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

*"I Still Have Nightmares About That Class"**

PRA: why it's complicated and why it doesn't have to be

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Division of Risk Analysis

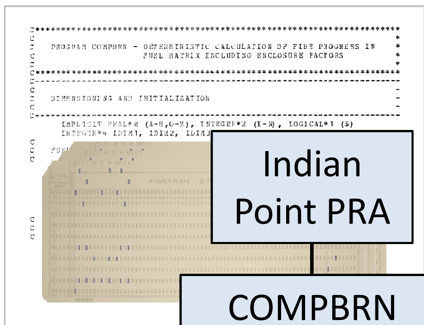
RES Staff Technical Seminar (Virtual) – Part 1
May 13, 2021 (2:00-3:00)

Special Guests:

Prof. George Apostolakis
Dr. Harold S. Blackman
Dr. Dennis C. Bley
Dr. Robert J. Budnitz
Prof. Ali Mosleh
John W. Stetkar
Dr. Thomas R. Wellock

After 40+ years, PRA seems intuitive to me…

Typewriters, punch cards => laptops
“It can’t be done” => “modern risk-informed regulator”



- 1975: Browns Ferry Fire, WASH-1400
- 1980: Join PLG
- Indian Point PRA
- COMPBRN (NRC-support)
- Join MIT
- **Summer at NRC**
- Join INL
- Quad Cities IPEEE
- **Join NRC**
- 9/11
- Fukushima
- COVID-19

1975 1980 1985 1990 1995 2000 2005 2010 2015 2020

Punch card graphic adapted from: https://en.wikipedia.org/wiki/Punched_card#/media/File:FortranCardPROJ039.agr.jpg. Publicly available under Creative Commons Attribution-Share Alike 2.5 Generic conditions,

...but it might not be to others

An old survey...

	Carolyn (12)	Kenny (9)	Christopher (4)
Who does Daddy work for?	The Nuclear Regulatory Commission	Wha? The government	Me
What does he do?	Makes sure nuclear plants don't go overboard or something like that	He reads a lot of stuff and goes to meetings	Write

More recently...

"You no longer need to be a mathematical genius to run a reliability or risk analysis."

- Ola Bäckström (2021)[1]

[1]Ola Bäckström, "The role of digital insight in a safer nuclear industry," *Power*, January 28, 2021. (Available from: https://www.powermag.com/the-role-of-digital-insight-in-a-safer-nuclear-industry/)

Talk Outline

- PRA: what is it and why do it?
- Challenges and complications
- Strategies for reducing complexity
- Closing remarks

Alphabet Soup

PRA = Probabilistic Risk Assessment
RIDM = Risk-Informed Decision Making

PRA: WHAT AND WHY

Risk Assessment

- "Risk" (per Kaplan and Garrick,[1] adopted by NRC[2])
  - What can go wrong?
  - What are the consequences?
  - How likely is it?
- ***Qualitative as well as quantitative***
- ***Non-prescriptive, flexible***
  - Does not define "wrong" or prescribe metrics for consequences or likelihood
  - Does not define "how" risk is to be assessed

What's in a word?

a●nal●y●sis, *n.*, process of separating an entity into its constituent elements; process as a method for studying the nature of something or determining its essential features and their relationships

as●sess●ment, *n.*, an estimation or judgment of **value** [emphasis added] or character

[1]S. Kaplan and B.J. Garrick, "On the quantitative definition of risk," *Risk Analysis*, **1**, 1981.
[2]See, for example:
- "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.

PRA ≡ Risk assessment where likelihood is quantified in terms of probability

- ***Still flexible*** – definition does not mandate specific methods (e.g., event tree/fault tree analysis)
- Typically: engineering analysis process
  - Models facility/process as an integrated system
  - Attempts to address all important scenarios (within study scope)
  - Attempts to use all practically available, relevant information (not just statistics)

Subjective Interpretation of Probability[1]

- Probability quantifies "degree of belief"
- Appropriate for decision support
- Inherent in current PRAs (e.g., Bayesian updating)
- Not universally accepted
  - Subjectivity uncomfortable for many
  - Technical objections (appropriateness of a lottery model for characterizing subjective uncertainty)

[1]See:
- G. Apostolakis, "Probability and risk assessment: the subjectivistic viewpoint and some suggestions," *Nuclear Safety*, **9**, 305–315(1978).
- G. Apostolakis, "The concept of probability in safety assessments of technological systems," *Science*, **250**, 1359–1364(1990).
- M. Granger Morgan, "Use (and abuse) of expert elicitation in support of decision making for public policy," National Academy of Sciences Proceedings (NASP), **111**, No. 20, 7176-7184, May 20, 2014.

Why PRA?

PRA Policy Statement (1995)[1]

- 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

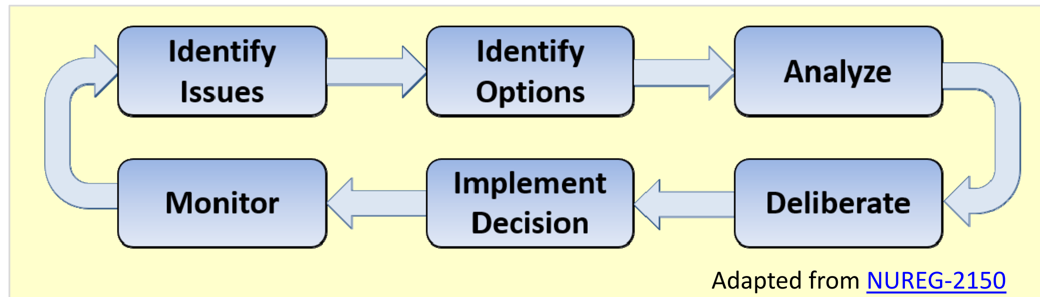
"Risk assessment is a set of tools, not an end in itself. The limited resources available should be spent to generate information that helps risk managers to choose the best possible course of action among the available options."
- *National Research Council*, 1994

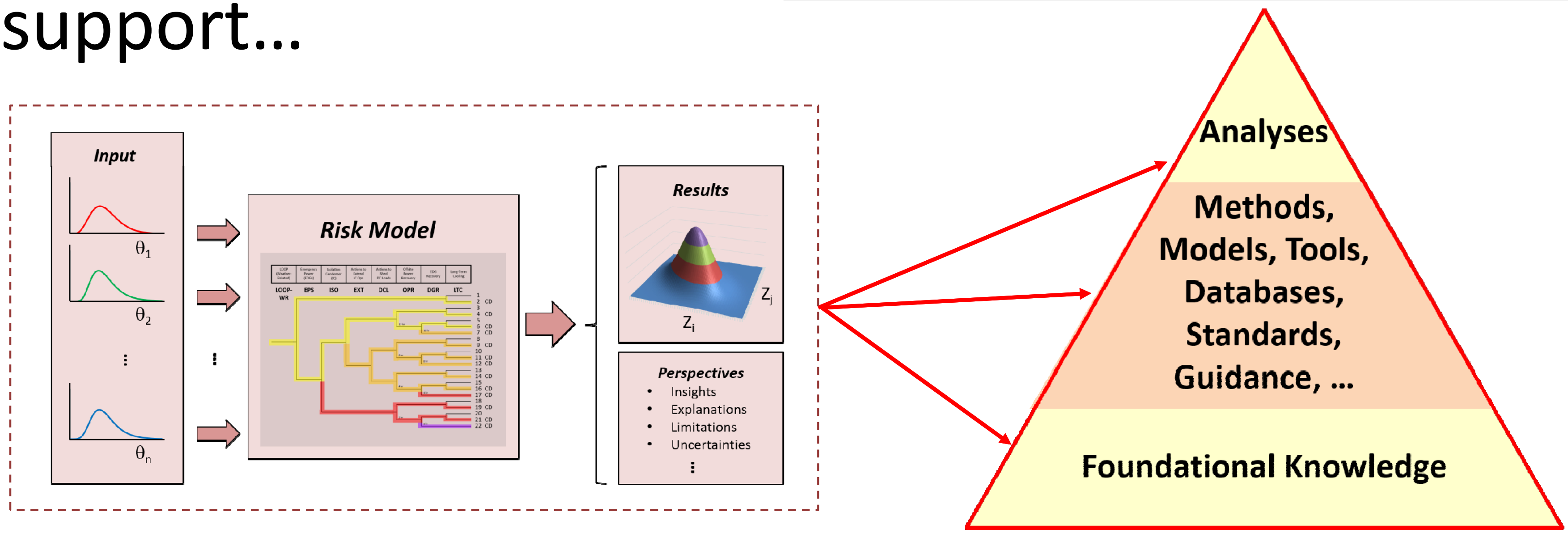
"It [fire PRA] ain't perfect but it's the best thing we've got."
- *G. Holahan*

"Our tendency is to focus on things that are interesting and make them important. The thing that we have to do is focus on what really is important…"
- *R. Rivera*, 2020

[1]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

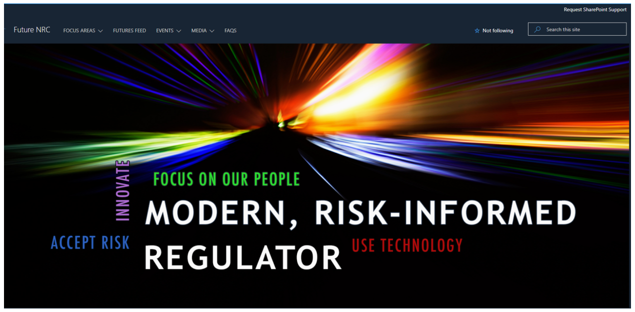
Risk information has uses beyond immediate decision support…

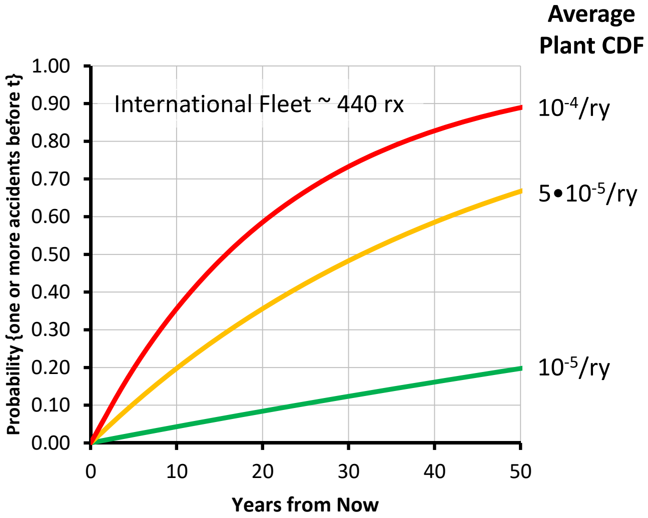




Moving Forward

- Past successes[1] => expectation of future successes
- Past results => anticipation of future challenges
- Continued investment => readiness to meet challenges, maintain NRC international leadership

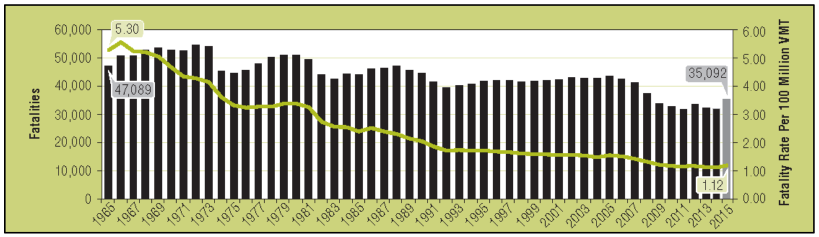




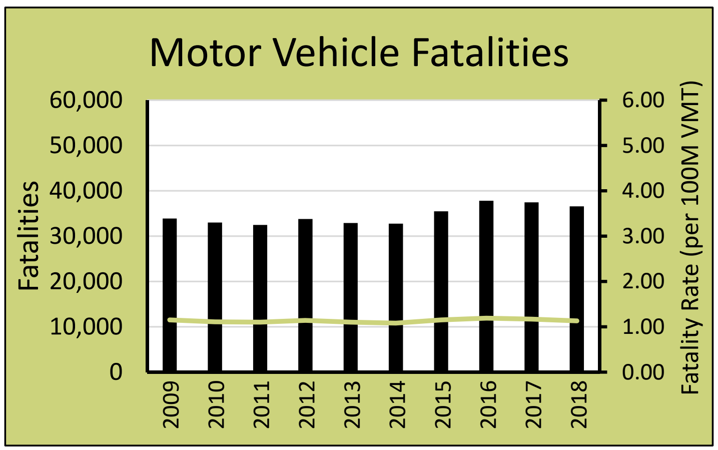
[1]For examples, see "Probabilistic Risk Assessment and Regulatory Decisionmaking: Some Frequently Asked Questions," NUREG-2201, September 2016.

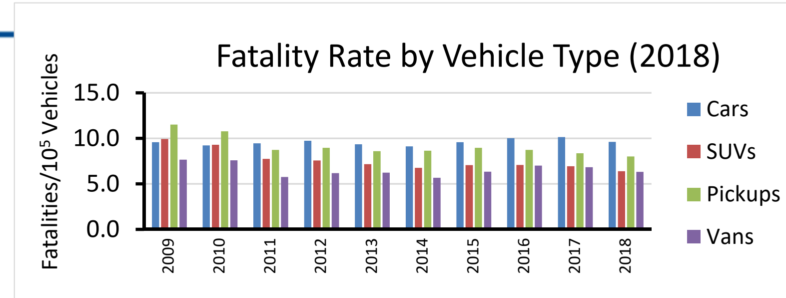
NPP PRA: IT'S CHALLENGING

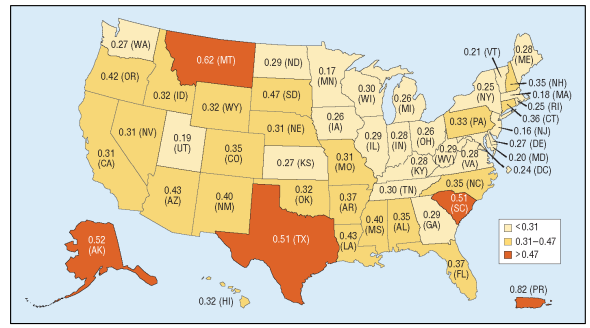
Lots of Data => Statistical Analysis



From "Traffic Safety Facts: Research Note," U.S. Dept. of Transportation, 2016.

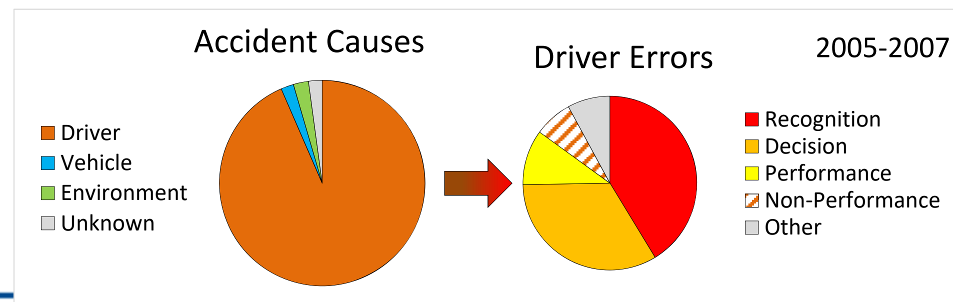






Alcohol-Impaired Driving Fatality Rates per 10^6 VMT (2018)

U.S. Average: 0.32
Maryland: 0.20



Data from https://crashstats.nhtsa.dot.gov

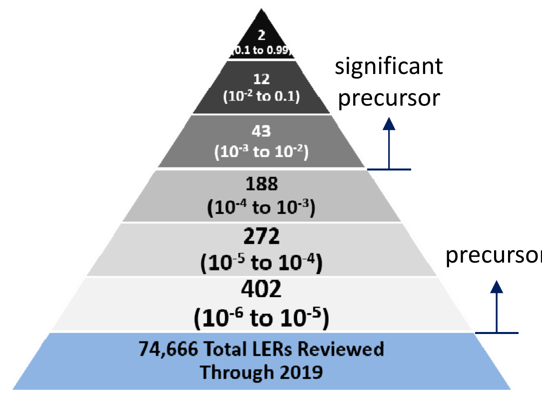
Fundamental NPP PRA Challenge: Little/No Plant-Level Data

- Sparse data
  - Few accidents/serious incidents
  - Statistical relevance challenged by design and operational changes
  - Interest in specific plant => further reduced data set
- Coping strategies
  - Decomposition-based systems modeling (e.g., event trees, fault trees)
  - Specialized estimation procedures (e.g., Bayesian statistics, expert elicitation) for model elements

=> Complexity ("no free lunch")

Accident	In a nutshell…	Note
TMI 2 (1979)	Anticipated transient + additional failures and errors	Unlikely confluence of "likely" events
Chernobyl 4 (1986)	Systems test in unstable regime, violating procedures	Single-minded aim to perform test
Fukushima Daiichi 1-3 (2011)	Beyond design basis tsunami	Extremely unlikely catastrophic event

2021: ~18700 reactor-years



Licensee Event Reports 1969-2019 (~4360 ry)
(No significant precursors since 2002; one under review)

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PRA Complications

- Inherent in problem, e.g.,
  - Complex phenomenology (often beyond experience)
  - Multiple technical disciplines, roles, and perspectives
- Highlighted (or even introduced) by coping strategies for sparse data

com•pli•cat•ed, *adj*. consisting of many parts not easily separable; difficult to analyze, understand, explain, etc.

"For many years, risk assessment required a high level of abstraction and an elite team of analysts fully immersed in the ways of every single component and their failure profiles. A heady task for any risk analyst, but one made doubly hard by the exacting requirements of nuclear."

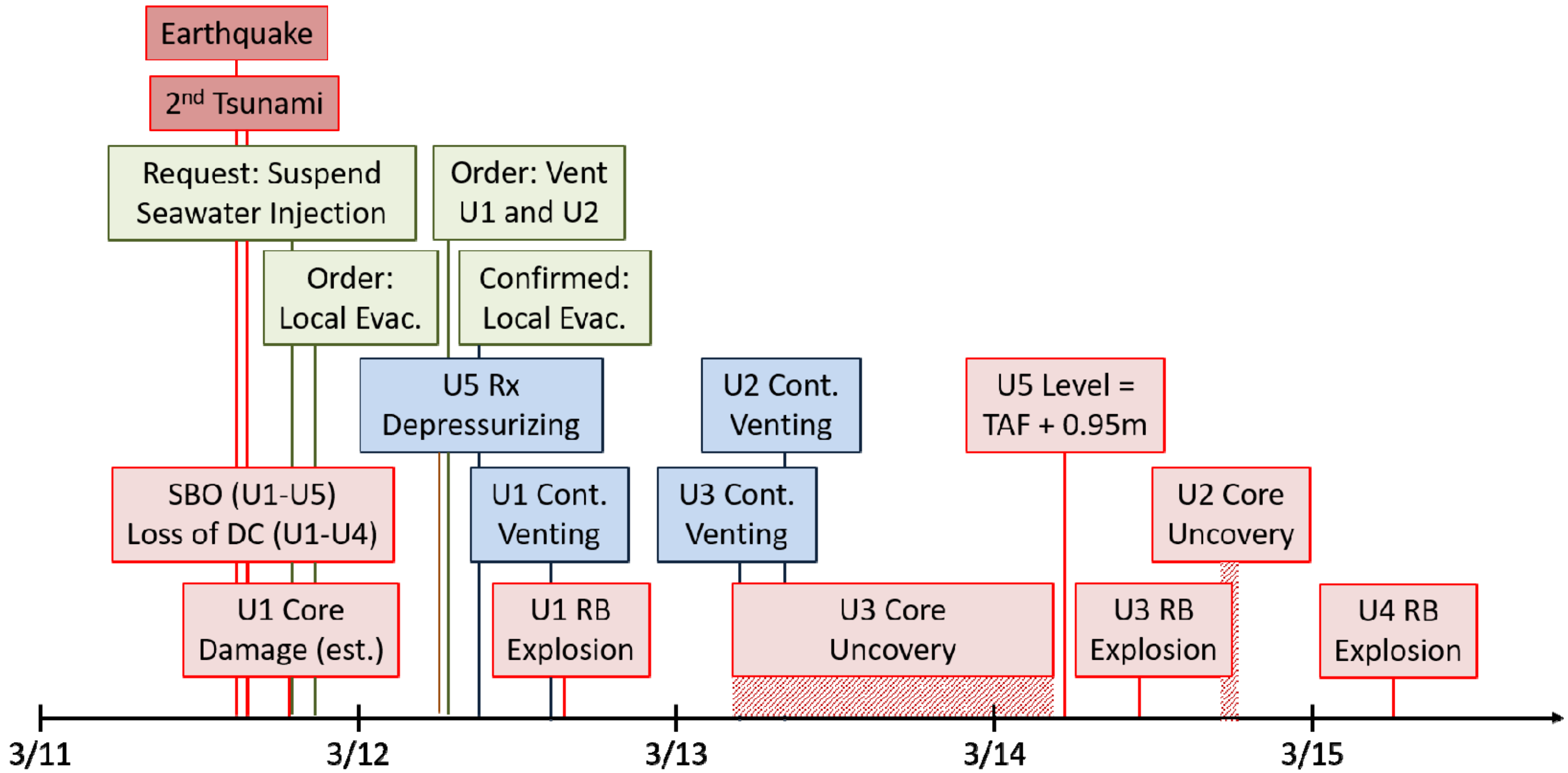
- Ola Bäckström (2021)[1]

[1]Ola Bäckström, "The role of digital insight in a safer nuclear industry," *Power*, January 28, 2021. (Available from: https://www.powermag.com/the-role-of-digital-insight-in-a-safer-nuclear-industry/)

Complex Phenomenology: Scenario Dynamics (1)

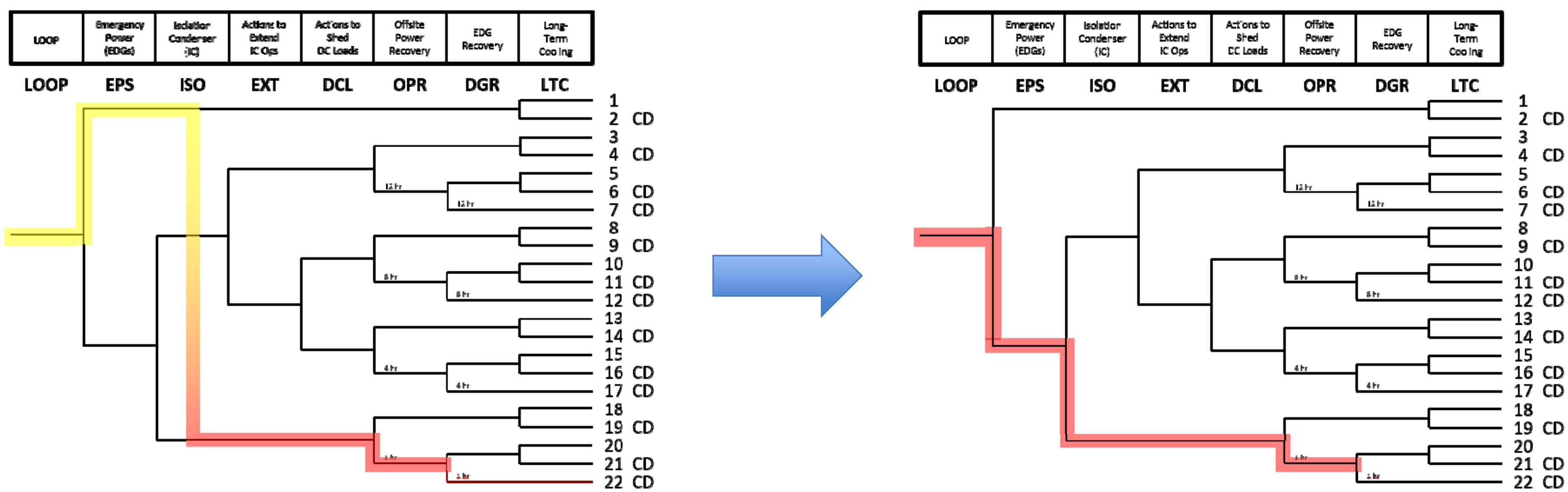
Time	Δ Time	Hazard	Systems	Indications	Operators/Workers	ERC/ER team	EP
14:46	0:00	Earthquake	Scram				
14:47	0:01		MSIVs close, turbine trips, EDGs start and load	Rx level drops			
14:52	0:06		ICs start automatically	RV pressure decreases; RV level in normal range			
15:03	0:17		ICs removed from service	Cooldown rate exceeding tech spec limits	Manually remove IC from service		
15:06	0:20						Disaster HQ established in TEPCO Tokyo
15:10	0:24				Determine only 1 train IC needed; cycle A train		
15:27	0:41	First tsunami arrives					
15:35	0:49	Second tsunami arrives					
15:37	0:51		Loss of AC				
15:37	0:51		1537-1550: Gradual loss of instrumentation, indications (including IC valve status, RV level), alarms, MCR main lighting		Determine HPCI unavailable		
15:42	0:56						TEPCO enters emergency plan (loss of AC power); ERC established
16:35	1:49			D/DFP indicator lamp indicates "halted"			
16:36	1:50			Review accident management procedures, start developing procedure to open containment vent valves without power	Cannot determine RV level or injection status; work to restore level indication; do not put IC in service	Review accident management procedures, start developing procedure to open containment vent valves without power	Declared emergency (inability to determine level or injection)

Complex Phenomenology: Scenario Dynamics (2)



Coping with Dynamics

- Aggregation ("bundling")
- Simplified timing + success criteria



For an early discussion of transitions between sequences, see G. Apostolakis and T.L. Chu, "Time-dependent accident sequences including human actions," *Nuclear Technology*, **64**, 115-26 (1984).

Complication: Multiple Disciplines, Multiple Roles

Different points of view:

- What's important to the analysis?
- What's an acceptable solution approach?

Plant Systems

Electrical

Mechanical

Civil

Materials

Nuclear

Operational Experience

NPP PRA

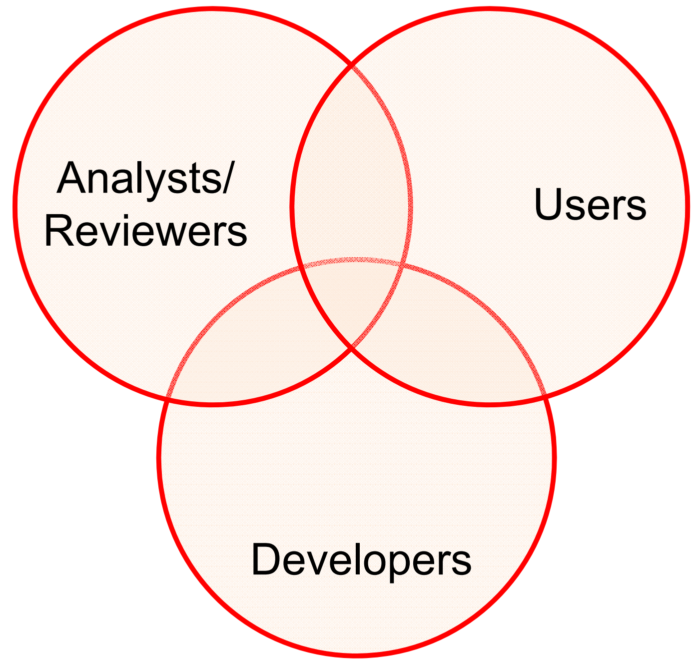
Human Factors

Fire Protection

Earth Sciences

Probability & Statistics

Systems Science

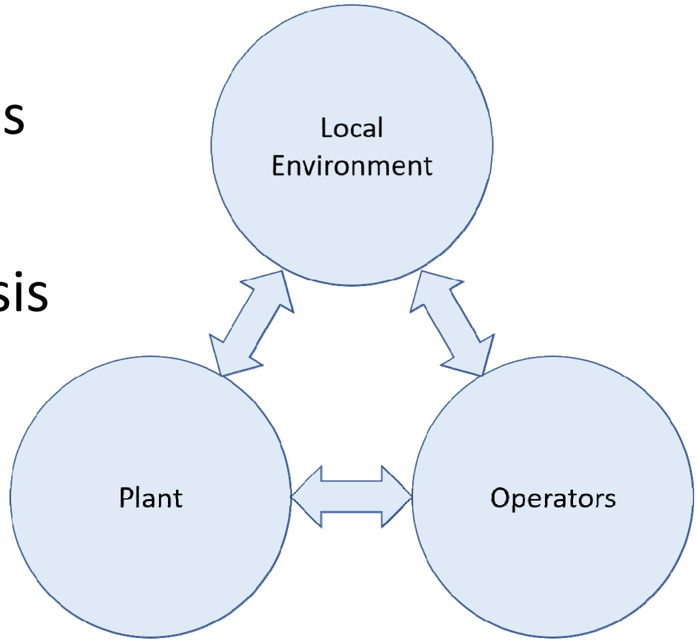


External Flooding at Plant X: Model Scope?

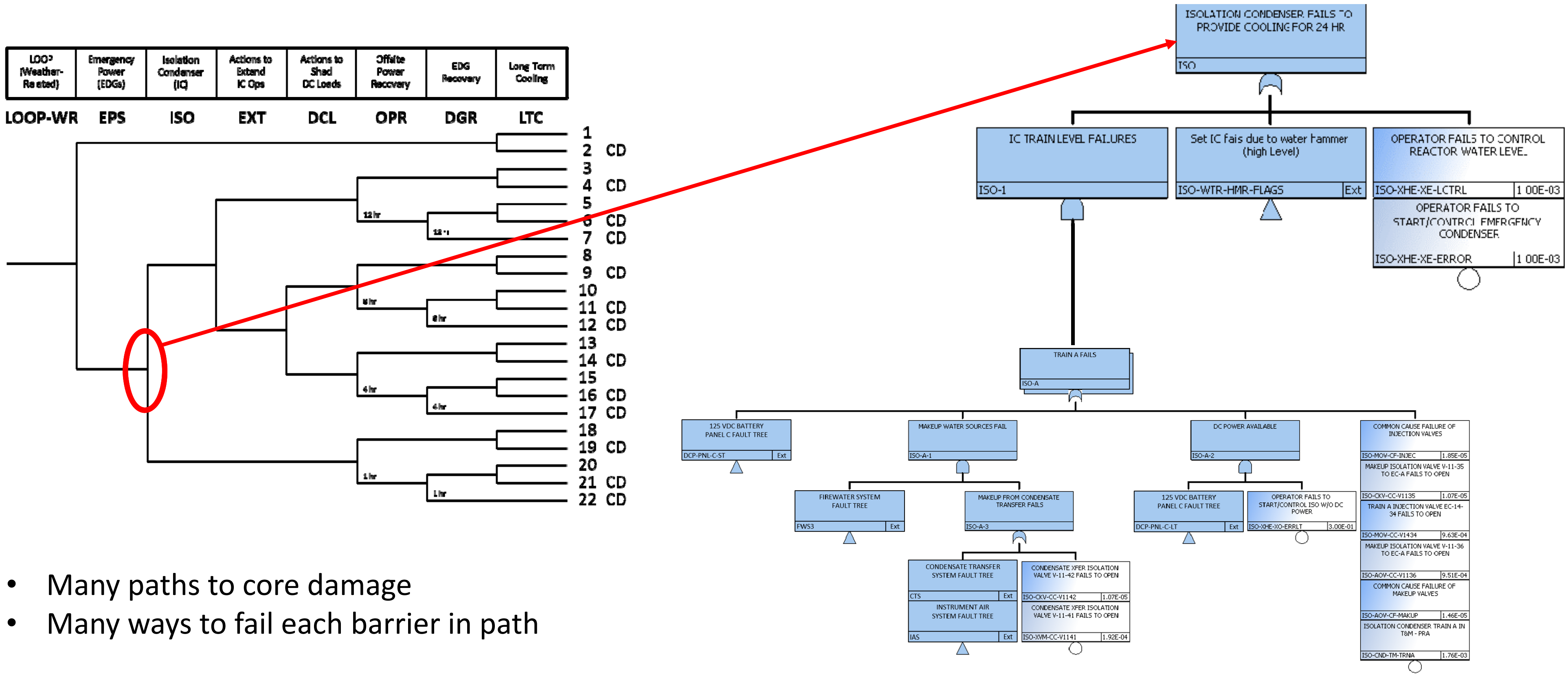
U.S. watershed image from https://www.nps.gov/miss/riverfacts.htm

Diverse Views: From Coping to Benefitting? From "**You** PRA Guys/Gals to "**Us** PRA Guys/Gals"?

- Clear definition of analysis needs, interfaces
- Stakeholders 101: early, open engagement
- Future: integrated "native language" analysis (e.g., dynamic PRA)?



Complication: Numerous Possibilities



- Many paths to core damage
- Many ways to fail each barrier in path

Coping with Multiple Scenarios

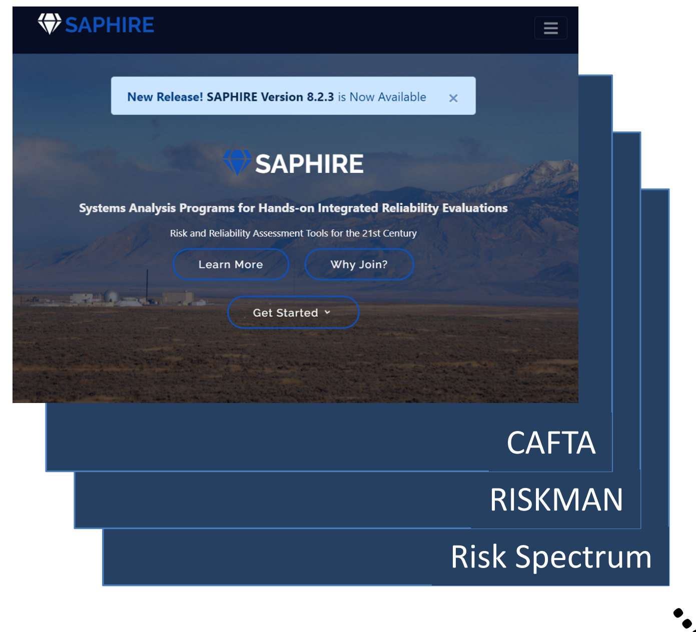
- Model simplifications, e.g.,
  - Screening
  - Grouping (often with bounding quantification)
- Boolean algebra, reliability theory,[1] e.g.,

$$\prod_{k} \coprod_{i \in MCS_k} P\{i\ failed\} \le P\{system\ failed\} \le \coprod_{j} \prod_{i \in MPS_j} P\{i\ failed\}$$

for independent basic events, where

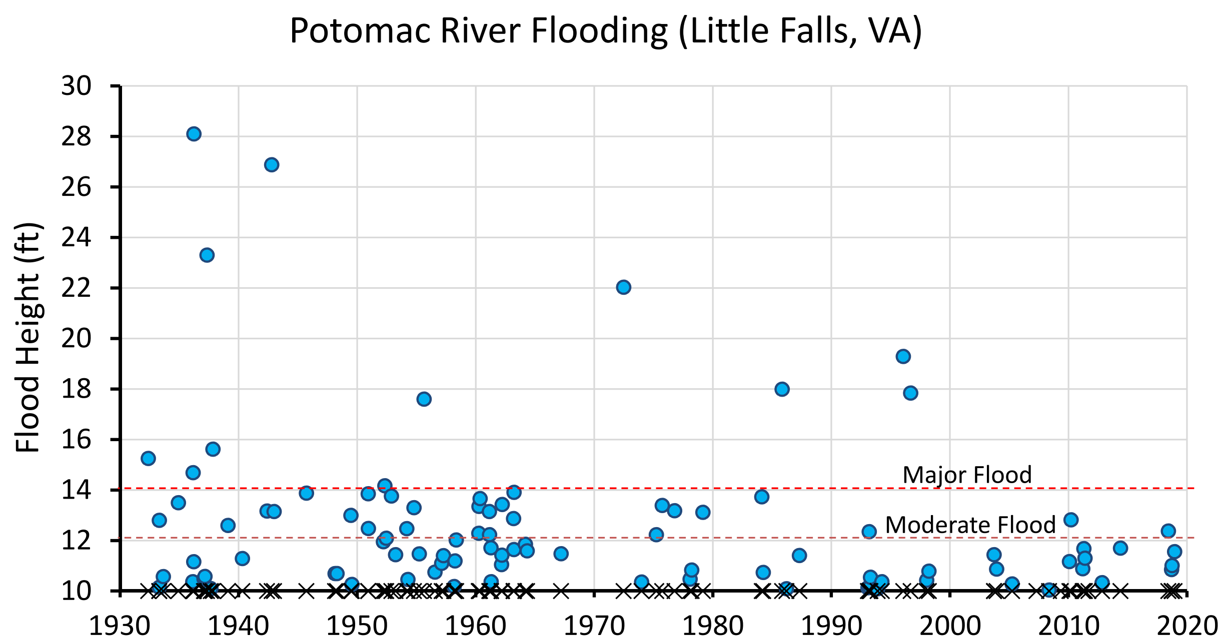
$$\prod_{i=1}^{M} p_i \equiv p_1 p_2 \cdots p_M \qquad \coprod_{j=1}^{N} p_j \equiv 1-(1-p_1)(1-p_2)\cdots(1-p_N)$$

- Software tools to implement theory



[1] See, for example, R.E. Barlow and F. Proschan, *Statistical Theory of Reliability and Life Testing Probability Models*, To Begin With, Silver Spring, MD, 1975. (Available in the NRC Technical Library: TS173.B37 c.1)

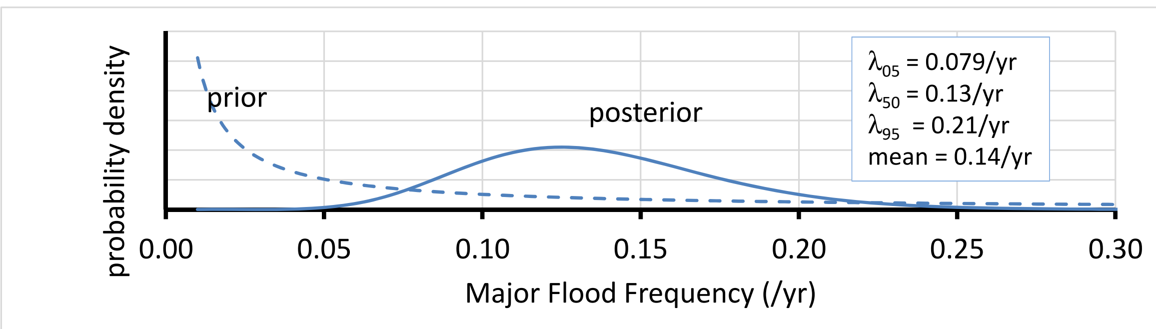
Complication: Sparse Data



Data from: https://water.weather.gov/ahps2/crests.php?wfo=lwx&gage=brkm2&crest_type=historic

Coping with Sparse Data: Modeling + Bayesian Estimation

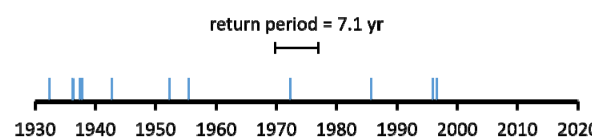
- "First cut" bounding analysis: major flood[1] => catastrophic flood
- Frequency of major flooding (λ)
  - Prior state-of-knowledge: minimal
  - Evidence: 12 major floods over 1932-2019 (87 years)
  - Bayes' Theorem: $$\pi_1(\lambda|r,T) = \frac{L(r,T|\lambda)\pi_0(\lambda)}{\int_0^\infty L(r,T|\lambda)\pi_0(\lambda)d\lambda}$$ ($L(r,T|\lambda)$: Poisson; $\pi_0(\lambda)$: Non-informative)
  - Posterior state-of-knowledge:



- More sophisticated analysis if needed (e.g., frequency-magnitude analysis (perhaps with expert elicitation)

Potomac River (Little Falls, VA)[1]

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



[1] Data from: https://water.weather.gov/ahps2/crests.php?wfo=lwx&gage=brkm2&crest_type=historic
[2] Major Flood: height > 14 ft

More Complications: Expert Elicitation >> "BOGGSAT"[1]

- Mechanism to support decision making
  - Diverse, authoritative views
  - Broad range of evidence
- Social process => social biases; need
  - Formal elicitation processes (e.g., SSHAC[2])
  - Sufficient time and resources
- Need to remember purpose and context; follow-on experimentation, analysis, etc. may be needed

what "we" know

what "we" believe → $P\{X|C,H\}$

proposition/event of concern

conditions of probability statement

Level	Characteristics
1	TI only (literature review, personal experience)
2	TI interacts with proponents and resource experts
3	TI brings together proponents and resource experts
4	TFI organizes expert panel to develop estimates

TI = Technical Integrator
TFI = Technical Facilitator/Integrator

[1]BOGGSAT: Bunch of guys and gals sitting around a table
[2]SSHAC: Senior Seismic Hazard Analysis Committee. See R. J. Budnitz, et al., "Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts," *NUREG/CR-6372*, 1997.

"You no longer need to be a mathematical genius to run a reliability or risk analysis."

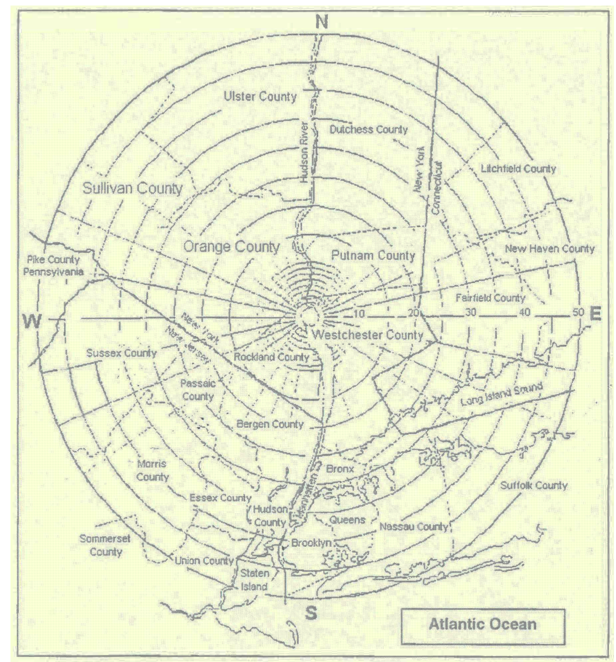
- Ola Bäckström (2021)[1]

SO PRA CAN BE COMPLICATED.
DOES IT HAVE TO BE?

[1]Ola Bäckström, "The role of digital insight in a safer nuclear industry," *Power*, January 28, 2021. (Available from: https://www.powermag.com/the-role-of-digital-insight-in-a-safer-nuclear-industry/)

It depends. (Tough problems => increased complexity)

- Technically challenging
  - Complex phenomenology
  - Multiple disciplines, roles, perspectives
  - …
- Tough decisions (higher-fidelity solutions)
  - high stakes
  - multiple stakeholders
  - multiple risk attributes
  - uneven distribution of risks and benefits
  - large uncertainties



From Indian Point Emergency Plan (ML15357A005)

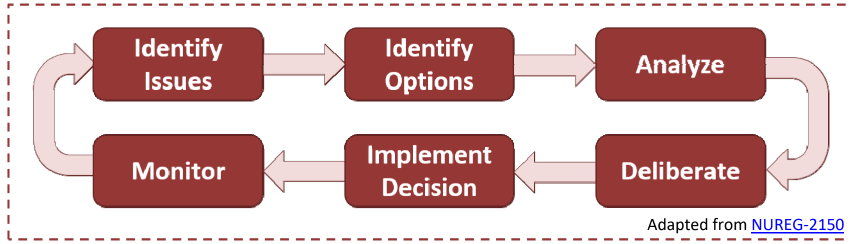
Reducing PRA Complexity

Source	Simplification Strategy	BUT…
Complex phenomenology	• Simplify regulated systems/processes • Increase certainty in rarity of off-normal conditions (facilitates screening) • Obtain more empirical data (reducing need for sub-modeling) • Improve PRA technology[1] to improve focus on what's important	• Beware of simplistic characterizations (e.g., "gravity never fails" => "natural circulation cooling will always work") • Remember real-world testing and maintenance needs => extra bits and pieces, "off normal" configurations and procedures • Remember even simple systems can have complex behaviors (e.g., dynamic resonances)
Multiple disciplines, roles, perspectives	Improved communication	Beware of unintended side effects (e.g., reducing diversity through forcing a view)
Tough decision problem (driving need for high-fidelity PRA model)	Reduce stakes (e.g., by reducing potential consequences), enabling lower-fidelity model	• Recognize some risk metrics (e.g., for enterprise risk) might be less sensitive to design/operational changes • Recognize technical arguments for reduced concern might not be accepted

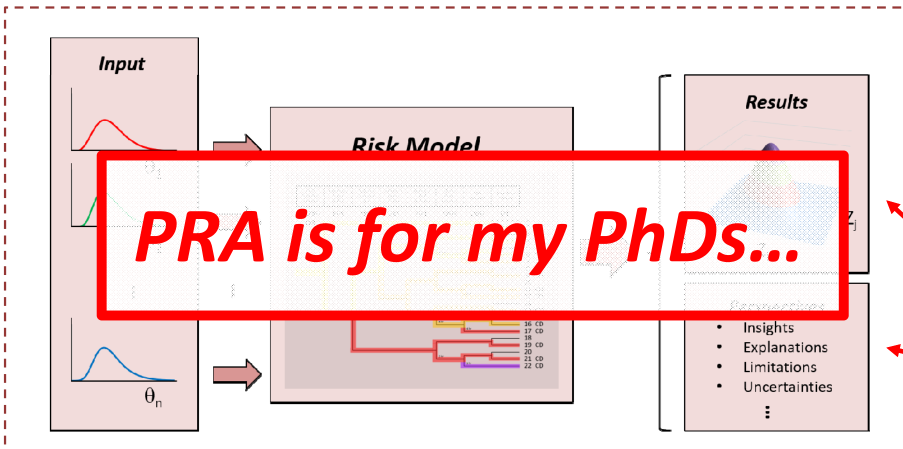
[1]"PRA Technology" = PRA methods, models, tools, data

Internal Risk Communication Challenge

- Principle: the decision maker should be an informed consumer of risk information
- What do the DMs need to know? Is perceived complexity a barrier to effective communication?



Barriers?



Quantitative

Qualitative

Other Considerations

- Current regulations
- Safety margins
- Defense-in-depth
- Monitoring

Reducing Perceived Complexity

Strategy	BUT…
Improve training and communication: ensure focus is on what DMs need to know	• Beware of turning PRA into a "black box" oracle; DMs need to appreciate (without overemphasizing) limitations and uncertainties • Ensure NRC has (or has access to) experts who understand and can communicate limitations and uncertainties, especially when addressing novel applications (designs, processes, decision problems)
Improve PRA technology[1] to increase focus on what's important (e.g., analytics-informed automated PRA)	Same as above but ever so much more so
Wait: take advantage of growing societal experience with and acceptance of analytics (e.g., sports), modeling (e.g., weather), real-world risk scenarios[2] and trade-offs (e.g., climate change, pandemics)	Don't wait too long (technology rejection is the result of social processes, established attitudes can be difficult to overcome)

[1]"PRA Technology" = PRA methods, models, tools, data
[2]According to https://www.etymonline.com, the current, common use of *scenario* (Italian, "sketch of the plot of a play") as an imagined situation first occurred in 1960 as a reference to hypothetical nuclear wars.

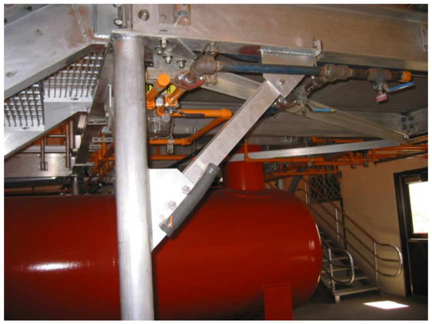
We’re Not Alone

- Other industries and other countries perform risk assessments for a wide range of applications (simple to complex). Examples:
  - Chemical process industry
  - NASA
  - Netherlands (all industries, all hazards)
- Potentially instructive: review of requirements and practices for lower-risk applications

[1]Oosterscheldedam photo from https://commons.wikimedia.org/wiki/File:Oosterscheldedam_storm_Rens_Jacobs.jpg

Example: Layers of Protection Analysis (LOPA)[1]

- Intention: reduce inconsistency in qualitative assessments without requiring full PRA
- Purpose: estimate risk (order-of-magnitude frequencies, qualitative consequences), assess adequacy of protection layers
- Adequacy assessed via risk matrix



Consequence Severity Categories

Cat.	Safety	Environmental	Economic	Cat.	Safety	Environmental	Economic
A	Multiple fatalities	Major release requiring multiple years to remediate	>$500 million	D	Recordable Injury	Release requiring days to remediate	$10-30 million
B	Single Fatality	Major release requiring a year to remediate	$100-500 million	E	First Aid Injury	Environmental permit violation	$2-10 million
C	Permanent Partial Disability	Release requiring months to remediate	$30-100 million				

Likelihood Class

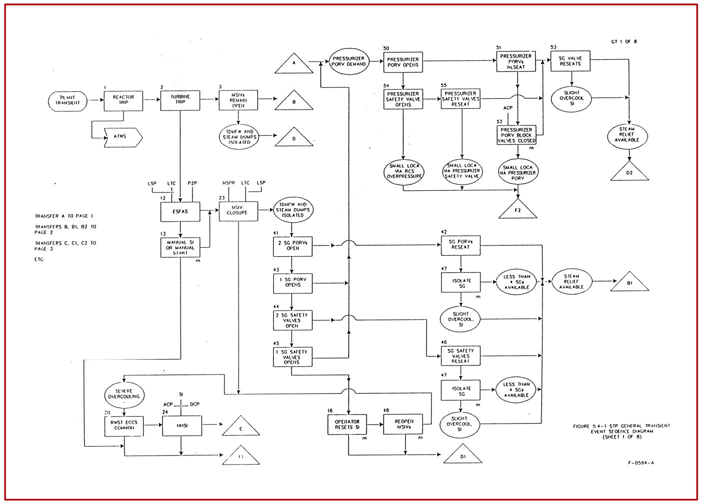
Severity Class	5 (10^{-5}/yr)	4 (10^{-4}/yr)	3 (10^{-3}/yr)	2 (10^{-2}/yr)	1 (10^{-1}/yr)
A	Marginal	Undesirable	Undesirable	Critical	Critical
B	Marginal	Marginal	Undesirable	Undesirable	Critical
C	No Action	Marginal	Marginal	Undesirable	Undesirable
D	No Action	No Action	Marginal	Marginal	Undesirable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

[1]See M. Kazarians and K. Busby, "Use of simplified risk assessment methodology in the process industry," *Proceedings International Conference Probabilistic Safety Assessment and Management (PSAM 14)*, Los Angeles, CA, September 16-21, 2018.

Change Emphasis to Improve Communication?

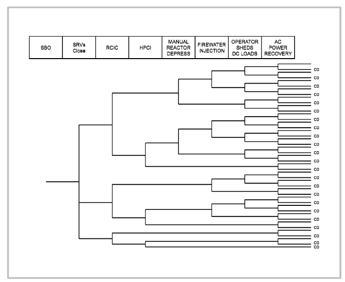
(And Banish Nightmares?)

The Engineering "Story"

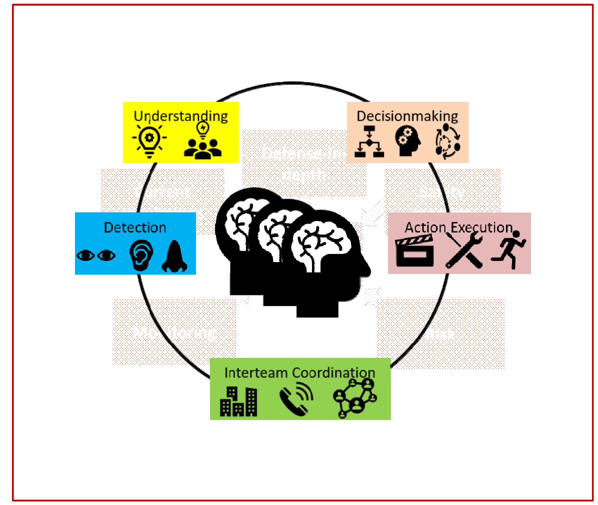


System Familiarization:

- How do things work?
- How can they fail?



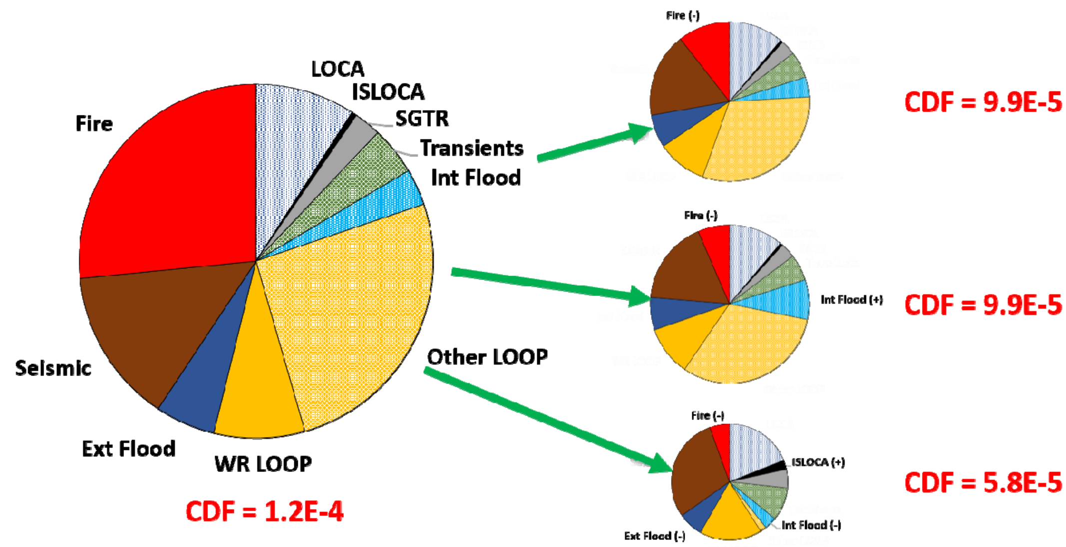
Scenario Analysis



Risk-Informed Decision Making

PRA Simplification: Some Cautionary Notes

- Past NPP PRA simplifications have gravitated to more detailed models
  - RSSMAP/IREP[1] => NUREG-1150
  - ASP plant class models => SPAR
- Simplified model results and insights can be harder to interpret and use
  - Reduced scope => unknown importance of out-of-scope contributors
  - “Game over” conservatism => masking of important contributors
- Better, cheaper, **and** faster – realistic result of learning or wishful thinking?



Risk Reduction Alternatives (notional)

[1]RSSMAP = Reactor Safety Study Methodology Applications Program (4 plants, 1978-1982)
IREP = Interim Reliability Evaluation Program (4 plants, 1980-1982)

CONCLUDING REMARKS

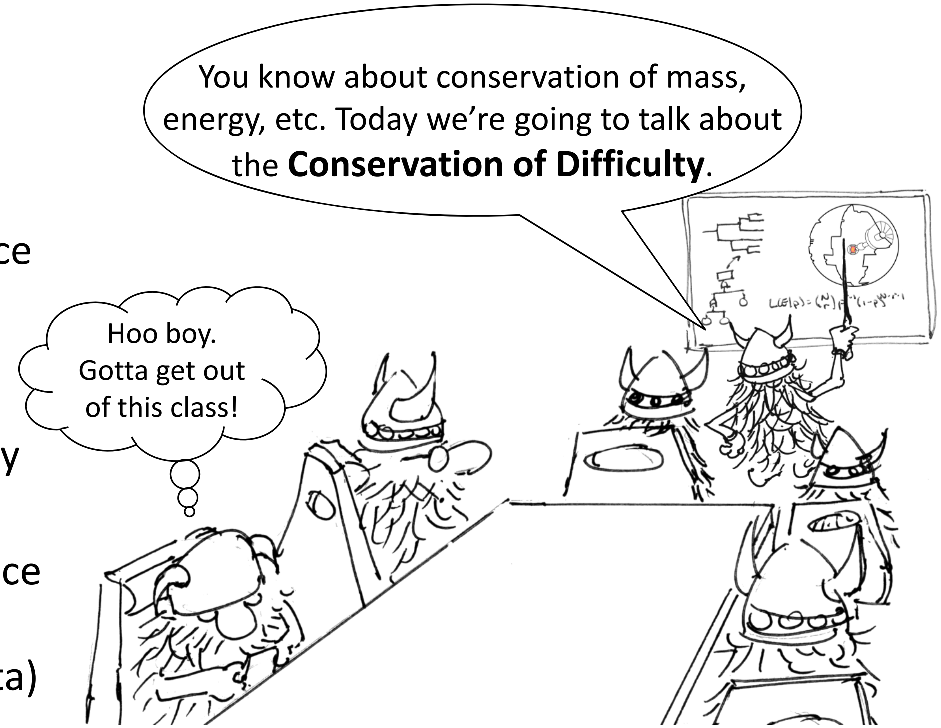
The Bottom Line

PRA can be complicated…

- Inherent problem complexities
  - Systems and phenomenology
  - High-stakes issues
- Coping strategies for problem complexity can introduce technical complexity
  - Modeling simplifications and math
  - Estimation procedures to address sparse data
- Multiple disciplines/communities => added complexity

but complexity can [sometimes] be reduced

- Simplify problem (e.g., simplify analyzed system, reduce stakes of decision)
- Improve PRA technology (methods, models, tools, data)
- Improve training



Acknowledgments

My views on PRA have, of course, been strongly influenced by my interactions with others. I can truthfully say that I've learned from all of my colleagues and that I'm still digesting some of these lessons. Special acknowledgments go to Professor George Apostolakis (my adviser and mentor in grad school and beyond, who gave me a framework and tools for thinking about PRA and its use); Dr. B. John Garrick (the importance of aiming for the truth, even if unpopular); Professor Norman Rasmussen (the importance of pragmatic engineering approaches even in R&D, there's no such thing as a "worst case"), John Stetkar (the basics of practical NPP PRA "in the field"); Dr. Harold Blackman (the importance and rigor of human factors engineering); Professor Ali Mosleh, Dr. Dennis Bley, and Dr. Robert Budnitz (gracious sounding boards for ideas, wild or otherwise); and Dr. Thomas Wellock (the early history of PRA and what skeptics think about the enterprise). My particular thanks go to Dr. Dana Kelly, gone too soon, for fruitful discussions. I regret that we never got to write the "Details Matter" paper we were toying with.

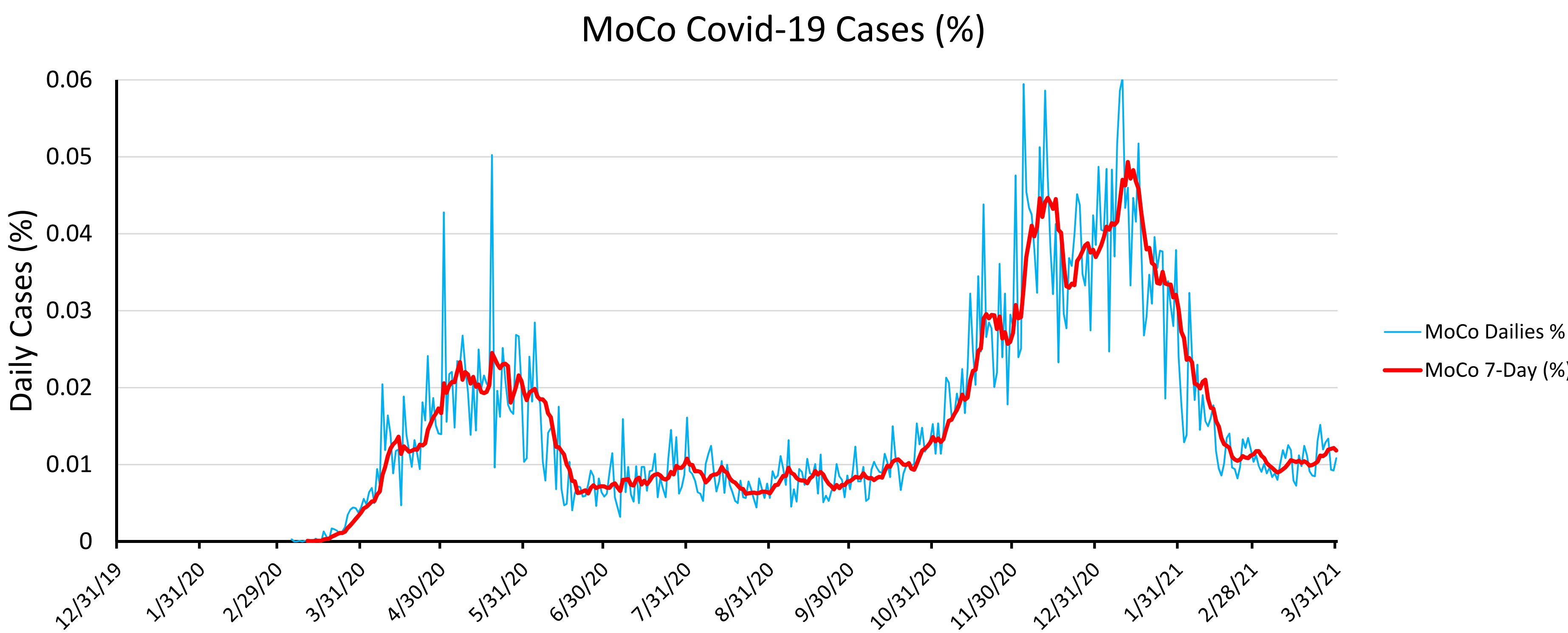
ADDITIONAL SLIDES

Everyday Risk-Informed Decisions

- Should I
  - Go for a run in the woods?
  - Cross the street against the light?
  - Eat that last doughnut?
  - Click on that emailed link?
  - Go to the office when I'm coughing?
  - Get vaccinated?
  - Visit NYC?
- What do I "know"?[1] What are the current conditions?
- What are the risks? The benefits?[1]
- N.B. Risk is input to decision problem (choice among alternatives), not just FYI

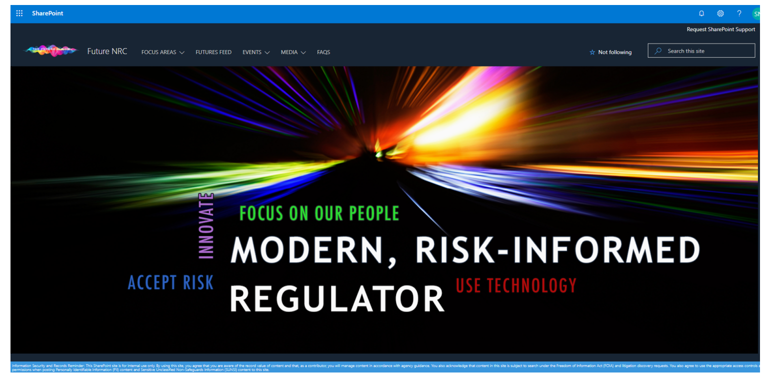
[1] And of course: What are the rules? What are the margins? Is there any defense in depth? Can I monitor the outcome(s) to influence future choices?

Risk information – not always for decision support. (Sometimes people just want to know.)



COVID-19 data from: https://coronavirus.maryland.gov/datasets/mdcovid19-casesbycounty
Estimated population for Montgomery County (2020): 1M

RIDM: A Changing Environment



- Internal
  - Overall direction (“transformation”)
  - Initiatives (e.g., Be riskSMART)
- External
  - Risk communication: risk maps, e.g.,
    - Tsunami inundation zones (explicit), e.g., https://www.conservation.ca.gov/cgs/tsunami/maps
    - Industrial risks (explicit), e.g., https://www.risicokaart.nl/
    - Wildfire extent (implicit), e.g., https://inciweb.nwcg.gov/
    - COVID-19 extent (implicit), e.g., https://coronavirus.maryland.gov/
  - Explicit representation of uncertainties (e.g., hurricane tracks)
  - Explicit acknowledgment of expert judgment informed by models (e.g., weather forecasting)
  - Tough, widely discussed risk problems (e.g., climate change, COVID-19)

On Using the Right Tool: Some Cautions

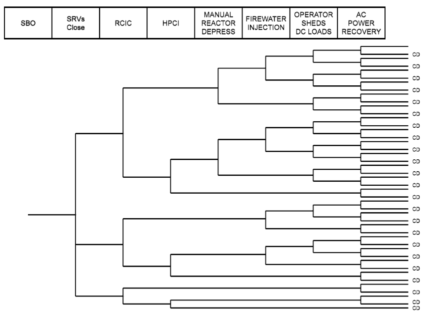
- If all you have is a hammer…

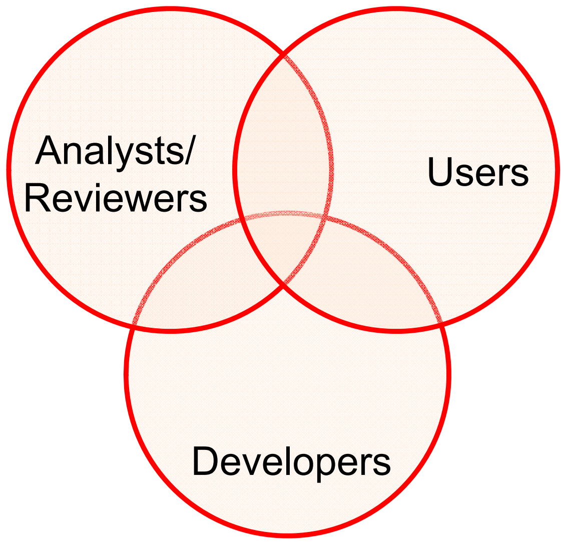
  Event tree/fault tree analysis for a fundamentally continuous process?

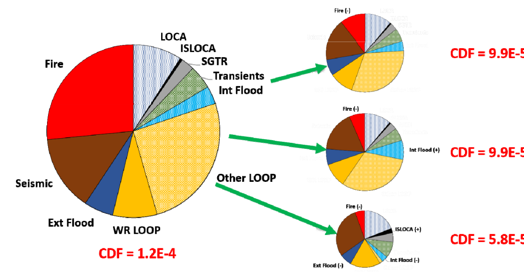
- Using the wrong tool might not only be ineffective or inefficient, it might damage the tool

  Using PRA to "prove" a facility/process is safe?

Complexity: In the Eye of the Beholder





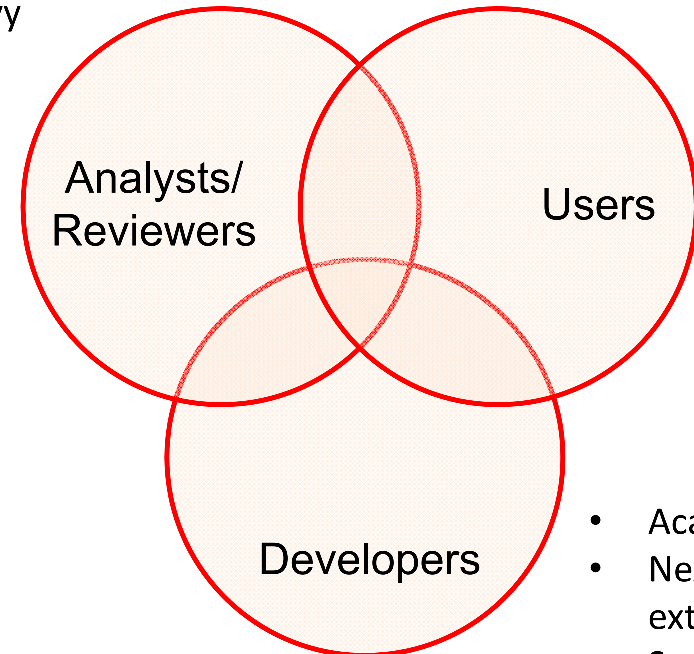


$$\frac{\partial \pi(i,\vec{x},t)}{\partial t} + \nabla \cdot [\vec{q}_i \pi(i,\vec{x},t)] + \lambda_i(\vec{x})\pi(i,\vec{x},t) = \sum_{j \neq i} p(j \rightarrow i|\vec{x})\pi(j,\vec{x},t)$$

$$\frac{d\vec{x}}{dt} = \vec{q}_i(\vec{x}), \qquad \vec{x}(0) = \vec{x}_0, \qquad i = 1, \cdots, n$$

Challenges and What's Important: In the Eye of the Beholder

- Near-term solutions: heavy time/budget pressure
- Huge problem size and complexity
- Multiple technical communities/cultures
- State of technology: Too much/little diversity, "Holes"



- Fundamental nature of risk problem (complexity, uncertainty, multiple consequence types and potentially large magnitude, multiple stakeholders, …)
- Competing problems with attentional and resource demands

- Academic contribution
- Nexus between personal/professional and external interests
- Support (especially with declining budgets)

Increasing Model Completeness (and Confidence)

Information Sources

- Hazard analysis tools, e.g.,
  - Failure Modes and Effects Analysis (FMEA)
  - Hazard and Operability Studies (HAZOPS)
  - Master Logic Diagrams (MLD)
  - Heat Balance Fault Trees
  - System-Theoretic Accident Model and Processes/Systems-Theoretic Process Analysis (STAMP/STPA)
- Past events
- Other studies

Attitude

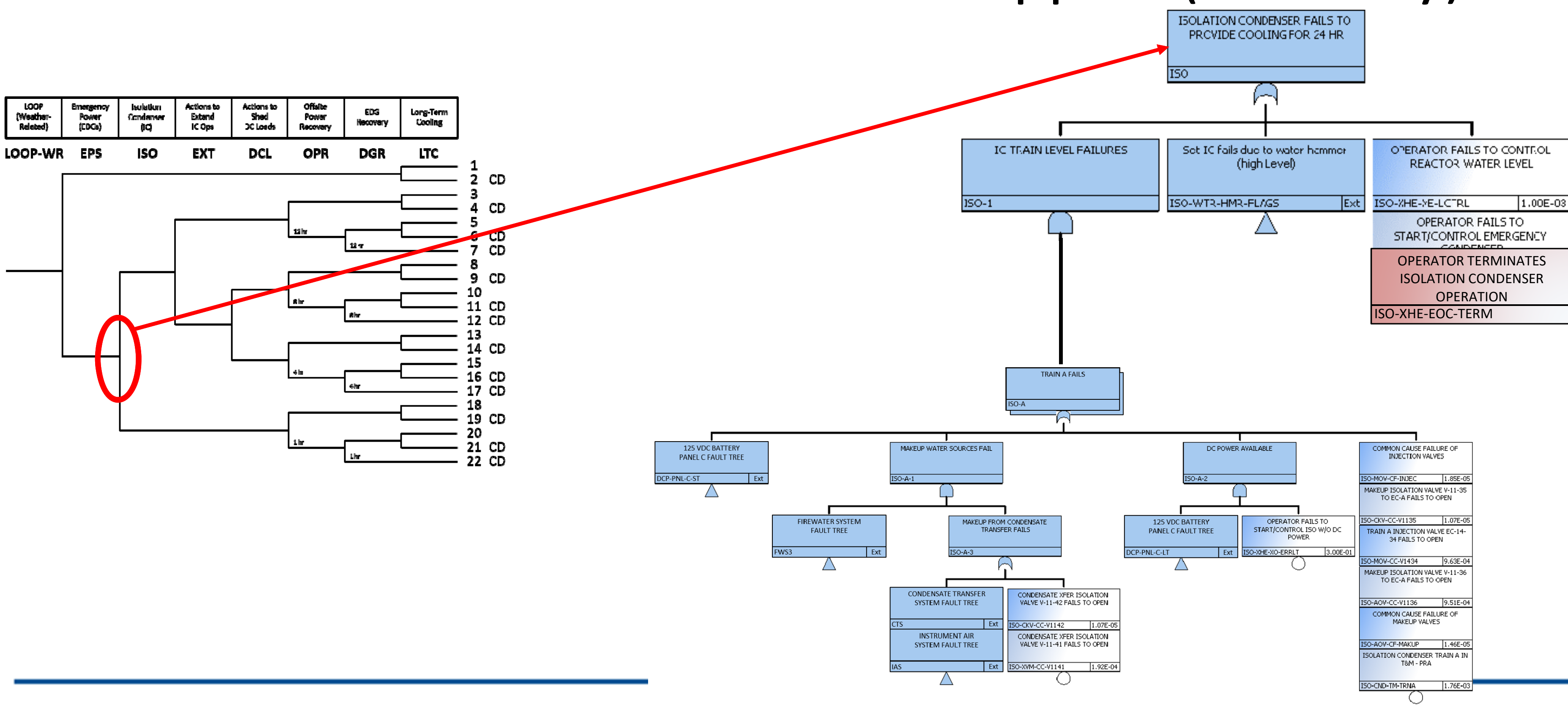
- Be open to possibilities
- Use checklists but also search for ways to get in trouble, e.g.,
  - What might prompt operators to operate in an unstable regime? Disable safety systems?
  - What could cause a complete loss of AC and DC power?
  - What could cause coolant channel blockage?
  - What could cause removal of all control rods?

"…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 …"

\- W.F. Libby (1956)[1]

[1]W. F. Libby (Acting Chairman, AEC) – March 14, 1956 response to Senator Hickenlooper. [See D. Okrent, *Reactor Safety*, University of Wisconsin Press, 1981. (NRC Technical Library TK9152 .O35, multiple copies)]

Harnessing Imagination:
Credible Possibilities Need Support (Causality)



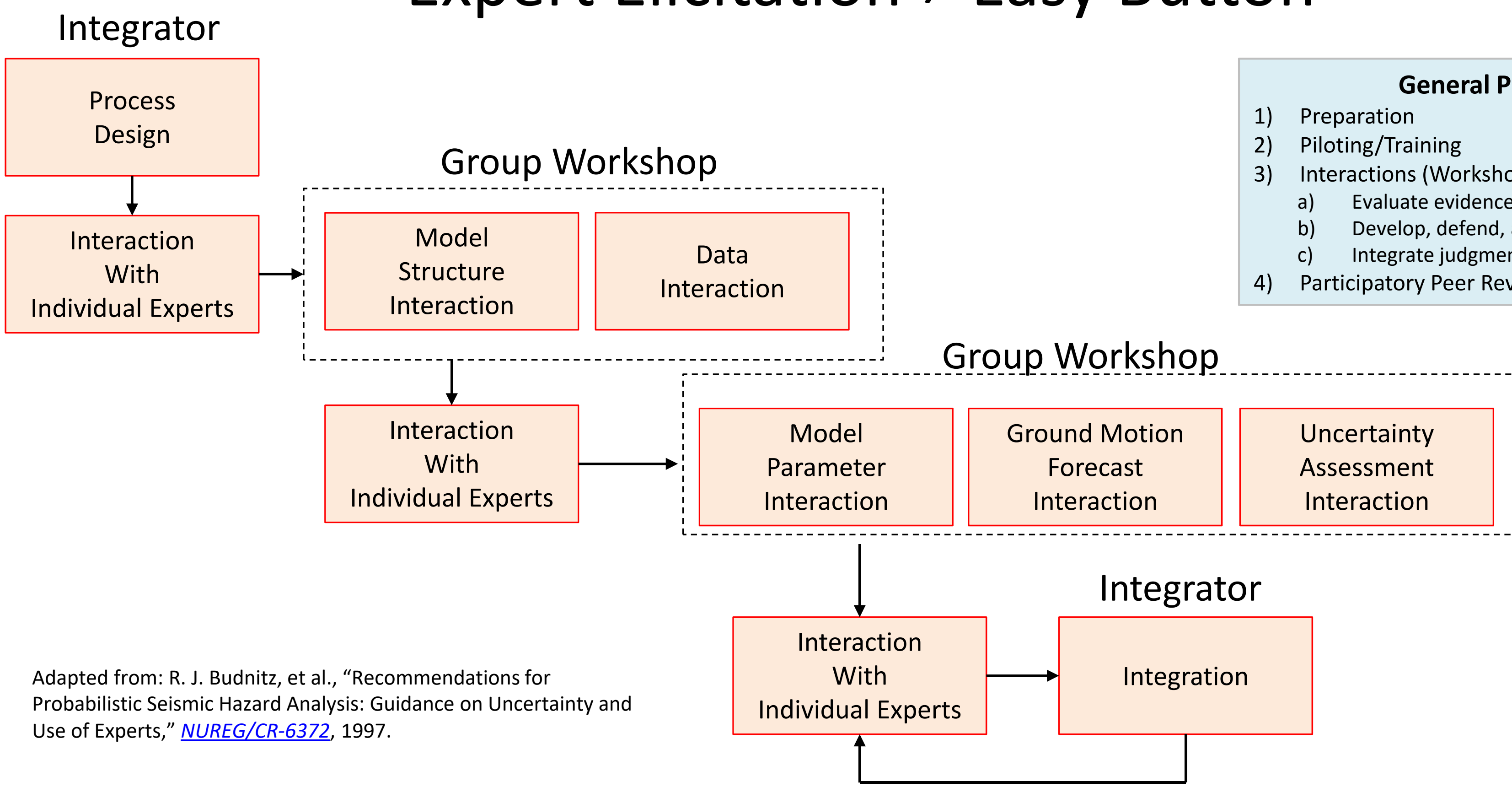
Possible but plausible?

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

Expert Elicitation ≠ Easy Button

General Process

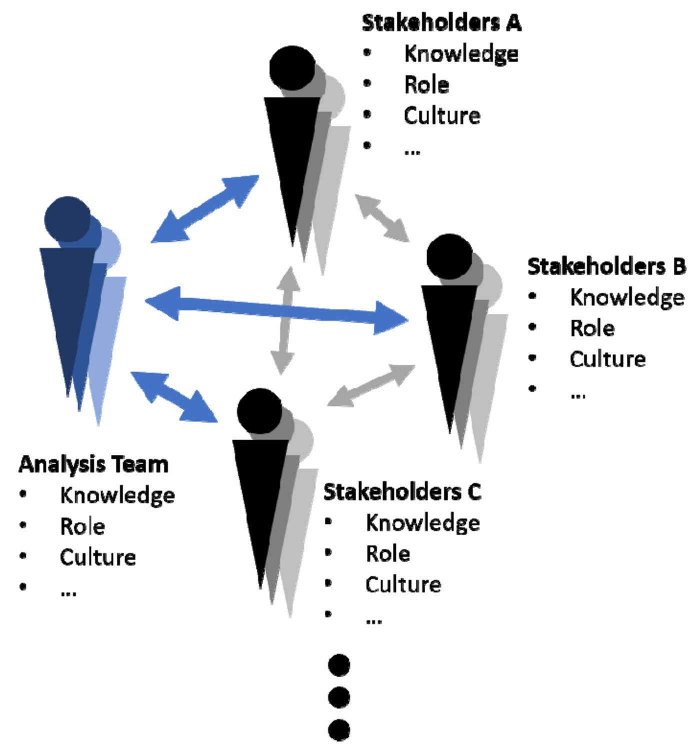
1) Preparation
2) Piloting/Training
3) Interactions (Workshops)
   a) Evaluate evidence
   b) Develop, defend, and revise judgments
   c) Integrate judgments
4) Participatory Peer Review



Adapted from: R. J. Budnitz, et al., "Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts," *NUREG/CR-6372*, 1997.

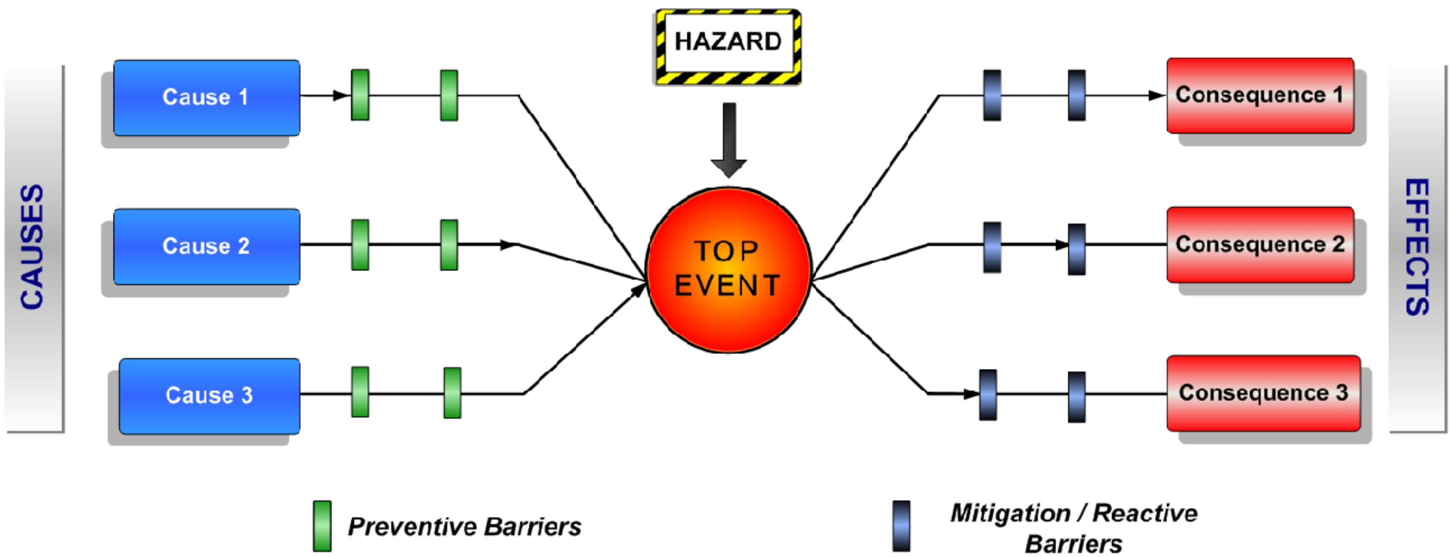
Sources of Risk Communication Breakdowns[1]

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



[1]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). Listed causes are for breakdowns between risk managers and the public, but appear to be relevant to internal risk communication as well.

Bowtie Diagrams:
Different Visualization => Different Insights? Decisions?



From W. Nelson, "How Things Fail – e.g. Deepwater Horizon and Fukushima – and Occasionally Succeed," presentation to U.S. Nuclear Regulatory Commission, Det Norske Veritas AS, November 2, 2011.