ_i: Parameters
Ω: Universe

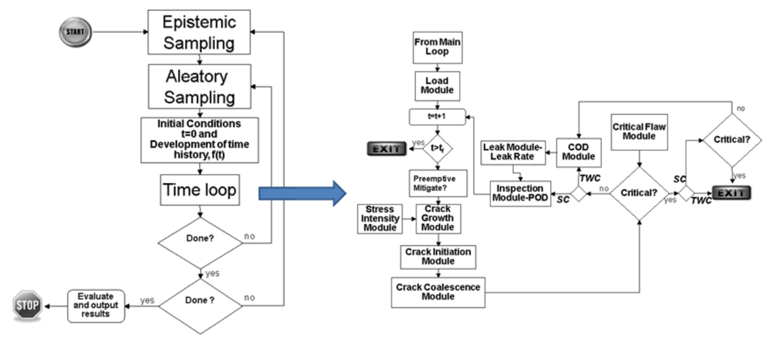
Ageing Effects (4/5): Benefits of Enhancement

- Analyses
  - Risk-informed treatment of other degradation mechanisms (potential)
- Technology
  - Capabilities should regulatory need arise (e.g., "subsequent license renewal")
  - Improved perspectives and approaches to mechanistic modeling (including the treatment of uncertainties)
  - Improved synergy with non-PRA technical communities
- Knowledge
  - Improved insights supporting awareness and prioritization of mechanisms/scenarios/mitigation measures (as compared with other risk contributors)
  - Improved understanding of modeled mechanisms

Ageing Effects (5/5): Status and Challenges

- Current status (U.S.)
  - U.S.: long history of R&D, PTS application*
  - International: research with demonstration applications (European Union Aging PSA Network)
- Challenges
  - Data
  - Physics of failure modeling
  - Recognition and treatment of other trends, e.g.,
    - Technology (NDE, prognostics, …)
    - Workforce
    - Fleet (“unique reactors”)
  - Implementation
    - Separating advocacy “wants” from RIDM “needs”
    - Incorporation in RIDM standards and guidance)

Blending mechanistic and statistical perspectives changes PRA approach?



D. Rudland and C. Harrington, “xLPR Pilot Study Report,” *NUREG-2110*, 2012. ([ML12145A470](#))

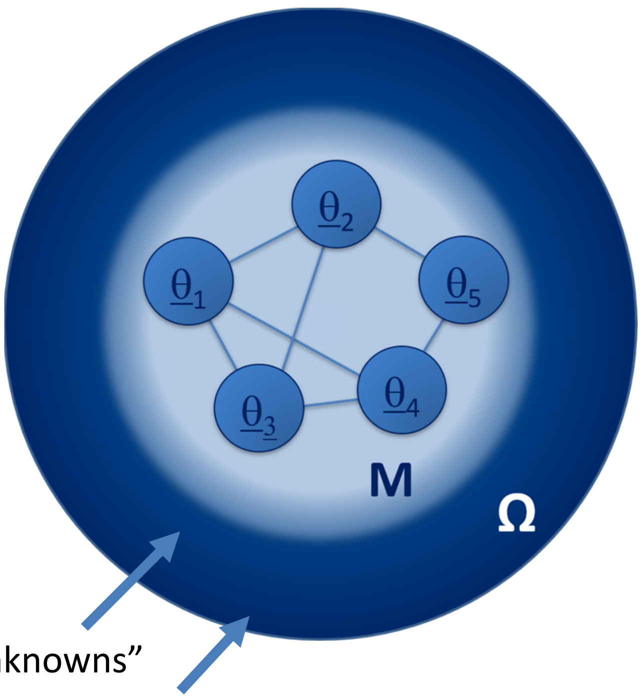
M. EricksonKirk, et al., “Technical Basis for Revision Of the Pressurized Thermal Shock (PTS) Screening Limit in the PTS Rule (10 CFR 50.61): Summary Report,” [NUREG-1806](#), 2006.

Topics

Perspectives on the analysis and communication of uncertainties for RIDM

TREATMENT OF PARAMETER, MODEL, AND COMPLETENESS UNCERTAINTY

Parameter, Model, and Completeness Uncertainty



"Known Unknowns"

"Unknown Unknowns"

M ("Model of the World"): Scope, structure

θ_i: Parameters

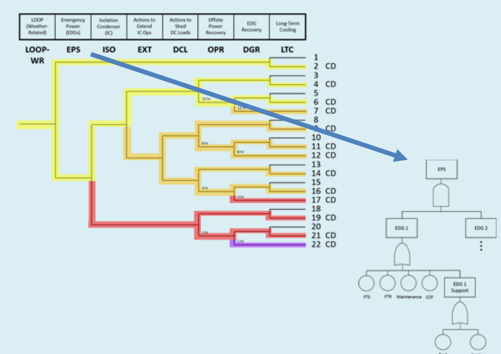
Ω: Universe

mod•el, *n.* a representation of reality created with a specific objective in mind.

A. Mosleh, N. Siu, C. Smidts, and C. Lui, *Model Uncertainty: Its Characterization and Quantification*, Center for Reliability Engineering, University of Maryland, College Park, MD, 1995. (Also NUREG/CP-0138, 1994)

PRA models for NPPs

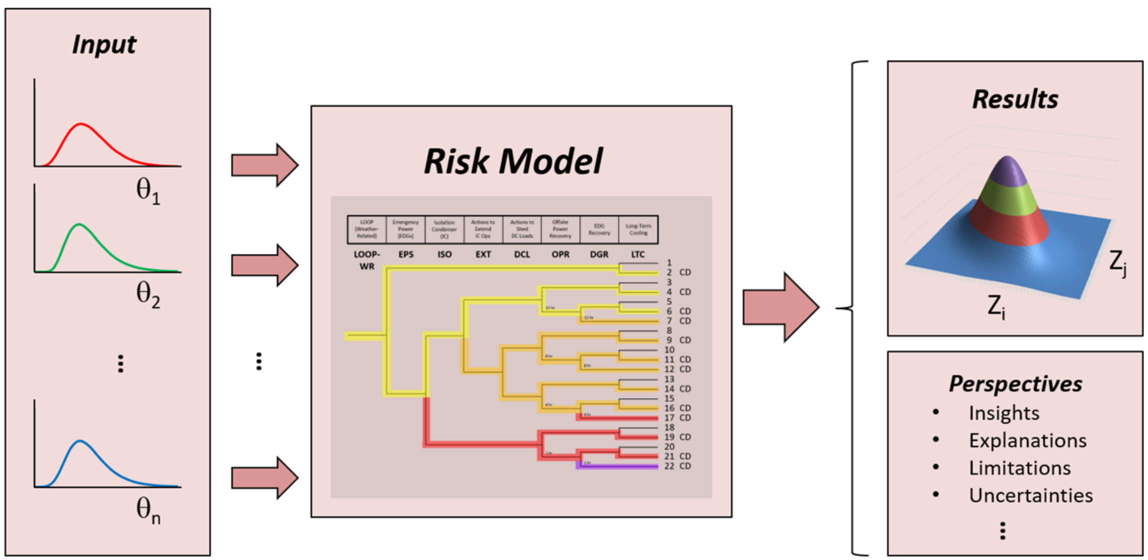
- Distinctions are not necessarily crisp
- Regardless of allocation to categories, need to consider in characterization of uncertainties



See:
- M. Drouin, et al., "Guidance on the Treatment of Uncertainties Associated with PRAs in Risk-Informed Decisionmaking," *[NUREG-1855, Rev. 1](#)*, 2017.
- U.S. Nuclear Regulatory Commission, "An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis," *[Regulatory Guide 1.174, Revision 3](#)*, January 2018.

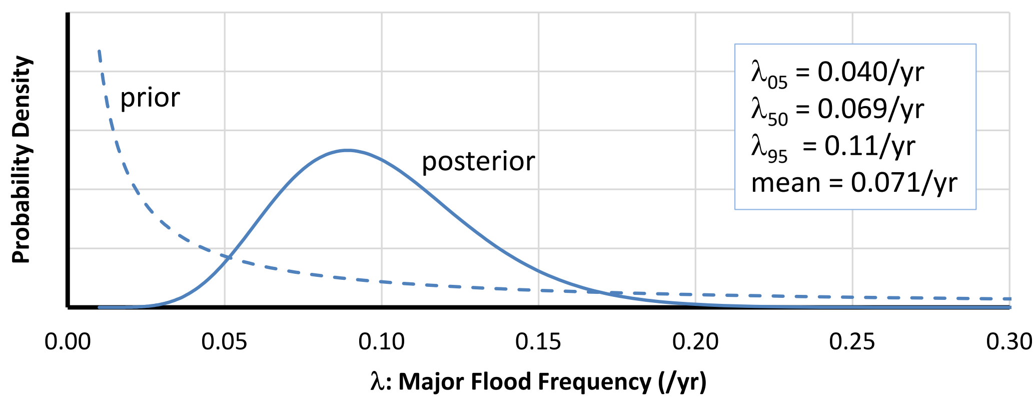
Parameter Uncertainty (1/3): Current Practice

Routinely estimated (Bayesian inference) and propagated (e.g., direct Monte Carlo, Latin Hypercube)



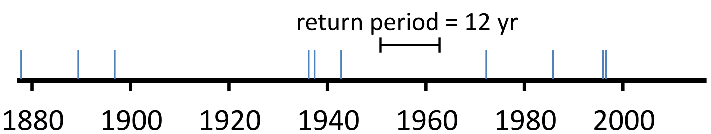
Parameter Uncertainty (2/3): Bayesian Example

- Parameter of interest: frequency of "major" flooding (λ)
- Prior state-of-knowledge: minimal
- Evidence: 10 events over 1877-2017 (140 years)
- Bayes' Theorem: $$\pi_1(\lambda|r,T) = \frac{L(r,T|\lambda)\pi_0(\lambda)}{\int_0^\infty \underbrace{L(r,T|\lambda)}_{\text{Poisson}}\underbrace{\pi_0(\lambda)}_{\text{Non-informative}}d\lambda}$$
- Posterior state-of-knowledge:



Potomac River (Harper's Ferry, VA)*

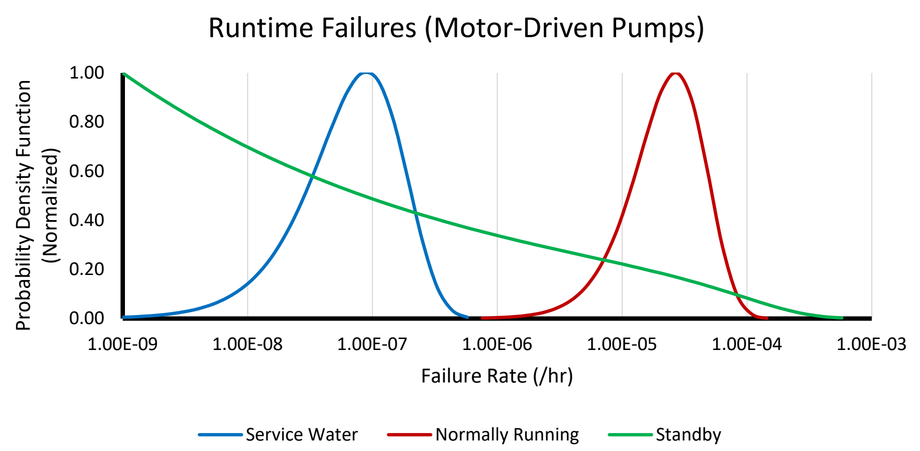
Date	Flood Height (ft)
3/19/1936	36.5
6/1/1889	34.8
10/16/1942	33.8
10/1/1896	33.0
11/6/1985	30.1
9/8/1996	29.8
1/21/1996	29.4
11/25/1877	29.2
4/27/1937	29.0
6/23/1972	27.7



*Notes:
1) Data from: https://water.weather.gov/ahps2/crests.php?wfo=lwx&gage=hfew2&crest_type=historic
2) "Major Flood:" height > 24 ft

Parameter Uncertainty (3/3): Challenges

- **Data pre-processing**
  - **Selection**
  - **Interpretation**
- Effect of analysis shortcuts
  - Standard (e.g., "non-informative") prior distributions
  - Simplified expert elicitation
  - Independence assumption
- Ensuring correspondence with state-of-knowledge
  - Basic events (micro view)
  - Overall results (macro view)



- 2015 Industry-wide estimates from: https://nrcoe.inl.gov/resultsdb/AvgPerf/
- Service Water Pumps: 2 failures in 16,292,670 hours
- Normally Running Pumps: 225 failures in 59,582,350 hours
- Standby Pumps (1st hour operation): 48 failures in 437,647 hours

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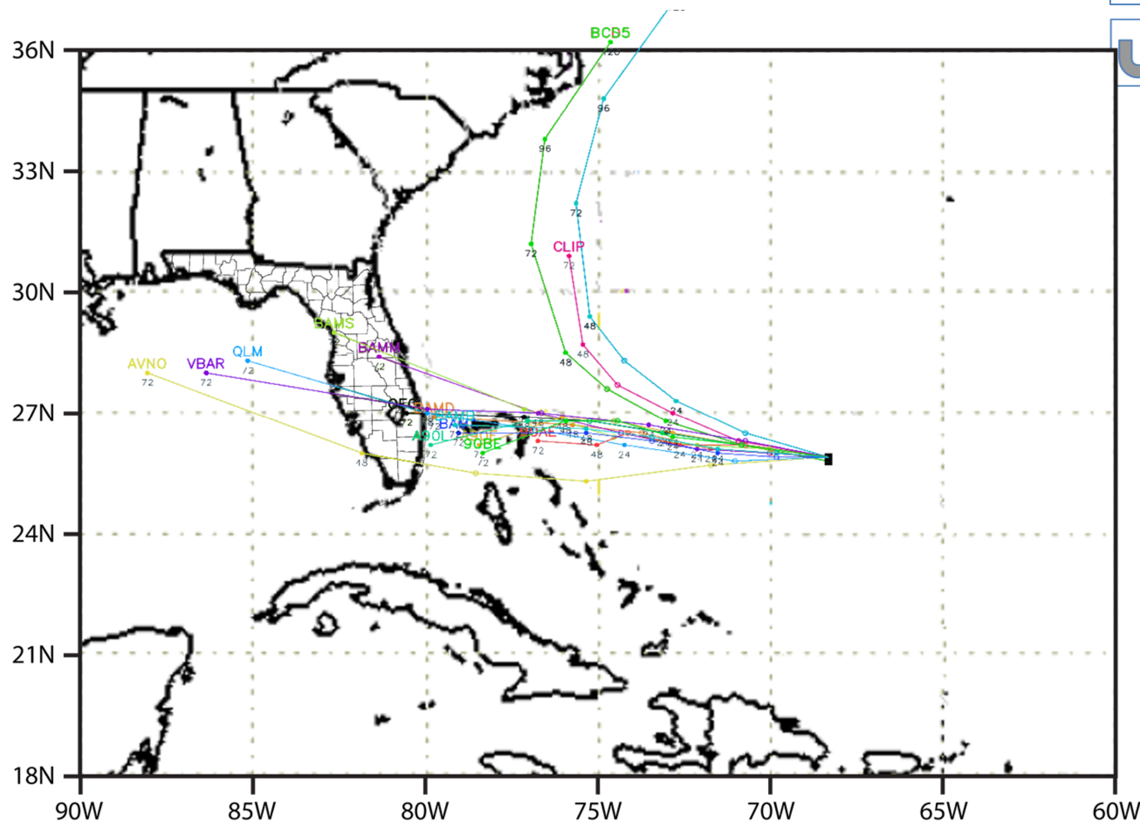
Model Uncertainty (1/6): Hurricane Example

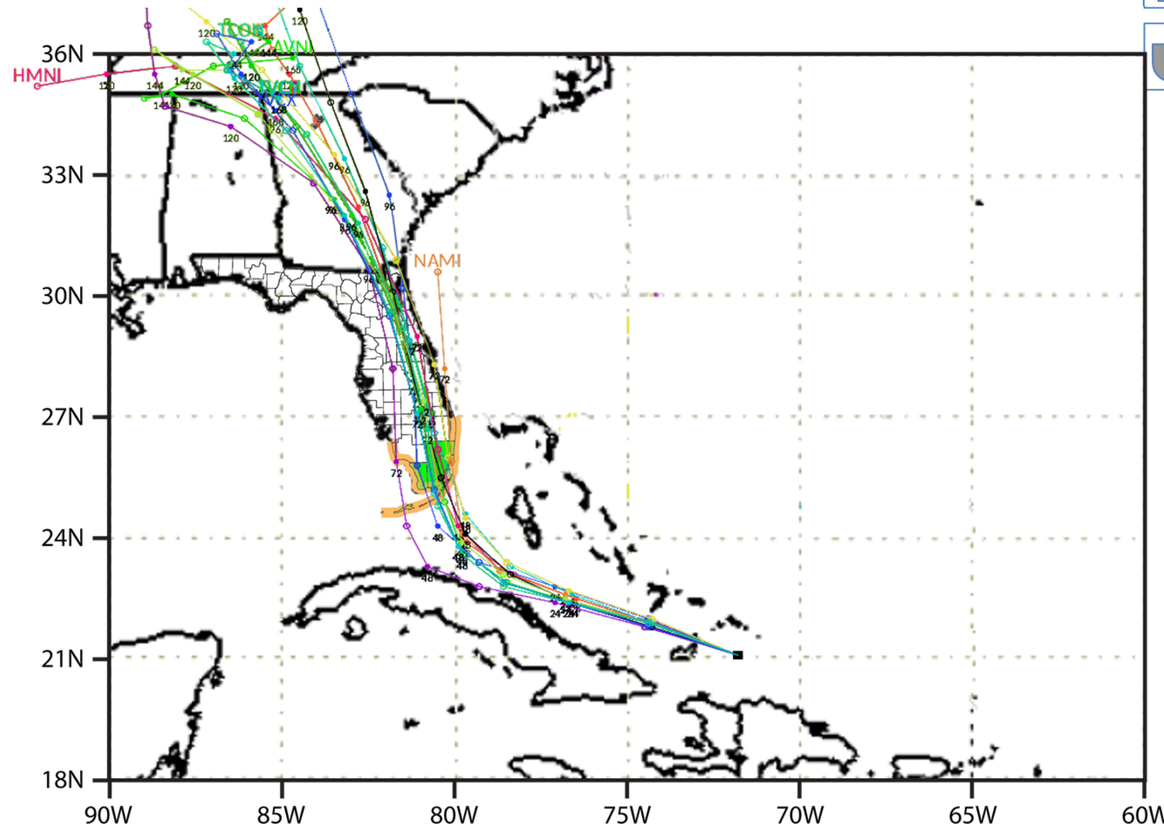
Hurricane Andrew: 8/22/1992, 1200 UTC (about 2 days before FL landfall)



Hurricane tracks adapted from University of Wisconsin-Milwaukee: (https://web.uwm.edu/hurricane-models/models/archive/)
Emergency response based on data from National Hurricane Center: (https://www.nhc.noaa.gov/1992andrew.html)

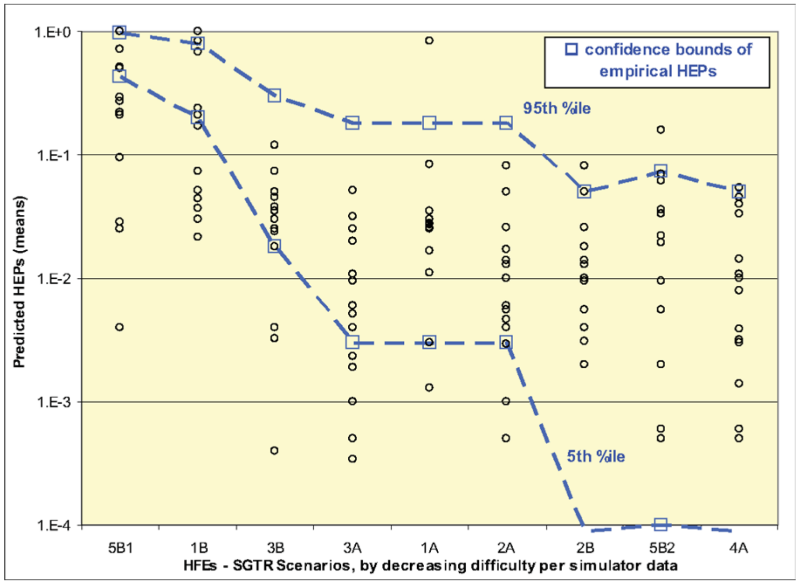
Model Uncertainty (2/6): Hurricane Example

Hurricane Irma: 9/8/2017, 0000 UTC
(about 2 days before FL landfall)

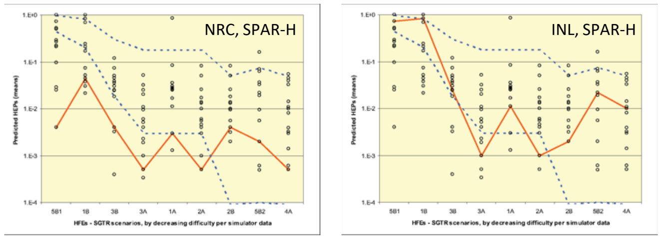


Hurricane tracks adapted from University of Wisconsin-Milwaukee: (https://web.uwm.edu/hurricane-models/models/archive/)
Emergency response based on data from National Hurricane Center: (https://www.nhc.noaa.gov/1992andrew.html)

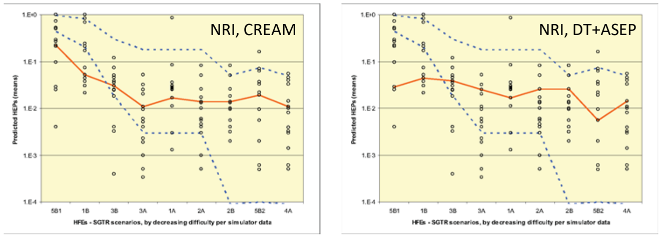
Model Uncertainty (3/6): HRA Example



All teams, all methods



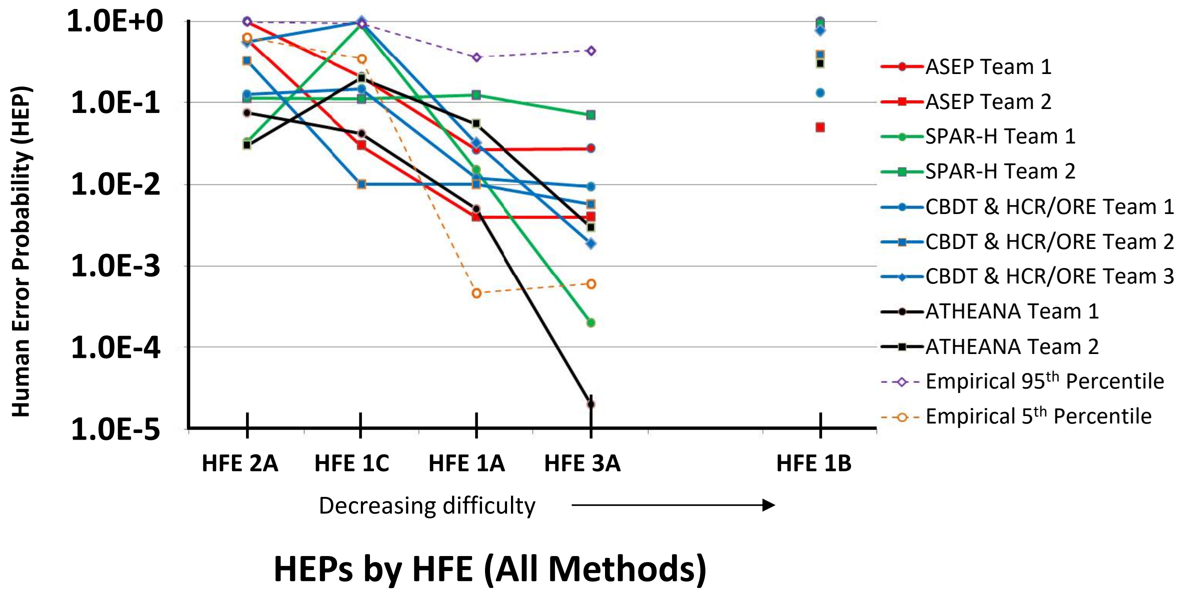
Same method, different teams



Same team, different methods

A Bye, et al., "International HRA Empirical Study," [NUREG/IA-0216](#), August 2011.

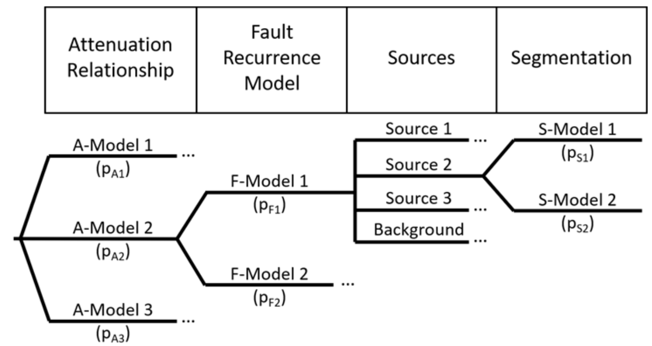
Model Uncertainty (4/6): HRA Example



Adapted from NUREG-2156

Model Uncertainty (5/6): Current Approaches

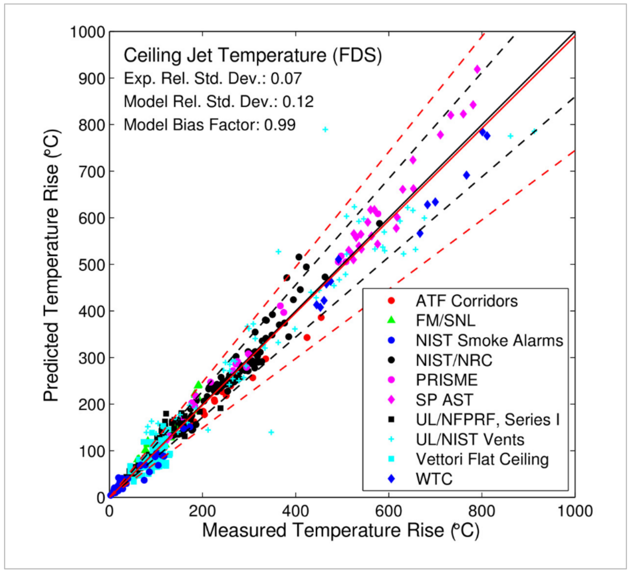
- Important to acknowledge and treat (in context of decision)
- Standards and guidance: "characterize"
- Alternatives
  - Consensus model
  - Sensitivity analysis
  - Weighted alternatives (e.g., SSHAC)
  - Output uncertainties



Adapted from V.M. Andersen, "Seismic Probabilistic Risk Assessment Implementation Guide," *EPRI 3002000709*, Electric Power Research Institute, Palo Alto, CA, December 2013

Model Uncertainty (6/6): Challenges

- Different technical points of view on treatment:
  - Competition between models vs. multiple (correlated) sources of evidence
  - Quantify vs. "characterize"
  - Include or exclude user effects
- Methods to quantify "model output uncertainty" exist;* challenges include
  - Uncertainties in unmeasured parameters
  - Sub-model limits of applicability
  - Representativeness of computed results



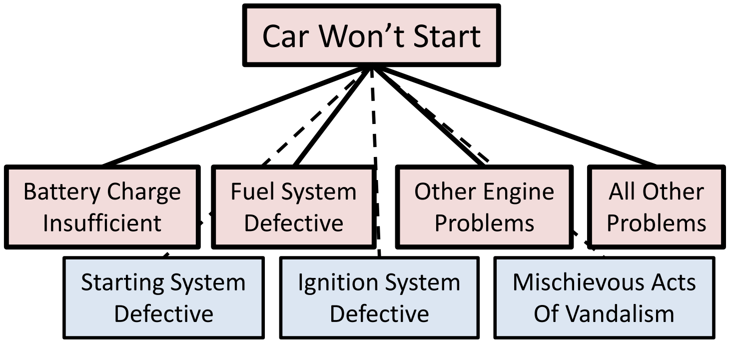
M.H. Salley and A. Lindeman, "Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications," NUREG-1824 Supplement 1/EPRI 3002002182, November 2016.

* See, for example, E. Droguett and Ali Mosleh, "Bayesian methodology for model uncertainty using model performance data," *Risk Analysis*, **28**, No. 5, 1457-1476, 2008.

Completeness Uncertainty (1/8)

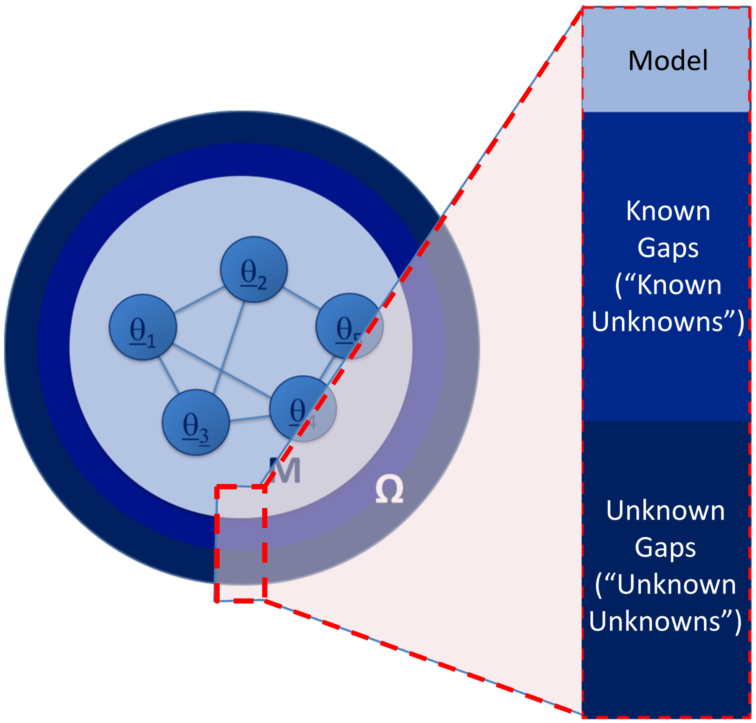
- Sources
  - Known gaps ("missing scope")
  - Unknown gaps
- Concerns
  - Excessive amplification ("Fear of the dark")
  - Excessive discounting (availability heuristic: "Out of sight, out of mind")

"It would cease to be a danger if we could define it."
- *Sherlock Holmes*
(The Adventure of the Copper Beeches)



Adapted from B. Fischhoff, P. Slovic, S. Lichtenstein, "Fault trees: Sensitivity of estimated failure probabilities to problem representation," *Journal of Experimental Psychology: Human Perception and Performance*, **4**(2), May 1978, 330-344.

Completeness Uncertainty (2/8): Terminology



- Explicit or implicit?
- Extent of coverage?

- "Known" by whom?
- "Known" when?
- Time from idea to theory to PRA implementation?

Viewpoint

Precise classification is important only if it affects:

- Understanding
- Communication
- Decision making

Completeness Uncertainty (3/8): Known Gaps*

- Broad scenario categories

Rationale	Common Example(s)
Out of scope	security/sabotage, operation outside approved limits
Low significance (pre-analysis judgment)	external floods (many plants pre-Fukushima)
Appropriate PRA technology* unavailable	management and organizational factors
PRA "not appropriate"	software, security

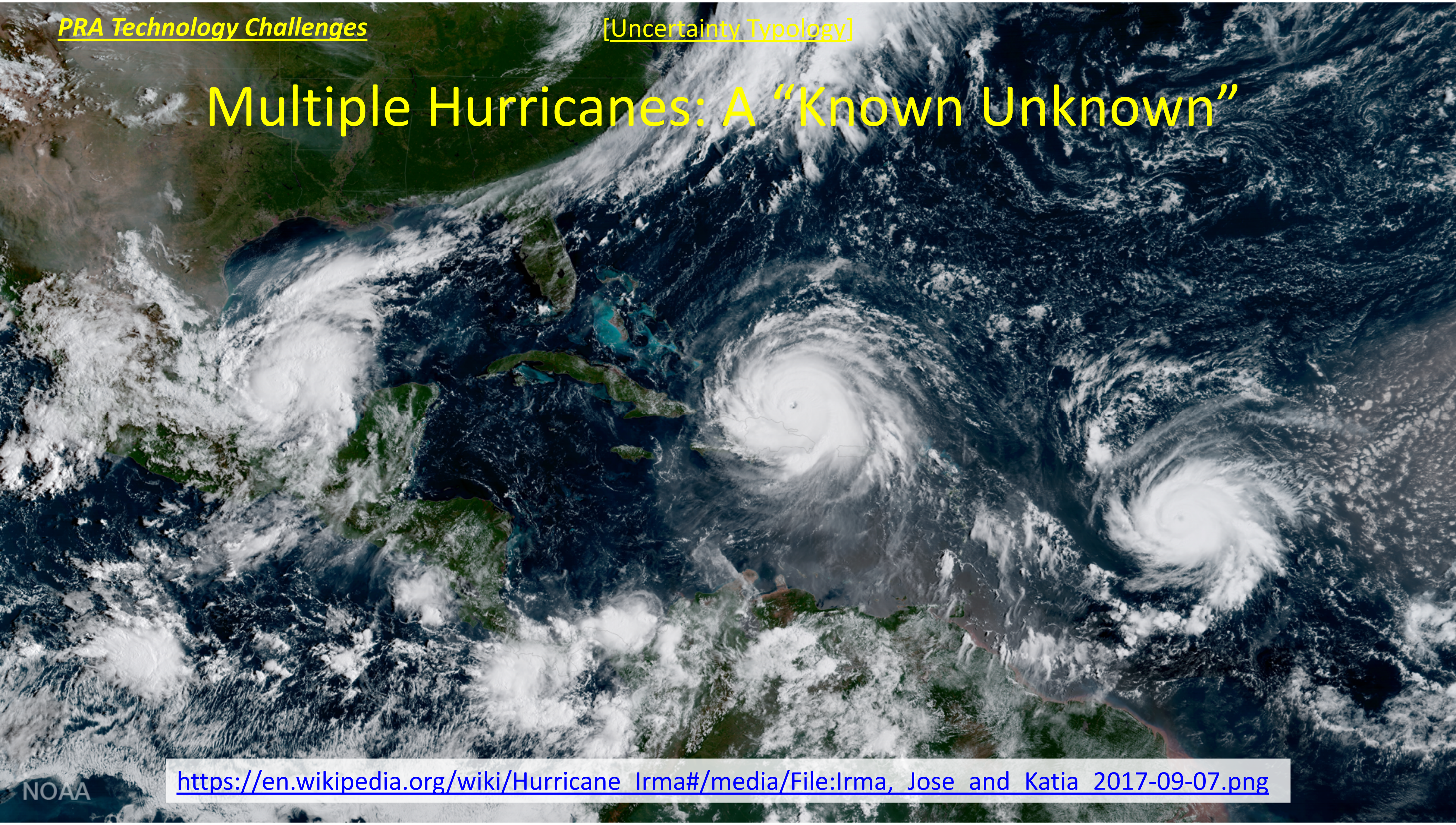
- Contributors within categories

Category	Example(s)
External hazards	multiple coincident or sequential hazards
Human reliability	errors of commission, non-proceduralized recovery
Passive systems	thermal-hydraulic reliability

* aka "Known Unknowns"

PRA Technology Challenges [Uncertainty Typology]

Multiple Hurricanes: A “Known Unknown”

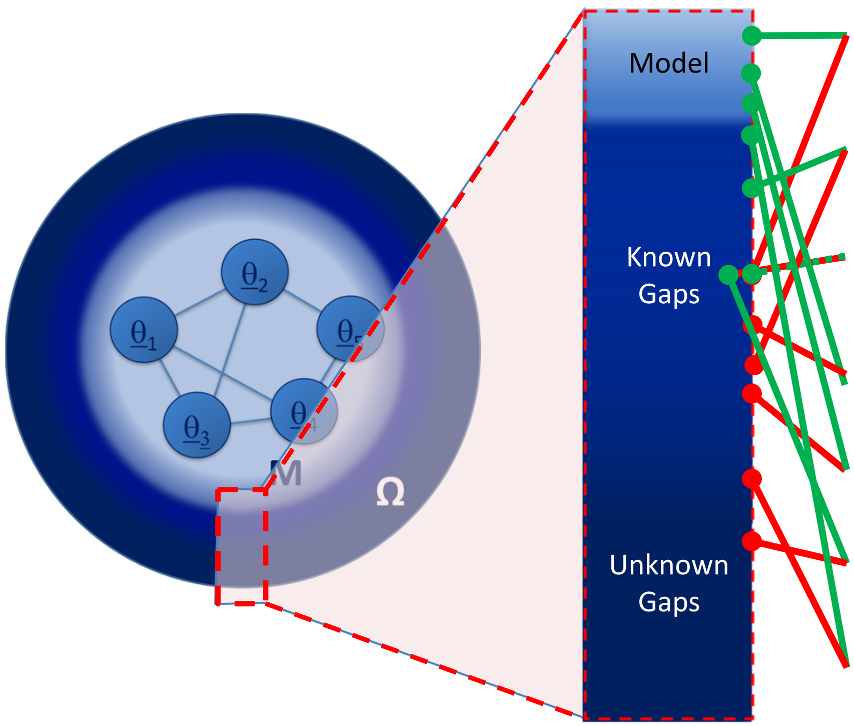


https://en.wikipedia.org/wiki/Hurricane_Irma#/media/File:Irma,_Jose_and_Katia_2017-09-07.png

Completeness Uncertainty (5/8): Unknown Gaps*

Then (a surprise?)

Now (treated in current PRAs?)



Browns Ferry fire (1975) – a long-recognized hazard; not in draft WASH-1400 but routinely treated now

TMI (1979) – precursors include Davis-Besse (1977); operator EOCs not in models; current recognition and some explorations

Chernobyl (1986) – precursor at Leningrad (1975); non-routine test during shutdown in any LPSD analyses?

Blayais flood (1999) – external floods often screened at time; current recognition, multi-hazard under development

Maanshan HEAF/SBO (2001) – HEAF phenomenon known, in any PRAs at time? Now included as an initiator; smoke effect?

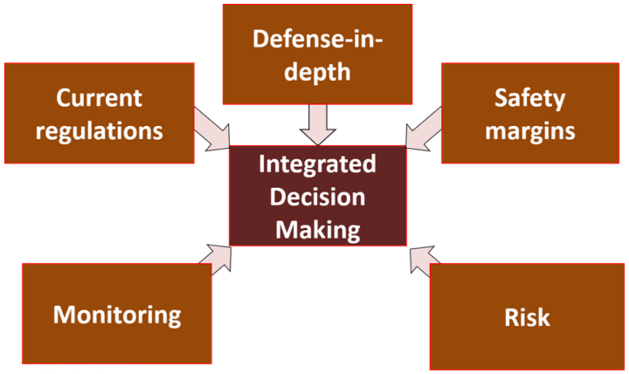
Davis-Besse RPV corrosion (2002) – RPV failure analyses focused on crack propagation; M&O failure not in PRAs

Fukushima Daiichi (2011) – precursors: Blayais (1999), Indian Ocean (2004), hazard under review at time; PRA models under development

* aka “Unknown Unknowns”

Completeness Uncertainty (6/8): Current Approaches

- "Mind the gap…"
  - Analysis guidance (NUREG-1855)
    - Progressive analysis (screening, bounding, conservative, detailed…)
    - Change scope of risk-informed application
  - ***Risk-informed decisionmaking (RG 1.174)***
- Fill (or at least reduce) the gap (R&D)



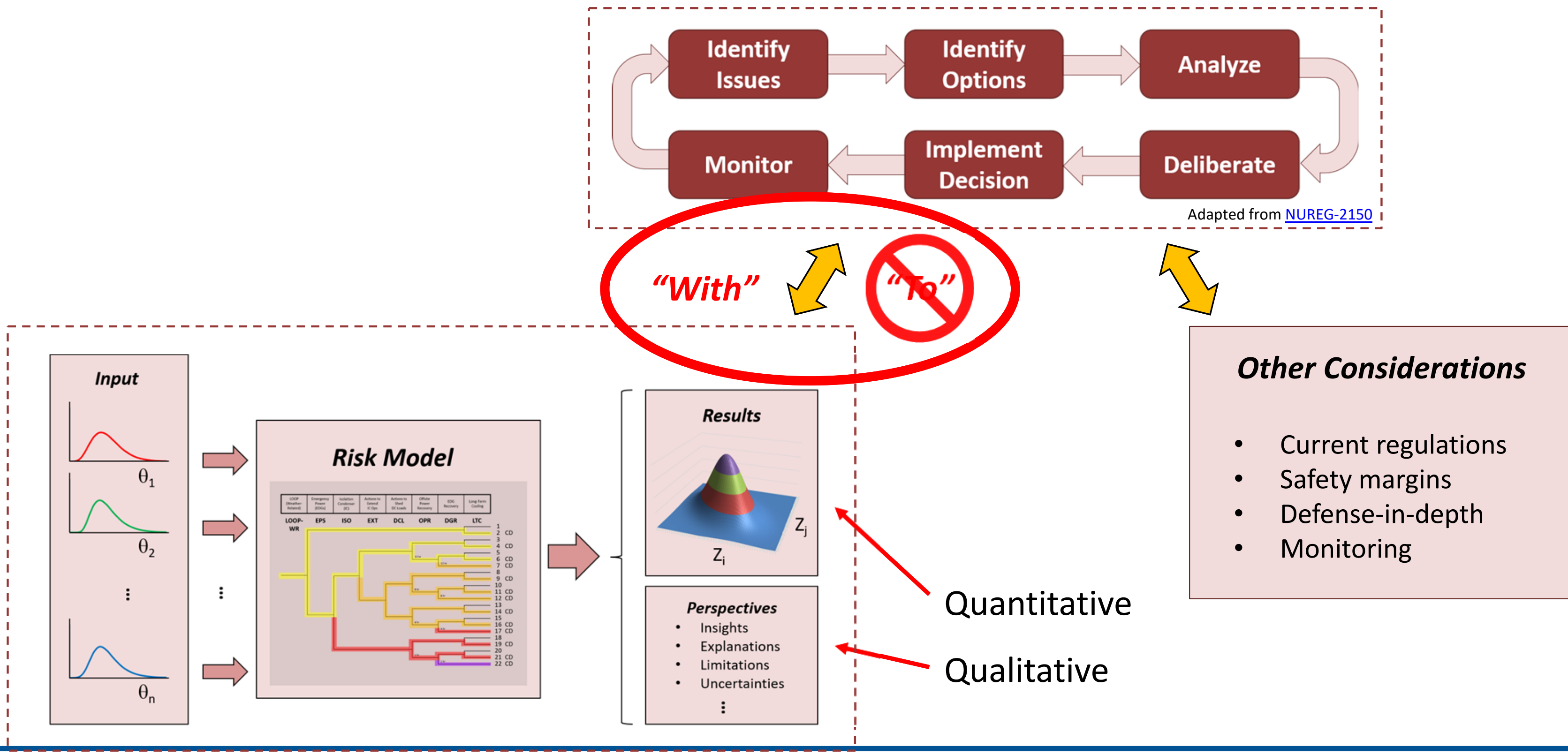
Completeness Uncertainty (7/8): Role of R&D

- Continue to develop technology to address known gaps
  - Risk-informed prioritization
  - Fully engage appropriate disciplines
  - Take advantage of general computational and methodological developments
- Facilitate re-emphasis on ***searching***
  - Demonstrate efficiency and effectiveness with current tools (e.g., MLD, HBFT) vs. checklist/screening
  - Develop improved tools (including OpE mining)

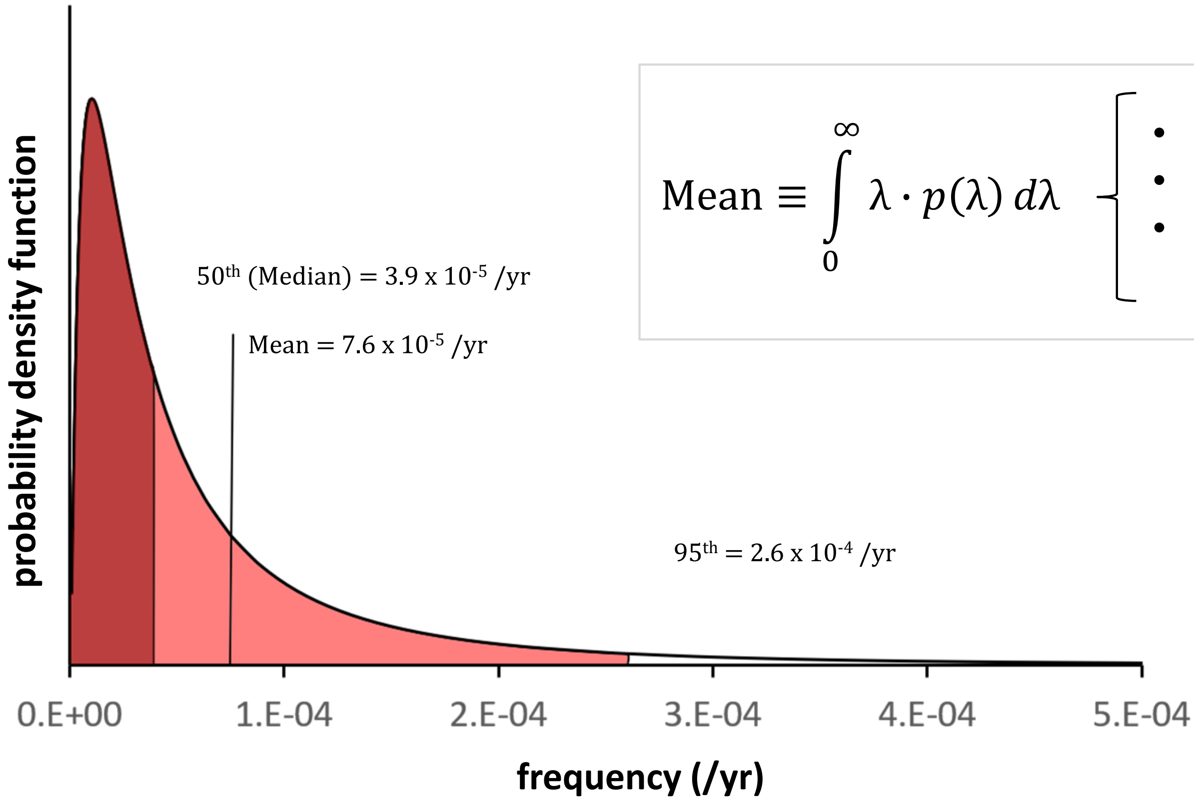
“Event” (NUREG/CR-4839), 1992
Aircraft impact
Avalanche
Coastal erosion
Drought
External flooding
Extreme winds and tornadoes
Fire
Fog
Forest fire
Frost Hail
High tide, high lake level, or high river stage
…

Completeness Uncertainty (8/8): From Lampposts to Search Beacons

Internal Risk Communication (1/9): Context



Internal Risk Communication (2/9): Reminder

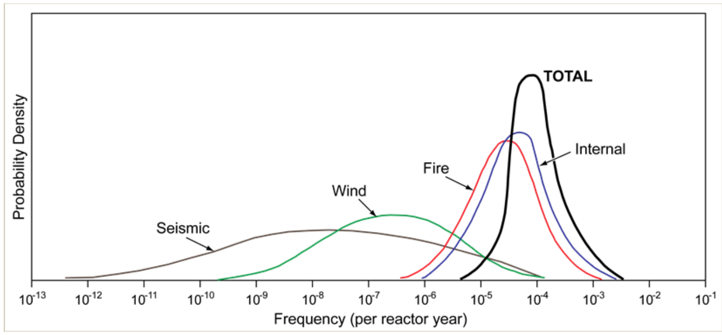


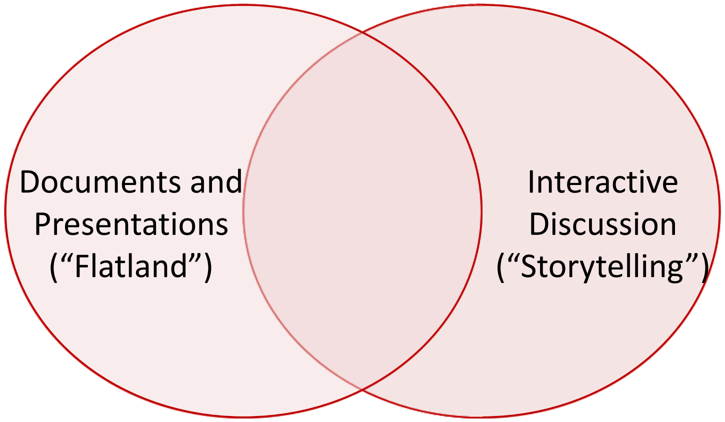
$$\text{Mean} \equiv \int_0^\infty \lambda \cdot p(\lambda)\, d\lambda$$

- Mathematically defined
- Affected by tail
- Does not correspond to a specific percentile

Internal Risk Communication (3/9): Current Practice

- Often implicit (focus on mean values)
- Various graphic displays
- Includes "story" as well as numbers



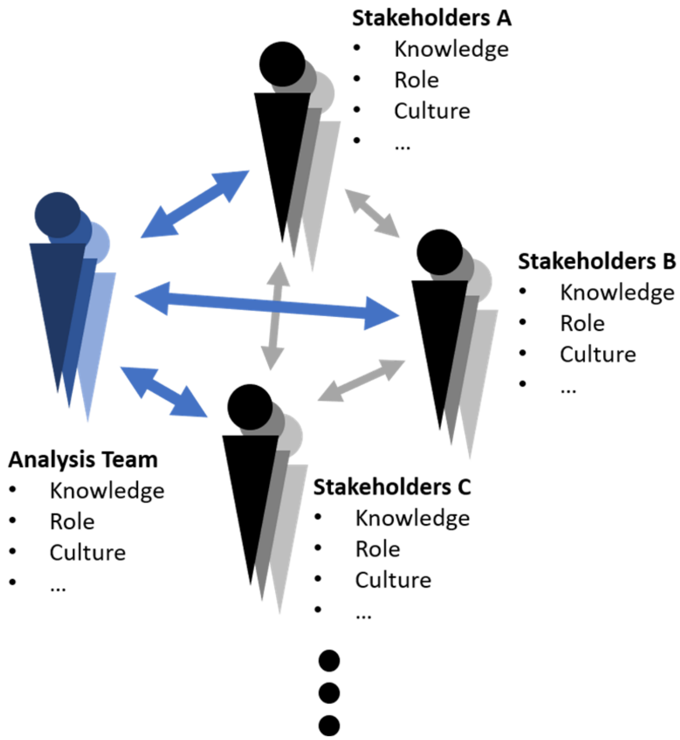


Likelihood Class

Severity Class	5 (10^{-5}/yr)	4 (10^{-4}/yr)	3 (10^{-3}/yr)	2 (10^{-2}/yr)	1 (10^{-1}/yr)
A	Marginal	Undesirable	Undesirable	Critical	Critical
B	Marginal	Marginal	Undesirable	Undesirable	Critical
C	No Action	Marginal	Marginal	Undesirable	Undesirable
D	No Action	No Action	Marginal	Marginal	Undesirable
E	No Action	No Action	No Action	Marginal	Marginal

Internal Risk Communication (4/9): Breakdowns*

- Differences in perception of information
  - Relevance
  - Consistency with prior beliefs
- Lack of understanding of underlying science
- Conflicting agendas
- Failure to listen
- Trust



*Sources of breakdowns with public, also at least partially relevant for internal risk communication. J.L. Marble, N. Siu, and K. Coyne, "Risk communication within a risk-informed regulatory decision-making environment," *International Conference on Probabilistic Safety and Assessment (PSAM 11/ESREL 2012)*, Helsinki, Finland, June 25-29, 2012. (ADAMS ML120480139)

Internal Risk Communication (5/9): Information Complexity

- Hyperdimensional
  - Scenarios
  - Likelihood
  - Multiple consequence measures
- Heterogeneous
  - Qualitative and quantitative
  - Multiple technical disciplines
- Dynamic
  - System changes (e.g., different operational modes, effects of decisions)
  - Changing information (learning, adding/discounting data)
  - New applications (and contexts)
- Uncertain
  - Sparse or non-existent data
  - Outside range of personal experience

Internal Risk Communication (6/9): More Complexities

- Individual user differences, e.g.,
  - Knowledge
  - Preferences/heuristics
- Social factors, e.g.,
  - Trust
  - Decision and group dynamics
- Situational context, e.g.,
  - Available time
  - Decision support vs. informational

> "Will somebody find me a one-handed scientist?!"
>
> *- Senator Edmund Muskie*
> *(Concorde hearings, 1976)*

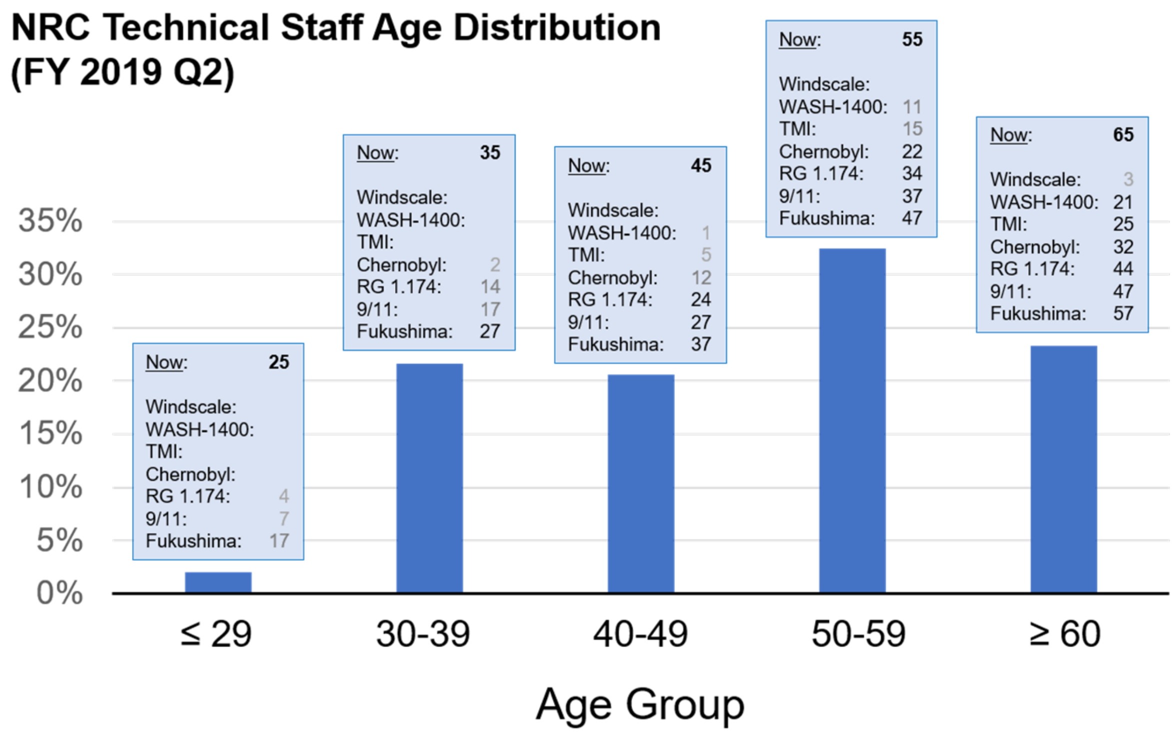
I. Flatow, "Truth, Deception, and the Myth of the One-Handed Scientist," October 18, 2012. Available from: https://thehumanist.com/magazine/november-december-2012/features/truth-deception-and-the-myth-of-the-one-handed-scientist

Internal Risk Communication (7/9): Stakeholder Trends

- Experiences, knowledge
- Information content and delivery preferences
- Comfort with analytics, risk, probability
- Mobility

"Language is not merely a tool for human communication; language is itself a means by which the realities of the world are divided and viewed."

- P.S. Dull, 1978



Source: https://www.nrc.gov/reading-rm/doc-collections/commission/slides/2019/20190618/staff-20190618.pdf

P.S. Dull, *A Battle History of the Imperial Japanese Navy (1941-1945)*, Naval Institute Press, Annapolis, MD, 1978

Internal Risk Communication (8/9): Solution Trends

- Tufte model: escape “Flatland” using rich displays and reports, encourage user to explore
  - Promotes active involvement of decision maker
  - Increases general trust?
- A graduated technical approach to assist?

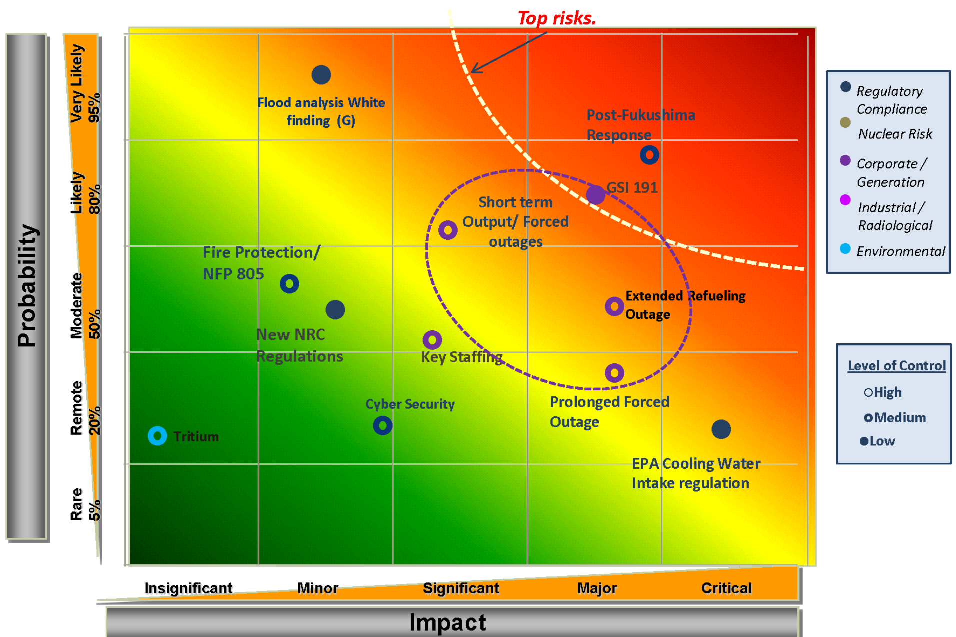
Time

Interface	Interaction Mode
- Hyperlinked dashboards, reports	- Manual
- Video	- AI assist
- Visual immersion	
- Multisensory immersion	

Continuing Challenges

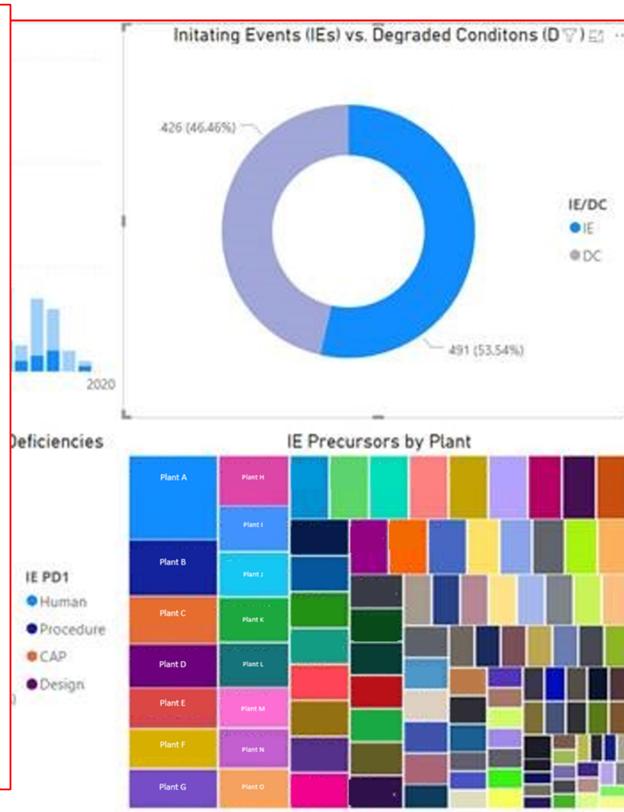
- Target audience(s)
  - Heterogeneous
  - Changing
  - Constrained resources
- Schema
  - No standards: currently an art
  - “Solutions” being developed intuitively; no scientific testing

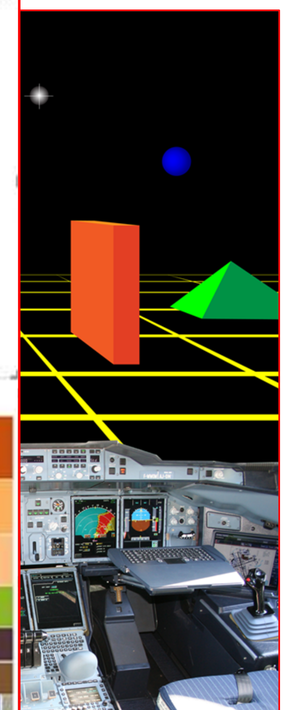
Internal Risk Communication (9/9): The Future?



Significant risks from site maps grouped / assigned based on significance to fleet

M. Korsnick, "Risk Informing the Commercial Nuclear Enterprise," *Promise of a Discipline: Reliability and Risk in Theory and in Practice*, University of Maryland, April 2, 2014.





33823904@N00/64156219/
(permission CC-BY-2.0)

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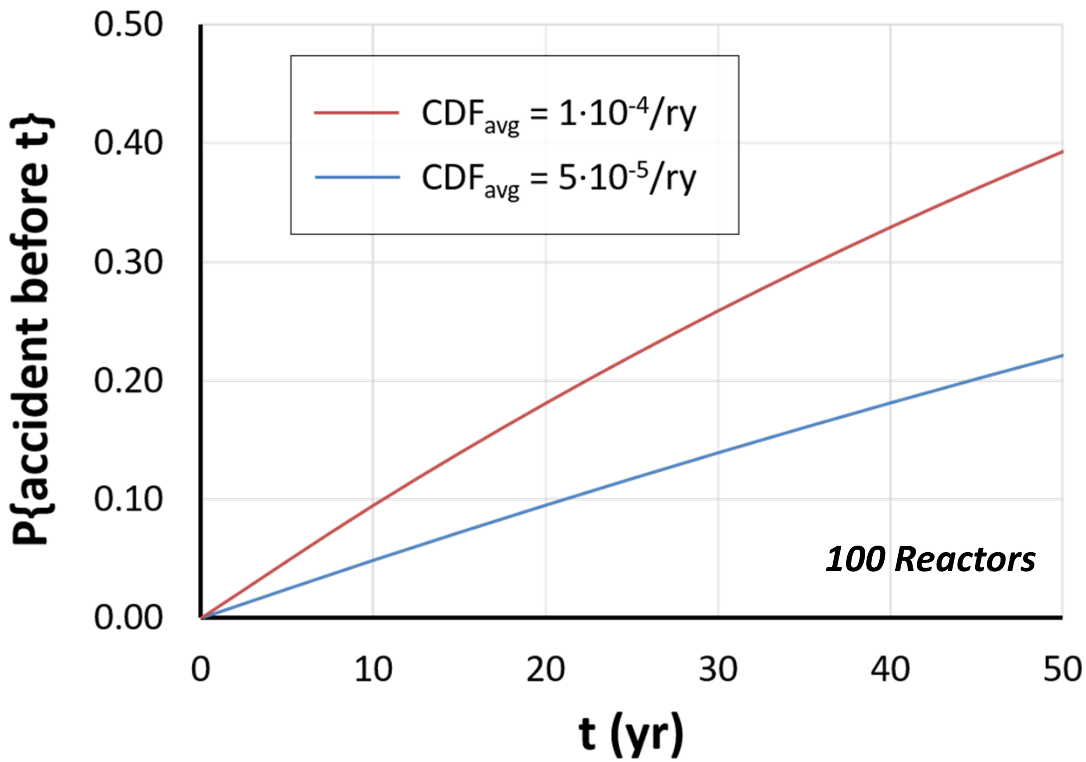
And what if the bird won't sing?

Nobunaga: Make it sing.
Hideyoshi: Make it want to sing.
Tokugawa: Wait.

- Eiji Yoshikawa (Taikō)

CLOSING THOUGHTS

Is Winter Coming?



"Anyone submitting a PRA for use in the LWR regulatory process should feel that his long-term technical reputation is on the line."

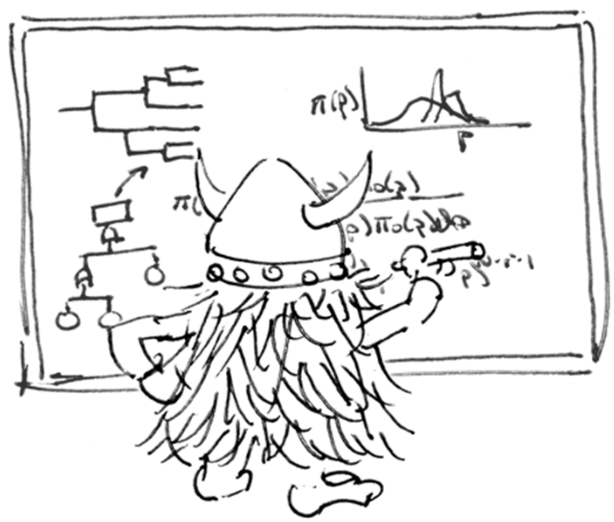
- D. Okrent (1981)

Increasing realism ≢ Reducing conservatism

Challenge to NRC/RES and Opportunities

To increase effectiveness and efficiency

- [Enterprise] risk-informed prioritization
- Consider new technical approaches
- Better target available resources (e.g., university grant funds)
- Leverage other programs
  - Observe (learn, provide feedback)
  - Cooperate
  - Collaborate
- Good ideas are welcome!



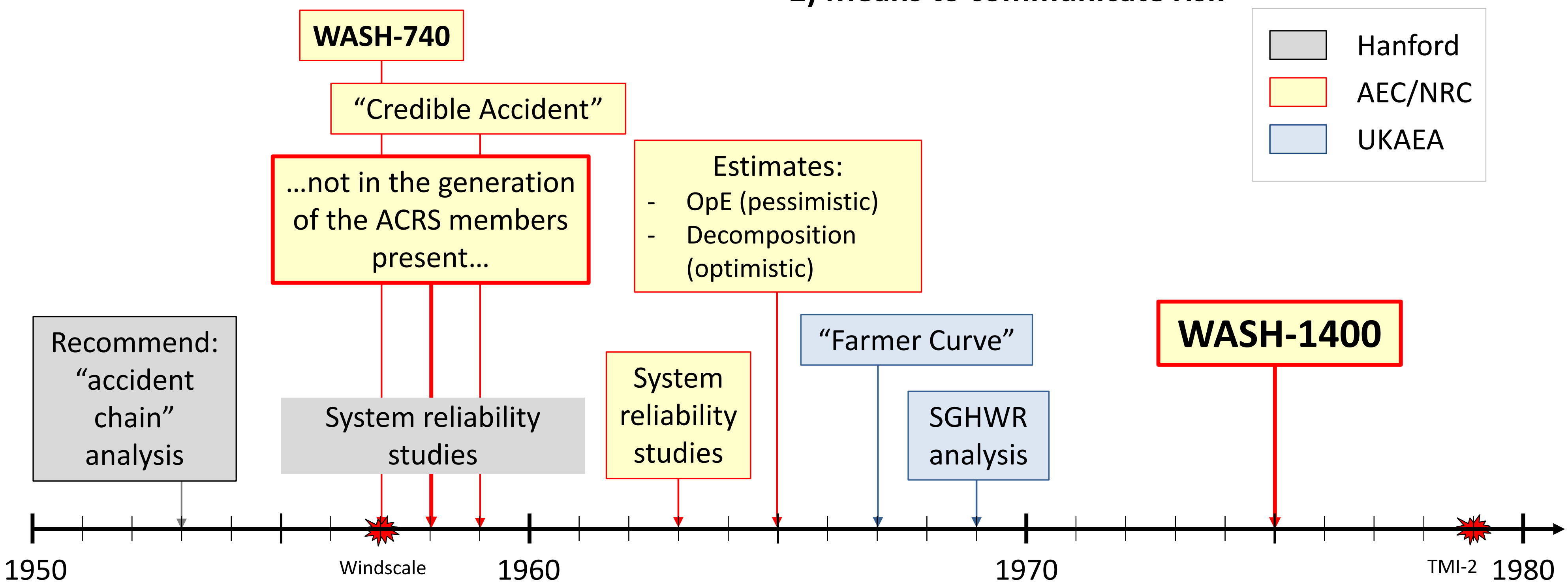
ADDITIONAL SLIDES

Additional Slides

PRA HISTORY: TREATMENT OF UNCERTAINTIES

From Hanford to WASH-1400

Technical Challenges: 1) Quantifying accident probability
2) Means to communicate risk



For more information: T.R. Wellock, "A Figure of Merit: Quantifying the Probability of a Nuclear Reactor Accident," *Technology and Culture*, **58**, No. 3, July 2017, pp. 678-721.

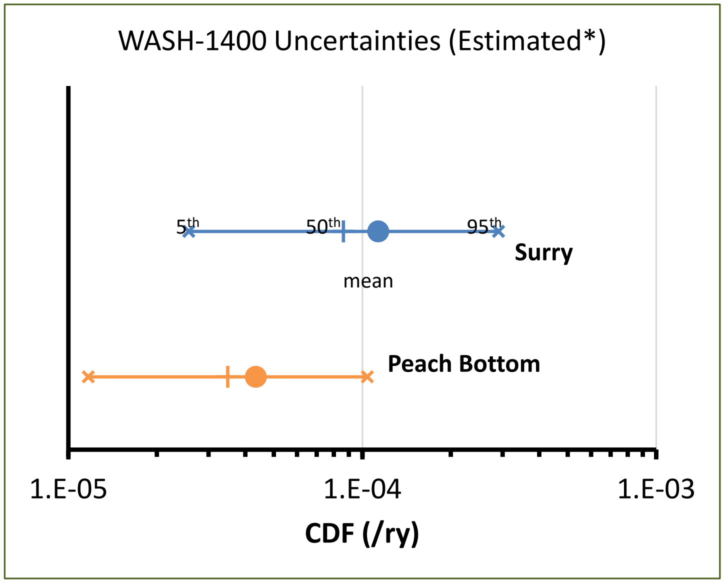
Early Views on Completeness

- W. F. Libby (Acting Chairman, AEC) – March 14, 1956 response to Senator Hickenlooper: "…it is incumbent upon the new industry and the Government to **make every effort to recognize every possible event or series of events** which could result in the release of unsafe amounts of radioactive material to the surroundings and to take all steps necessary to reduce to a reasonable minimum the probability that such events will occur in a manner causing serious overexposure to the public." [Emphasis added]
- L. Silverman (Chairman, ACRS) – October 22, 1960 letter to AEC Chairman John A. McCone: "**We believe that a searching analysis** which is necessary at this stage [reactor siting approval] **should be done** independently by the owner of the reactor…" [Emphases added]

WASH-1400 Uncertainties (Level 1)

WASH-1400: "…it is reasonable to believe that the core melt probability of about $5x10^{-5}$ per reactor-year predicted by this study should not be significantly larger and would almost certainly not exceed the value of $3x10^{-4}$ which has been estimated as the upper bound for core melt probability."

Risk Assessment Review Group (NUREG/CR-0400): "We are unable to define whether the overall probability of a core melt given in WASH-1400 is high or low, but we are certain that the error bands are understated. We cannot say by how much."



*Based on data from Tables V 3-14 (PWR) and 3-16 (BWR) of Appendix V, assuming distributions are lognormal; median values are somewhat higher than reported in Section 7.3.1 of the Main Report.

ACRS Concerns with WASH-1400 Methodology*

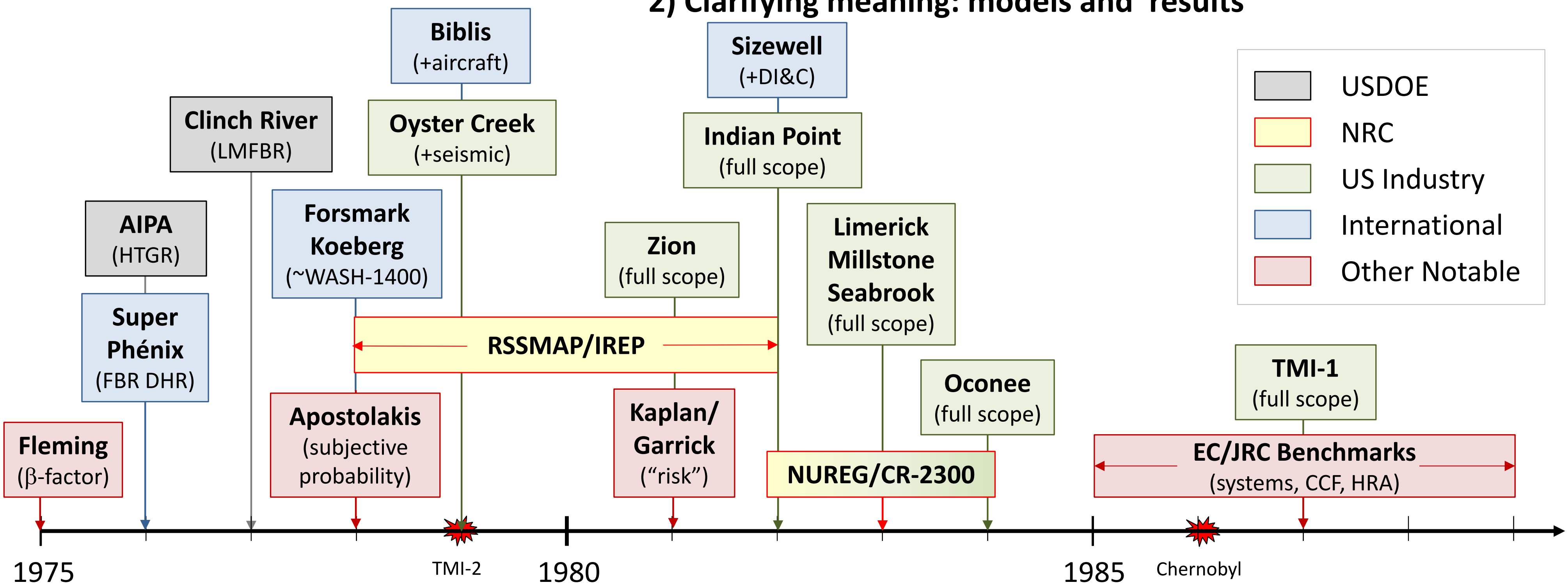
ACRS Concern	Example Events[1]	Post-WASH-1400
Accident initiator quantification (Presumably "external events")	Fukushima	Extensive treatment: fires, earthquakes Inconsistent treatment: floods
Atypical reactors	Fermi 1 [2]	Multiple PRAs for non-LWRs
Design errors	[3]	Many design and operational improvements identified by PRAs; database includes events involving design problems
Operator error quantification	TMI-2	Multiple methods emphasizing importance of context; still an active area of development
Consequence modeling	Chernobyl, Fukushima	Continuing, evolutionary improvements (MACCS)
Data	Many	Improved hardware database; fits and starts with HRA; extreme natural hazards a continuing challenge

*ACRS letter to Congressman Udall re: adequacy for estimating likelihood of low probability/high consequence events (Dec. 16, 1976)

Table Notes:
1. Events whose key characteristics (for the given topic) might not have been captured by a WASH-1400 vintage analysis.
2. Fermi 1 had limited fuel melting. However, without an analysis, it isn't clear if a WASH-1400 vintage analysis would have captured this scenario.
3. Design weaknesses have played a role in multiple events. More detailed review is needed to determine if: a) these are "errors," and b) if they would have been missed by a WASH-1400 vintage analysis.

Some Early Developments and PRAs

Challenges: 1) Filling known gaps (completeness uncertainty)
2) Clarifying meaning: models and results



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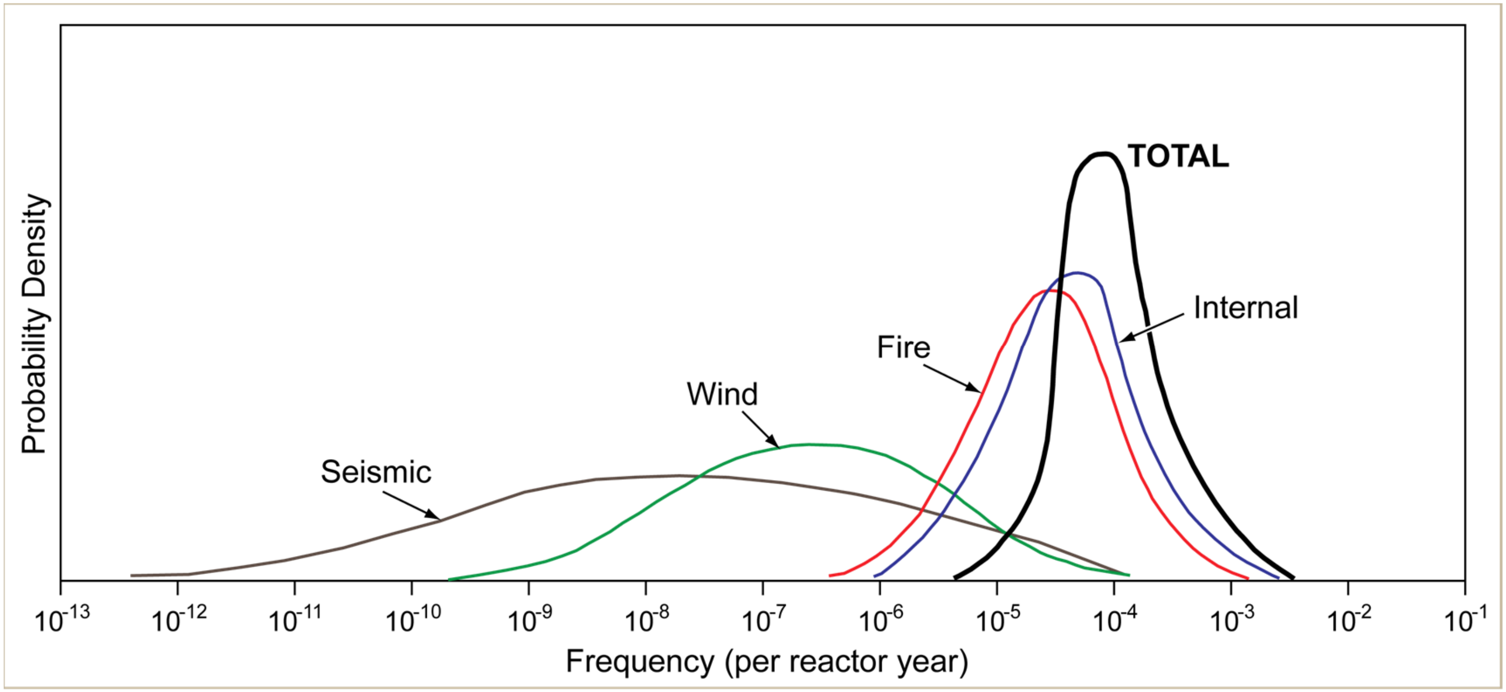
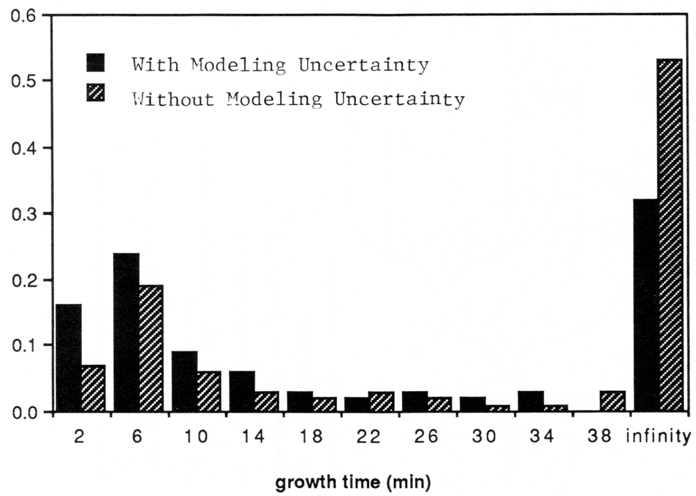
Sample Level 1 Results Display



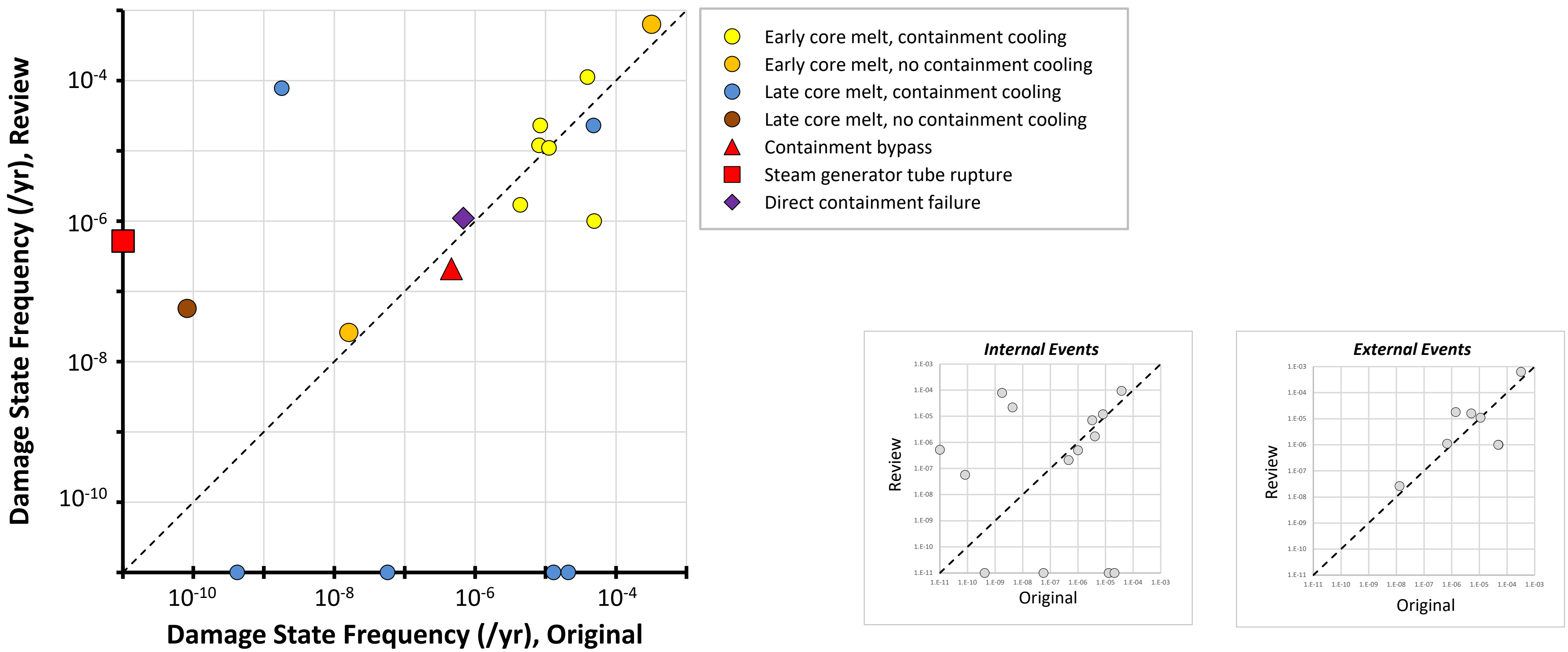
Sample Results – Sub-Model Uncertainty Effect



Effects of fire model (COMPBRN) uncertainty on fire growth time

N. Siu, "Modeling Issues in Nuclear Plant Fire Risk Analysis," in EPRI Workshop on Fire Protection in Nuclear Power Plants, *EPRI NP-6476*, J.-P. Sursock, ed., August 1989, pp. 14-1 through 14-16.

Sample Results – Model Uncertainty ("User Effect")

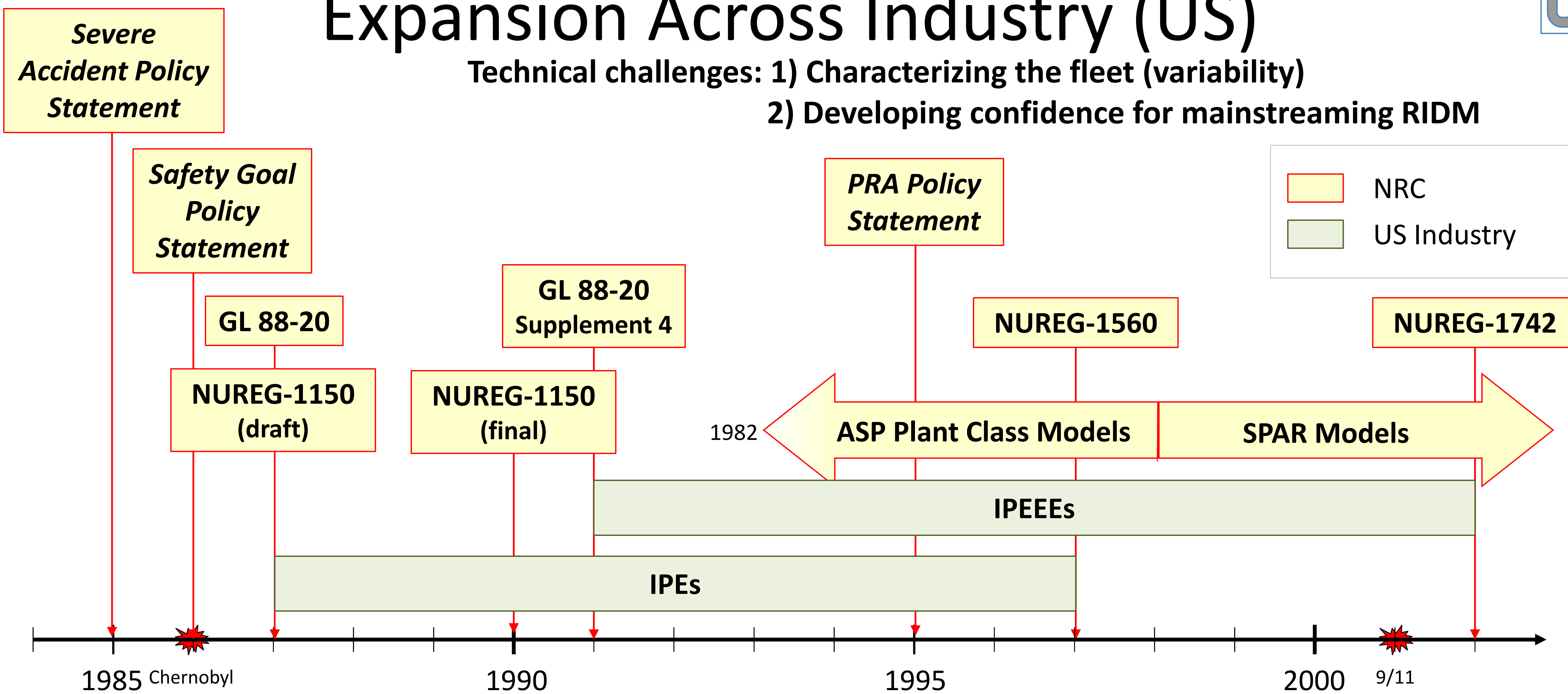


Data source: G.J. Kolb, et al., "Review and Evaluation of the Indian Point Probabilistic Safety Study," NUREG/CR-2934, December 1982. ([ML091540534](#))

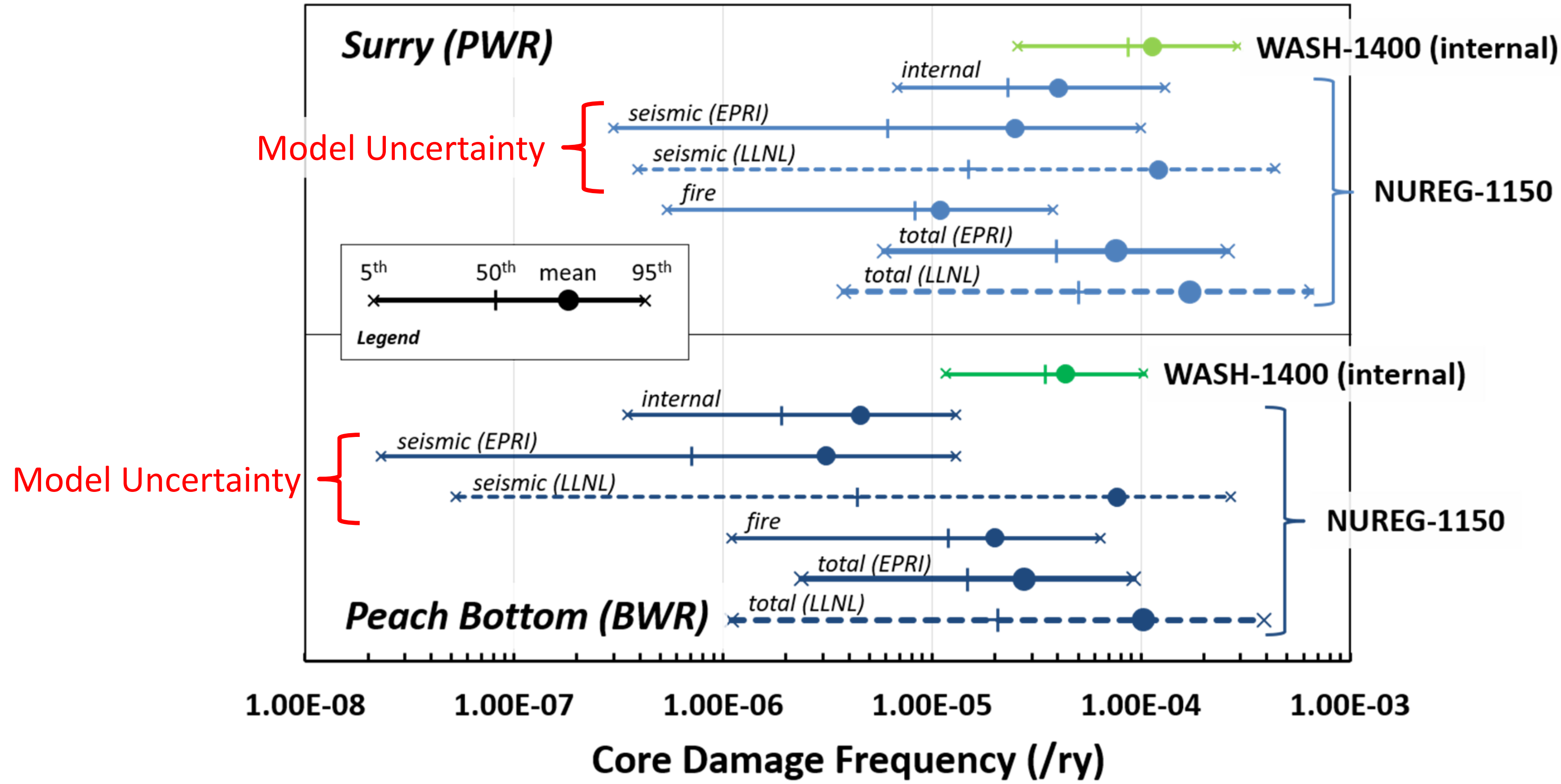
Expansion Across Industry (US)

Technical challenges: 1) Characterizing the fleet (variability)

2) Developing confidence for mainstreaming RIDM



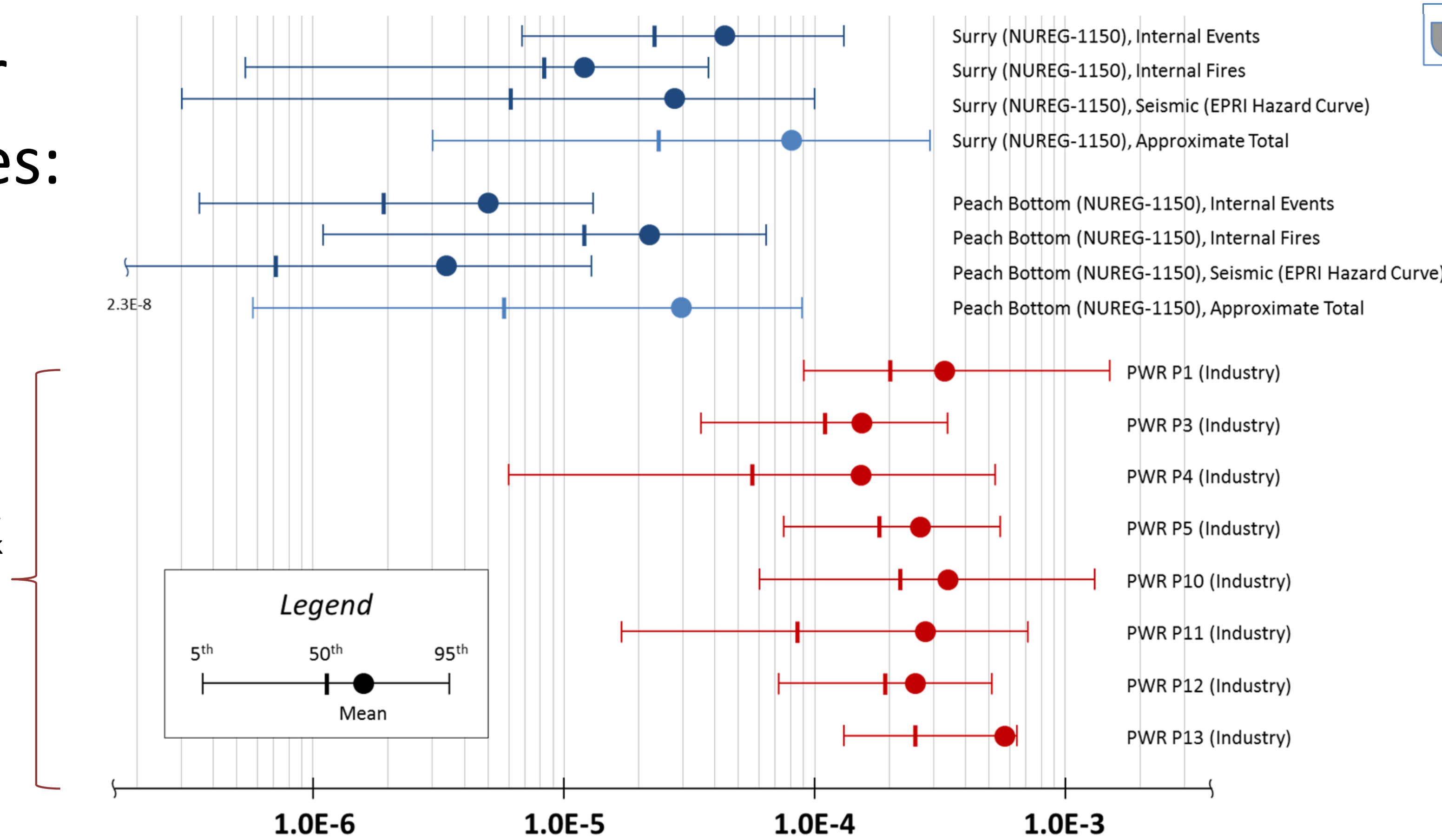
NUREG-1150 Estimated* Uncertainties (Level 1)



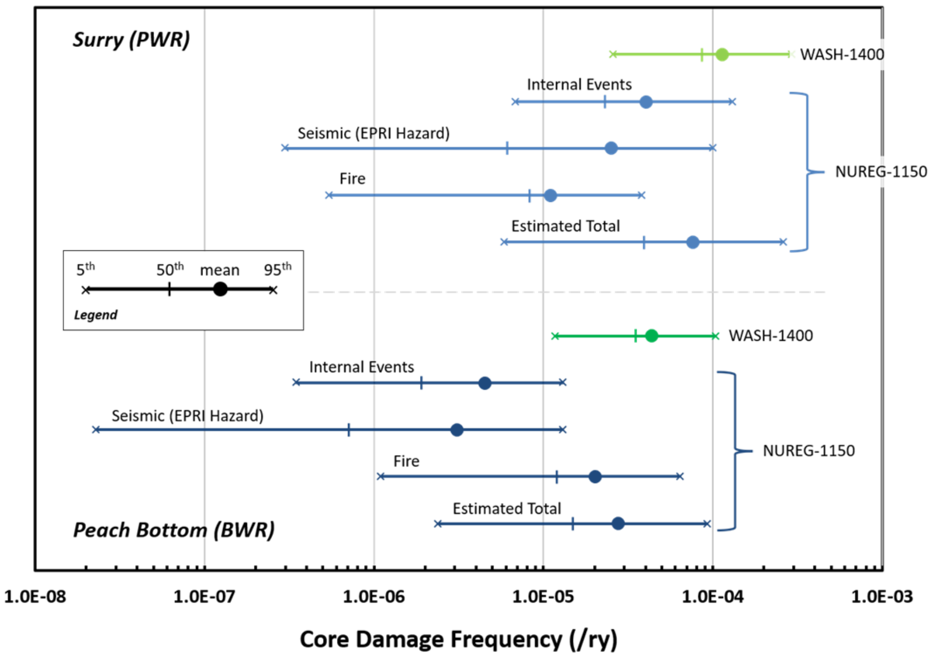
*Notes: totals shown are estimated.
1) NUREG-1150 does not aggregate the hazard-specific results. The totals shown are rough estimates assuming that the NUREG-1150 distributions are lognormal.
2) The WASH-1400 distributions are based on data from Tables V 3-14 (PWR) and 3-16 (BWR) of Appendix V, assuming that the distributions are lognormal. The median values are somewhat higher than reported in Section 7.3.1 of the Main Report

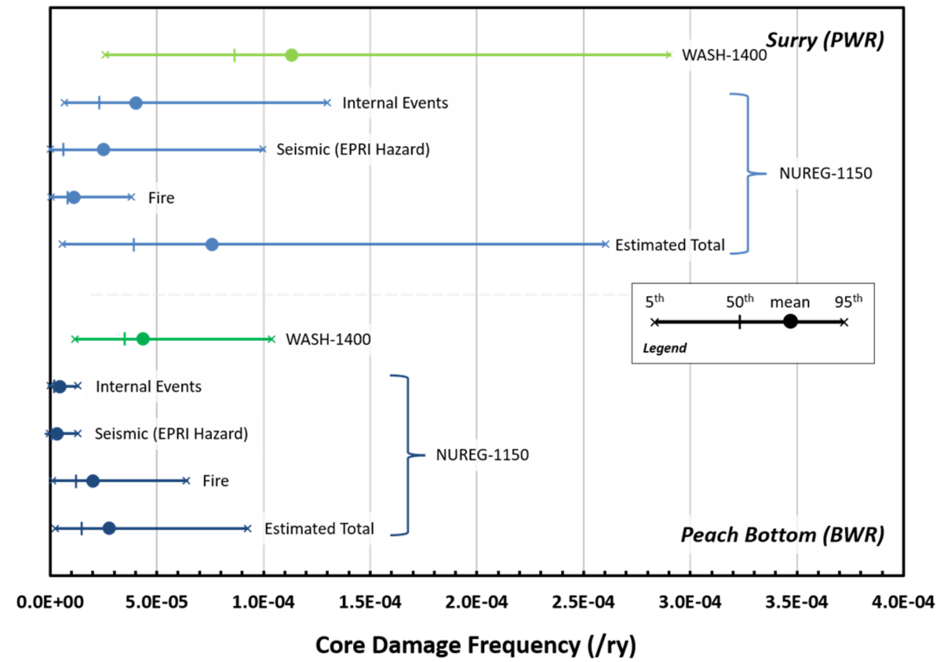
Parameter Uncertainties: Industry Studies

Industry results from: Garrick, B.J., “Lessons learned from 21 nuclear plant probabilistic risk assessments,” *Nuclear Technology*, **84**, No. 3, 319–339(1989).

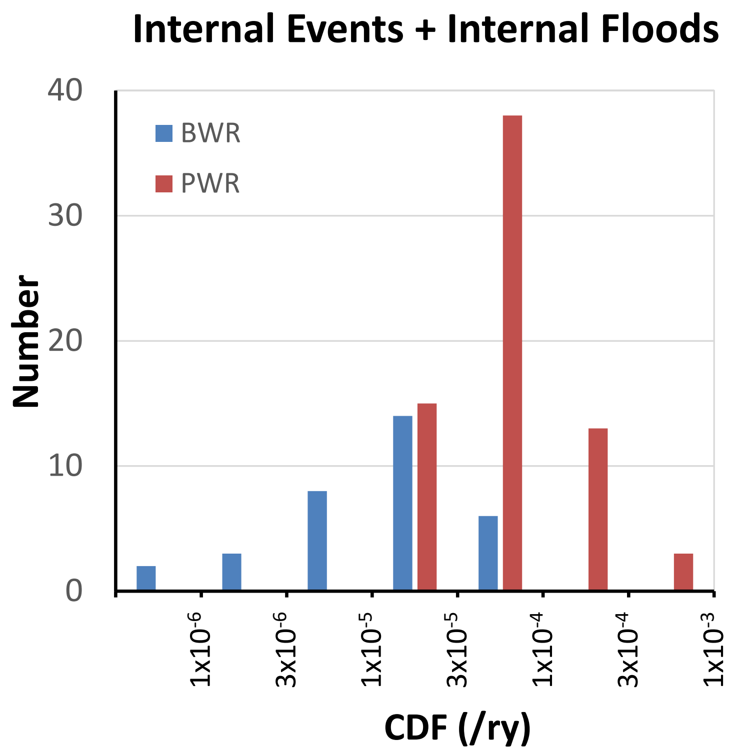


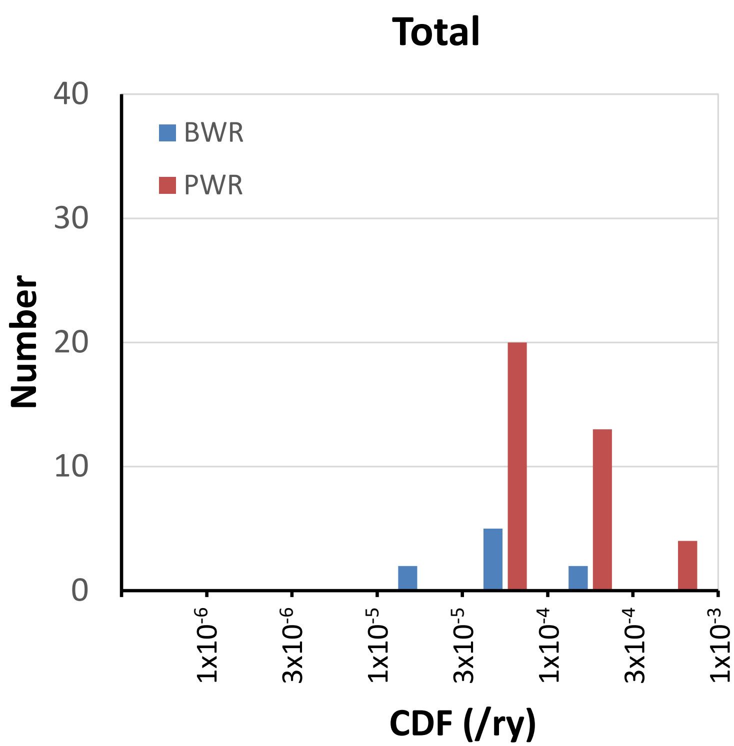
Parameter Uncertainties: Logarithmic vs Linear



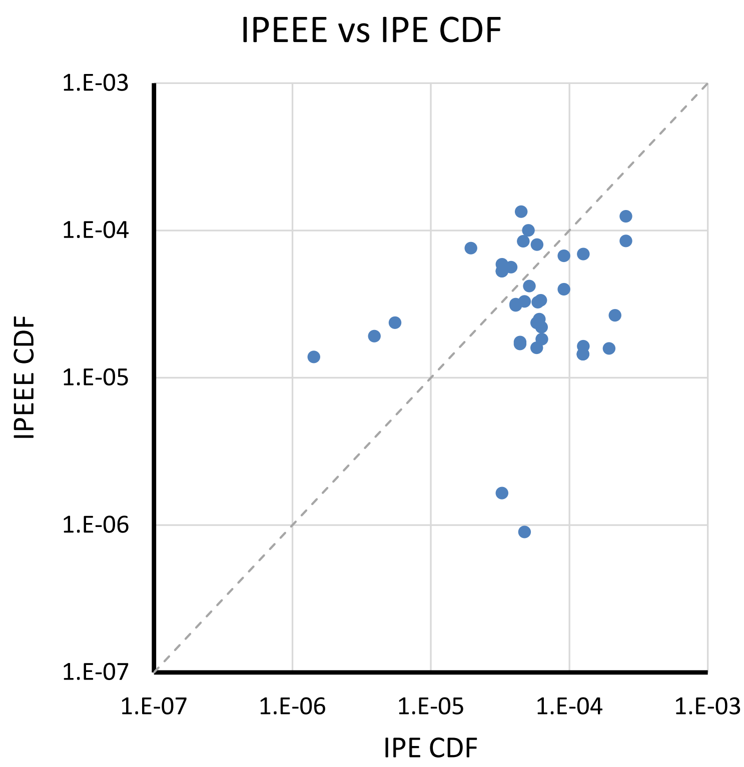


IPE/IPEEE – Variability Across Fleet



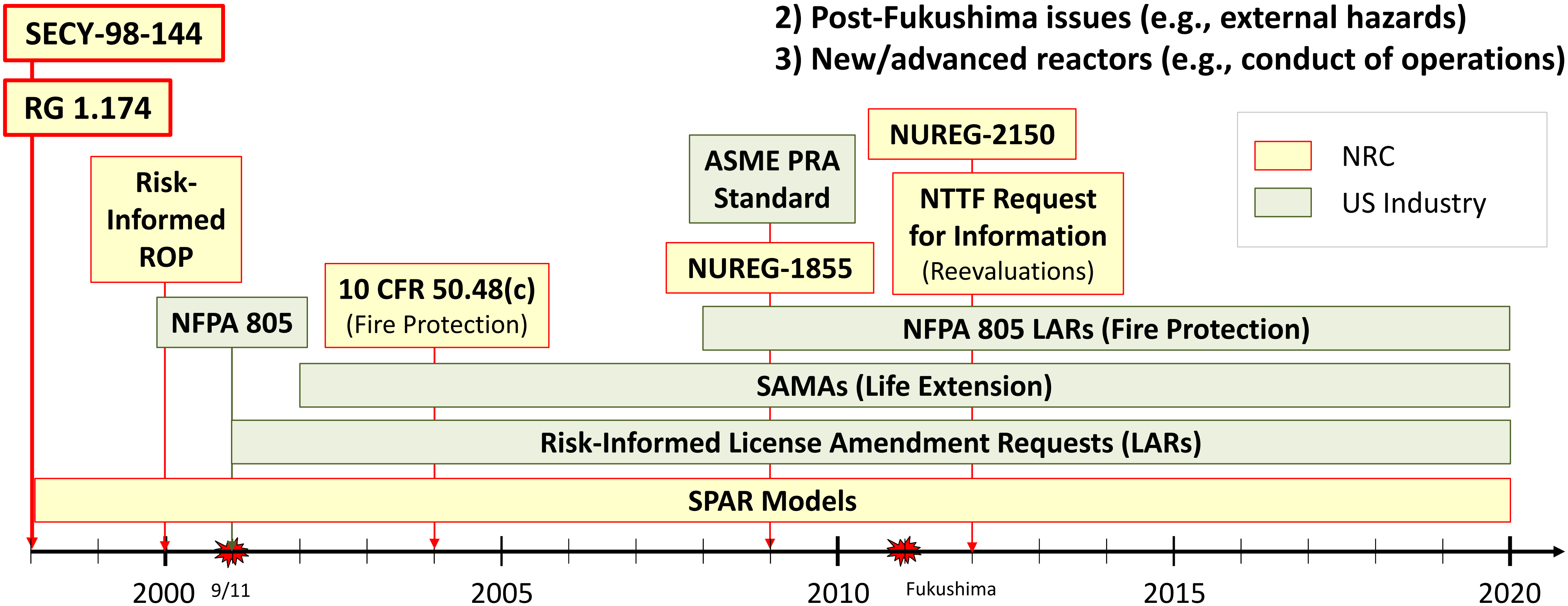


IPE/IPEEE – Contribution of “External Events”

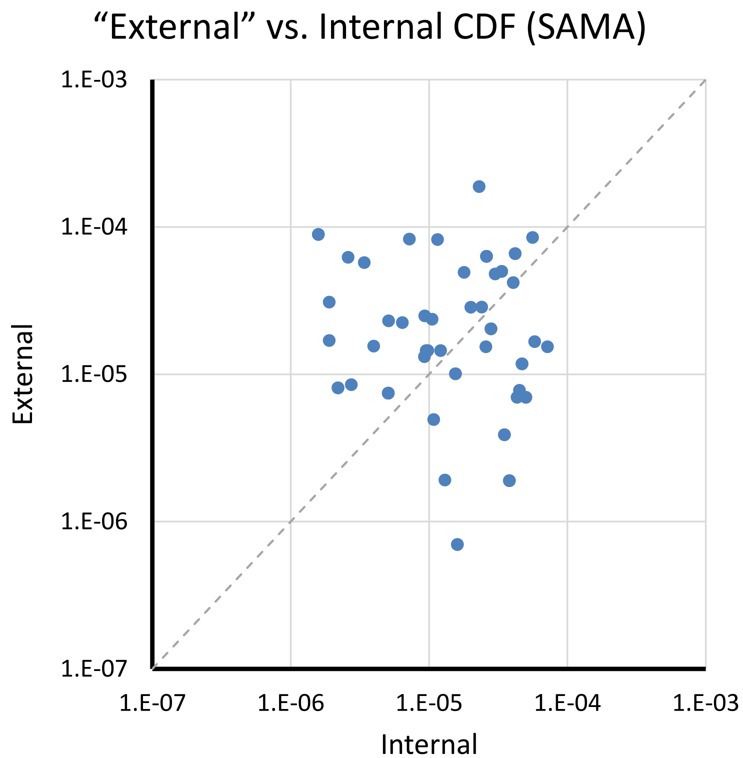


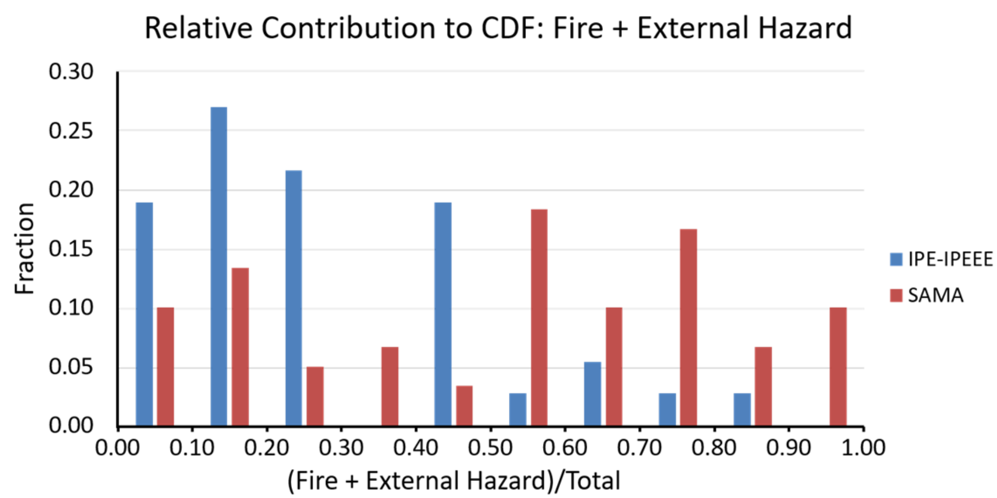
The Modern Era (US)

Technical challenges: 1) RIDM issues (e.g., realism, heterogeneity, aggregation)
2) Post-Fukushima issues (e.g., external hazards)
3) New/advanced reactors (e.g., conduct of operations)



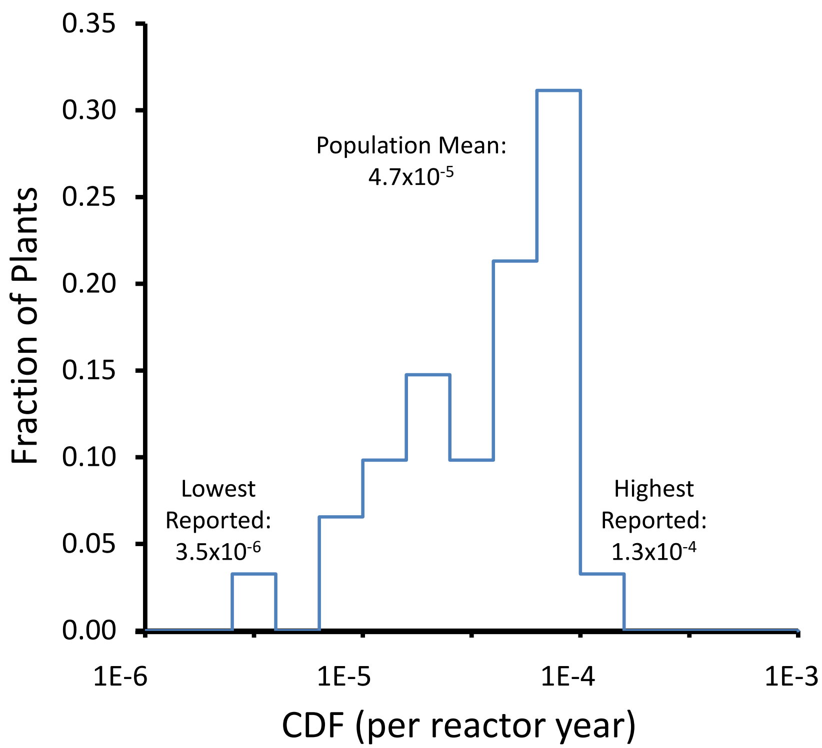
SAMA – Contribution of "External Events"





Note: "External" includes internal fires

Variability in Recent Results (Level 1)



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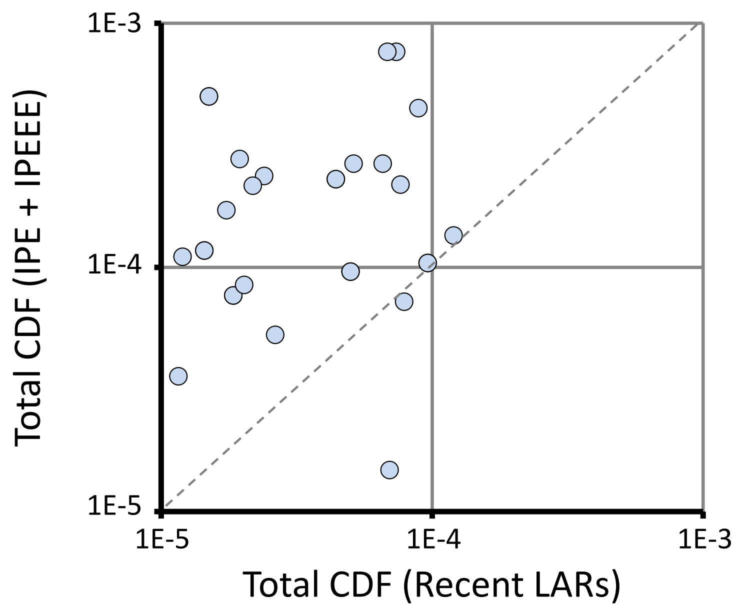
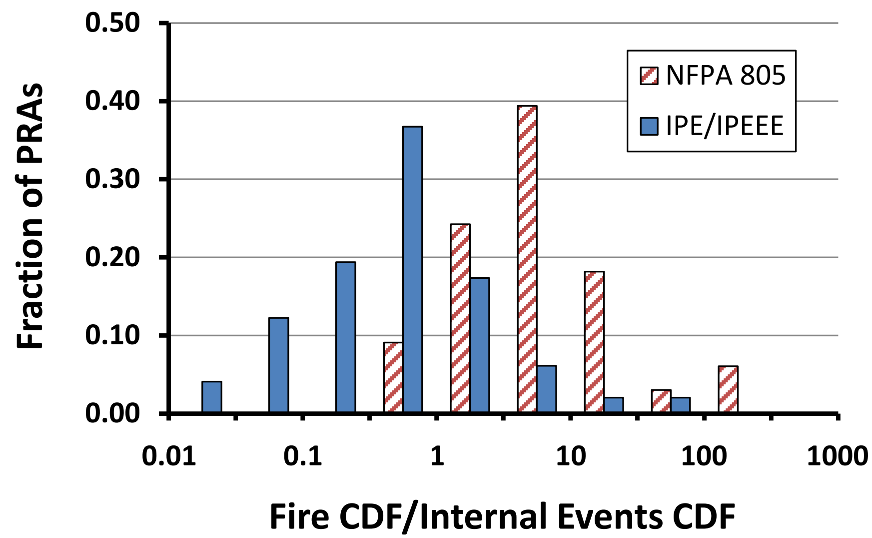
Variability in Results – Comparison with IPE/IPEEE





Additional Slides

DRIVE TO RIDM AND TRENDS

RIDM and NRC's Principles of Good Regulation

- *Independence*
- *Openness*
- *Efficiency*
- *Clarity*
- *Reliability*

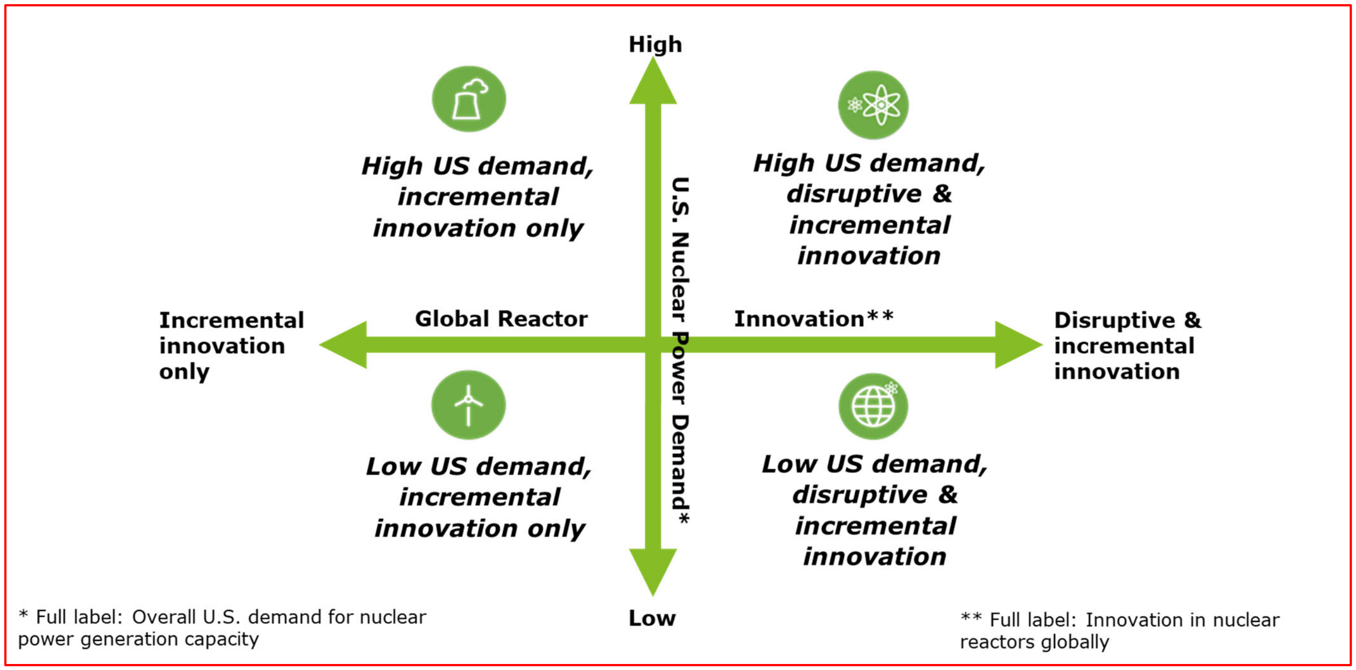
U.S. Nuclear Regulatory Commission, "Principles of Good Regulation" (ADAMS ML14135A076)

Drive to RIDM: Back to the Future

- Early years: progressive evolution of protection considering “maximum credible accident”
  - Remote siting
  - Containment
  - Engineered safeguards, single failure criterion
- Current: engineering solutions considered
  - Single failure
  - Containment?

SECY-19-0036, April 11, 2019 (ML19060A081): “…the staff is seeking Commission affirmation that the most damaging single active failure of safety-related equipment is required to be considered in performing design, and transient and accident analyses, unless such a failure can be shown with high confidence to not be credible.”
SRM-SECY-19-0036, July 19, 2019 (ML19183A408): “In any licensing review or other regulatory decision, the staff should apply risk-informed principles when strict, prescriptive application of deterministic criteria such as the single failure criterion is unnecessary to provide for reasonable assurance of adequate protection of public health and safety.”

Looking Ahead: Possible Futures



U.S. Nuclear Regulatory Commission, "The Dynamic Futures for NRC Mission Areas," 2019. (ADAMS ML19022A178)

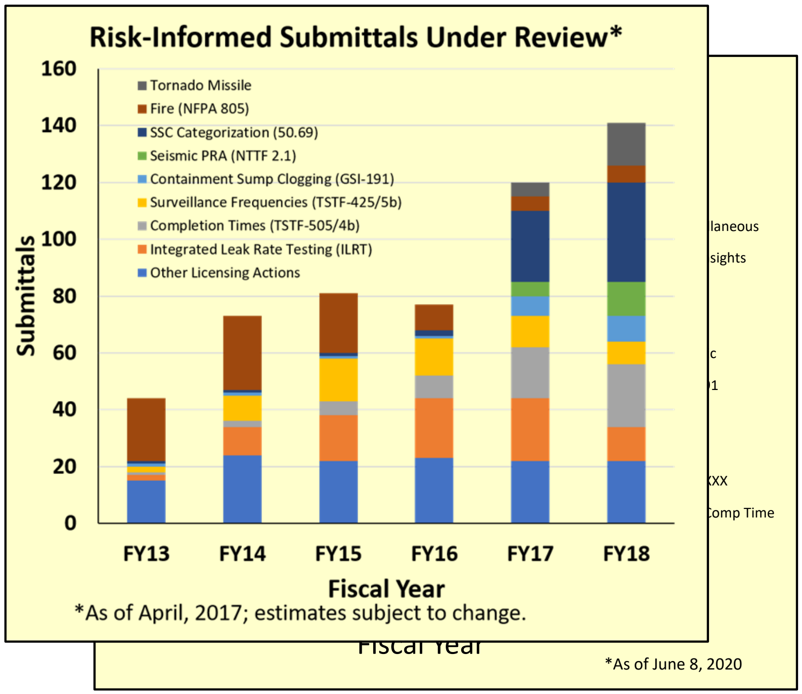
Drive to RIDM: Transformation

- Evolving situation (market forces, new nuclear technologies, new analytical methods and data, new professionals)
- Vision: make safe use of nuclear technology possible
- Continuing standard: reasonable assurance of adequate protection
- Attitude: recognize potentially different ways of achievement – embrace change

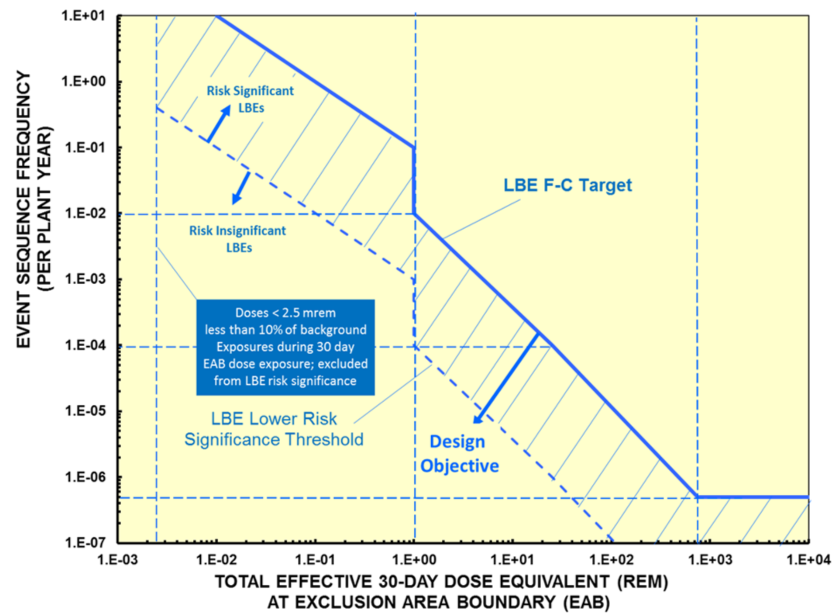
"Applying the Principles of Good Regulation as a Risk-Informed Regulator," October 15, 2019 (ADAMS ML19260E683)

Drive to RIDM: Effect of Market Forces

Operating Rx – More use of PRA models



New Rx – Early use of PRA in design



"Risk-Informed Performance-Based Technology-Inclusive Guidance for Non-Light Water Reactors," [NEI 18-04, Rev. 1](#), August 29, 2019.

Drive to RIDM: New Technologies

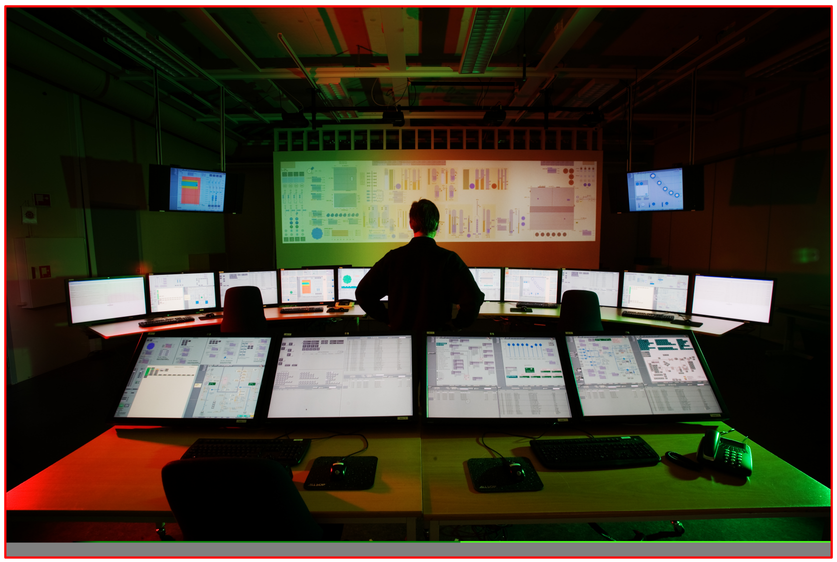
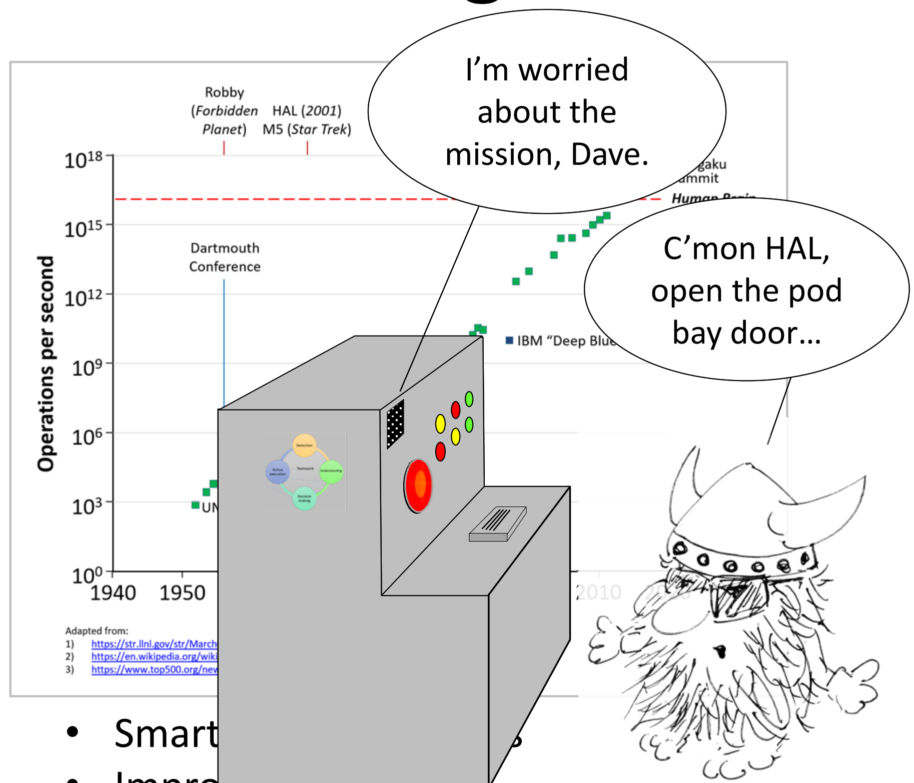


Photo courtesy of NEA Halden Reactor Project

- New designs
- New operational concepts



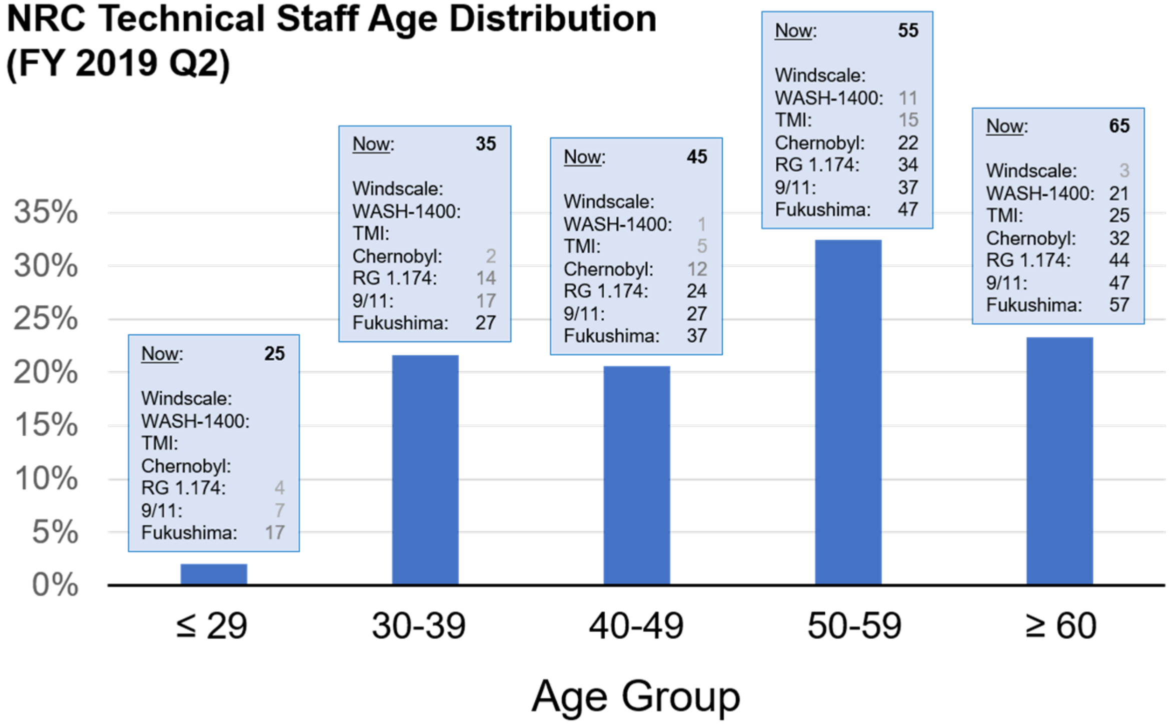
- Smart
- Improved Analysis

Drive to RIDM: New Professionals

Changing

- Experiences, knowledge
- Information content and delivery preferences
- Comfort with analytics, risk, probability
- Mobility

NRC Technical Staff Age Distribution (FY 2019 Q2)



Source: https://www.nrc.gov/reading-rm/doc-collections/commission/slides/2019/20190618/staff-20190618.pdf

Trends and Impacts: A Two-Way Street

Trends
- Increasing # RI-applications
- New licensing approaches
- New designs
- New operational concepts
- New technologies
- New analytical methods
- New professionals
- …

Decision Making
- Issue Identification
- Option Identification
- Analysis
- Deliberation
- Implementation
- Monitoring

PRA Technology
- Methods
- Models
- Tools
- Data

Challenge to NRC: Be Ready!

NRC/RES/DRA: The Cardinal Questions

Who?

Policy/Decision Makers

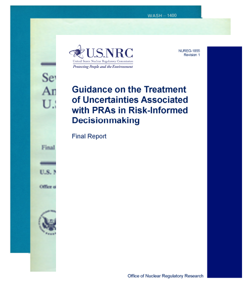
DRA

Users
- Needs
- Applications

Suppliers
- Contractors
- Grantees
- Collaborators

Non-NRC R&D

What?

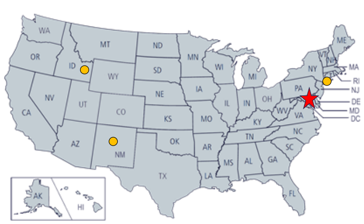


When?

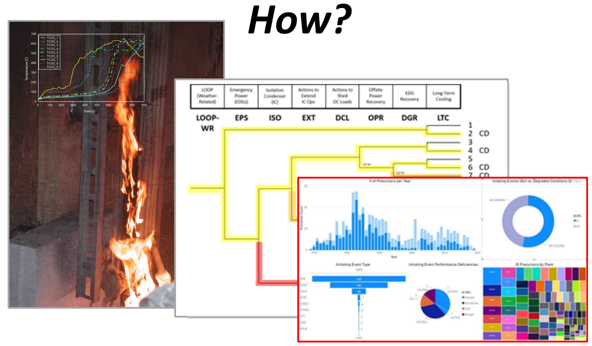
Near Term
("User Need")

Long Term
("Future-Focused")

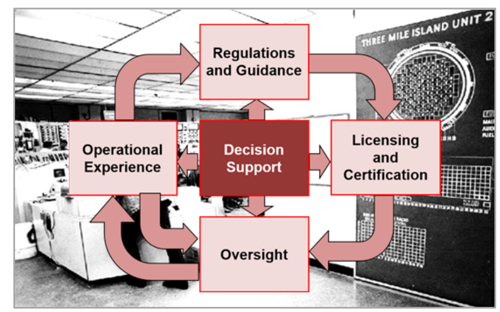
Where?



How?



Why?

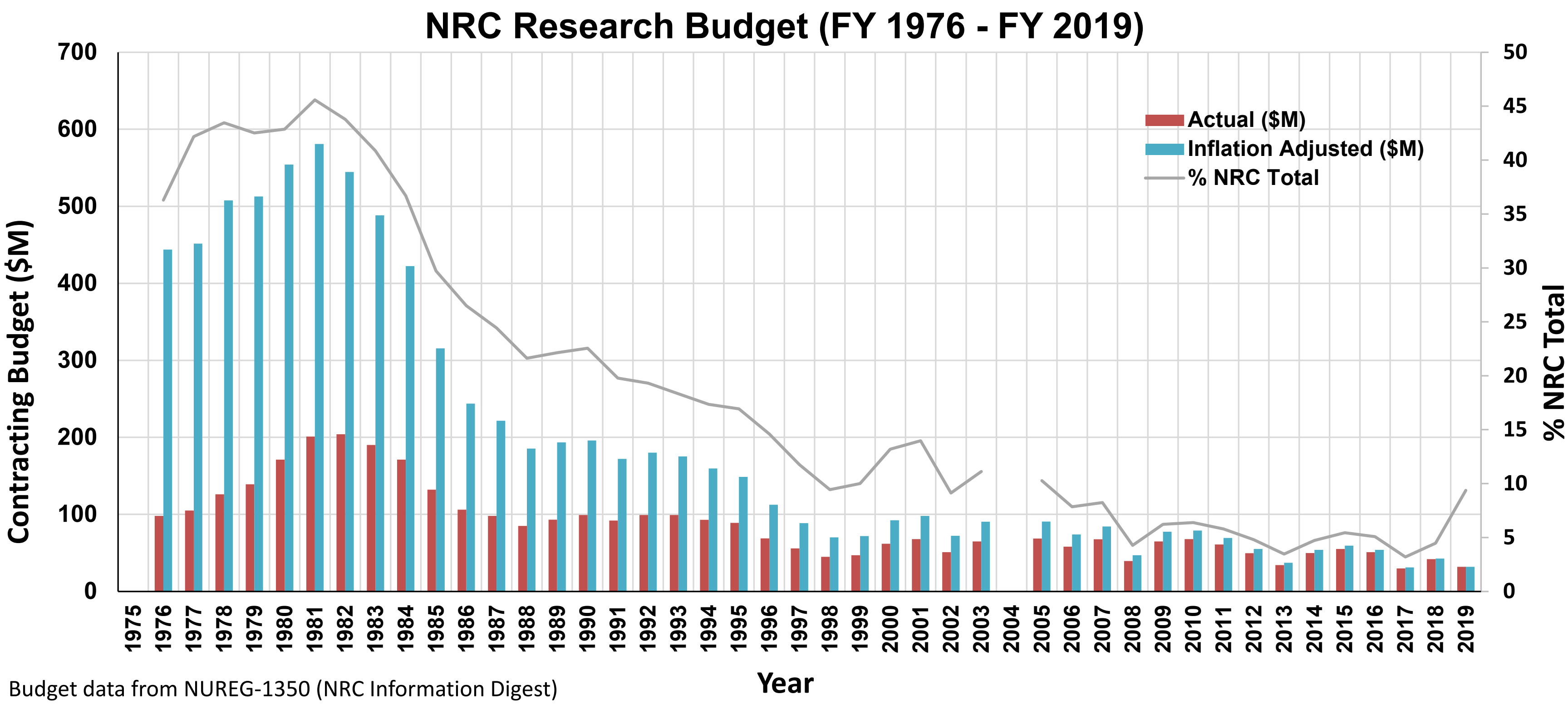


PRA/RIDM: Topic Areas for Potential R&D

Technical Area	Topic Area
Reactors	Level 1 internal events at power
	Level 2
	Level 3
	Low power and shutdown (LPSD)
	Operational data
	Event analysis
	Generic safety issues (GSI)
	Performance indicators and thresholds
	New reactors (evolutionary)
	Advanced reactors
	Research and test reactors
Non-Reactor Facilities and Activities	Geologic repositories
	High-level waste (HLW)
	Low-level waste/decommissioning
	Fuel cycle facilities
	Transportation
	Sources
Implementation and Application	PRA quality (e.g., guidance, standards)
	Risk-informed regulation infrastructure
	Risk-informed regulation applications
	Risk perception and communication

Technical Area	Topic Area
Special Topics	HRA
	Ageing
	Passive components
	Passive systems
	Digital systems
	CCF
	Design and construction
	Fire
	Seismic
	Other external events
	Security-related events
	EP&R
General Systems Analysis Methods and Tools	PRA tools
	Uncertainty and sensitivity analysis methods and tools
	Advanced computational methods
	Advanced modeling methods (e.g., simulation)
	Elicitation methods

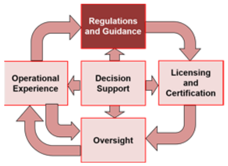
Need for Focus



Budget data from NUREG-1350 (NRC Information Digest)

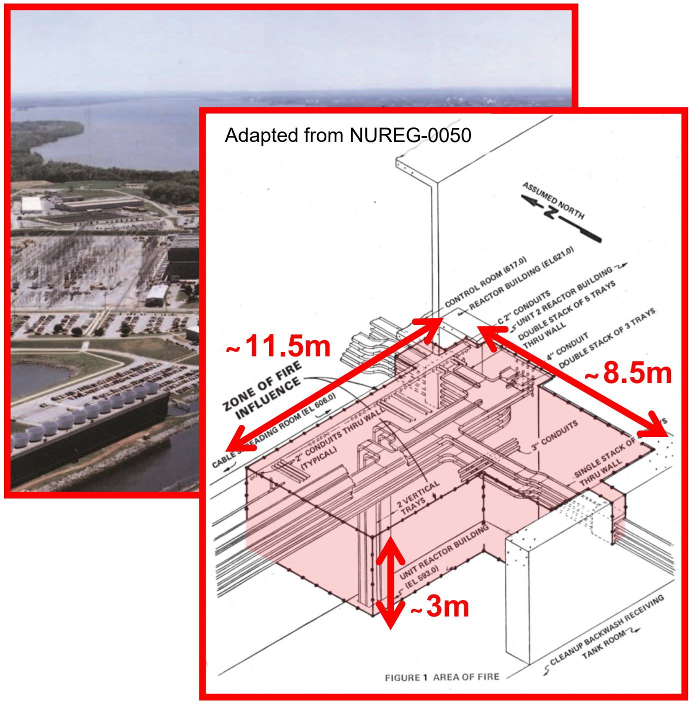
Additional Slides

RIDM APPLICATION EXAMPLES



Risk Info Uses – Regulations Example (Risk-Informed Fire Protection)

- Browns Ferry Nuclear Power Plant fire (3/22/75)
- Candle ignited foam penetration seal, initiated cable tray fire; water suppression delayed; complicated shutdown
- Second-most challenging event in U.S. nuclear power plant operating history
- Spurred changes in requirements and analysis



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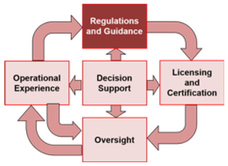
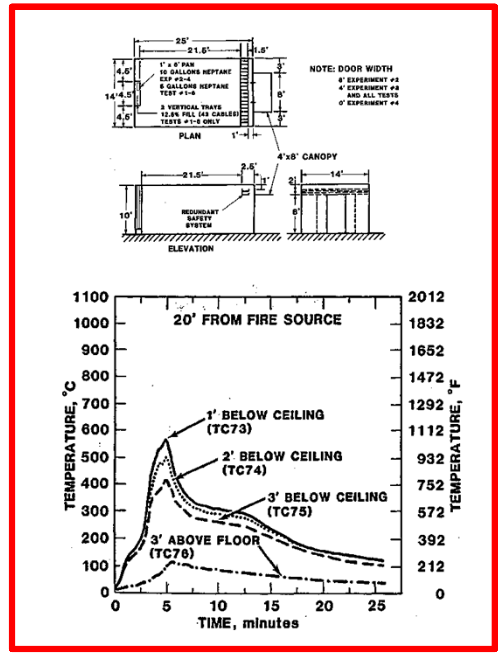
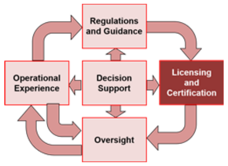


Risk Info Uses – Regulations Example (Risk-Informed Fire Protection)

- Post-Browns Ferry deterministic fire protection (10 CFR Part 50, Appendix R)
  - 3-hour fire barrier, OR
  - 20 feet separation with detectors and auto suppression, OR
  - 1-hour fire barrier with detectors and auto suppression
- Risk-informed, performance-based fire protection (10 CFR 50.48(c), NFPA 805)
  - Voluntary alternative to Appendix R
  - Deterministic and performance-based elements
  - Changes can be made without prior approval; risk must be “acceptable”
  - More than 1/3 U.S. fleet has completed transition
- Methods adopted by international organizations

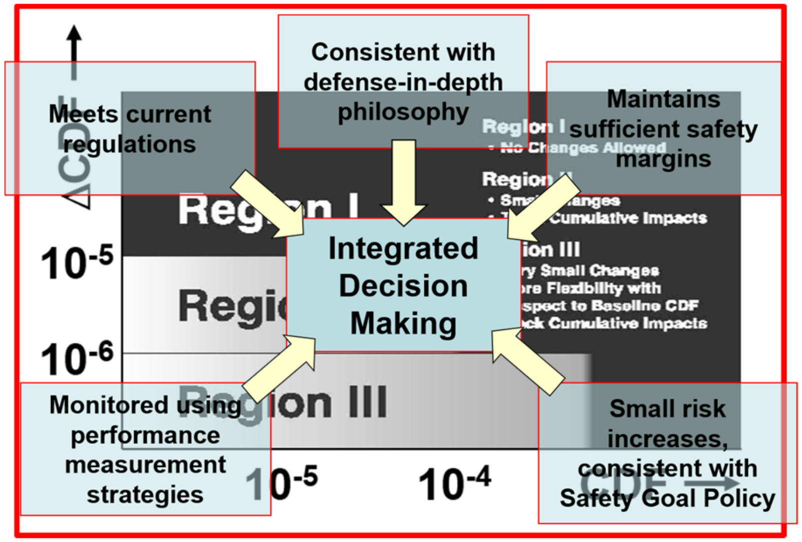


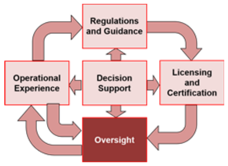
From Cline, D.D., et al., “Investigation of Twenty-Foot Separation Distance as a Fire Protection Method as Specified in 10 CFR 50, Appendix R,” NUREG/CR-3192, 1983.



Risk Info Uses – Licensing Example (Changes in plant licensing basis – RG 1.174)

- Voluntary changes: licensee requests, NRC reviews
- Small risk increases may be acceptable
- Change requests may be combined
- Decisions are risk-informed

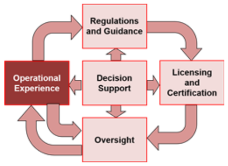




Risk Info Uses – Oversight Example (Reactor Oversight Program)

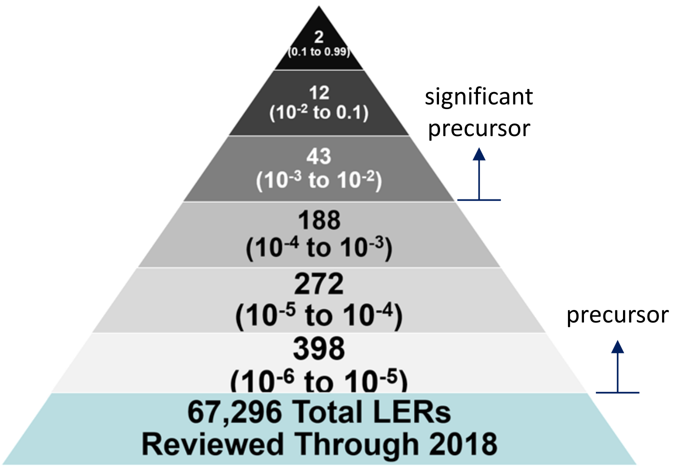
- Inspection planning
- Determining significance of findings
  - Characterize performance deficiency
  - Use review panel (if required)
  - Obtain licensee perspective
  - Finalize
- Performance indicators

ΔCDF < 1E-6 **ΔLERF < 1E-7**
1E-6 < ΔCDF < 1E-5 **1E-7 < ΔLERF < 1E-6**
1E-5 < ΔCDF < 1E-4 **1E-6 < ΔLERF < 1E-5**
ΔCDF > 1E-4 **ΔLERF > 1E-5**

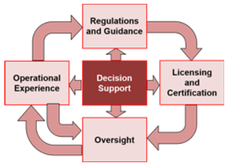


Risk Info Uses – OpE Example (Accident Sequence Precursor Program)

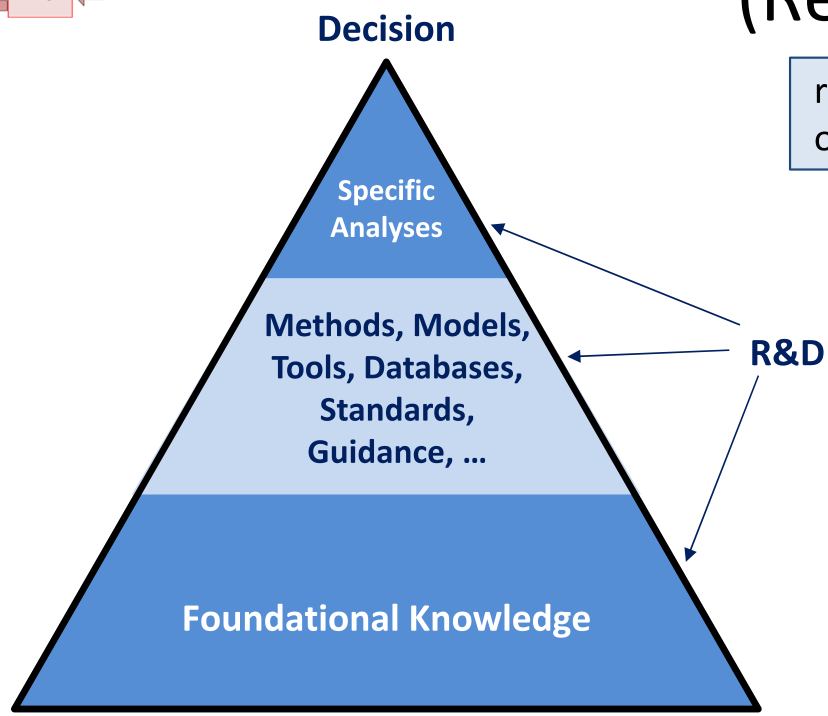
- Program recommended by WASH-1400 review group (1978)
- Provides risk-informed view of nuclear plant operating experience
  - Conditional core damage probability (events)
  - Increase in core damage probability (conditions)
- Supported by plant-specific Standardized Plant Analysis Risk models



Licensee Event Reports 1969-2018
(No significant precursors since 2002)



Risk Info Uses – Decision Support Example (Research)



Regulatory Decision Support

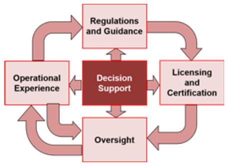
re•search, *n.* diligent and systematic inquiry or investigation in order to discover or revise facts, theories, applications, etc.

Typical products (regulatory research)

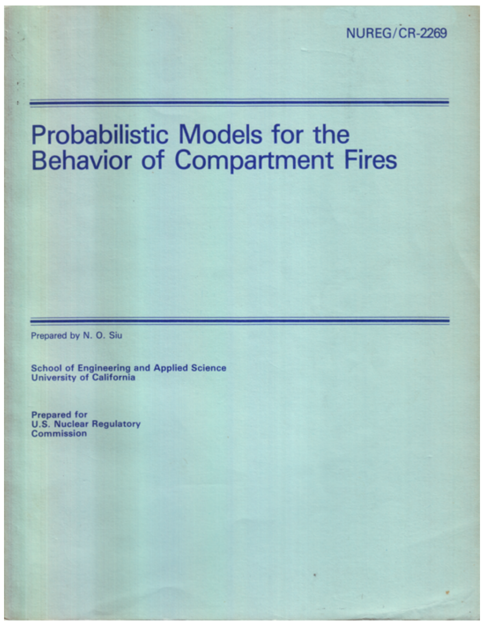
- Ways to look at and/or approach problems (e.g., frameworks, methodologies)
- Points of comparison (e.g., reference calculations, experimental results)
- Job aids (e.g., computational tools, databases, standards, guidance: best practices, procedures)
- Problem-specific information (e.g., results, insights, uncertainties)

Side benefits

- Education/training of workforce
- Networking with technical community



Risk Info Uses – Decision Support Example (Research: Frameworks/Methodologies)



NUREG/CR-2269

Probabilistic Models for the Behavior of Compartment Fires

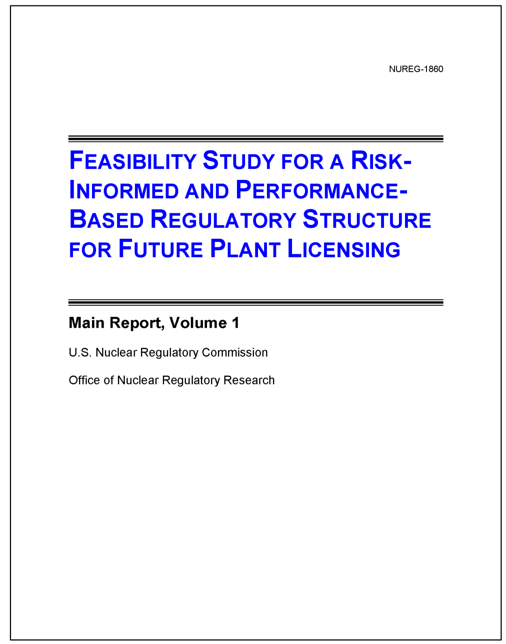
Prepared by N. O. Siu

School of Engineering and Applied Science
University of California

Prepared for
U.S. Nuclear Regulatory Commission

NRC-sponsored Fire PRA R&D (universities)

- Started after Browns Ferry fire (1975)
- Developed fire PRA approach first used in industry Zion and Indian Point PRAs (early 80s), same basic approach today
- Started path leading to risk-informed fire protection (NFPA 805)



NUREG-1860

FEASIBILITY STUDY FOR A RISK-INFORMED AND PERFORMANCE-BASED REGULATORY STRUCTURE FOR FUTURE PLANT LICENSING

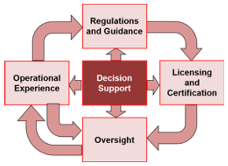
Main Report, Volume 1

U.S. Nuclear Regulatory Commission

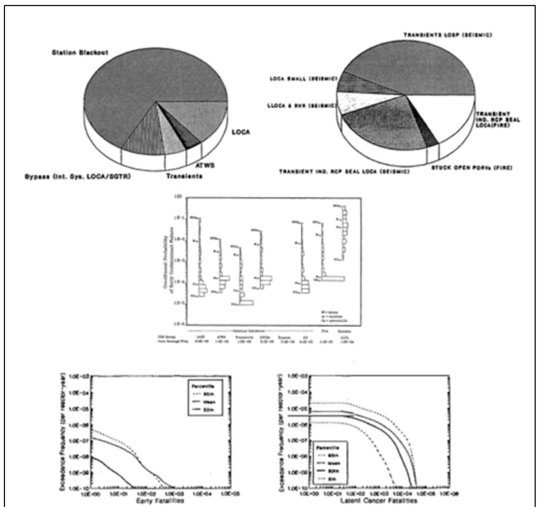
Office of Nuclear Regulatory Research

Technology Neutral Framework

- Explored use of risk metrics to identify licensing basis events
- Inspiration and part basis for current Licensing Modernization Program



Risk Info Uses – Decision Support Example (Research: Reference Points)



NUREG-1150 (Surry)

NUREG-1150

- Continuing point of comparison for Level 1, 2, 3 results
- Expectations ("ballpark")
- Basis for regulatory analysis (backfitting, generic issue resolution)

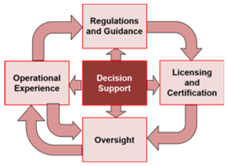
Peach Bottom

SOARCA

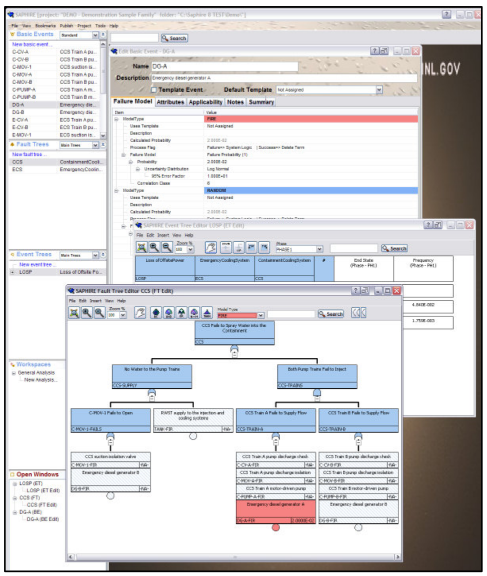
- Detailed analysis of potential severe accidents and offsite consequences
- Updated insights on margins to QHOs

Surry

Sequoyah



Risk Info Uses – Decision Support Example (Research: Methods/Models/Tools)



From https://en.wikipedia.org/wiki/SAPHIRE

SPAR

- Independent plant-specific models (generic data)
- All-hazards (many)
- Support SDP, MD 8.3, ASP, GSI, SSC studies
- Adaptable for specific circumstances

SAPHIRE

- General purpose model-building tool
- Multiple user interfaces

IDHEAS-G

- Improved support for qualitative analysis
- Explicit ties with cognitive science (models, data)
- General framework for developing focused applications (e.g., IDHEAS-ECA)
- Benefits from NPP simulator studies
- Consistent with current HRA good practices guidance (NUREG-1792)