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Technology for the Treatment of Uncertainties: History, Status, Commentary and Challenges

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Expanded version of a presentation originally developed for CRIEPI/NRRC and OECD/NEA Workshop on the Proper Treatment of Uncertainties in Reactor Safety Assessment

March, 2020

Foreword

On December 19, 2019, the Nuclear Risk Research Center (NRRC) of the Japan Central Research Institute of Electric Power Industry (CRIEPI) and the Organization for Economic Cooperation (OECD) Nuclear Energy Agency (NEA) invited the author to participate in a workshop on the improvement and enhancement of risk-informed decision making (RIDM) processes in reactor safety assessment. The workshop, titled "A Workshop on the Proper Treatment of Uncertainties in Reactor Safety Assessment," was to be held on May 26-27, 2020 in Tokyo, Japan. At the request of the workshop organizers, the author's talk was to be titled "Technology for the Treatment of Uncertainties: History, Status, and Some Challenges." On March 12, due to travel restrictions arising from the covid-19 pandemic, the author was directed to withdraw from the workshop. The following slides are an expanded version of the talk the author was planning on presenting.

Outline

- Framework for discussion
  - Parameter Uncertainties
  - Model Uncertainties
  - Completeness Uncertainties
  - Communication
- Current state of practice
- History
- Commentary and challenges

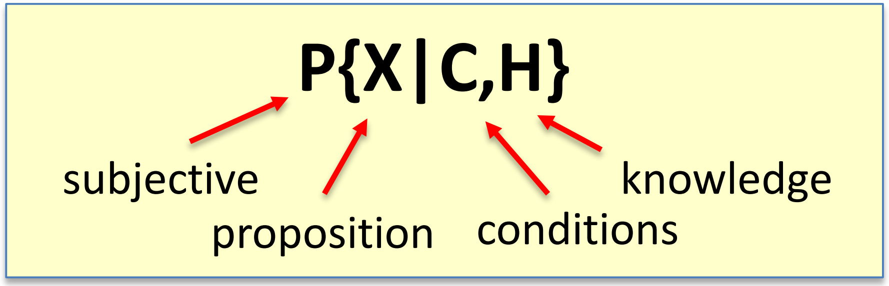
tech•nol•o•gy, *n.* the sum of techniques, skills, methods, and processes used in the production of goods or services or in the accomplishment of objectives, such as scientific investigation. [Wikipedia]

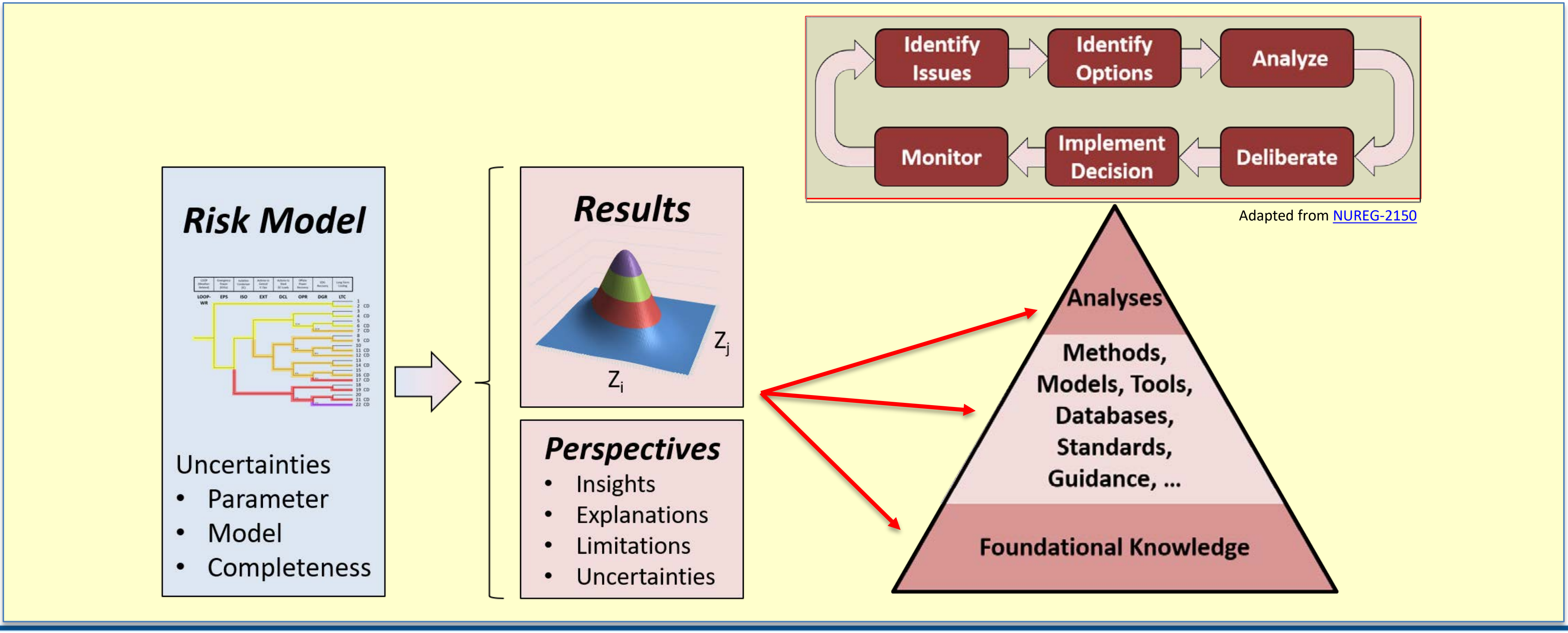
In this talk:
"technology" ≡ {methods, models, computational tools, guidance, data}

What are we talking about?

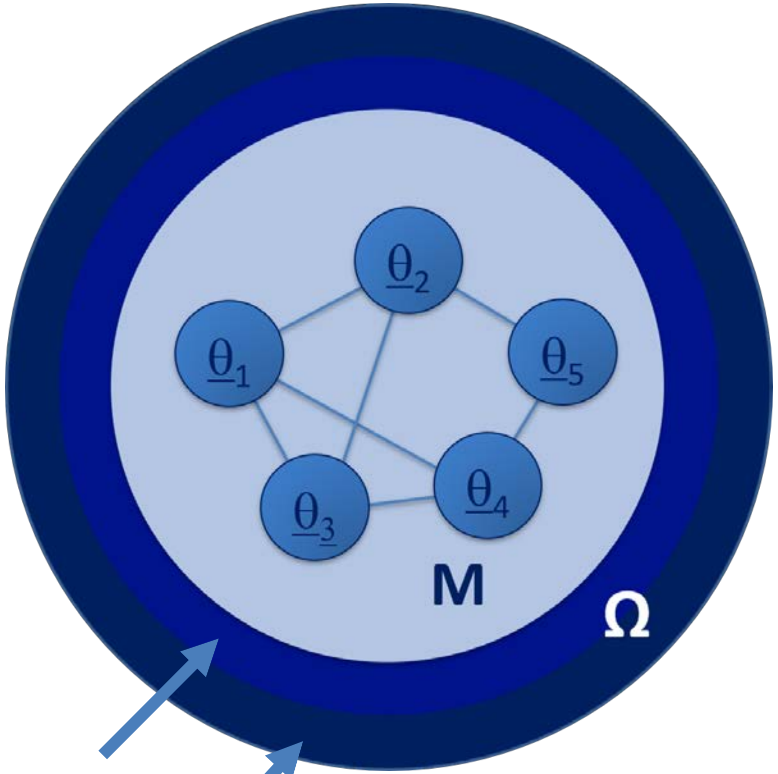
DISCUSSION FRAMEWORK

Context for Treatment of Uncertainties: Risk-Informed Decisionmaking (RIDM)





Parameter, Model, and Completeness Uncertainty: A Practical Categorization



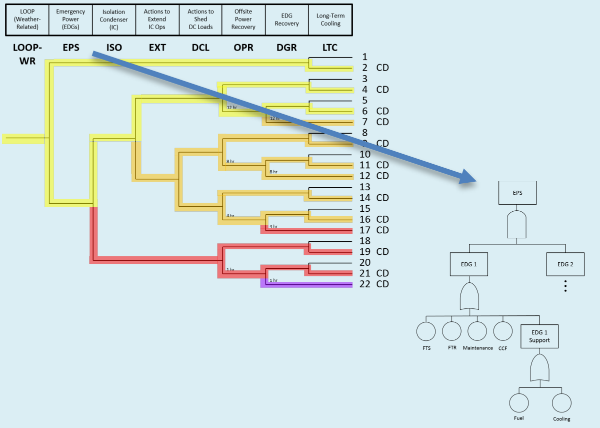
M ("Model of the World"):
Scope, structure
θ_i: Parameters
Ω: Universe

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

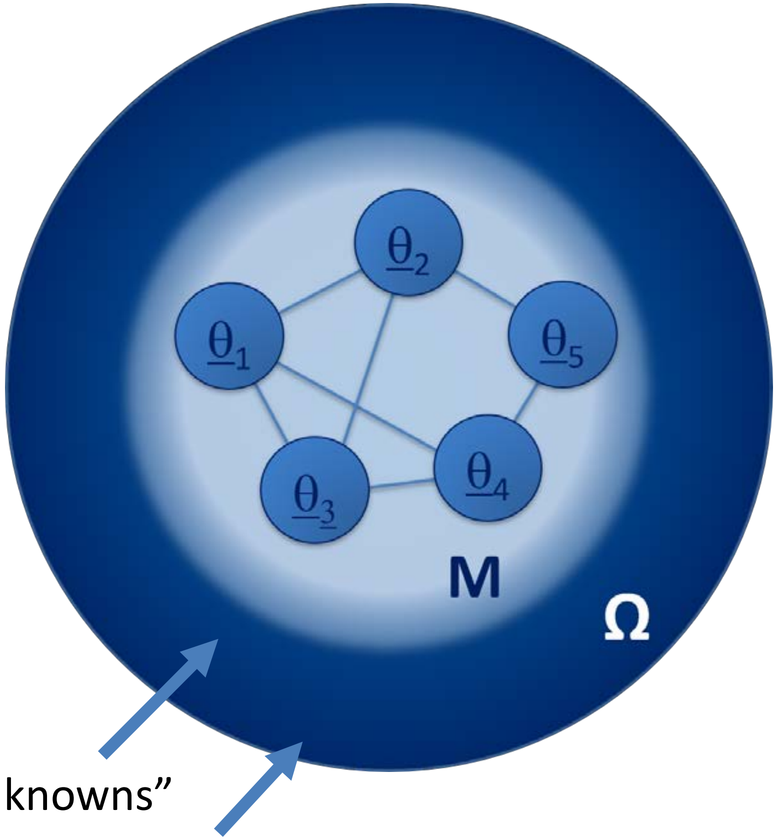
A. Mosleh, N. Siu, C. Smidts, and C. Lui, *Model Uncertainty: Its Characterization and Quantification*, Center for Reliability Engineering, University of Maryland, College Park, MD, 1995. (Also NUREG/CP-0138, 1994)

PRA models for NPPs

- Typically an assemblage of sub-models with parameters
- Implicitly include issues considered but not explicitly quantified



Parameter, Model, and Completeness Uncertainty: A Practical Categorization



"Known Unknowns"

"Unknown Unknowns"

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

θ_i: Parameters

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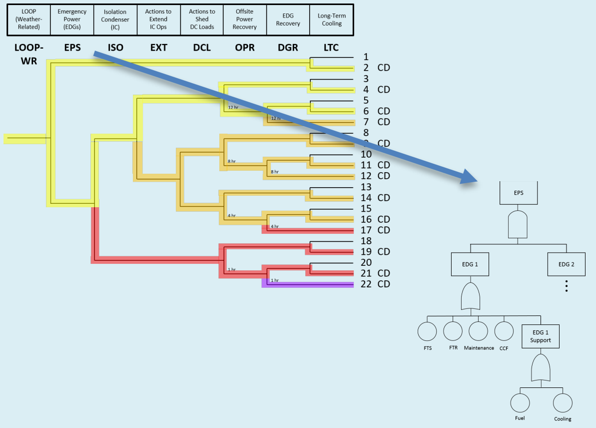
mod•el, *n.* a representation of reality created with a specific objective in mind.

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



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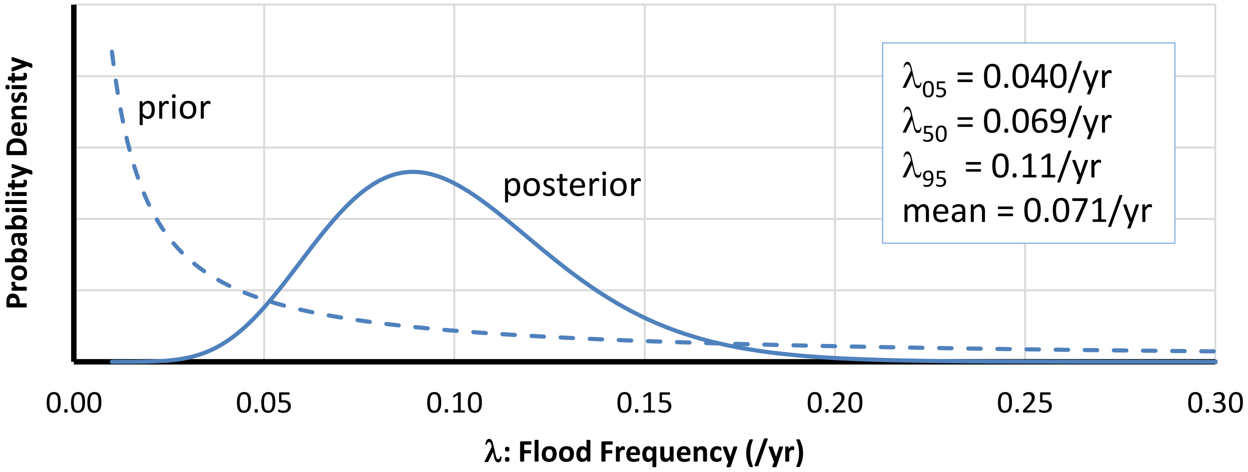
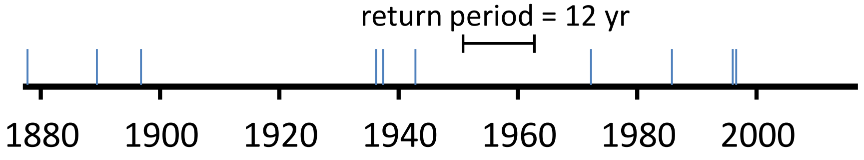
Parameter Uncertainty: An Example

- Parameter of interest: frequency of flooding (λ)
- Prior state-of-knowledge: minimal
- Evidence: 10 events over 1877-2017 (140 years)
- Posterior state-of-knowledge:



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



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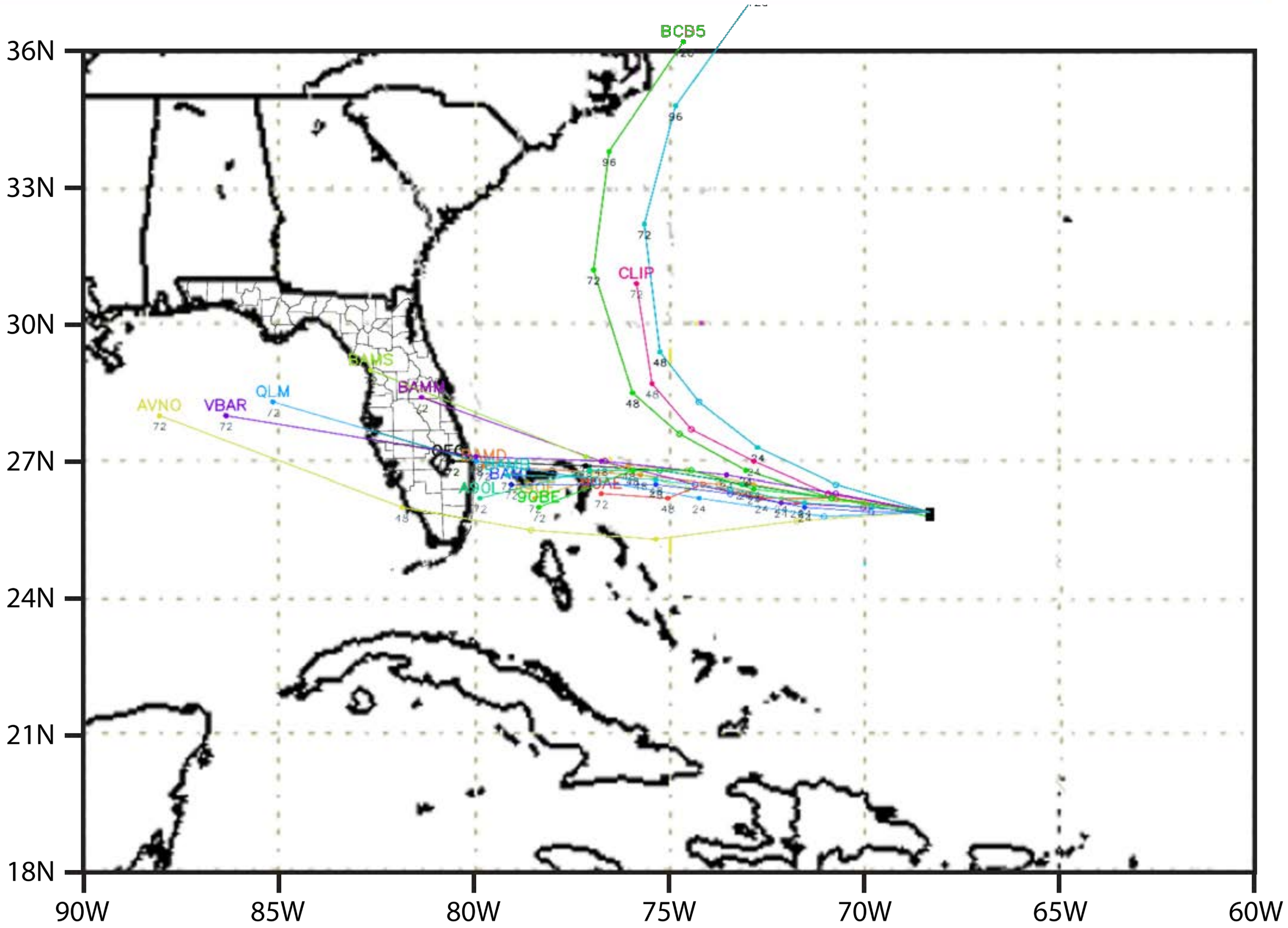
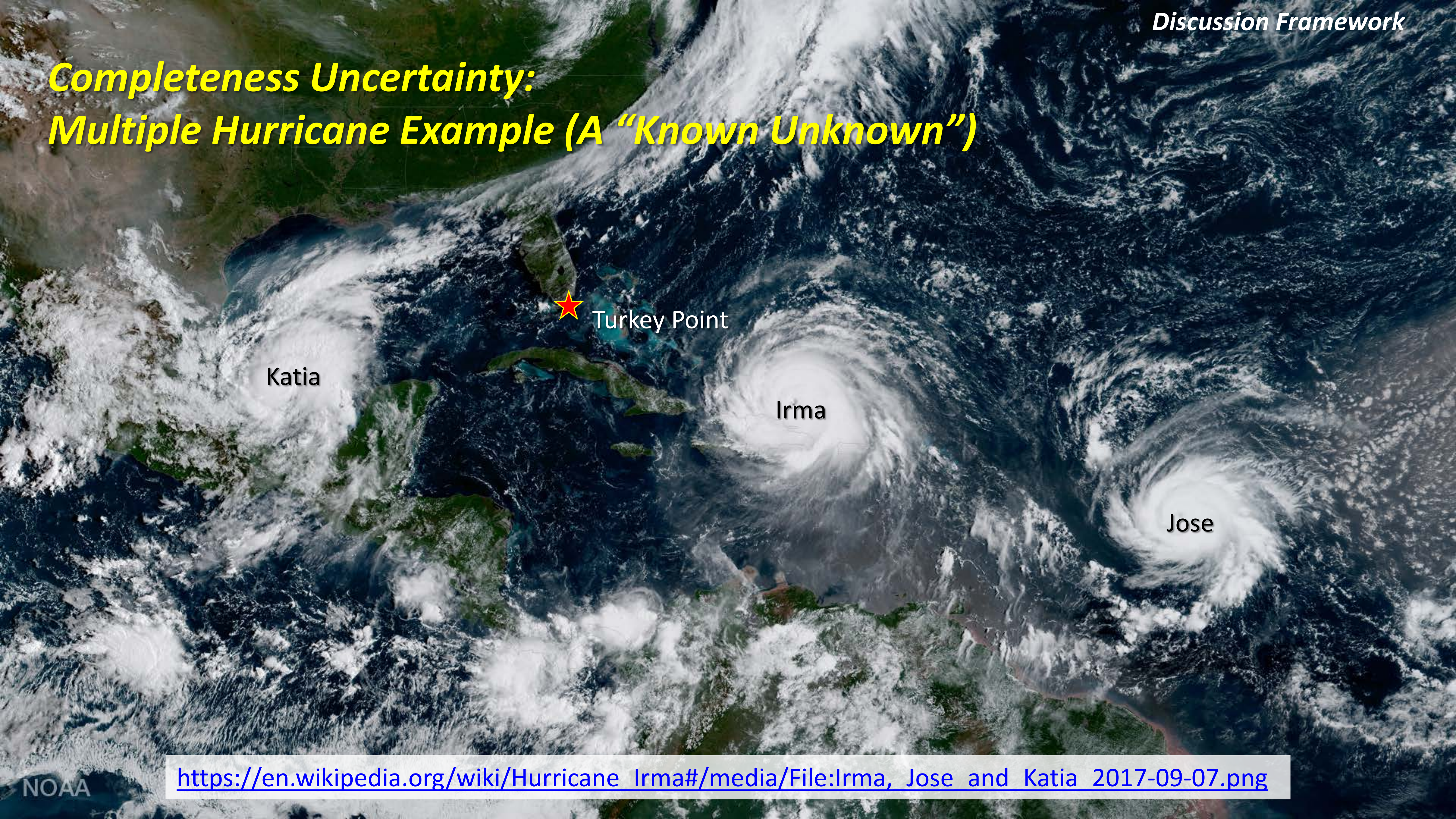
Model Uncertainty: Hurricane Example

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



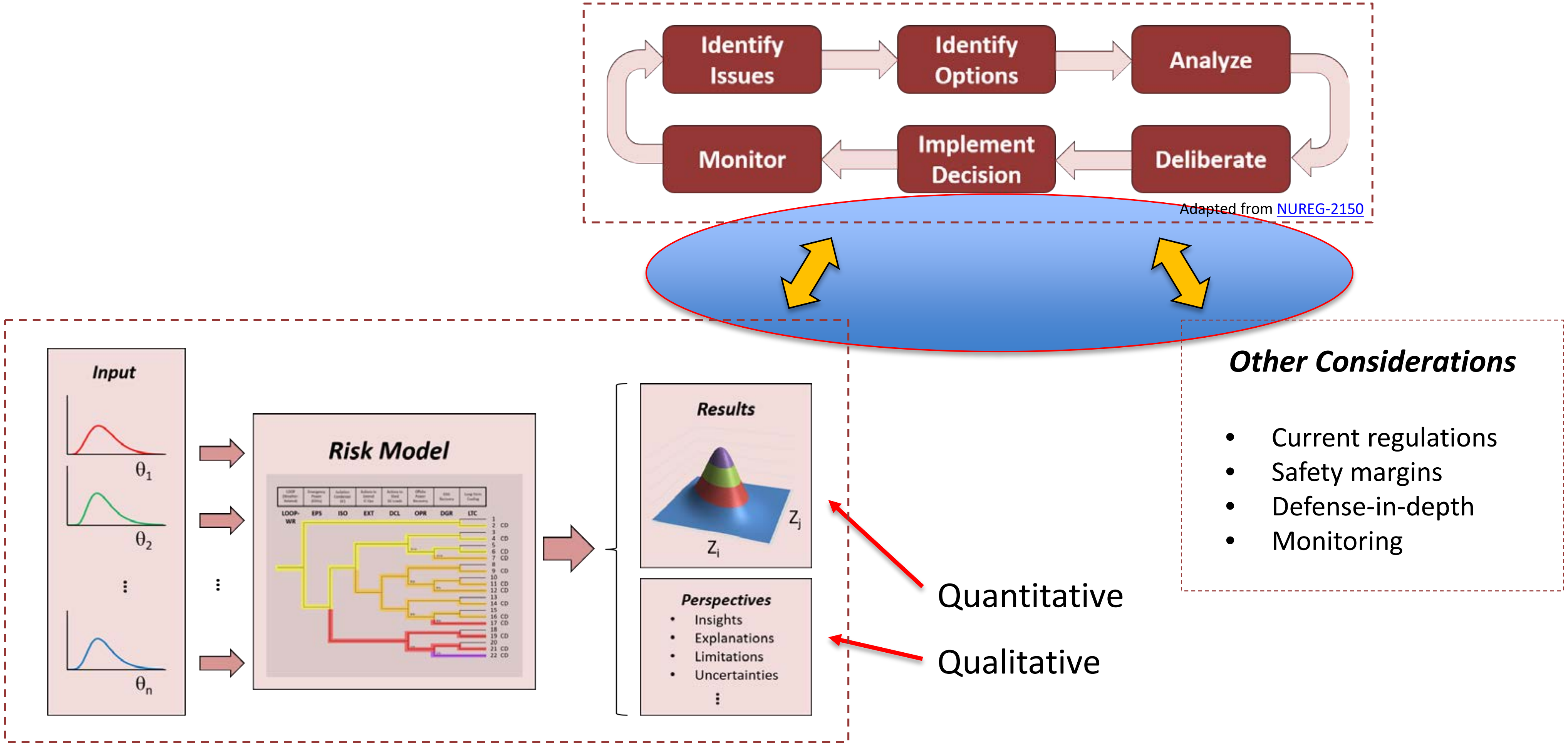
Plot adapted from University of Wisconsin-Milwaukee
(https://web.uwm.edu/hurricane-models/models/archive/)

Completeness Uncertainty: Multiple Hurricane Example (A "Known Unknown")



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

Risk Communication (Internal)

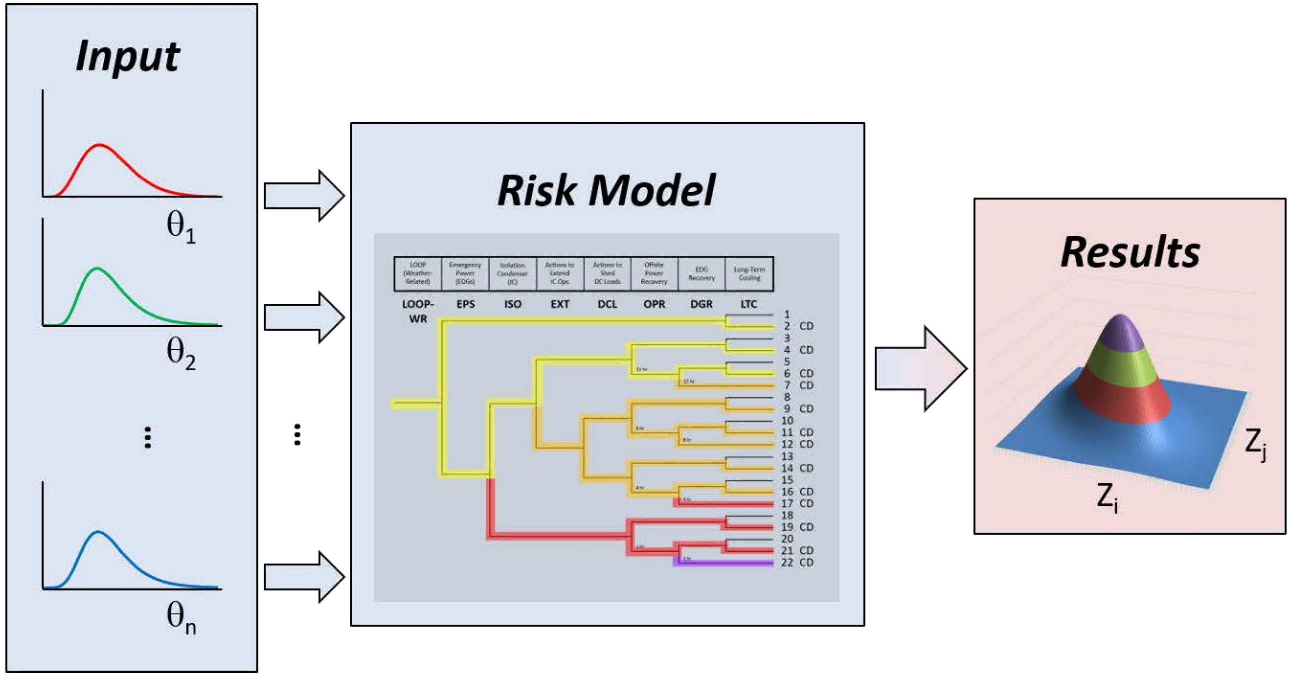


What do people do now?

CURRENT STATE-OF-PRACTICE

State-of-Practice: Parameter Uncertainties

- Treatment involves
  - Estimation (including expert elicitation)
  - Propagation
- Straightforward mathematics and mechanics
- Some practical challenges



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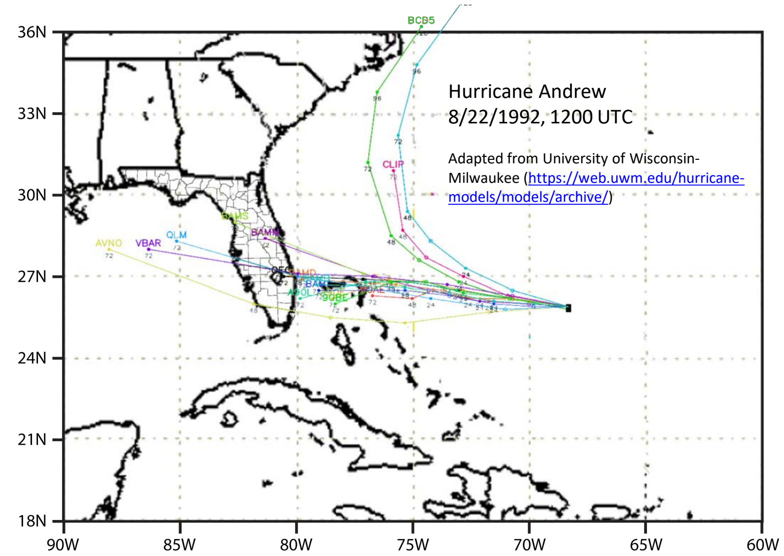
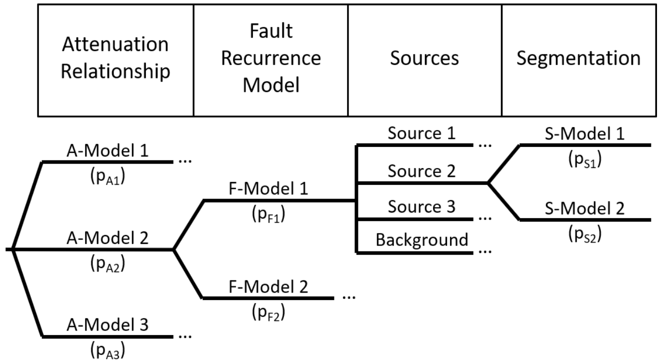
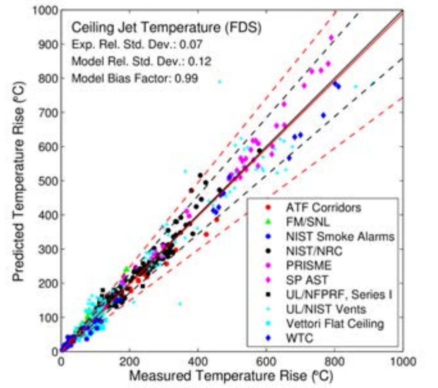
State-of-Practice: Model Uncertainties

- Important to acknowledge and treat (in context of decision)
- Multiple approaches
  - 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



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.

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State-of-Practice: Completeness Uncertainties

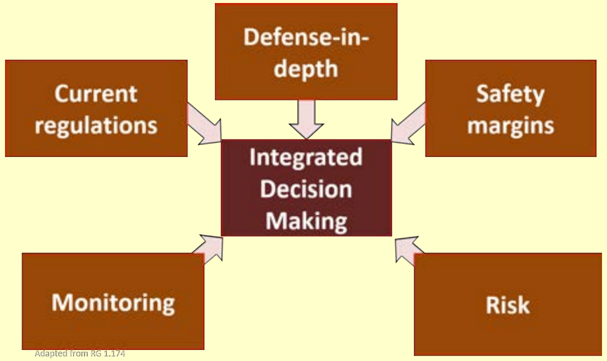
- Potential concerns
  - Known gaps (“missing scope”)
    - Scenario categories
    - Contributors within categories
  - Unknown gaps
  - Heuristics/biases
    - Excessive amplification (“fear of the dark”)
    - Excessive discounting (“out of sight, out of mind”)
- Treatment
  - Analysis guidance
  - Additional analysis/R&D
  - ***Risk-informed decisionmaking***

NUREG-1855 Rev. 1 (2017)

Options:

- Progressive analysis (screening, bounding, conservative, detailed…)
- Change scope of risk-informed application

RG 1.174 Rev. 3 (2019)



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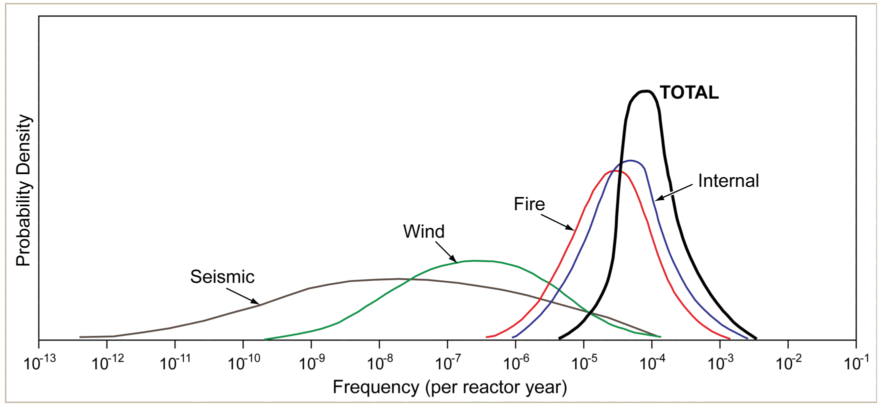
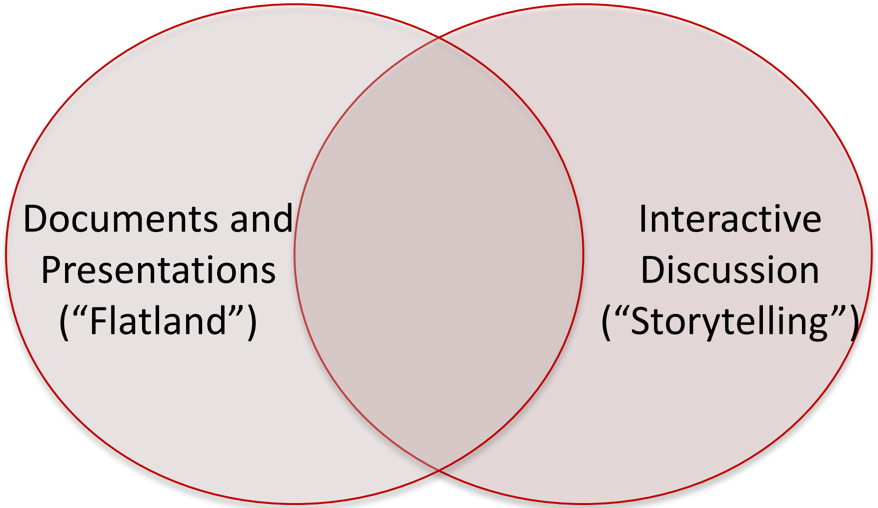
State-of-Practice: Internal Risk Communication

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



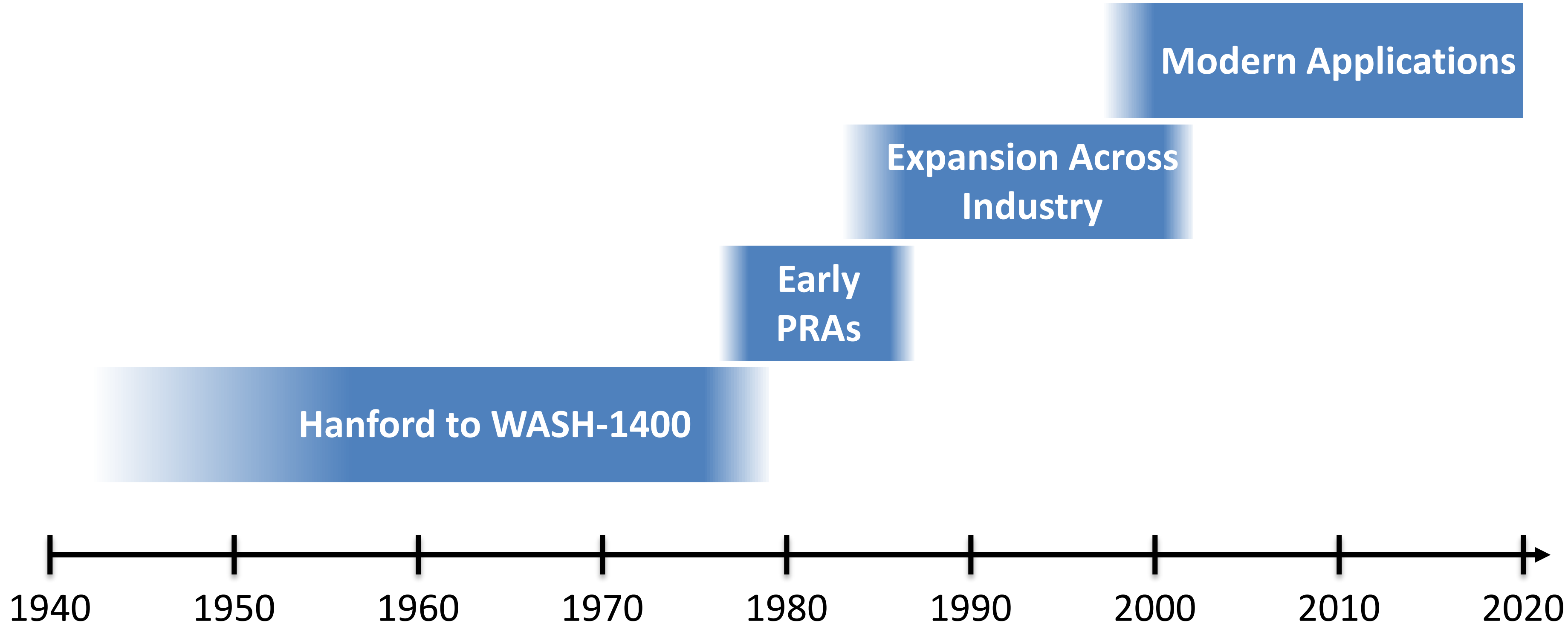


Severity Class	Likelihood Class: 5 (10^{-5}/yr)	4 (10^{-4}/yr)	3 (10^{-3}/yr)	2 (10^{-2}/yr)	1 (10^{-1}/yr)
A	Marginal	Undesirable	Undesirable	Critical	Critical
B	Marginal	Marginal	Undesirable	Undesirable	Critical
C	No Action	Marginal	Marginal	Undesirable	Undesirable
D	No Action	No Action	Marginal	Marginal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

How did we get here?

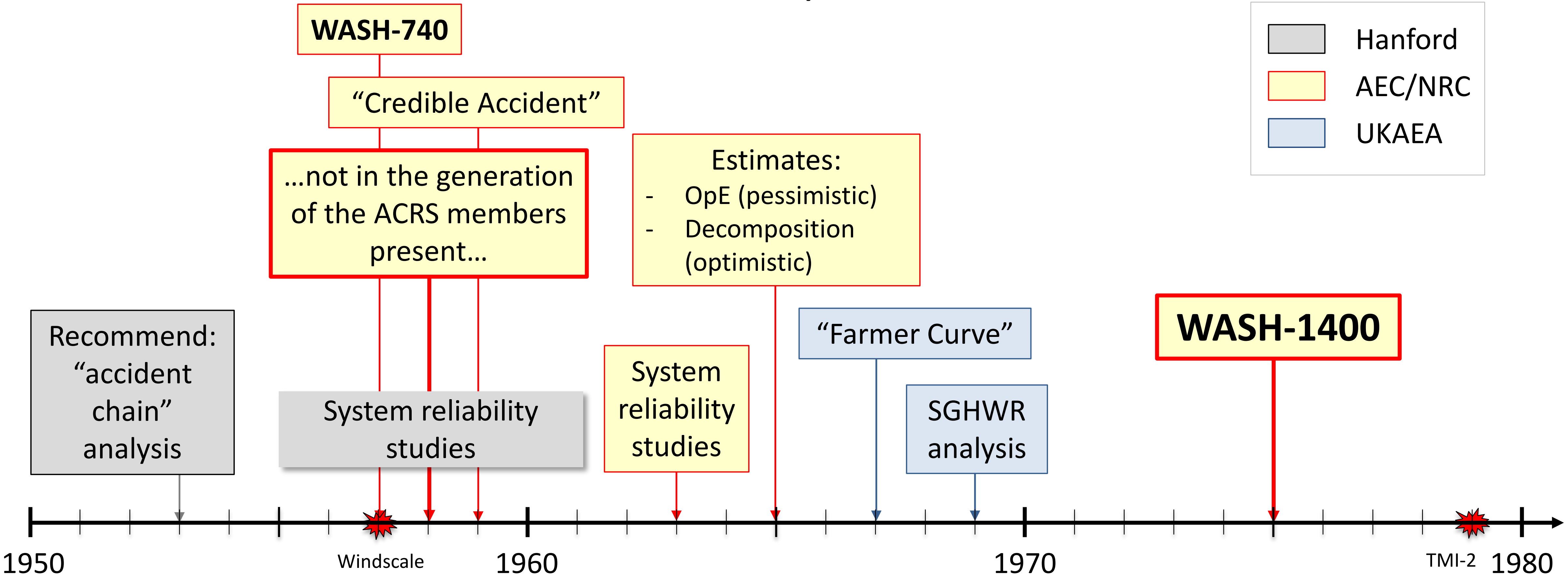
A BRIEF HISTORY

A Series of Challenges and Responses



From Hanford to WASH-1400

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

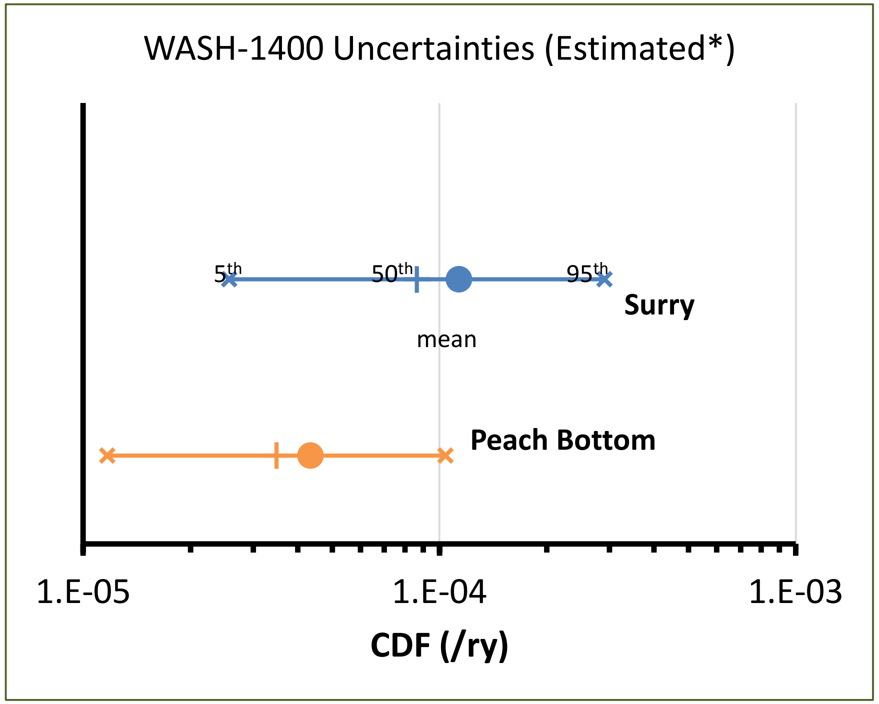


For more information: T.R. Wellock, "A Figure of Merit: Quantifying the Probability of a Nuclear Reactor Accident," *Technology and Culture*, **58**, No. 3, July 2017, pp. 678-721.

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."

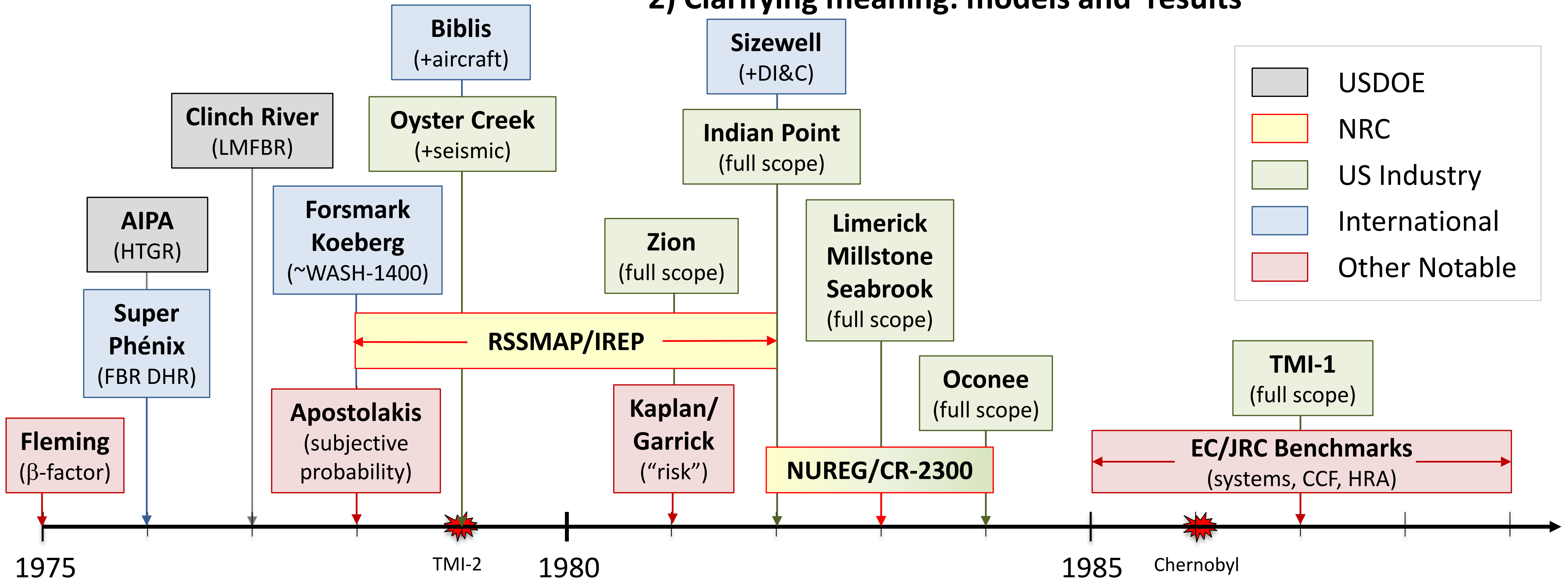
Risk Assessment Review Group (NUREG/CR-0400): "We are unable to define whether the overall probability of a core melt given in WASH-1400 is high or low, but we are certain that the error bands are understated. We cannot say by how much."



*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.

Some Early Developments and PRAs

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



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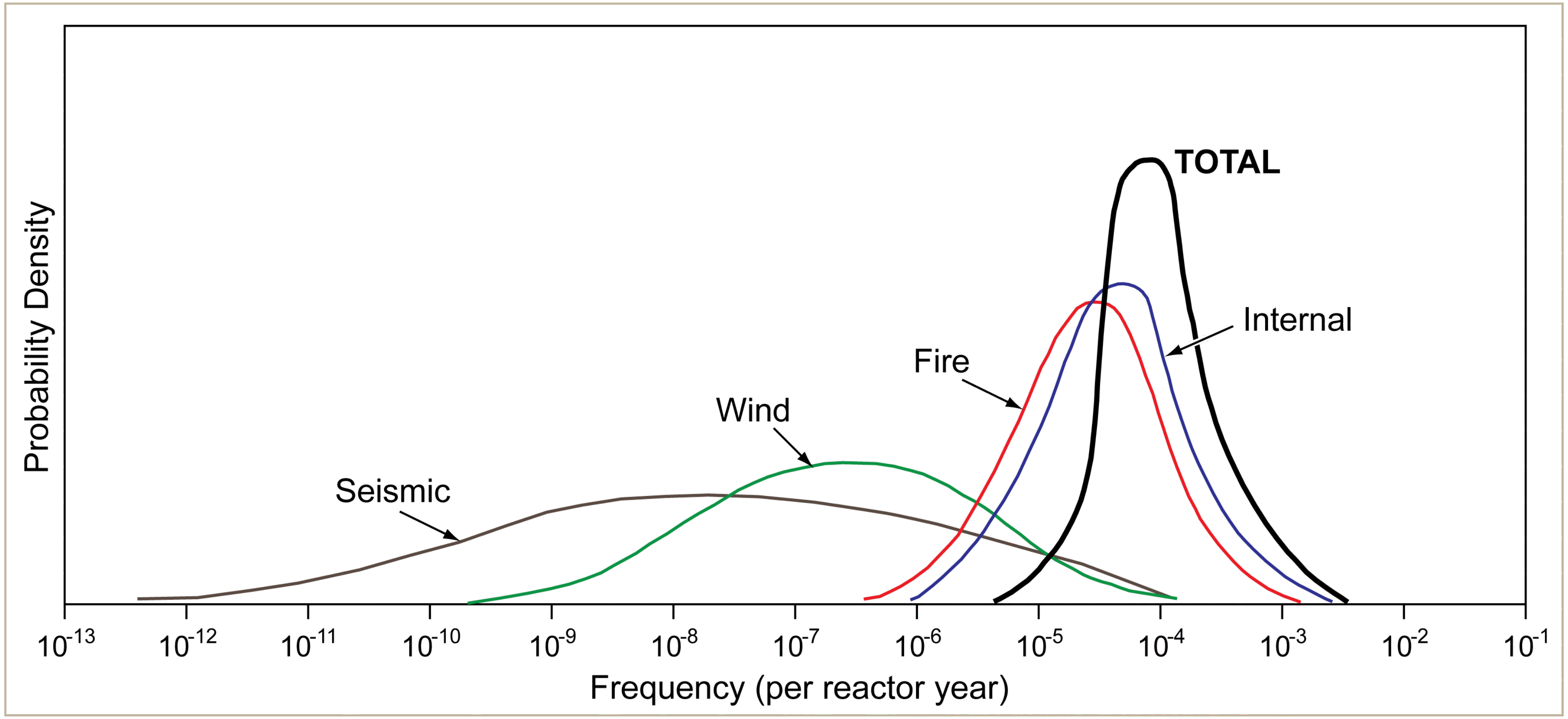
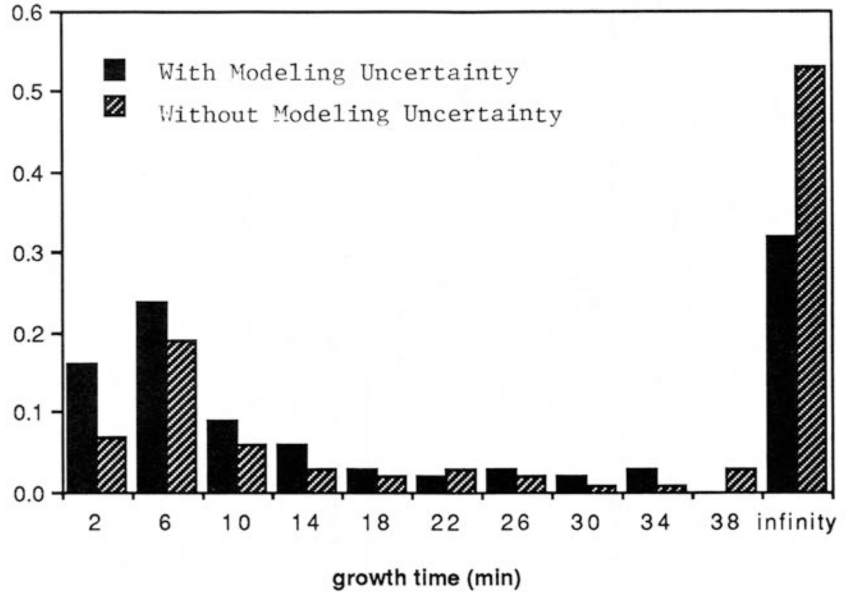
Sample Level 1 Results Display



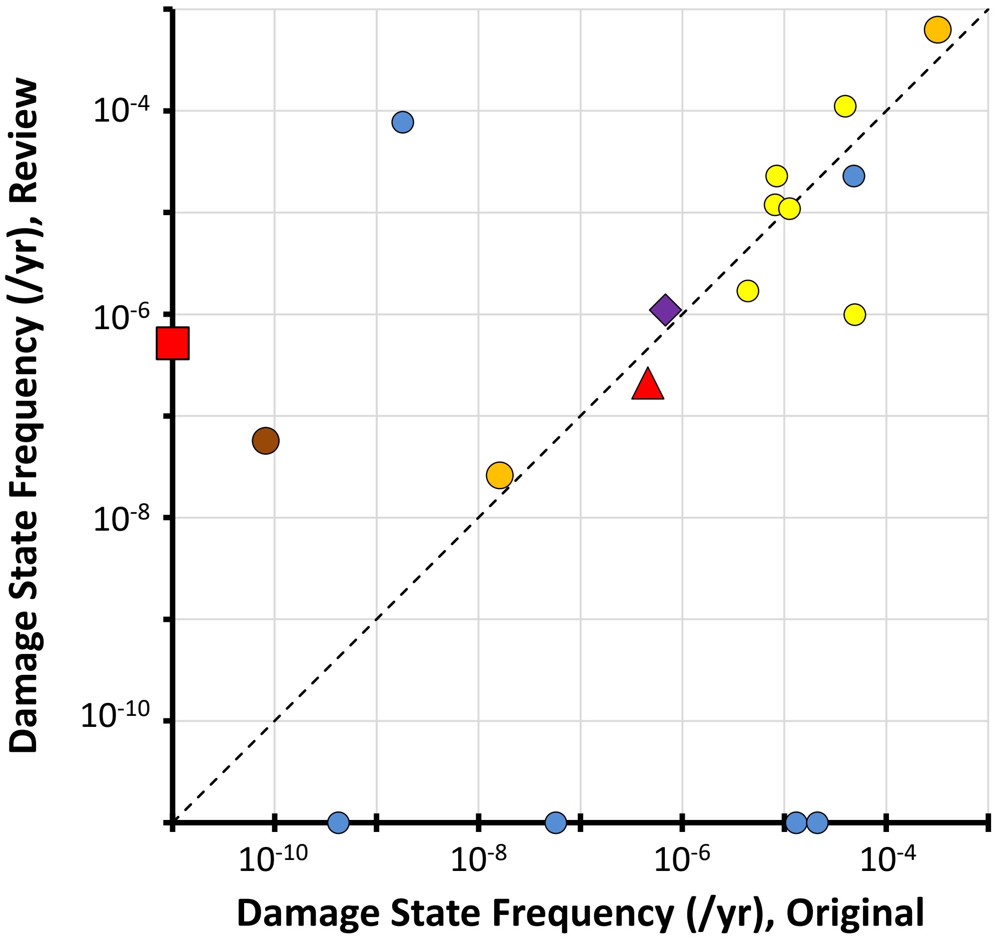
Sample Results – Sub-Model Uncertainty Effect

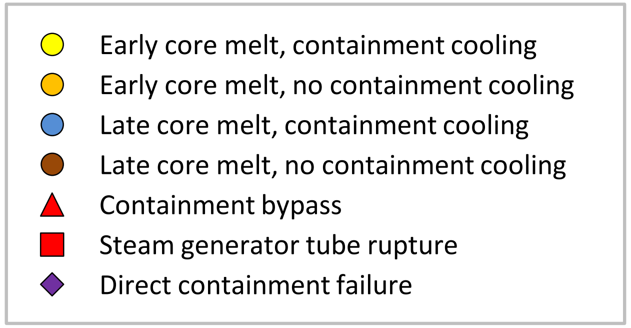


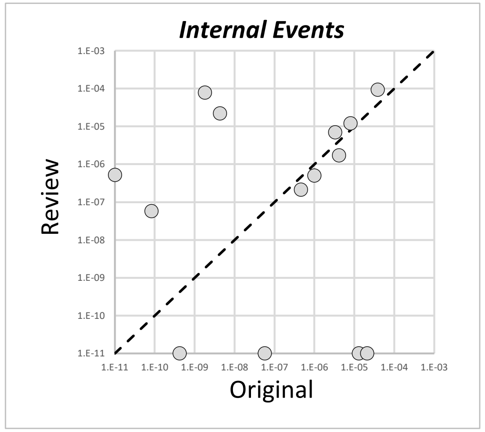
Effects of fire model (COMPBRN) uncertainty on fire growth time

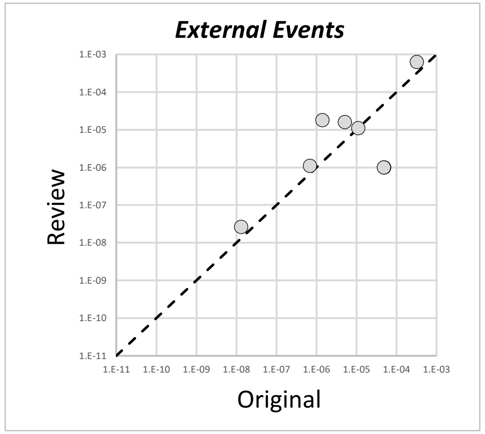
N. Siu, "Modeling Issues in Nuclear Plant Fire Risk Analysis," in EPRI Workshop on Fire Protection in Nuclear Power Plants, *EPRI NP-6476*, J.-P. Sursock, ed., August 1989, pp. 14-1 through 14-16.

Sample Results – Model Uncertainty ("User Effect")





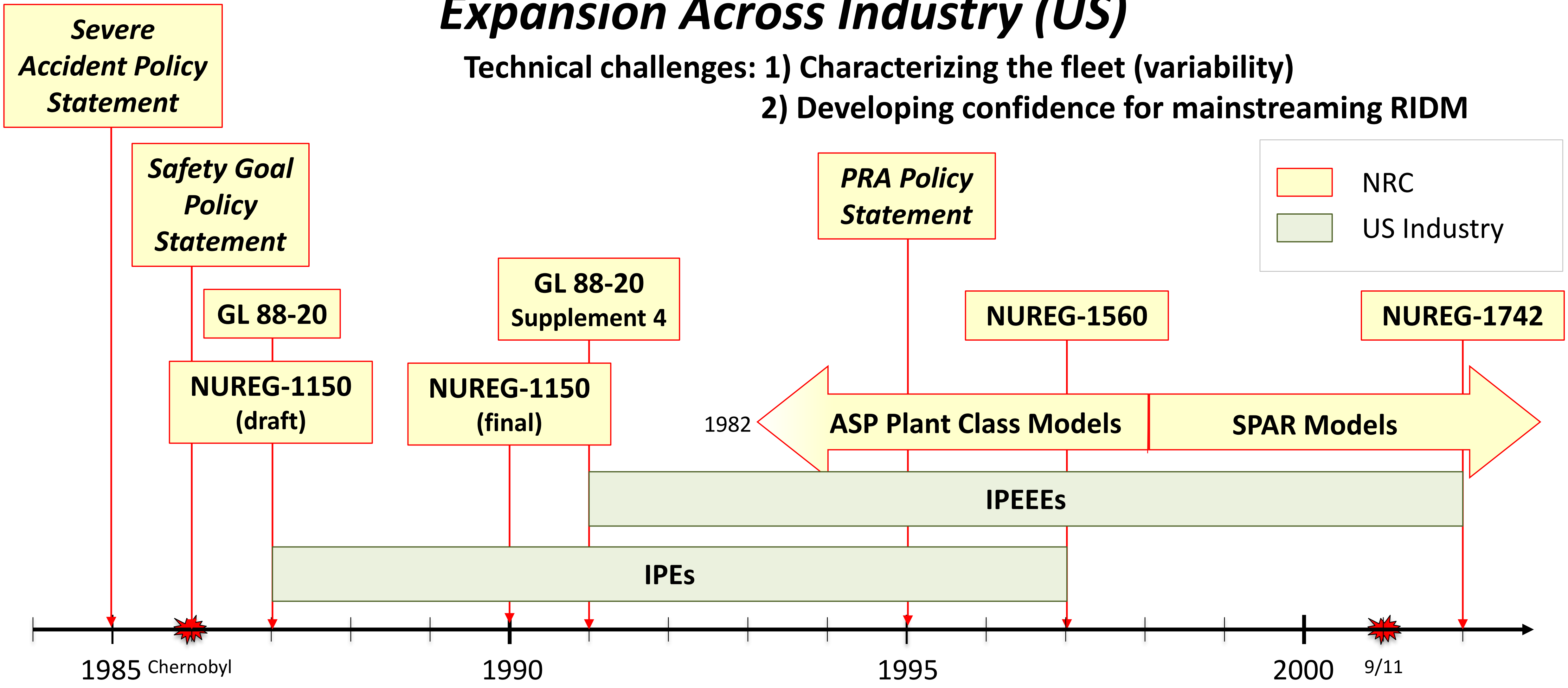




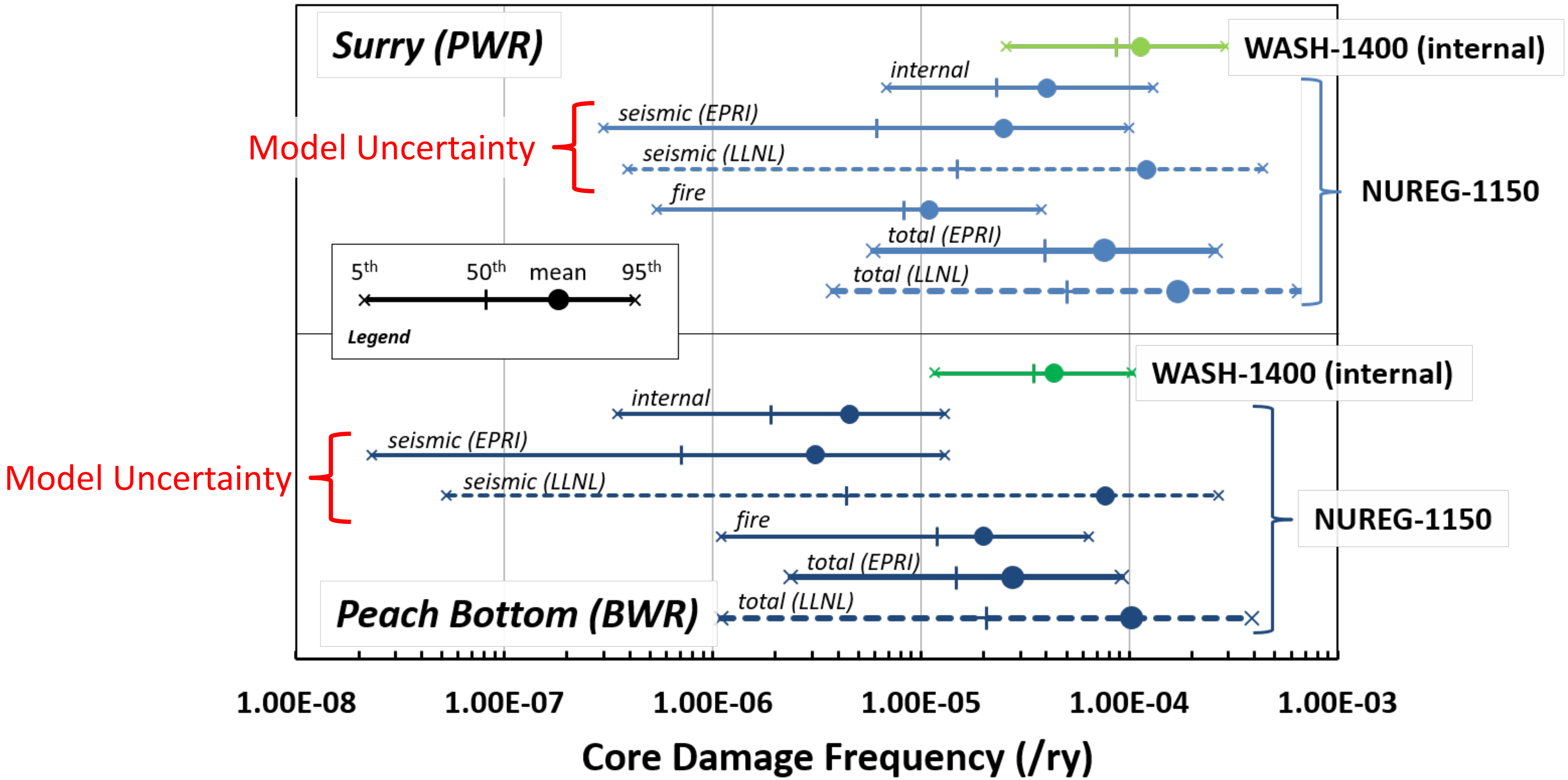
Data source: G.J. Kolb, et al., "Review and Evaluation of the Indian Point Probabilistic Safety Study," NUREG/CR-2934, December 1982. (ML091540534)

Expansion Across Industry (US)

Technical challenges: 1) Characterizing the fleet (variability)
2) Developing confidence for mainstreaming RIDM



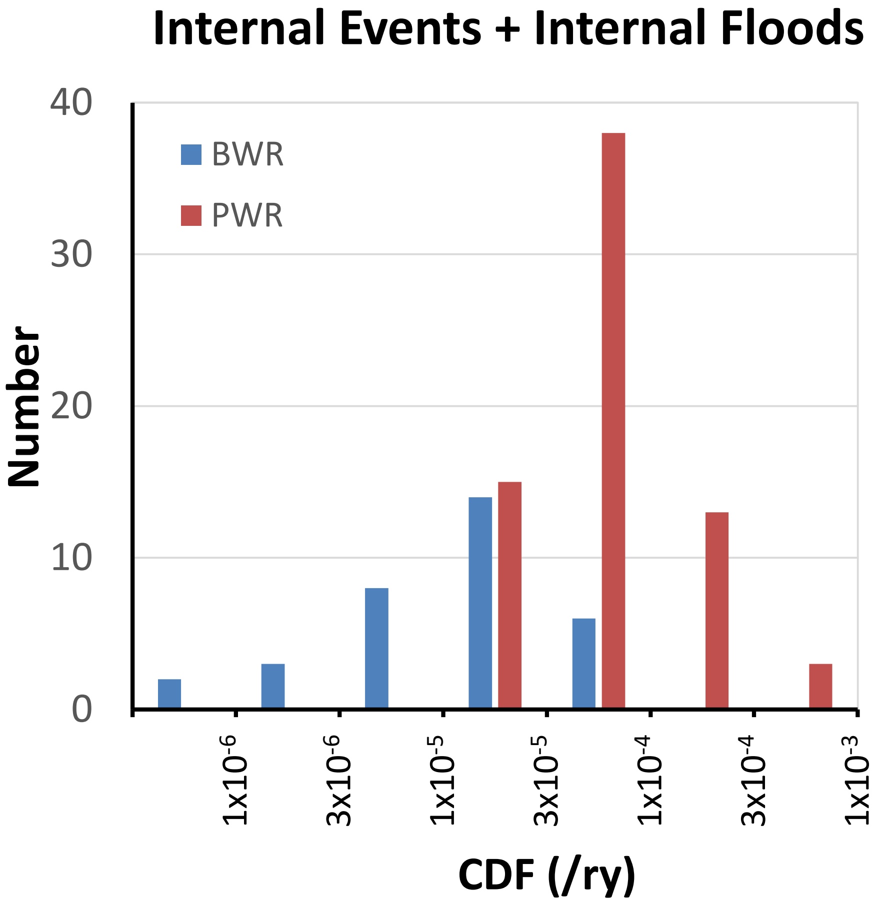
NUREG-1150 Estimated* Uncertainties (Level 1)

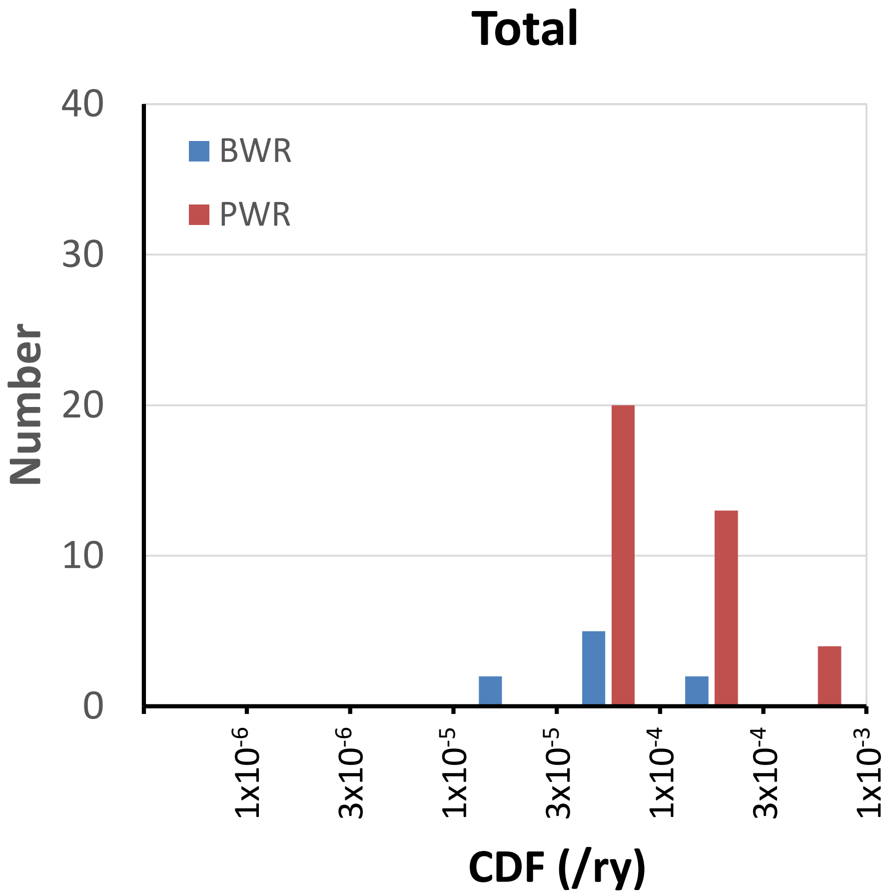


*Notes: totals shown in this

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

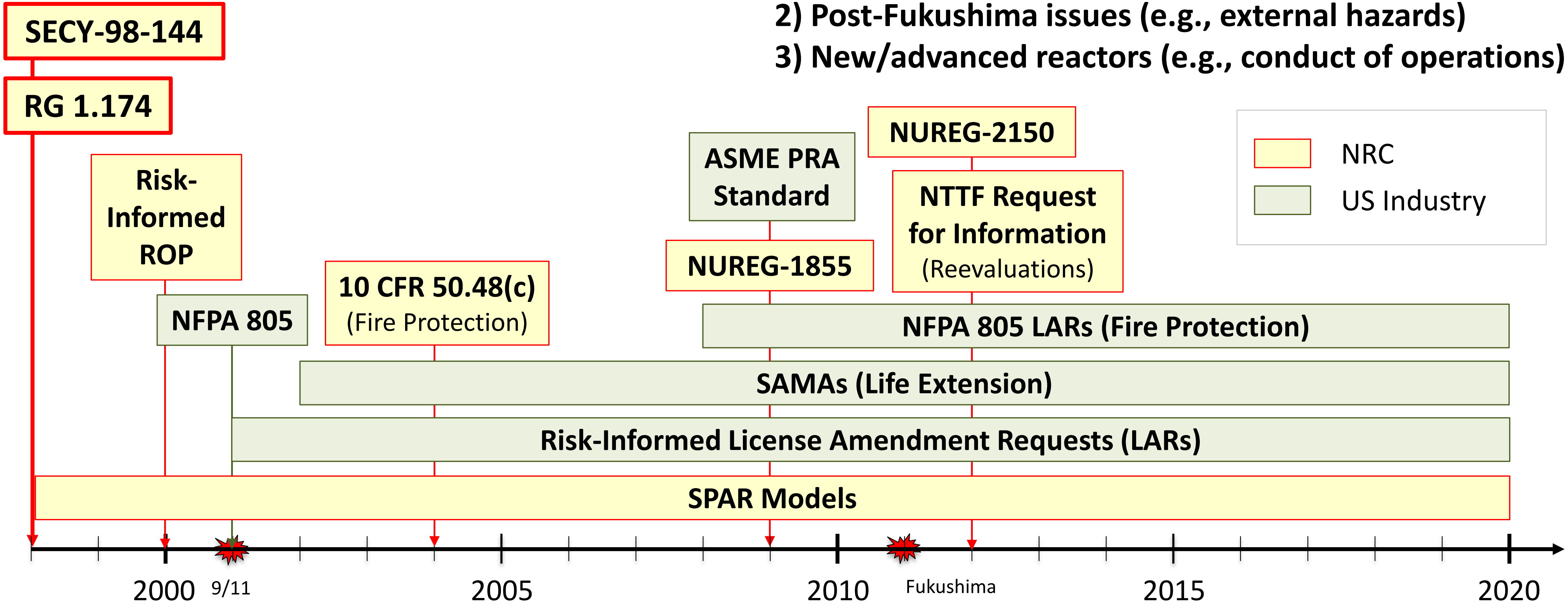
IPE/IPEEE – Variability Across Fleet



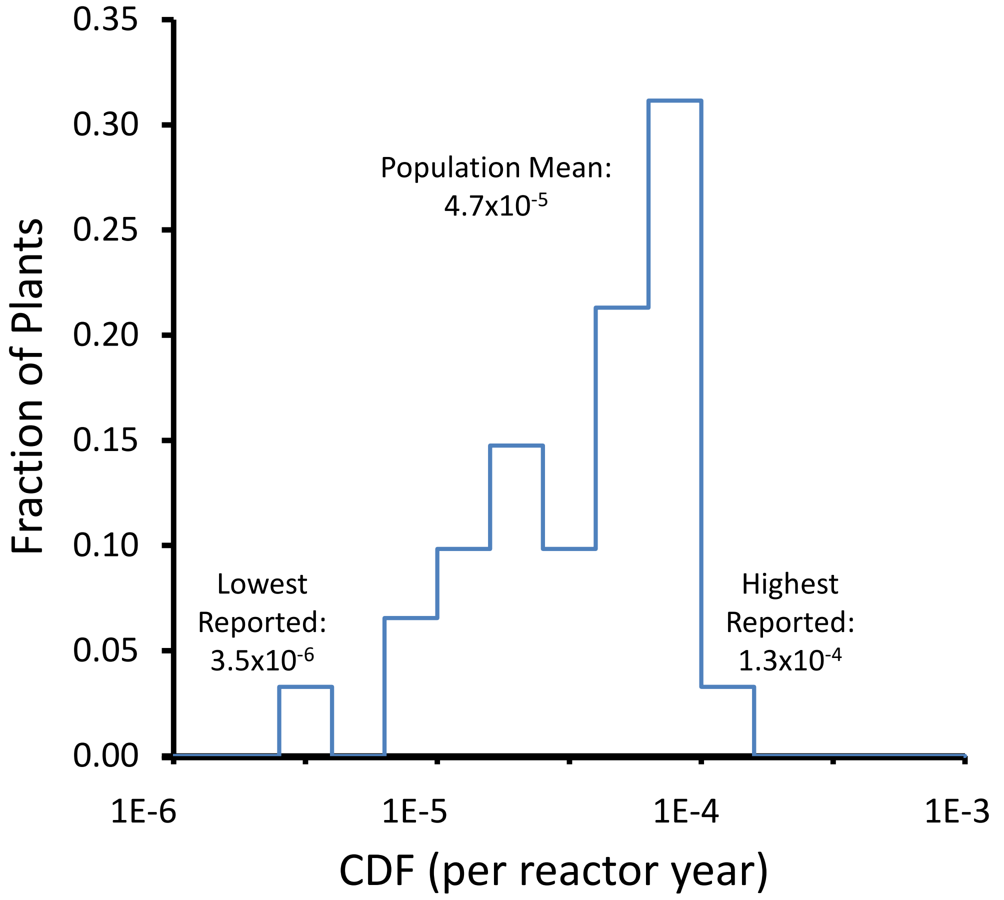


The Modern Era (US)

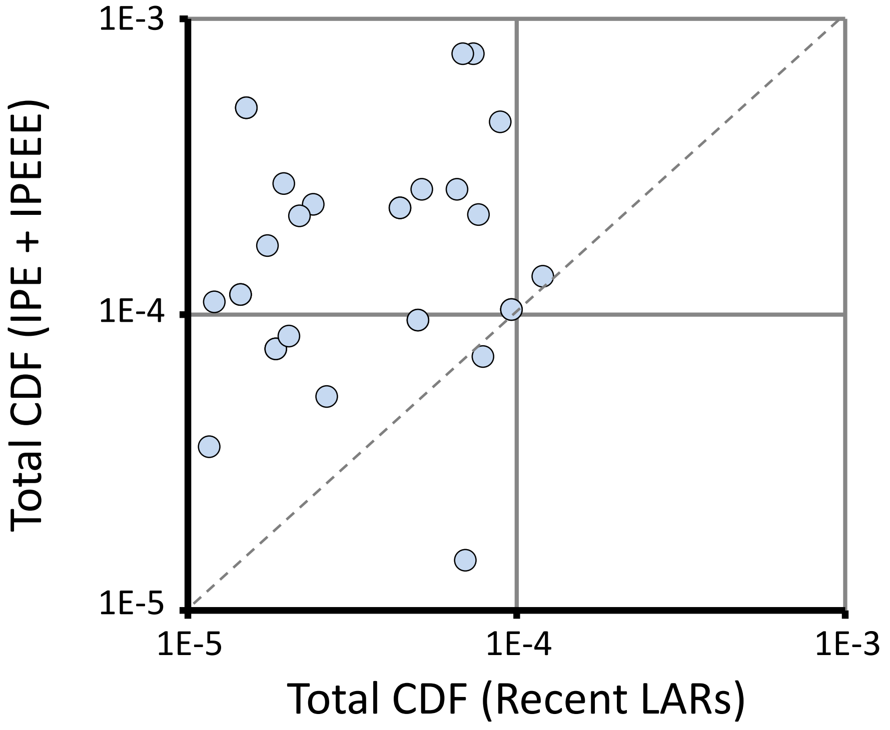
Technical challenges: 1) RIDM issues (e.g., realism, heterogeneity, aggregation)
2) Post-Fukushima issues (e.g., external hazards)
3) New/advanced reactors (e.g., conduct of operations)

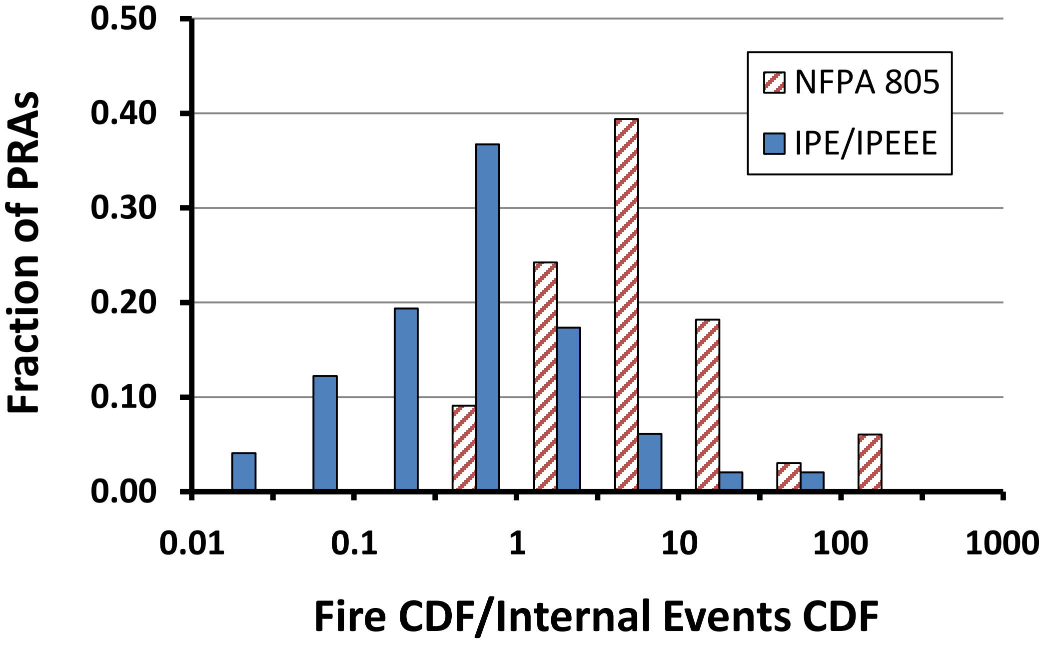


Variability in Recent Results (Level 1)



Variability in Results – Comparison with IPE/IPEEE





Where might we do better and how?

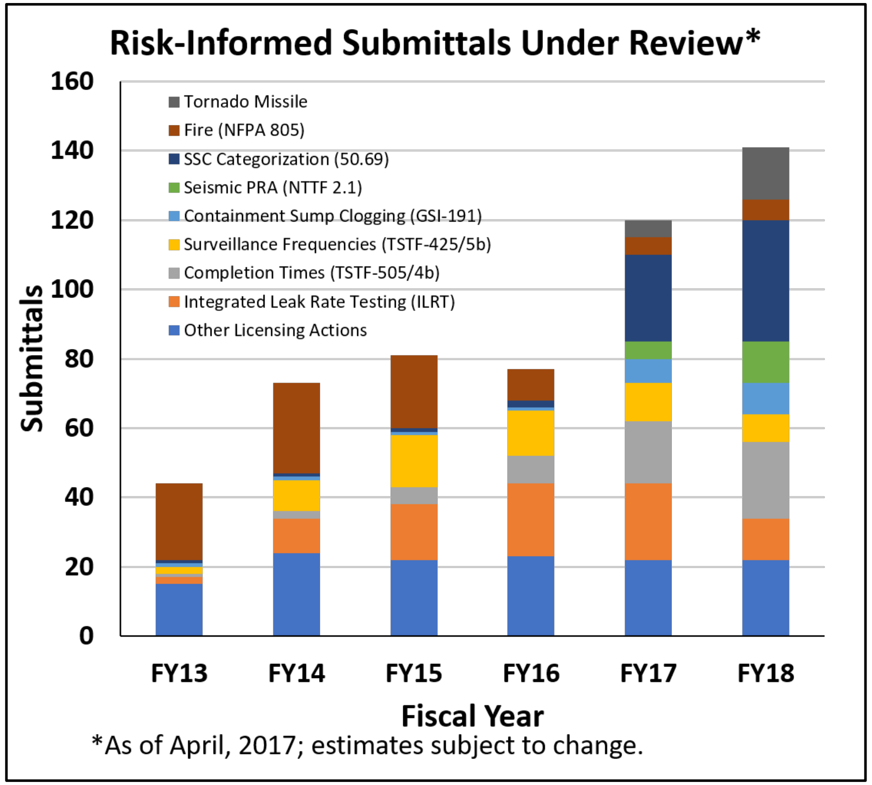
COMMENTARY AND CHALLENGES

An Important Note

- Challenges regarding the treatment of uncertainty in PRA and RIDM exist for non-probabilistic approaches as well; the PRA/RIDM approach acknowledges these challenges explicitly.
- The following slides are not a critique of the overall PRA/RIDM philosophy – they should be viewed in the framework of continuous improvement.

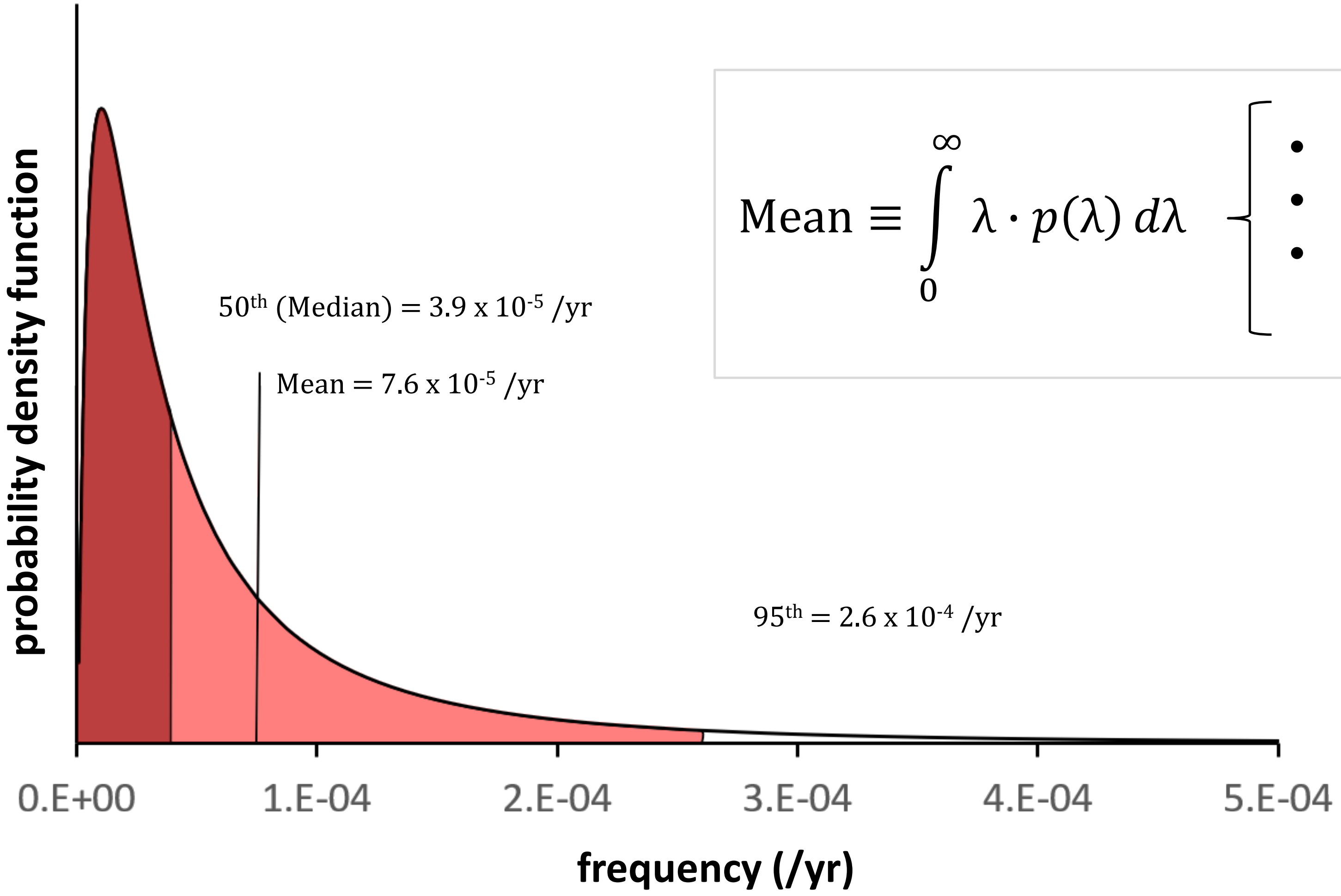
A Changing World

- Evolving situation*
  - market forces
  - new nuclear technologies
  - new analytical methods and data
  - new professionals
- Increased reliance on risk models, characterization of uncertainties



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

Reminder: Parameter Uncertainties and Mean Values



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

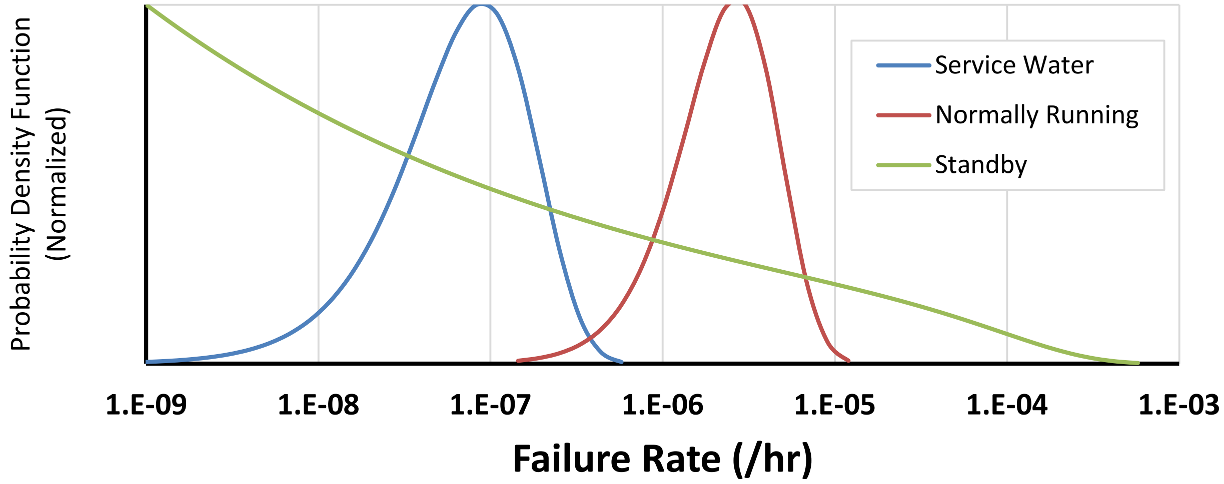
- Mathematically defined
- Affected by tail
- Does not correspond to a specific percentile

Parameter Uncertainties: Challenges

- Quantification generally required, diverse views on value added
- Technical challenges:
  - Effect of data pre-processing
    - Selection
    - Interpretation
  - Effect of analysis shortcuts
    - Standard prior distributions
    - Simplified expert elicitation
    - Independence assumption
  - Ensuring correspondence with actual state-of-knowledge
    - Basic events (micro)
    - Overall results (macro)

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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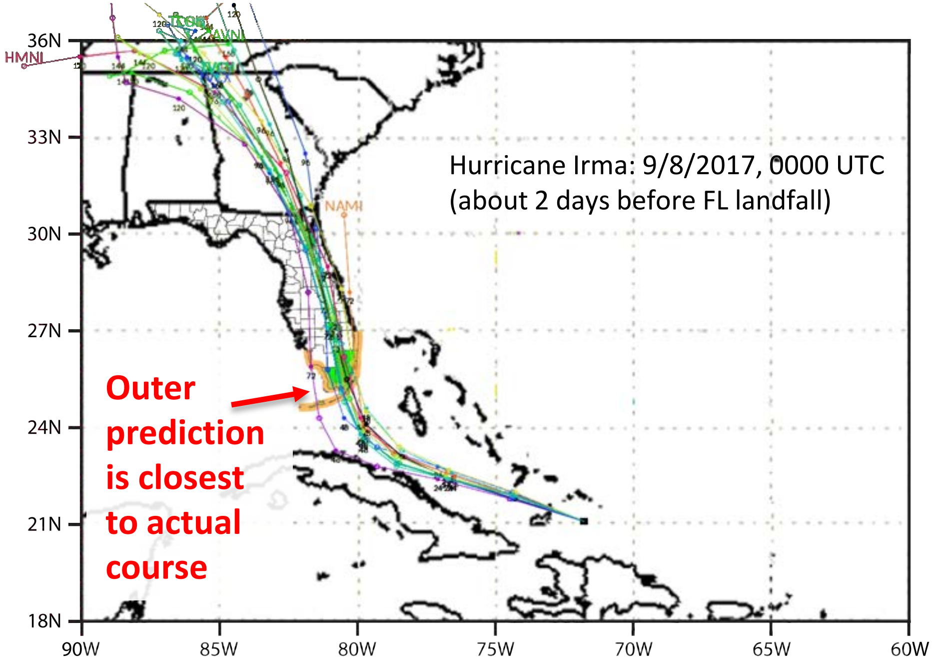
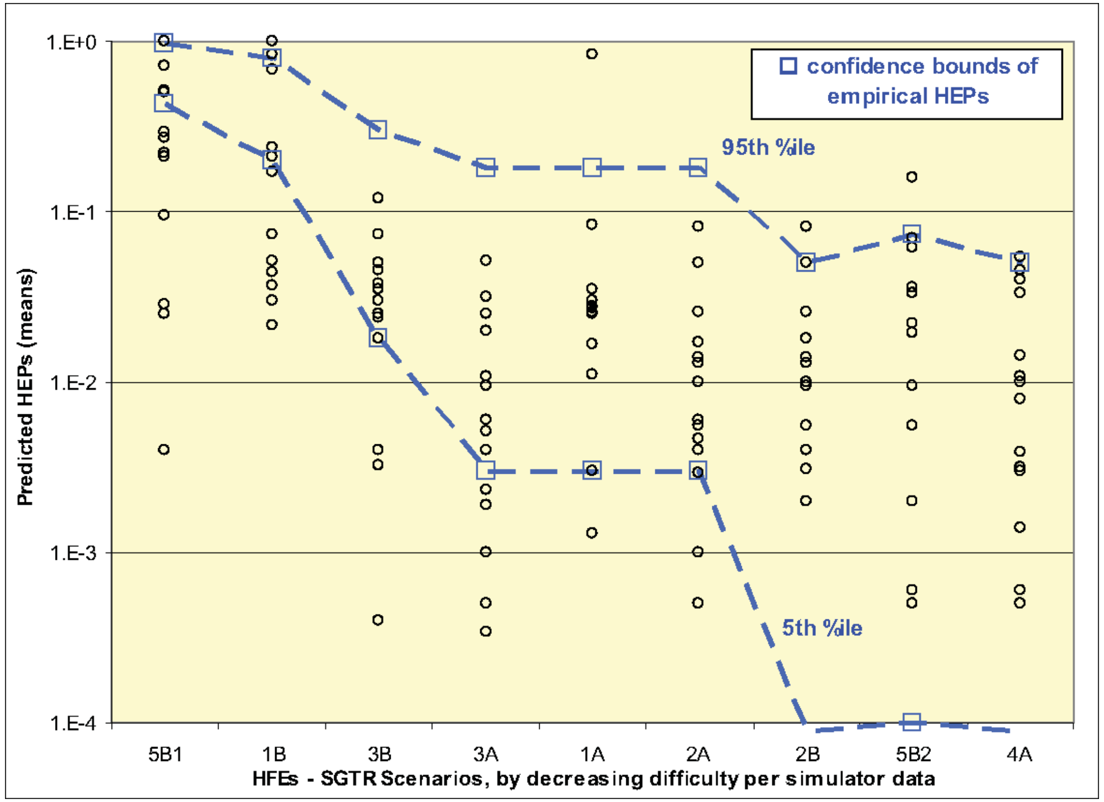
Model Uncertainties - Commentary

- Model uncertainties can be large; importance depends on decision
- Some practical approaches (e.g., consensus models, deterministic screening) can understate uncertainties
- Subjective probability framework =>
  - Need to include "user effect"
  - Raises question regarding fundamental meaning of weighted average approaches
- Model output uncertainty approach is appealing but care is needed in implementation

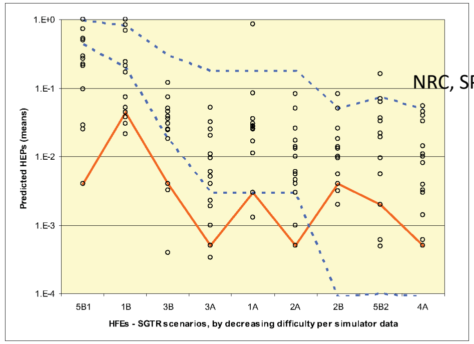


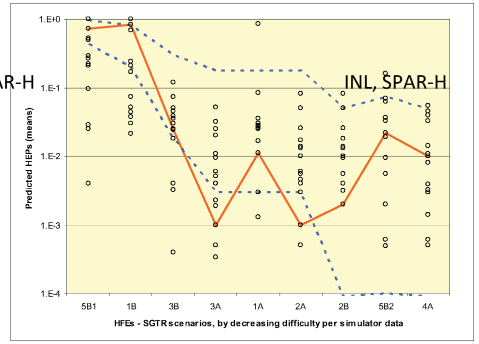
Plot adapted from University of Wisconsin-Milwaukee (https://web.uwm.edu/hurricane-models/models/archive/)

Model Uncertainty User Effects: HRA Example 1

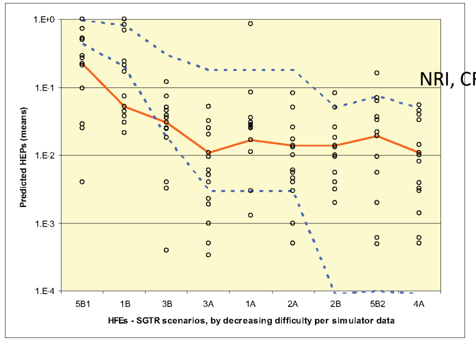


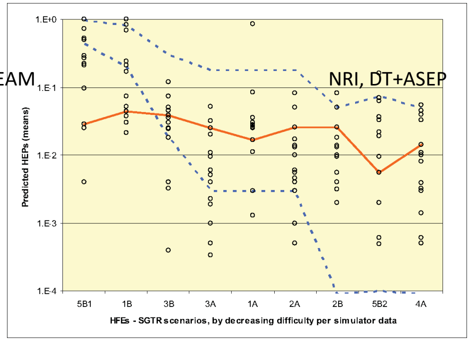
All teams, all methods





Same method, different teams

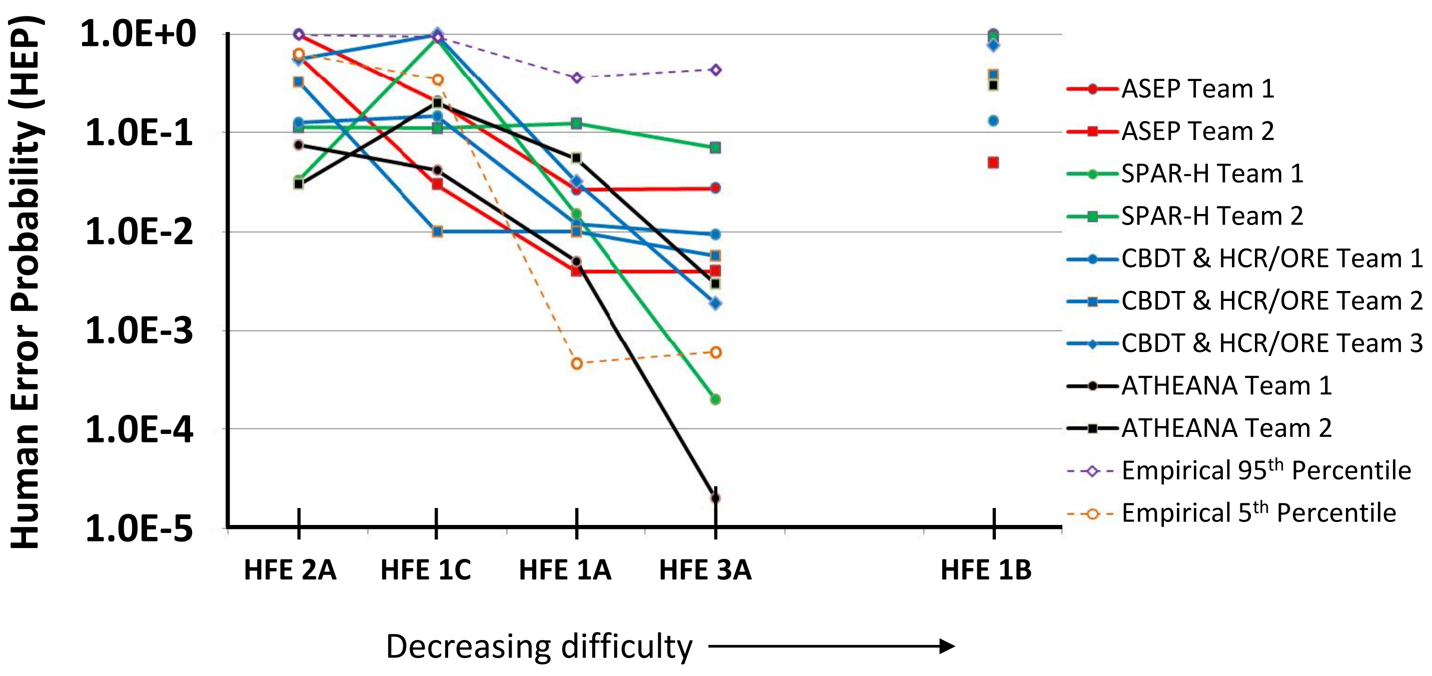




Same team, different methods

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

Model Uncertainty User Effects: HRA Example 2



Adapted from NUREG-2156

Challenges: Quantification of Model Output Uncertainty

- Bayesian methods
  - Framework consistent with overall PRA
  - Early approaches used in past PRAs
  - Can address practical issues (e.g., non-homogeneous data)*
- Challenges include
  - Uncertainties in unmeasured parameters
  - Sub-model limits of applicability
  - Representativeness of computed results

Data

Time (s)	Experiment (K)	DRM (K)
180	400	450
360	465	510
720	530	560
840	550	565

Output Uncertainty

	Temperature (K)	
Percentile	Assume Homogeneous Data	Assume Non-Homogeneous Data
1st	415.2	372.8
5th	437.5	400.7
50th	457.1	470.5
95th	479.7	559.4
99th	509.1	608.7

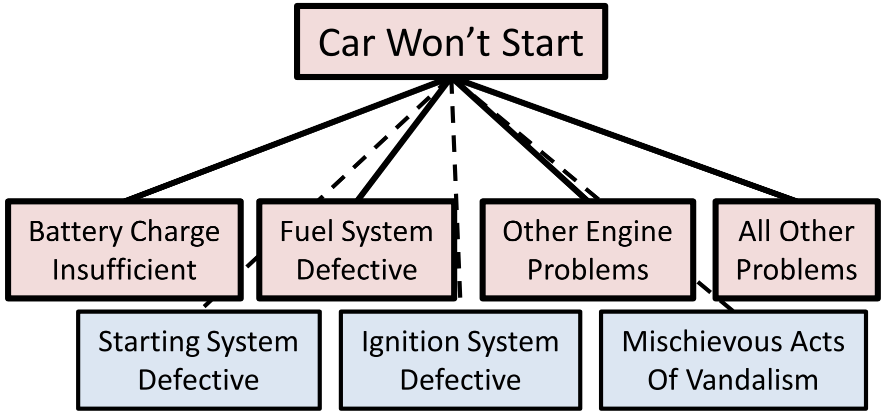
*See E. Droguett and Ali Mosleh, "Bayesian methodology for model uncertainty using model performance data," *Risk Analysis*, **28**, No. 5, 1457-1476, 2008.

Completeness Uncertainty

- 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)



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.

Known Gaps ("Known Unknowns")

- Broad scenario categories

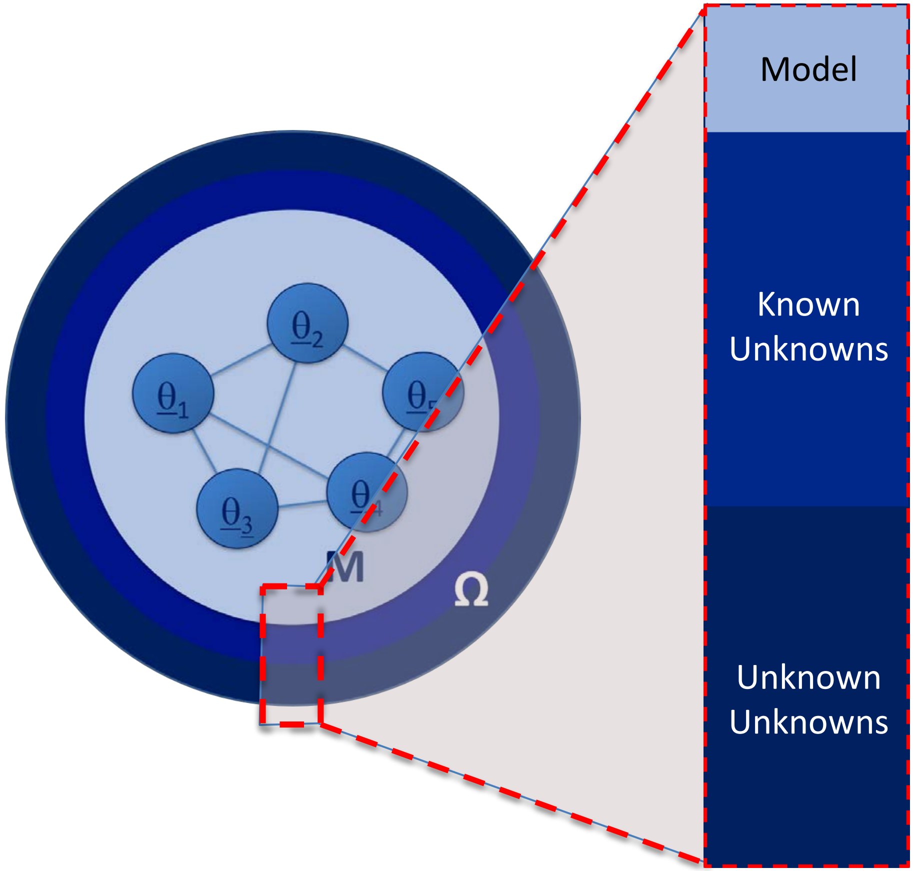
Rationale	Common Example(s)
Out of scope	security/sabotage, operation outside approved limits
Low significance (pre-analysis judgment)	external floods (many plants pre-Fukushima)
Appropriate PRA technology* unavailable	management and organizational factors
PRA "not appropriate"	software, security

- 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

*Technology = {methods, models, tools, data}

Unknown Unknowns: "You Say Tomāto…"



- Explicit or implicit?
- Extent of coverage?

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

Viewpoint

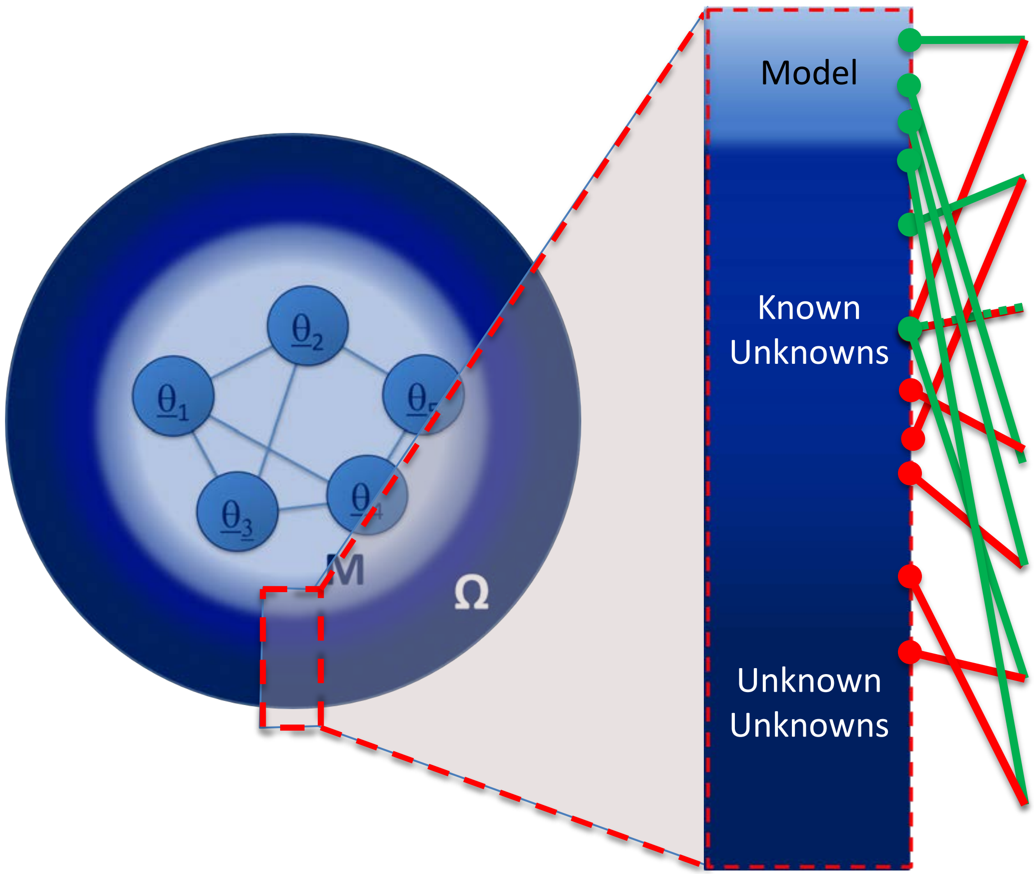
Precise classification is important only if it affects:

- Understanding
- Communication
- Decision making

Unknown Unknowns: A Demonstrated Problem?

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

Illuminating Uncertainties: From Lampposts to Search Beacons

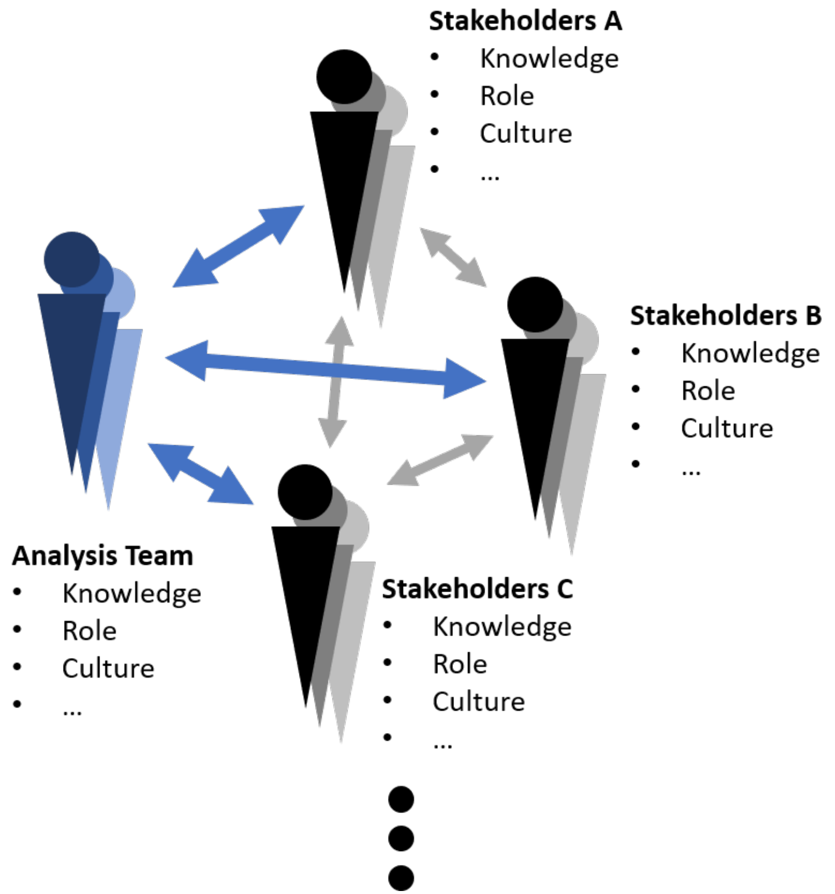
What Can "We" (PRA R&D) Do?

- 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
…

*Sources of Breakdowns: Risk Communication Between Risk Managers and Public**

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



*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)

Risk Information: Inherently Complex

- 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

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

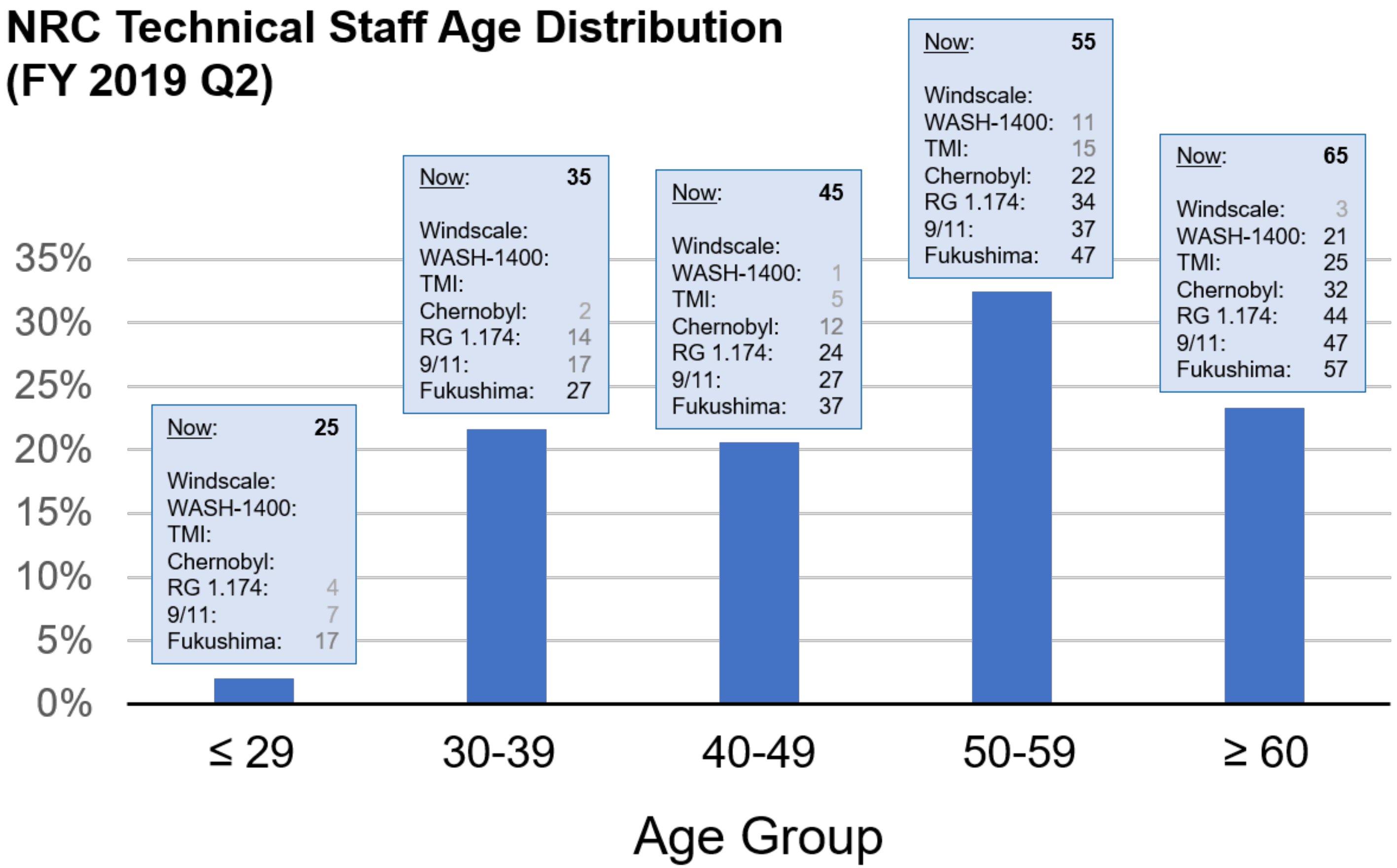
I. Flatow, "Truth, Deception, and the Myth of the One-Handed Scientist," October 18, 2012. Available from: https://thehumanist.com/magazine/november-december-2012/features/truth-deception-and-the-myth-of-the-one-handed-scientist

…and the World is changing…

- 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

Addressing Complexity (and Escaping "Flatland")

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

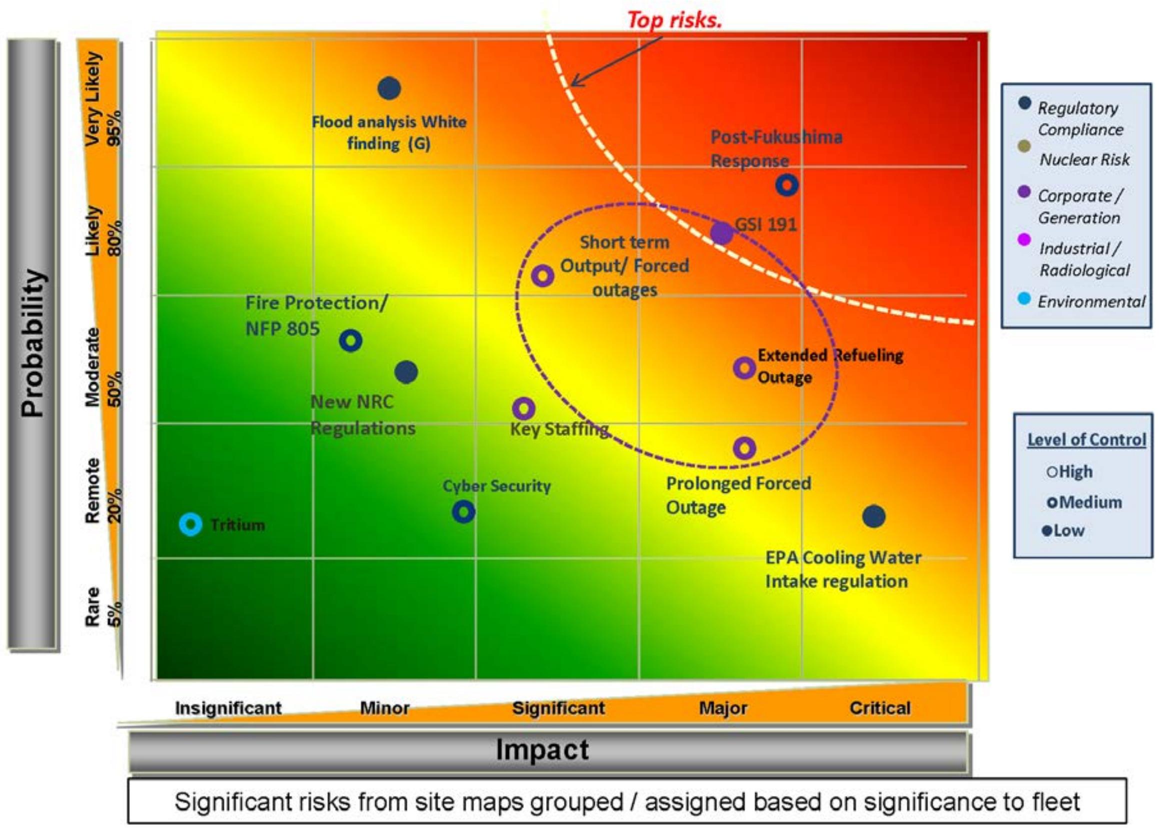
Time

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

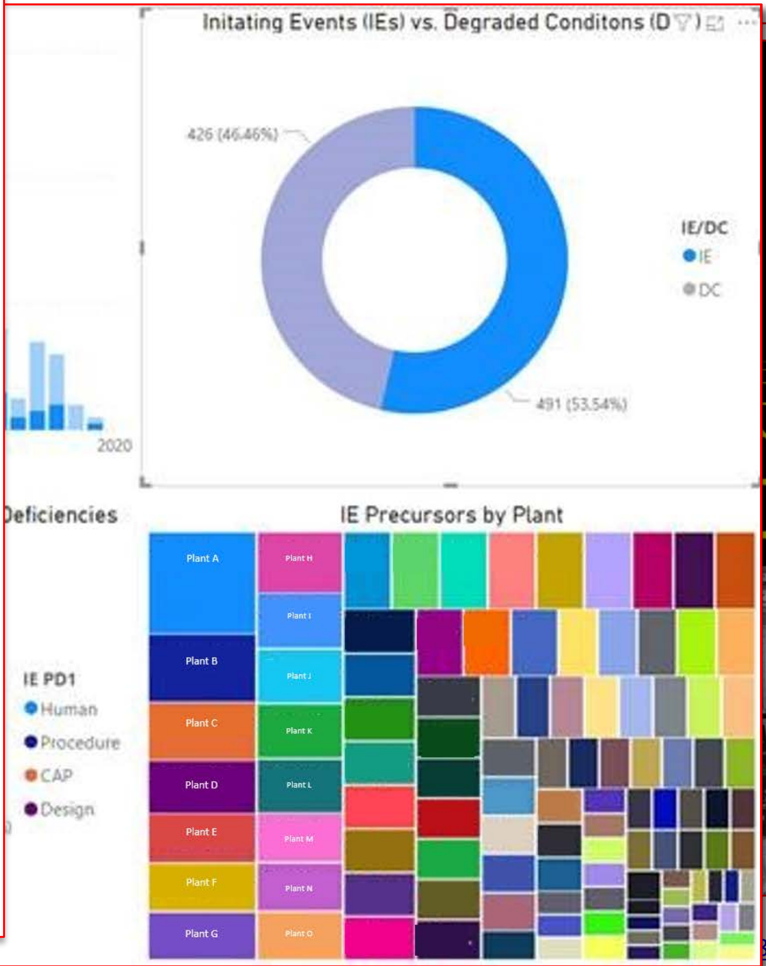
Continuing Challenges

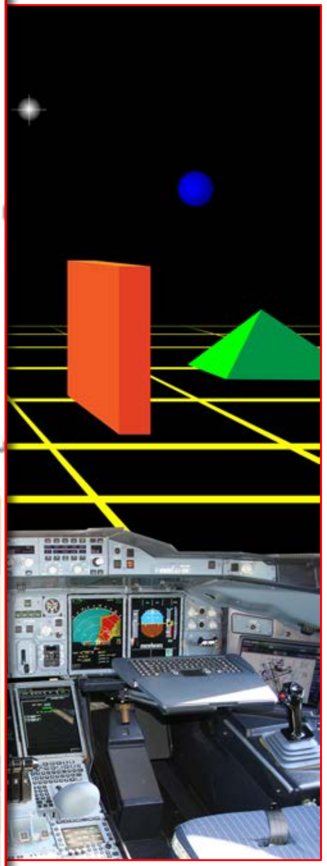
- Target audience(s)
  - Heterogeneous
  - Changing
  - Constrained resources
- Schema
  - No standards: currently an art
  - "Solutions" being developed intuitively; no scientific testing

From Static to Interactive Dashboard to Sci-Fi?



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.





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(permission CC-BY-2.0)

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

Closing Remarks

- RIDM, enabled by PRA, provides a practical approach to safety-related decisionmaking under uncertainty
- Appropriate application of RIDM requires appropriate characterization and communication of uncertainties, supported by technology
- Moving forward: bold exploration or avoidance? Jason/桃太郎 (Momotarō) or Pandora/浦島 太郎 (Urashima Tarō)?

> 多算勝，少算不勝，而況無算乎！
>
> "Many calculations bring success; few calculations bring failure. No calculations at all spell disaster!"
>
> - *Sun-Tzu (The Art of War)*

Acknowledgments

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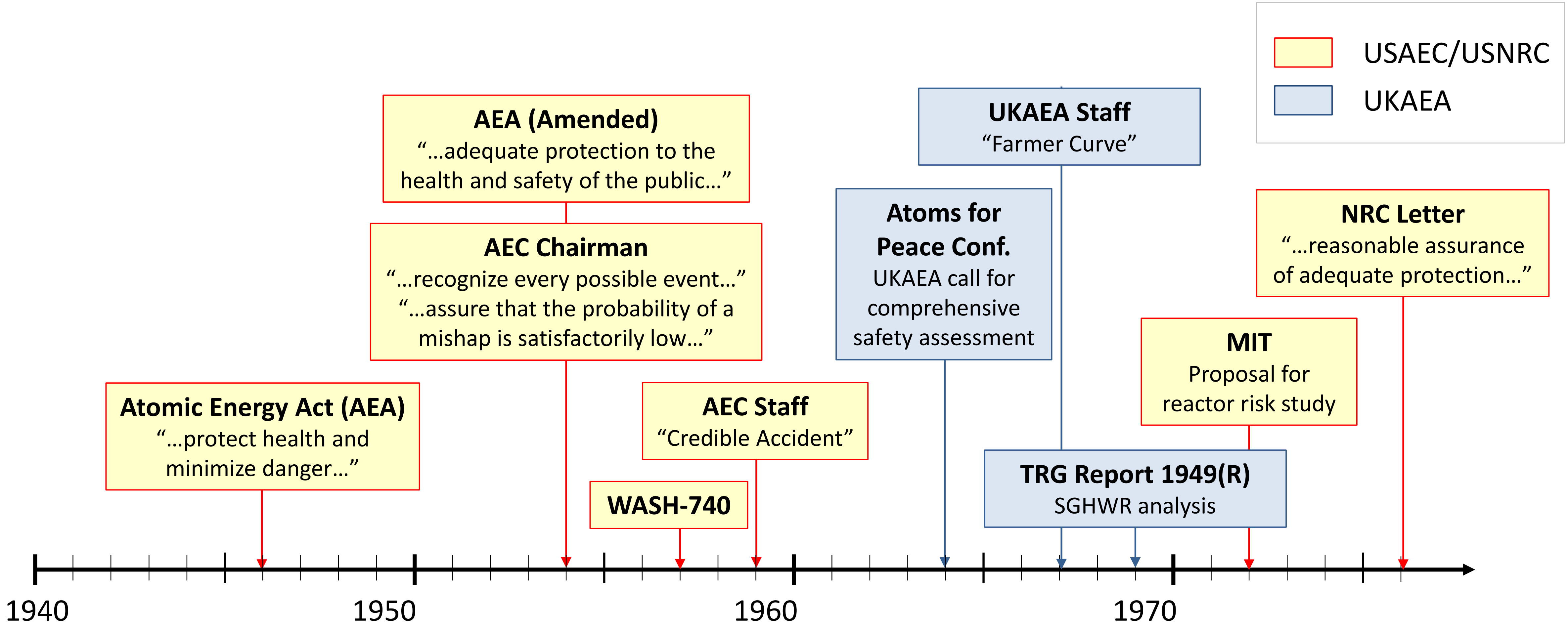
ADDITIONAL SLIDES

“Reasonable Assurance of Adequate Protection”



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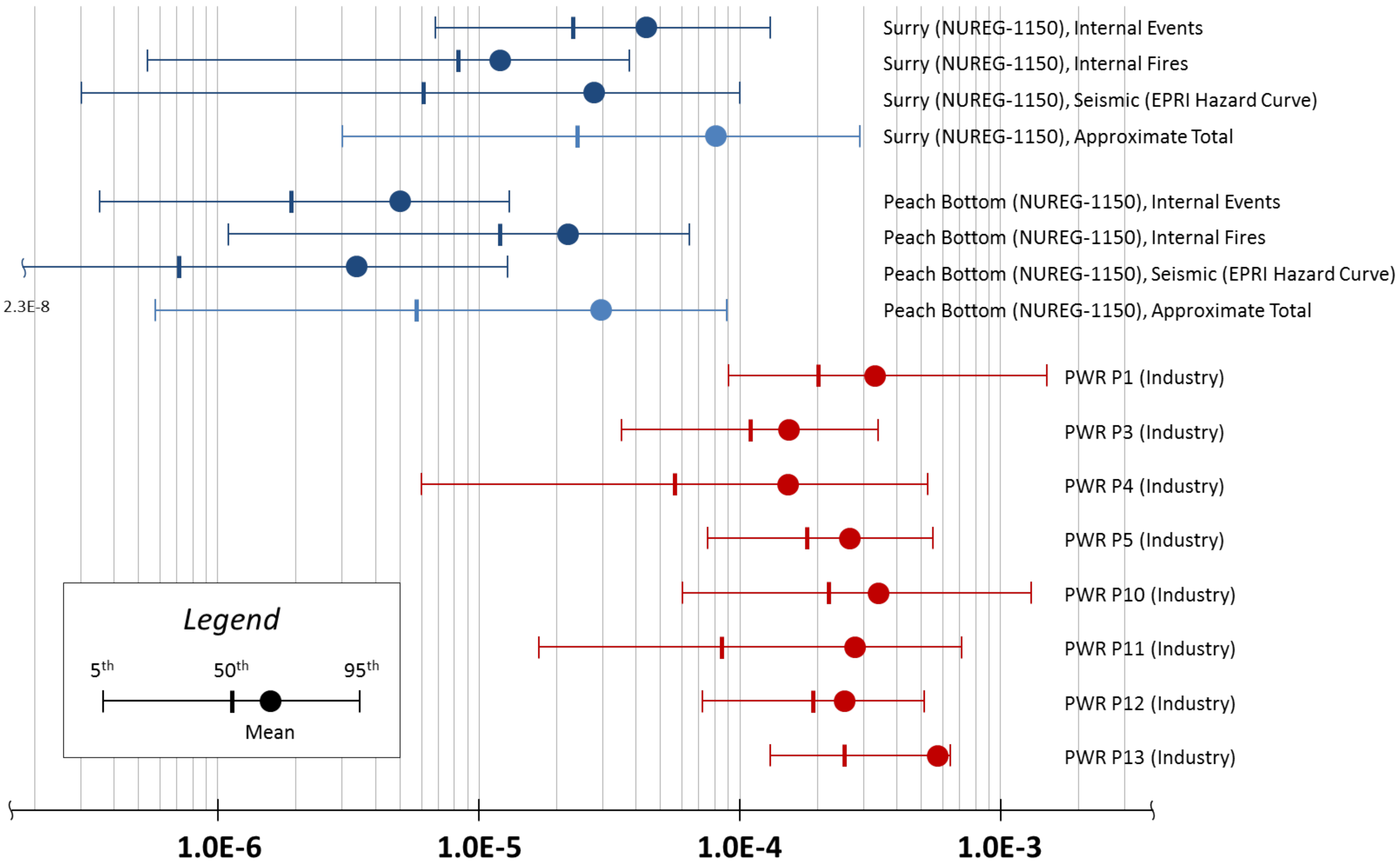
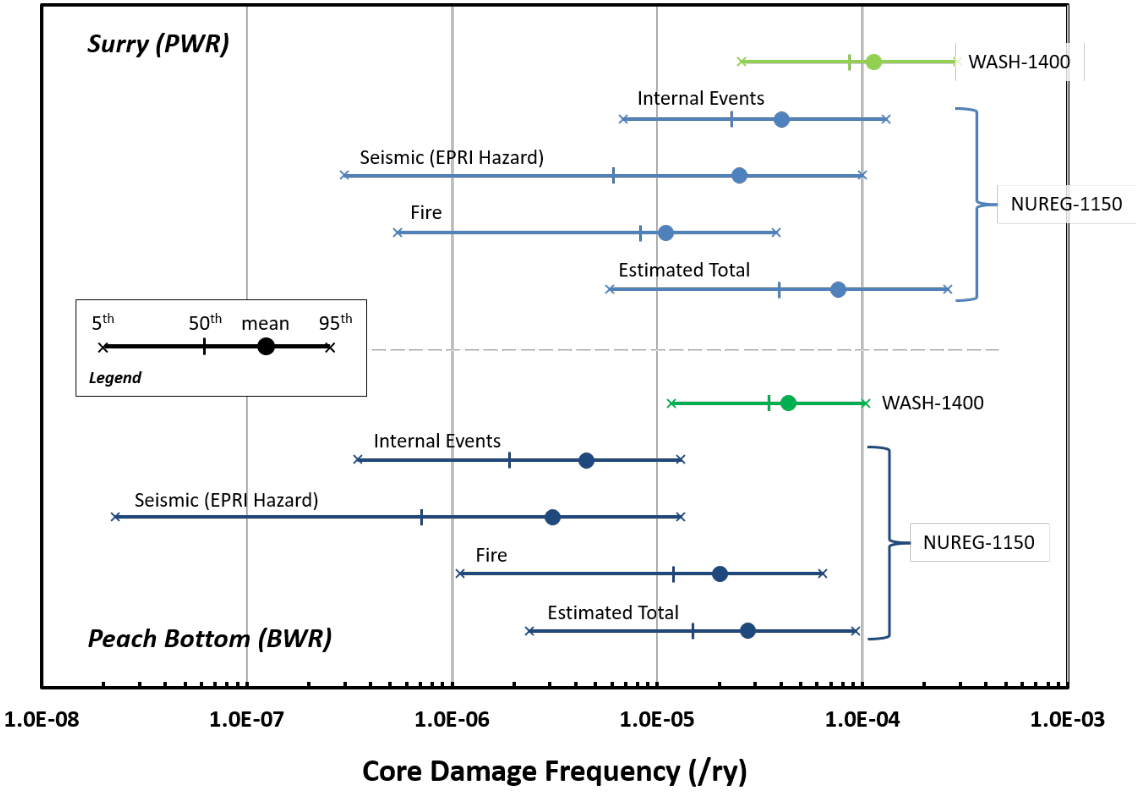
Protecting People and the Environment

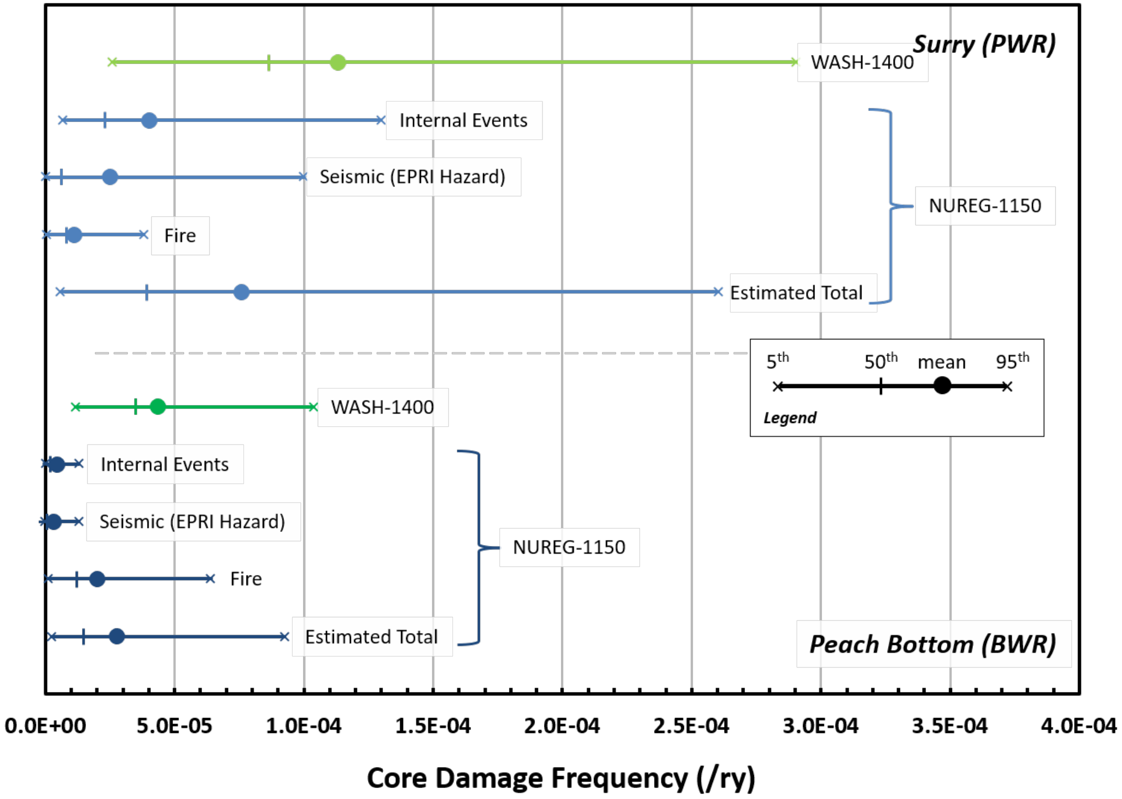
Parameter Uncertainties: Some Historical Results

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



"Uncertainty Reduction" – Perspective Depends on Scaling





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]

*ACRS Concerns with WASH-1400 Methodology**

Topic	Signature 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.

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

Some Other Interesting International 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).

External Hazards Scenario-Based Classification: An Aid for Completeness?