PRA and Risk-Informed Decisionmaking at the NRC: Status, Challenges, and Future Directions

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Prelude

Risk, PRA, and risk-informed decisionmaking

A Common Definition of "Risk"

$$\text{Risk} \equiv \sum_i p_i \times C_i$$

Decision support concerns:

- Purely quantitative
- Average value, equates
  – Low-probability/high-consequence
  – High-probability/low-consequence

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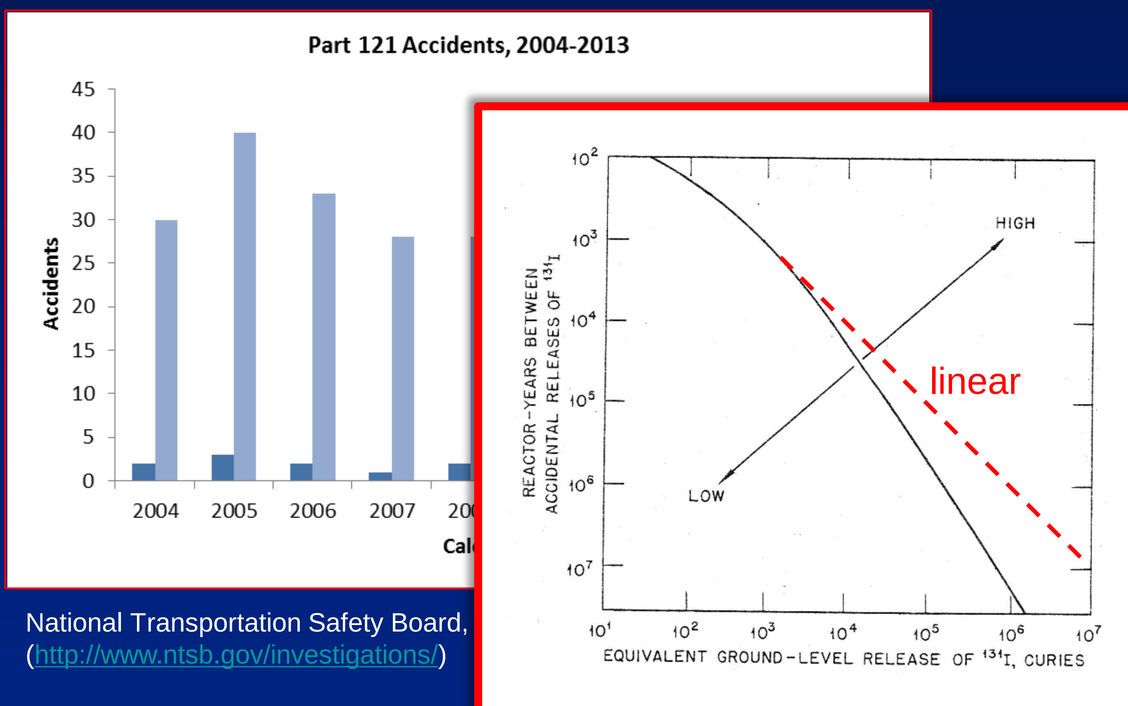
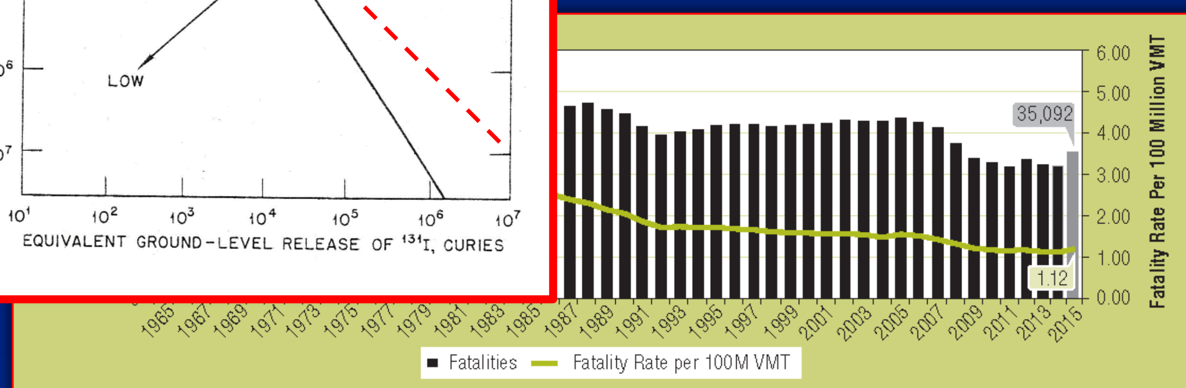
Low-Probability/High Consequence vs. High-Probability/Low Consequence



National Transportation Safety Board, (http://www.ntsb.gov/investigations/)

Adapted from Farmer, F.R., "Reactor safety and siting: a proposed risk criterion," *Nuclear Safety*, **8**, 539-548(1967).



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

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

$$\text{Risk} \equiv \{s_i, C_i, p_i\}$$

- 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," SECY-98-144, June 22, 1998.**

Probabilistic Risk Assessment (PRA)

- Answers the risk triplet questions
  - Addresses entire system
  - Includes event tree and fault tree analysis
- Supports decisions
  - Defined problem
  - Realistic
  - Practical
  - Treats uncertainties

Risk-Informed Regulatory Decisionmaking

Consider risk insights together with other factors

Risk-Informed ≠ Risk-Based

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Remainder of Talk

- PRA at the NRC
- Example Applications
- PRA Pointers/Reminders
- Current Challenges
- Future Directions
- Closing Thoughts

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Key Messages

- Risk is the answer to three questions
  - What can go wrong?
  - What are the consequences?
  - How likely is it?
- NRC uses PRA to support regulatory decision making
  - Risk-informed (not risk-based) decisionmaking
  - All regulatory functions
- Technical and implementation challenges are spurring research and other activities

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PRA at the NRC

How we use risk information and why

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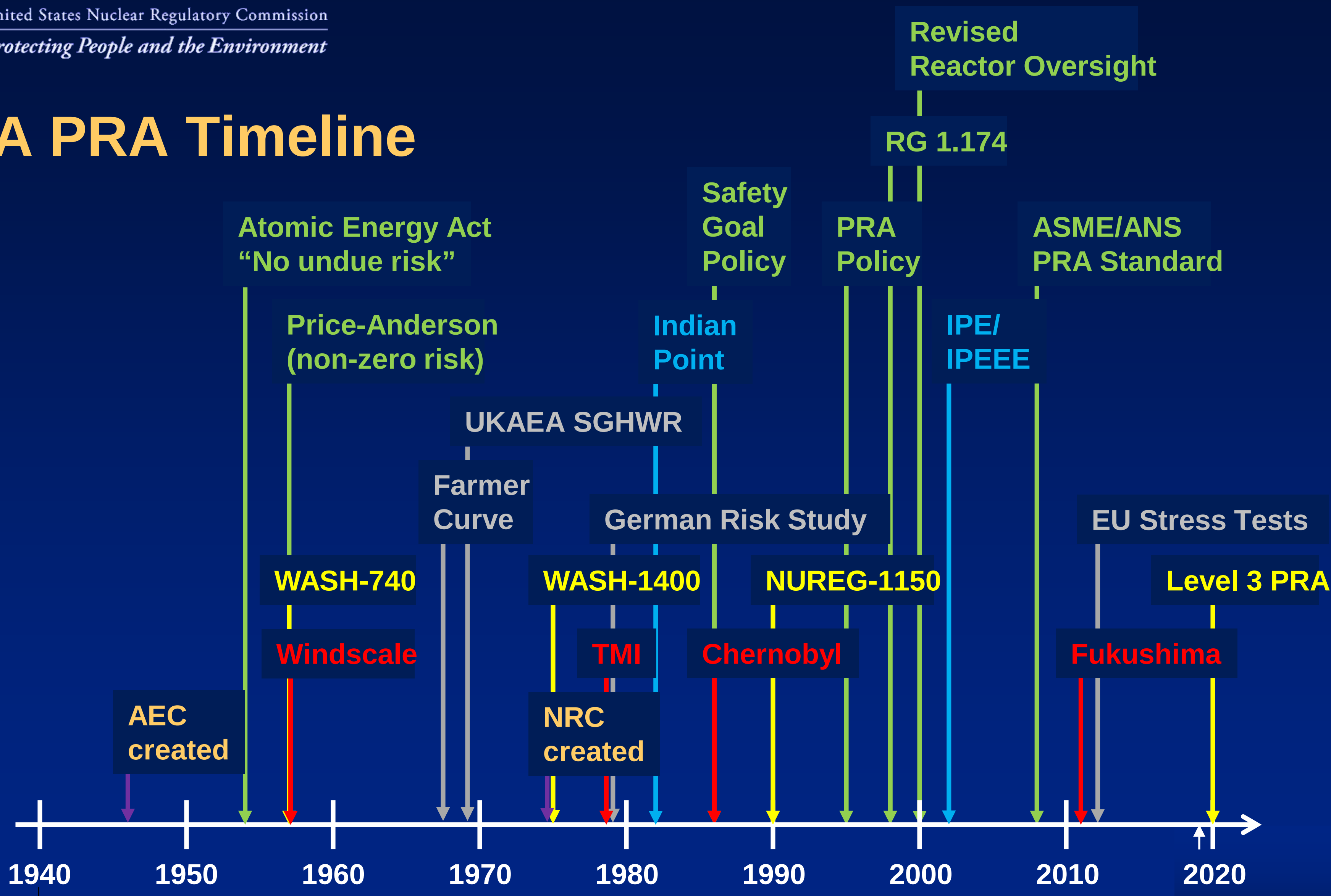
A PRA Timeline



1995 PRA Policy Statement

- 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

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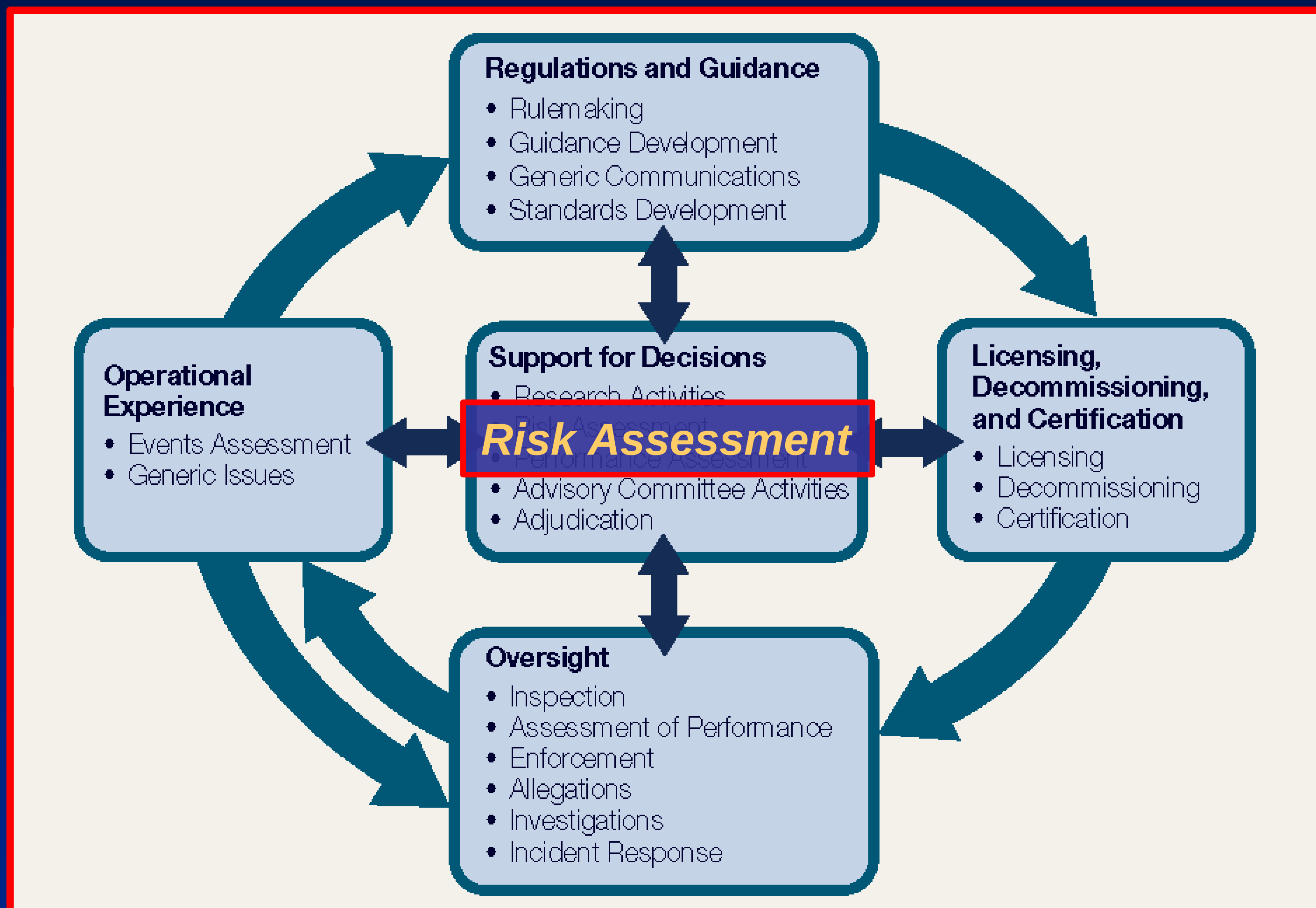
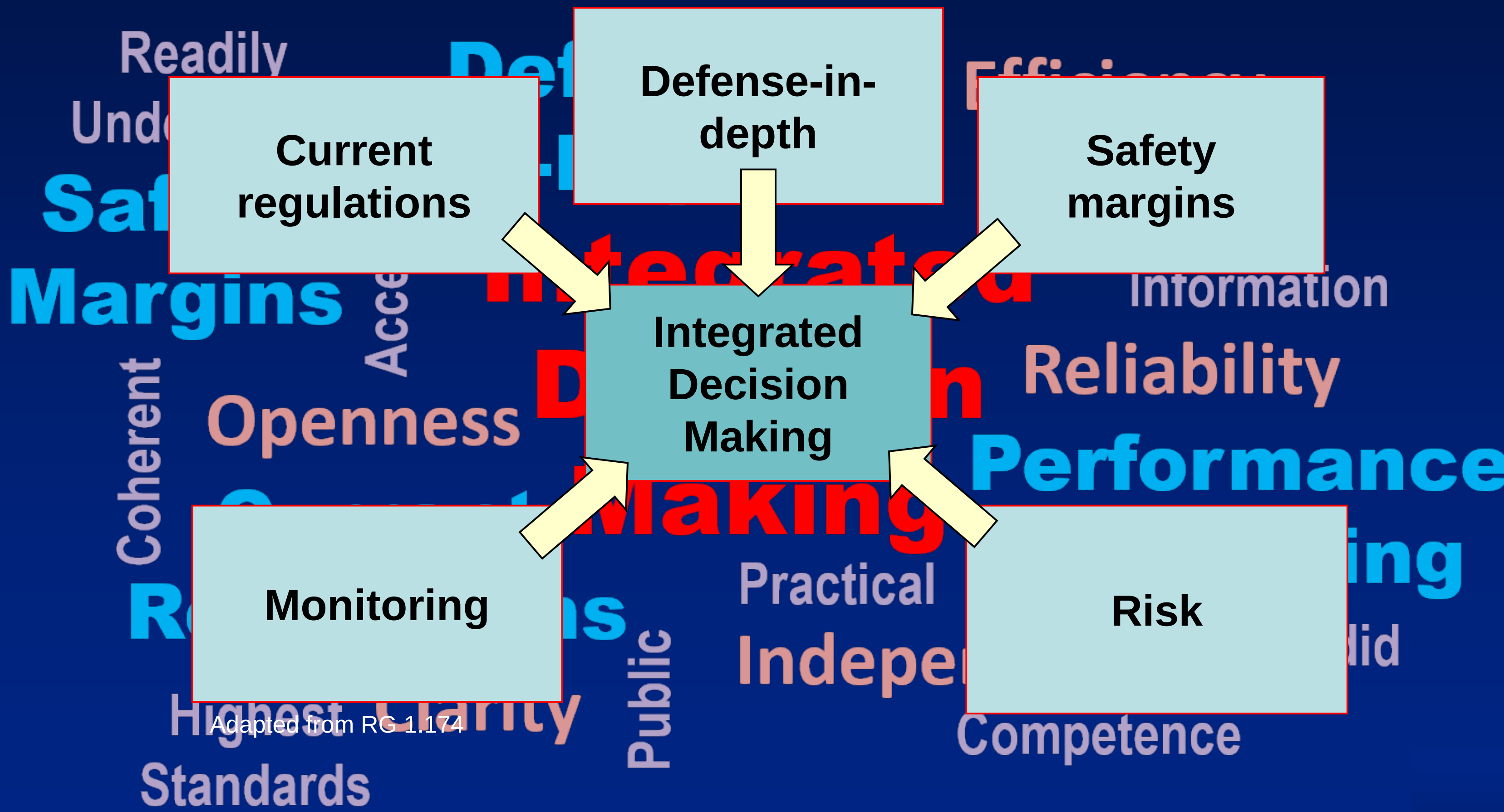
All regulatory matters

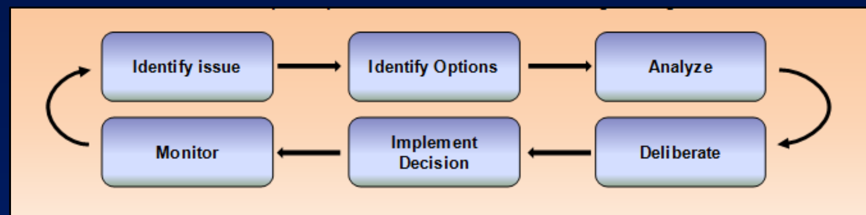


Complementing deterministic approach (1)

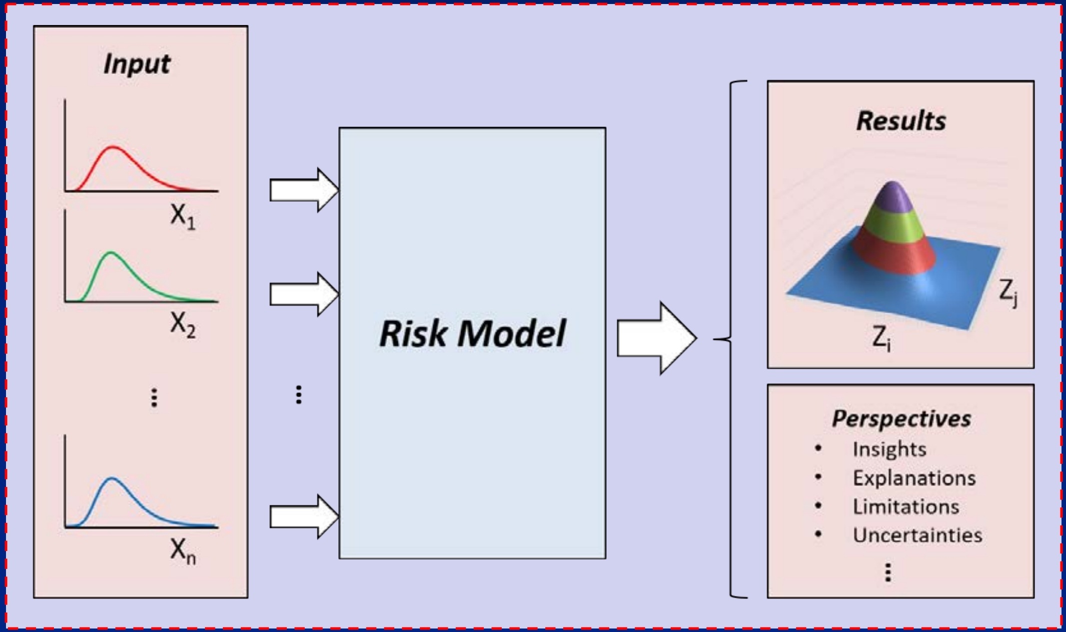


Adapted from RG 1.174

Complementing deterministic approach (2)



NUREG-2150

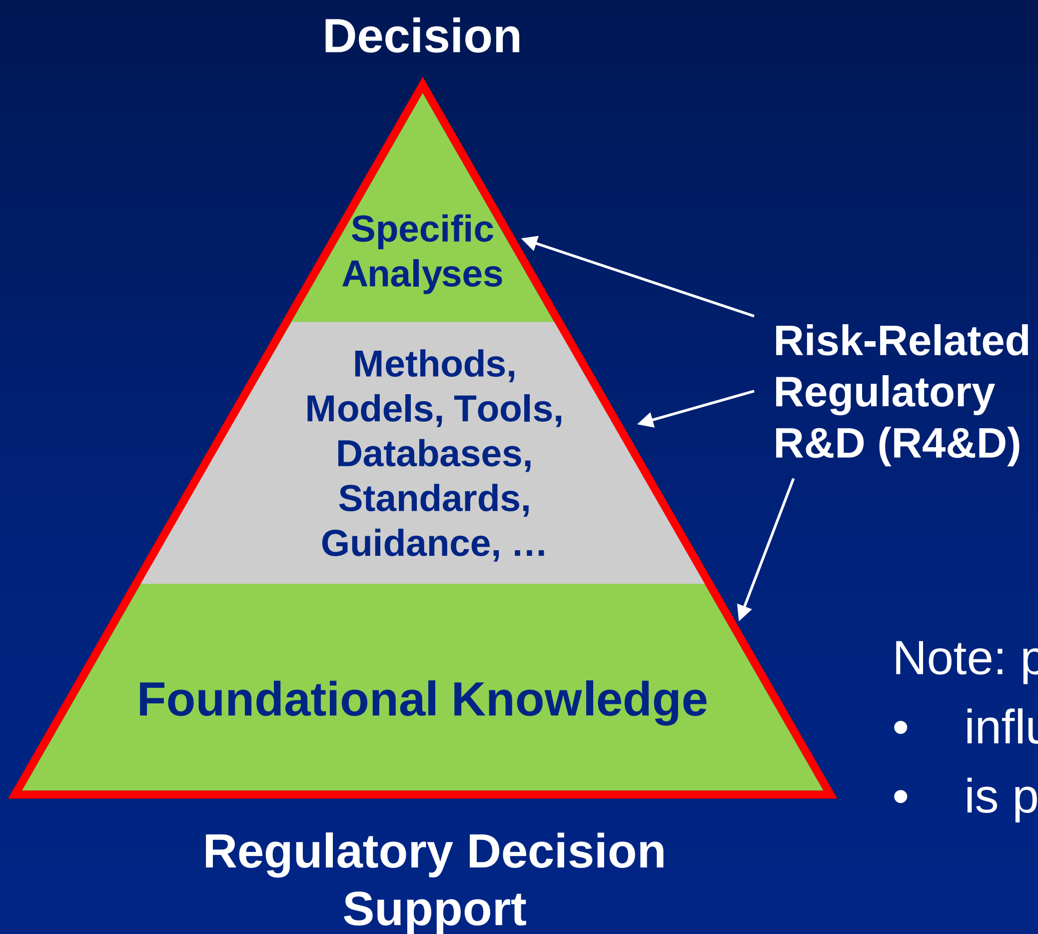


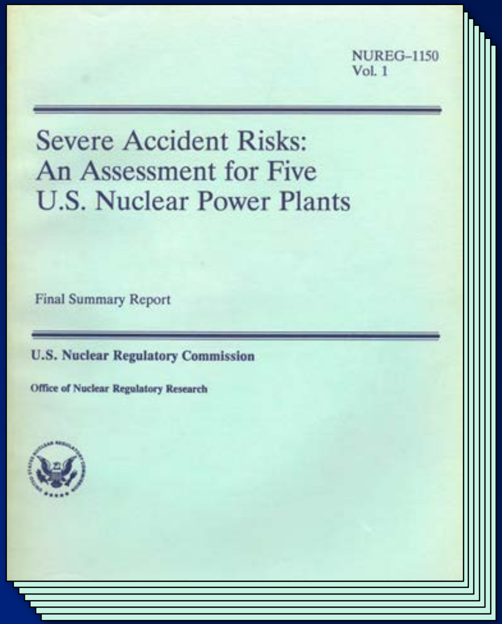
Other Considerations

- Current regulations
- Safety margins
- Defense-in-depth
- Performance monitoring

⋮

And before the immediate decision…





Note: prior, foundational knowledge:

- influences information processing
- is persistent

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PRA Applications

Some examples of PRA uses

Risk Management - General

- Decisions
  - Industry-wide and license-specific
  - Operating reactors: applications are voluntary
  - New reactors: PRAs required for design certification and licensing
- NUREG-2150: proposal to increase use of risk information

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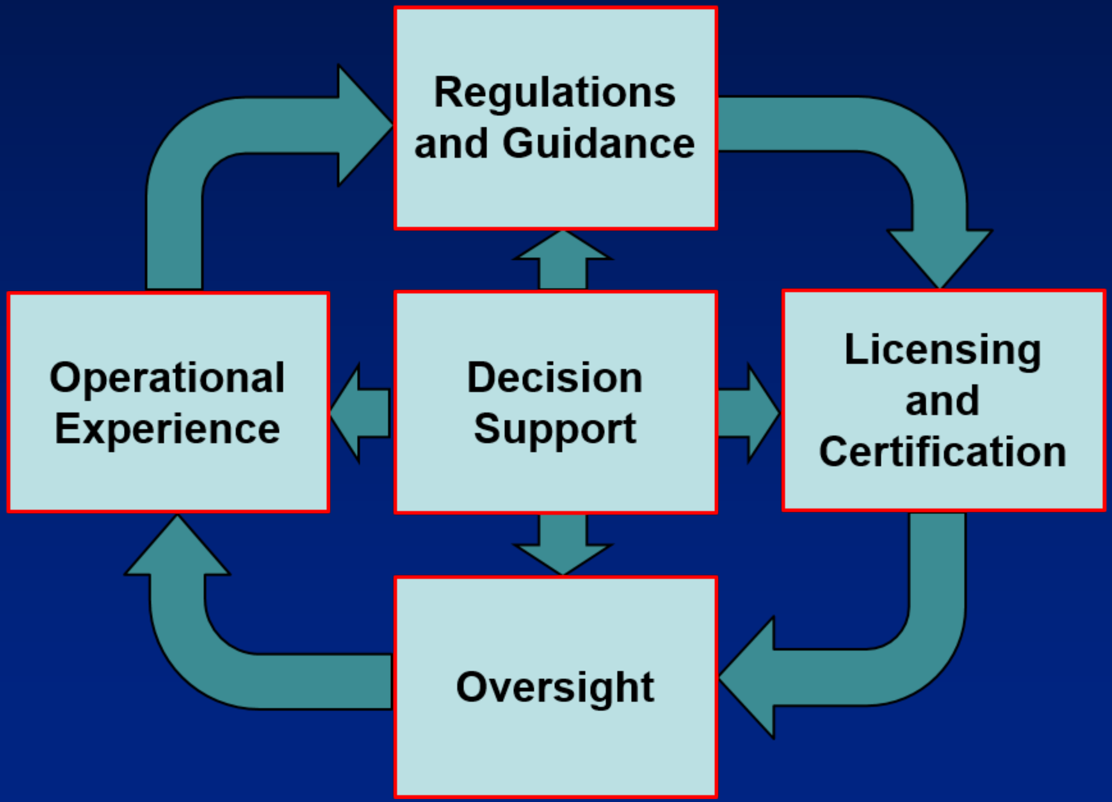
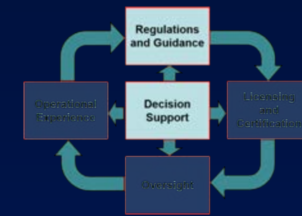
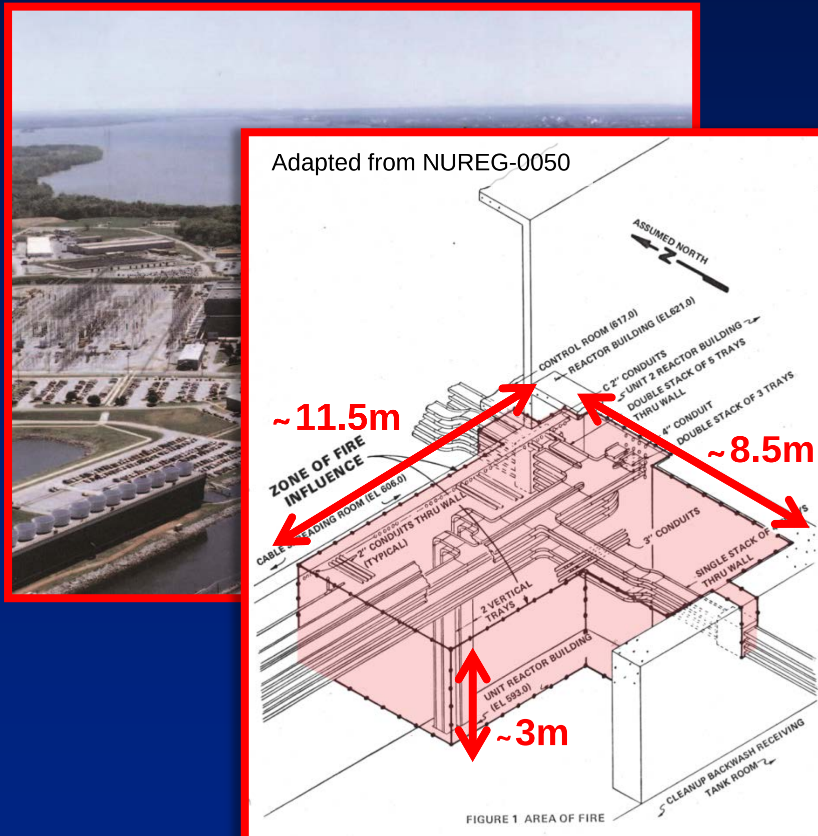
NRC Applications of Risk Information

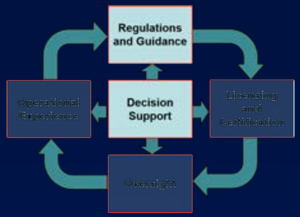




Fire Protection ("NFPA 805")

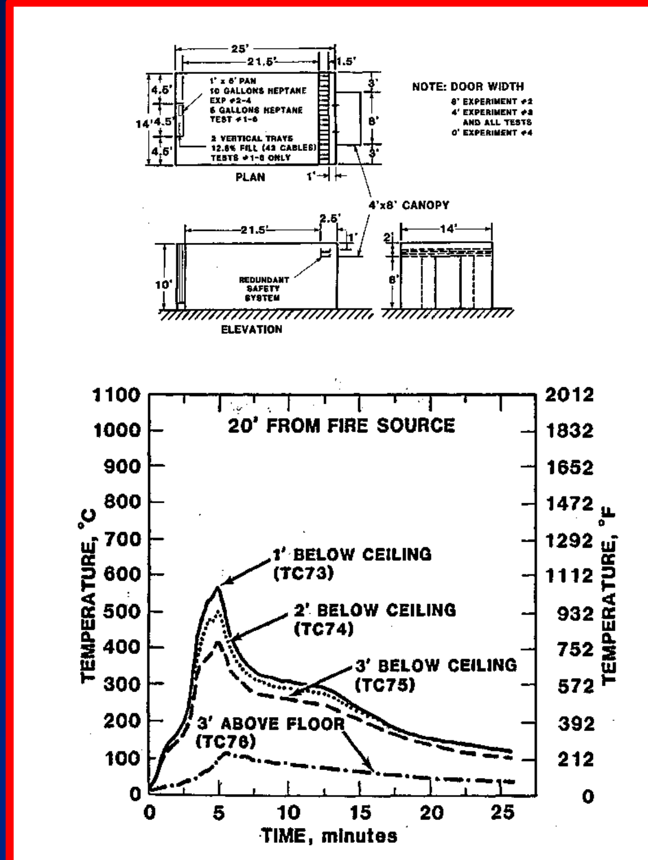
- Browns Ferry Nuclear Power Plant fire (3/22/75)
- Candle ignited foam penetration seal, initiated cable tray fire; water suppression delayed; complicated shutdown
- Second-most challenging event in U.S. nuclear power plant operating history
- Spurred changes in requirements and analysis



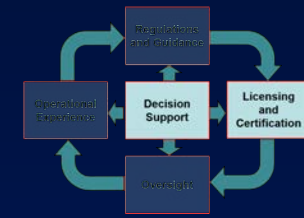


Fire Protection ("NFPA 805")

- Post-Browns Ferry deterministic fire protection (10 CFR Part 50, App 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"

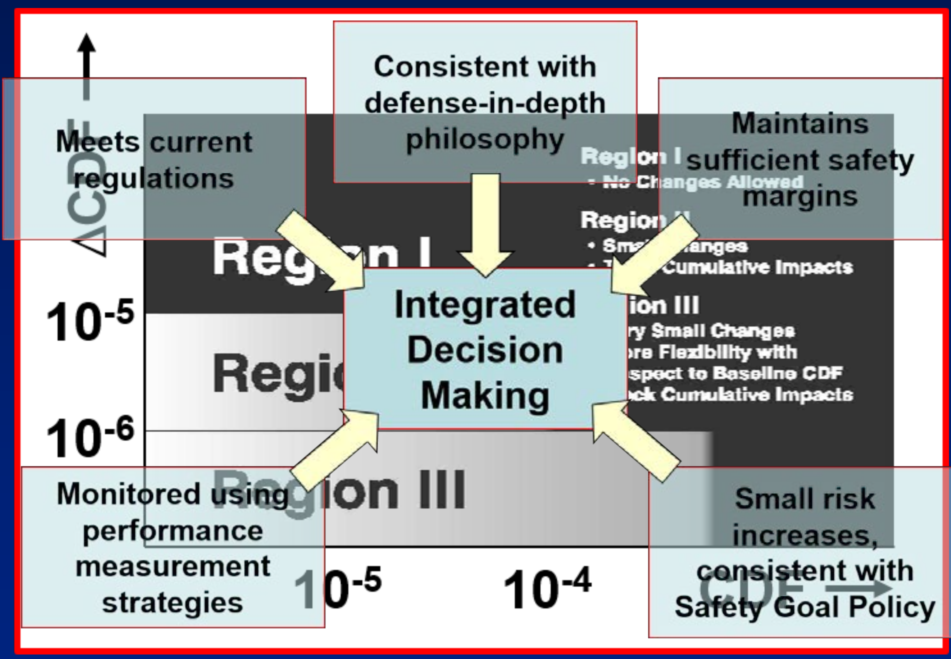


From Cline, D.D., et al., "Investigation of Twenty-Foot Separation Distance as a Fire Protection Method as Specified in 10 CFR 50, Appendix R," NUREG/CR-3192, 1983.

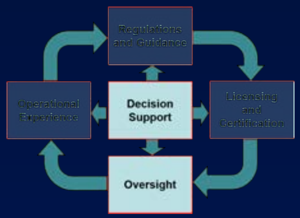


Changes in Plant Licensing Basis (RG 1.174)

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



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, 2018.

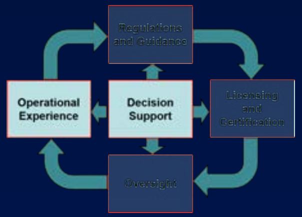


Reactor Oversight Program

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

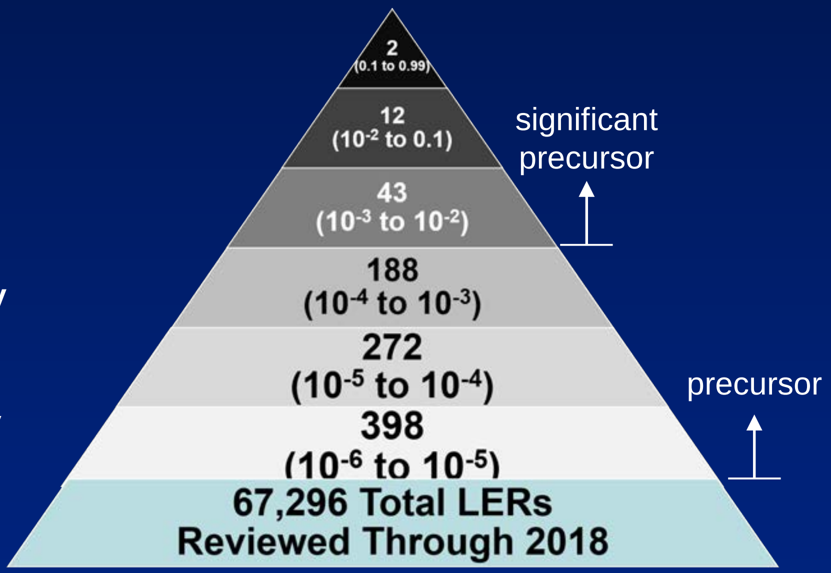
ΔCDF < 1E-6 ΔLERF < 1E-7
1E-6 < ΔCDF < 1E-5 1E-7 < ΔLERF < 1E-6
1E-5 < ΔCDF < 1E-4 1E-6 < ΔLERF < 1E-5
ΔCDF > 1E-4 ΔLERF > 1E-5

CDF = Core damage frequency
LERF = Large early release frequency



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)

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Keep in mind…

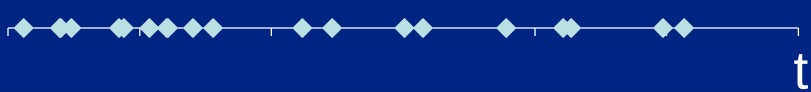
General PRA pointers and observations

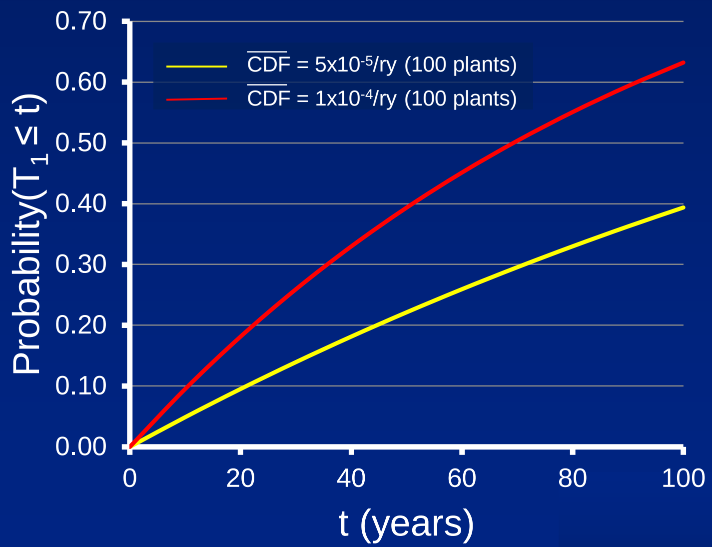
Core Damage Frequency (CDF) is a metric

- Governing equation

$$P\{N \text{ CD events in } (0,T)|CDF\} = \frac{(CDF \cdot T)^N}{N!} e^{-CDF \cdot T}$$

- Key assumptions
  - Independent events
  - No aging effects
- Clusters ≠> dependence



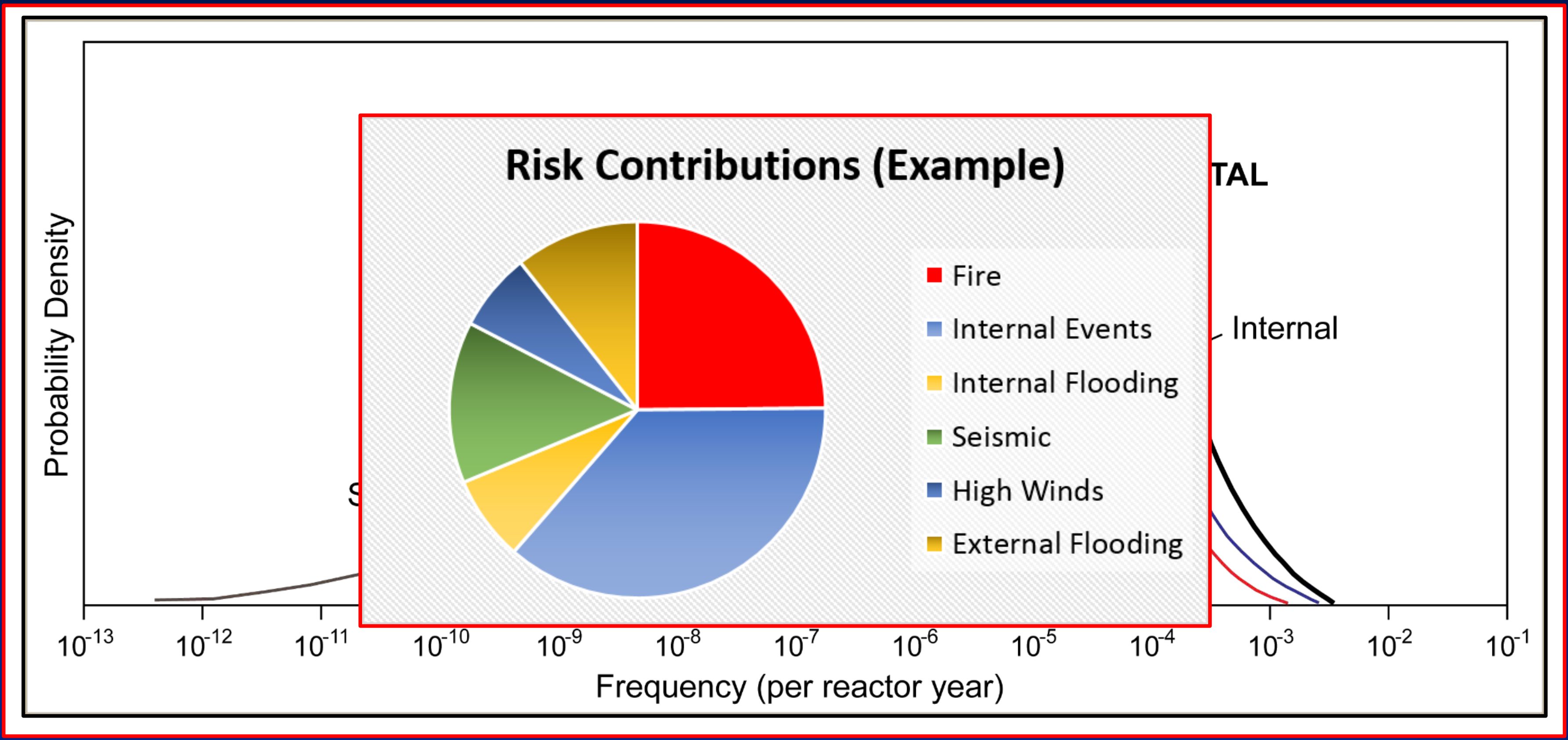


"P" in PRA reflects state of knowledge

P{X|C,H}

- P = Probability
- X = Proposition of concern (e.g., Plant X will have core melt in next 20 years)
- C = Conditions of assessment (e.g., key assumptions)
- H = State of knowledge:
  - Includes basic science/engineering, model predictions, empirical data, expert judgment
  - Dependent on assessor(s)

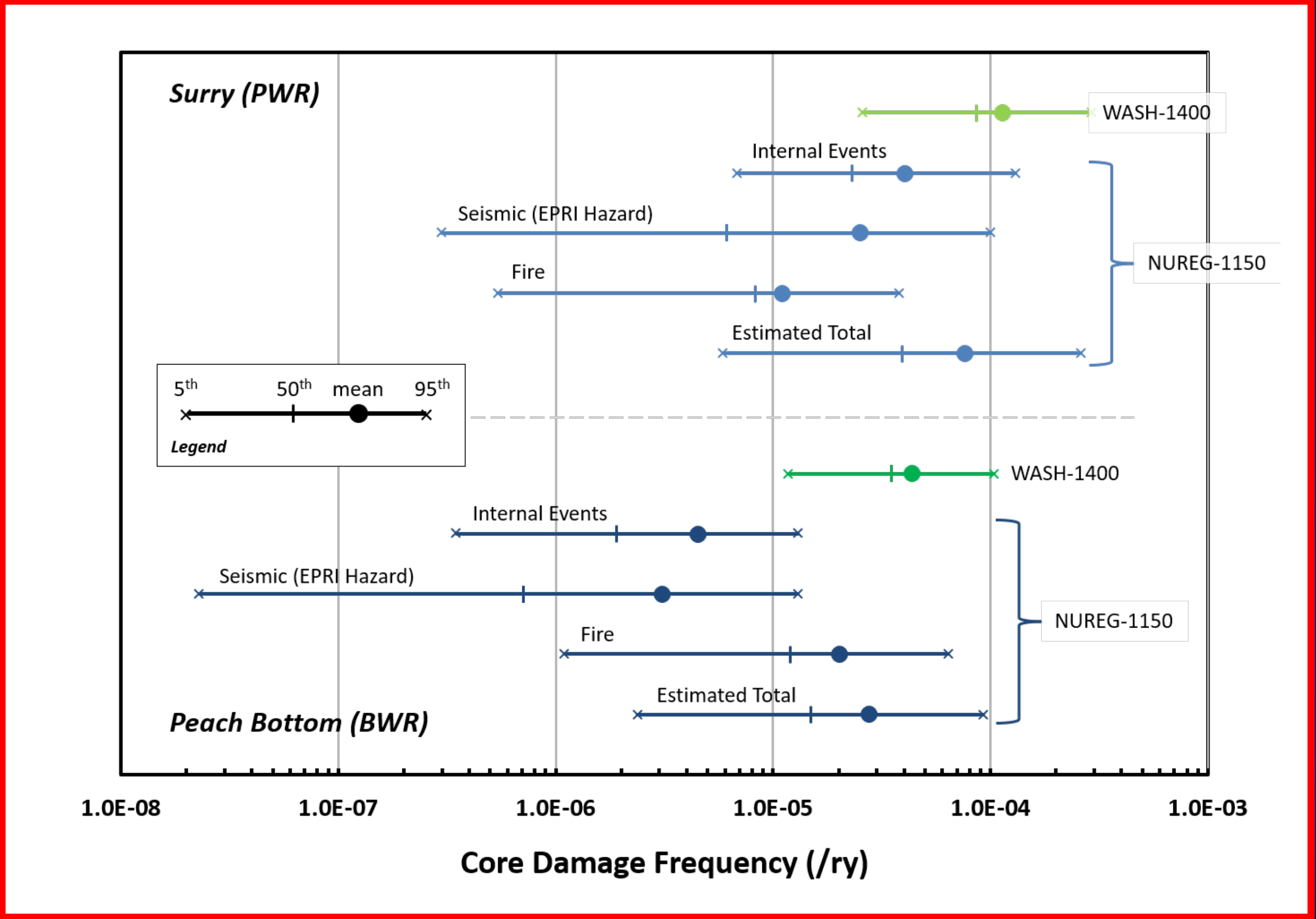
Multiple hazards can be important



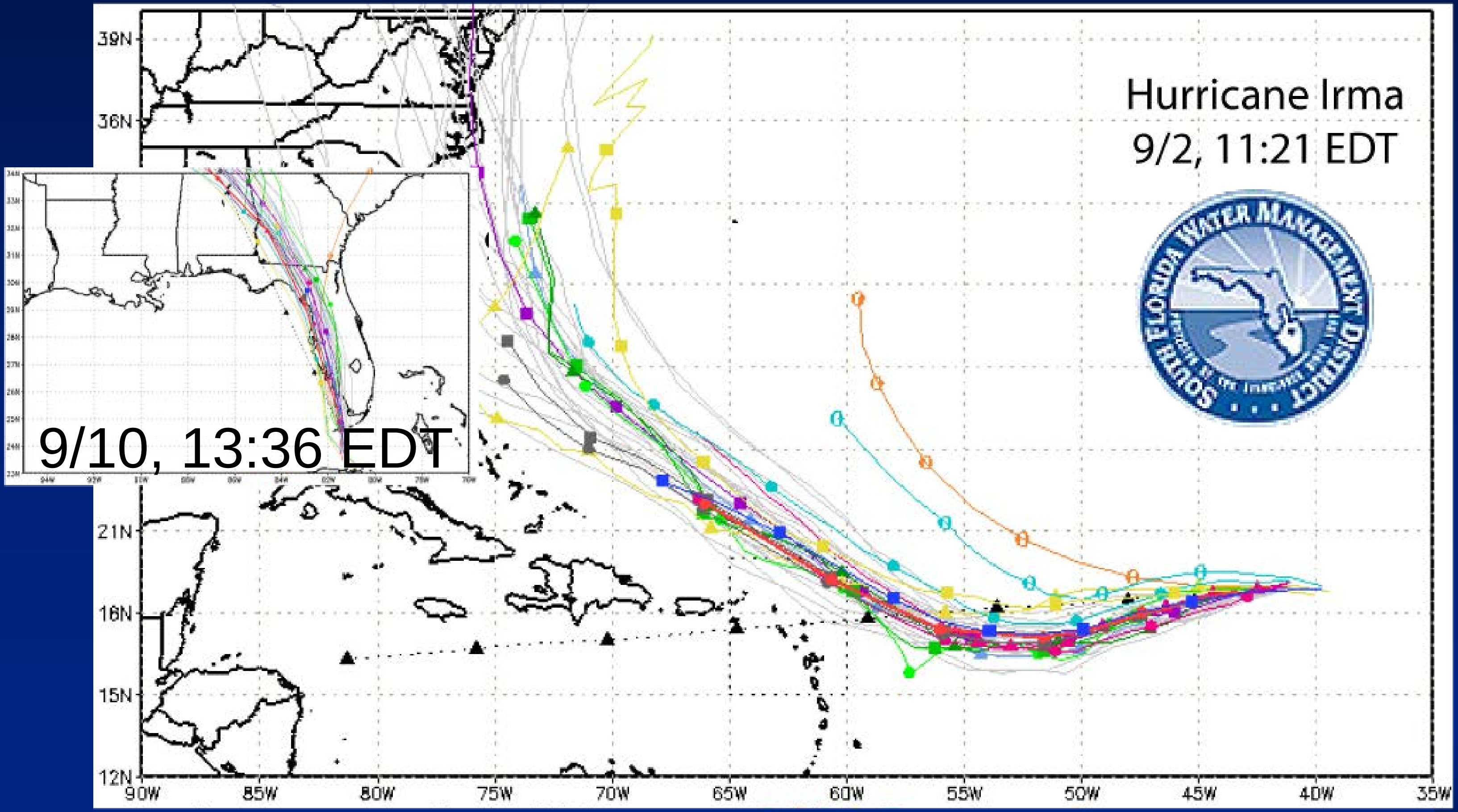
Accident data are sparse

- A good thing but subjectivity is inherent
  - Choice of relevant data
  - Modeling (what's in, what's out, level of detail)
  - Potential biases (personal knowledge, technical discipline focus)
- Need to make sure uncertainties are
  - Characterized (considering the views of the informed community)
  - Presented in digestible form

Uncertainties often ≥ order of magnitude



Uncertainties: important input to RIDM



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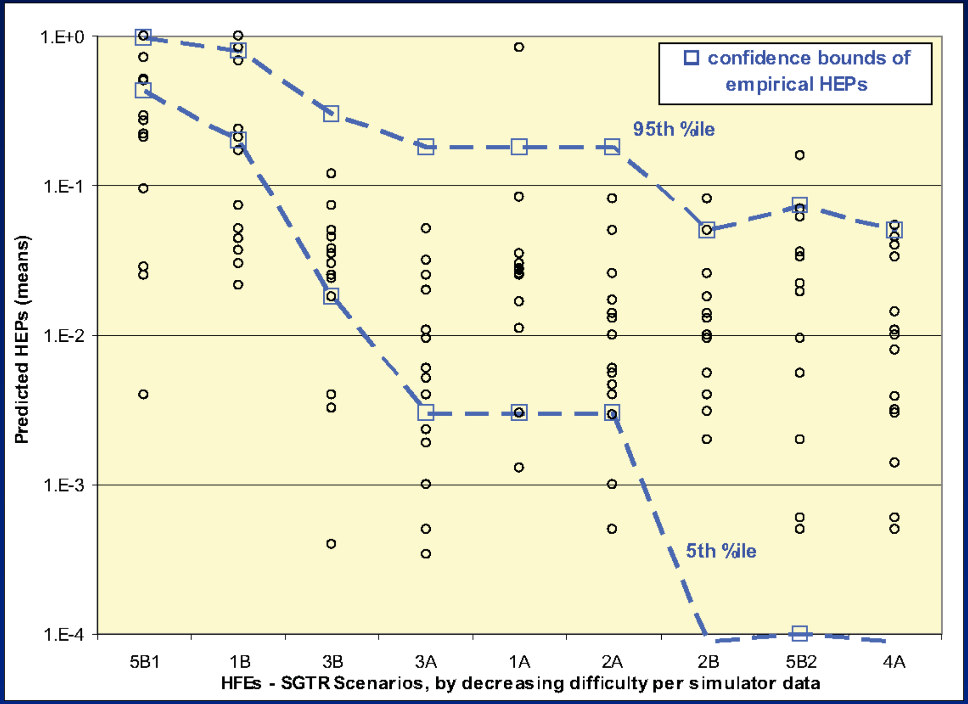
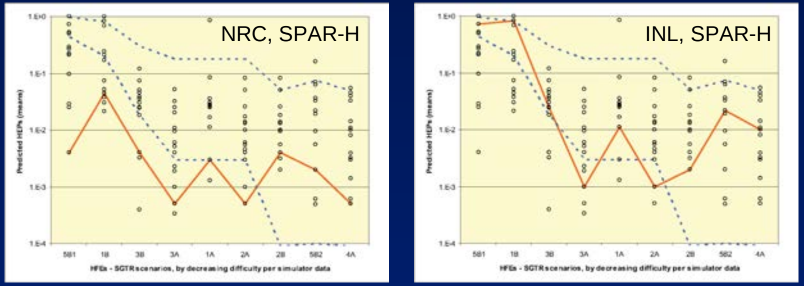
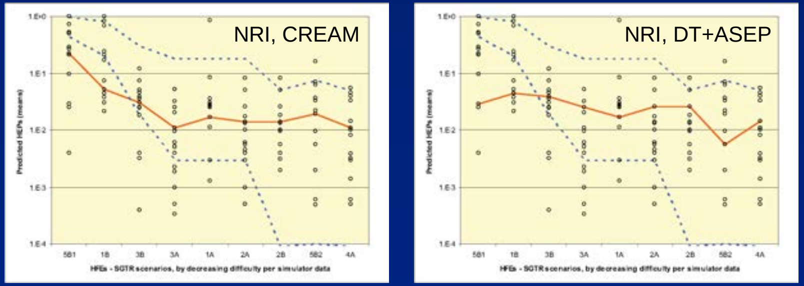
HRA example: model and user effects



All teams, all methods



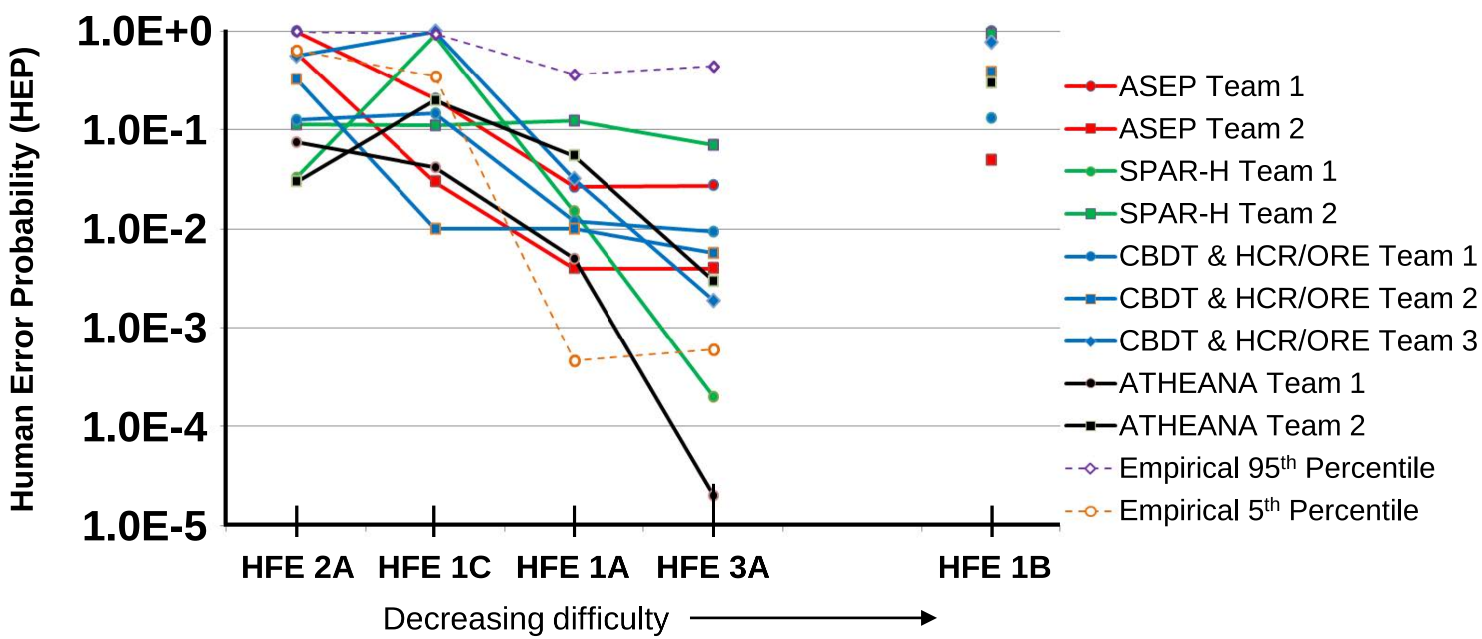
Same method, different teams



Same team, different methods

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

HRA example: second iteration



HEPs by HFE (All Methods)

Adapted from NUREG-2156

Some Challenges

Improving the technology and system

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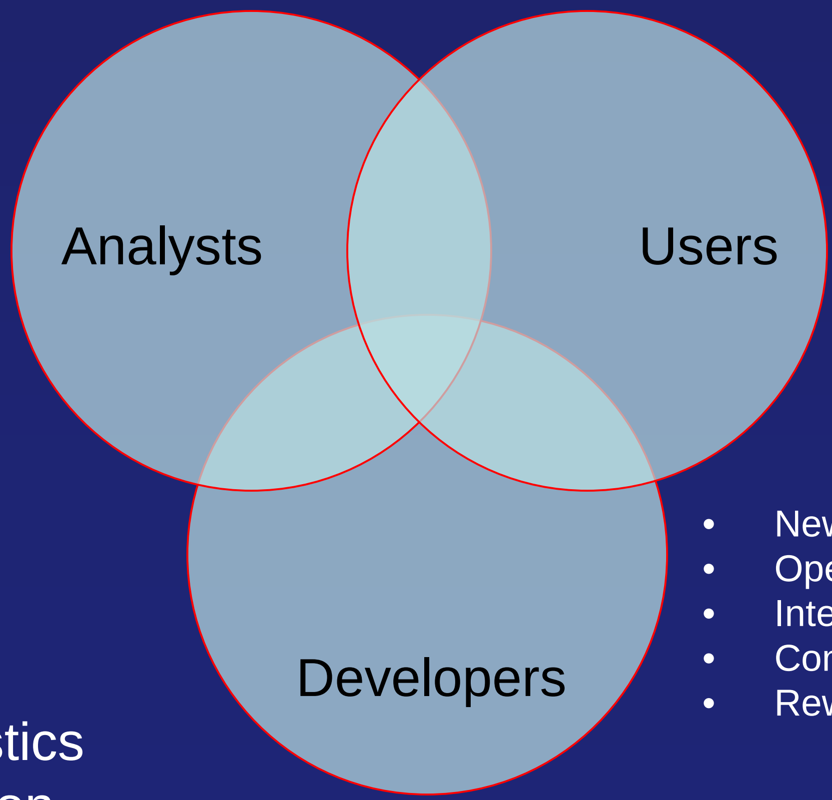
Example Challenges

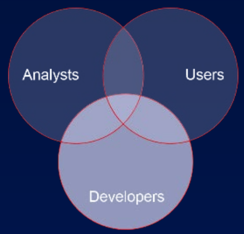
- Data
- Bounding/screening
- Guidance
- "Holes"
- Integration
- Imagination



- Understanding
- Uncertainties
- Heterogeneity and aggregation
- Confidence
- Other Factors (e.g., DID, safety margins)
- Stakeholders

- New science/engineering
- Operational experience
- Intended users/applications
- Computational limits
- Rewards

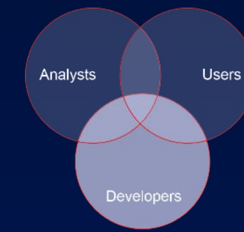
- Time
- Resources
- Biases/heuristics
- Communication



New Experiments and Analyses

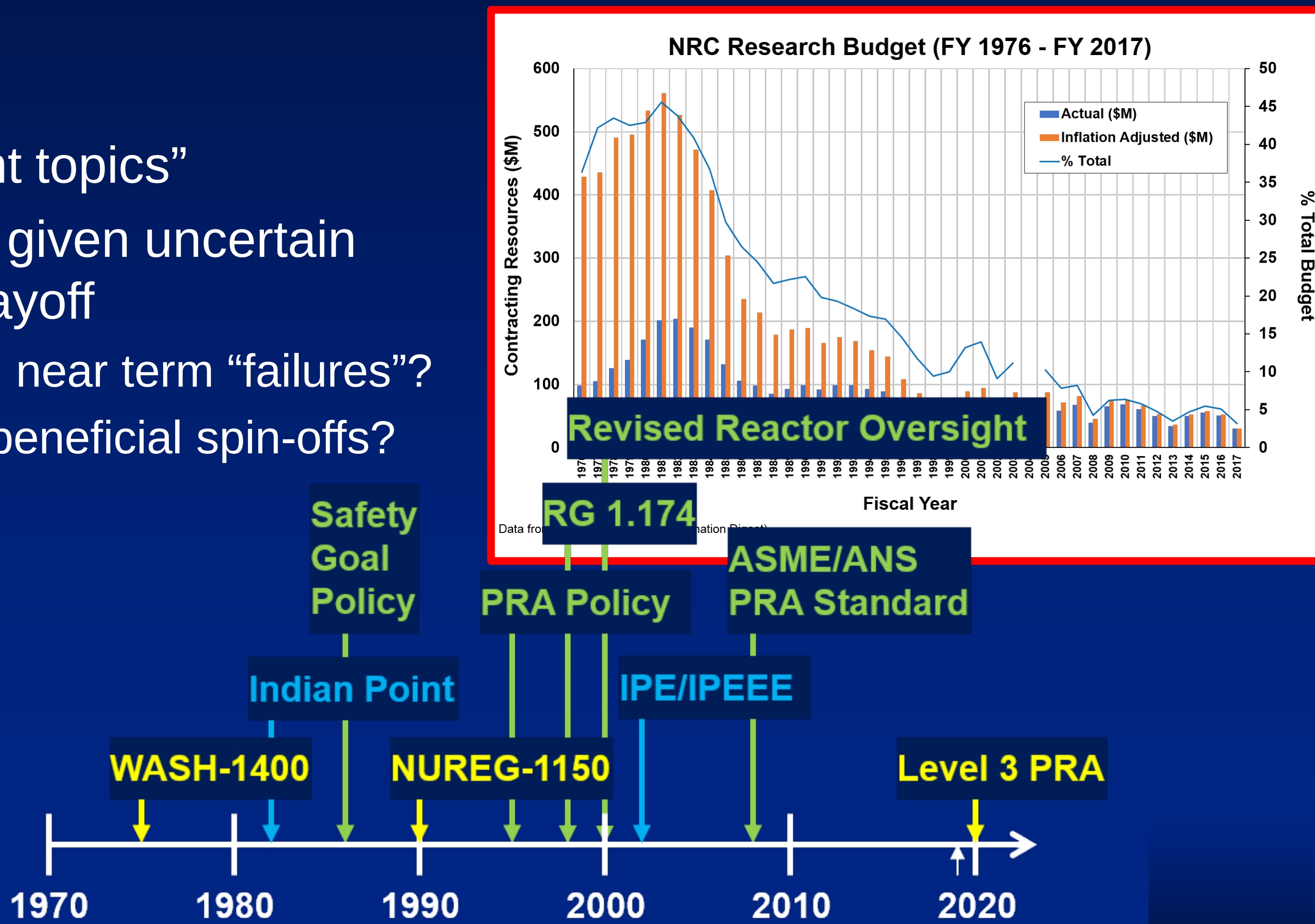
- High Energy Arc Faults (HEAF) in cabinets
- Aqueous transport of accident-generated wastewater
- State-of-the-Art Consequence Analysis (SOARCA)

- 600 V
- 40 kA
- 7 seconds



General R&D Challenges

- Resources
- Picking "right topics"
- Justification given uncertain long-term payoff
  - Allowable near term "failures"?
  - Delayed beneficial spin-offs?



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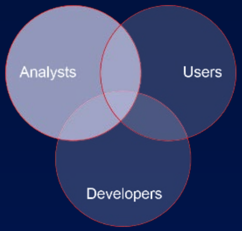
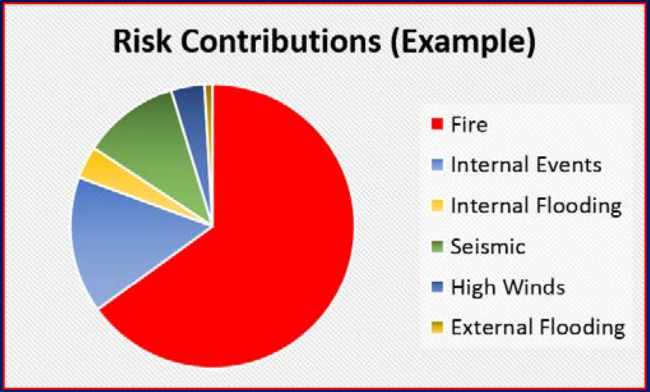
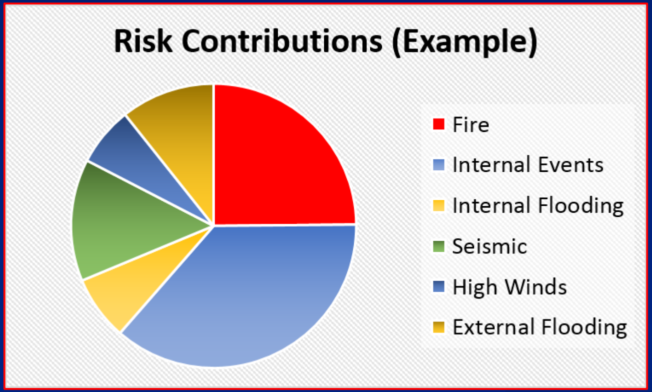
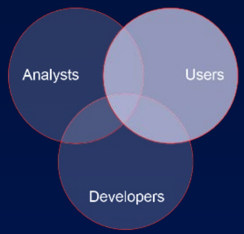


Bounding/Screening

- Needed to focus analysis on important scenarios
- Technical needs
  - Fundamental science/engineering
  - PRA methods, models, tools, data
  - Guidance
- Potential concerns
  - Overestimate total risk
  - Distort risk profile



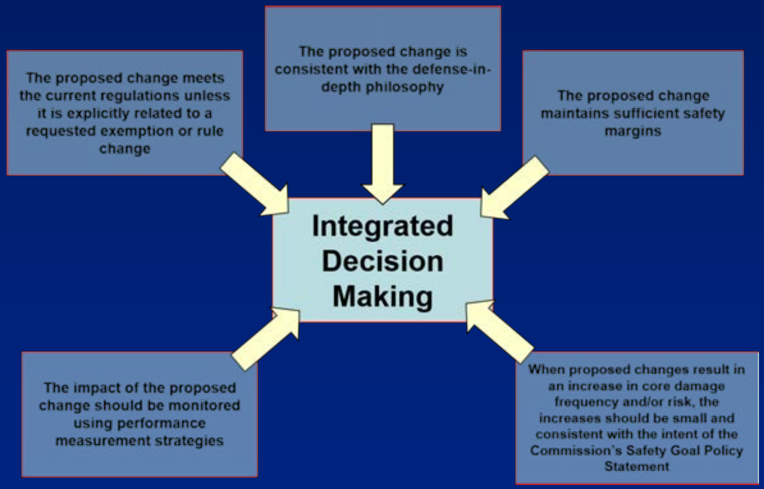




Stakeholder Views

NRC Risk-Informed Steering Committee

- Provides strategic direction to advance use of risk-informed decisionmaking
- Formed October 2013
- Public meetings
- Coordinated working groups
  - Technical adequacy (including new methods approval)
  - Uncertainty in decision making (including aggregation)
  - Credit for mitigating strategies



Adapted from RG 1.174

Future Directions

Near- and longer-term

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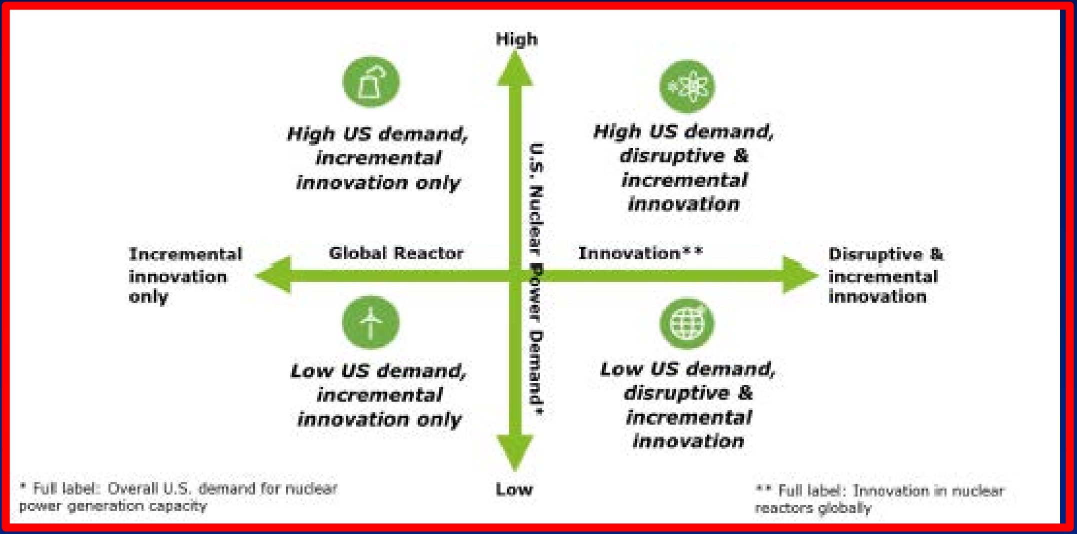
Influencing Factors

- Trends
- Initiatives and policies
  - Transformation
  - Single failure
- Potential implications for R4&D



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

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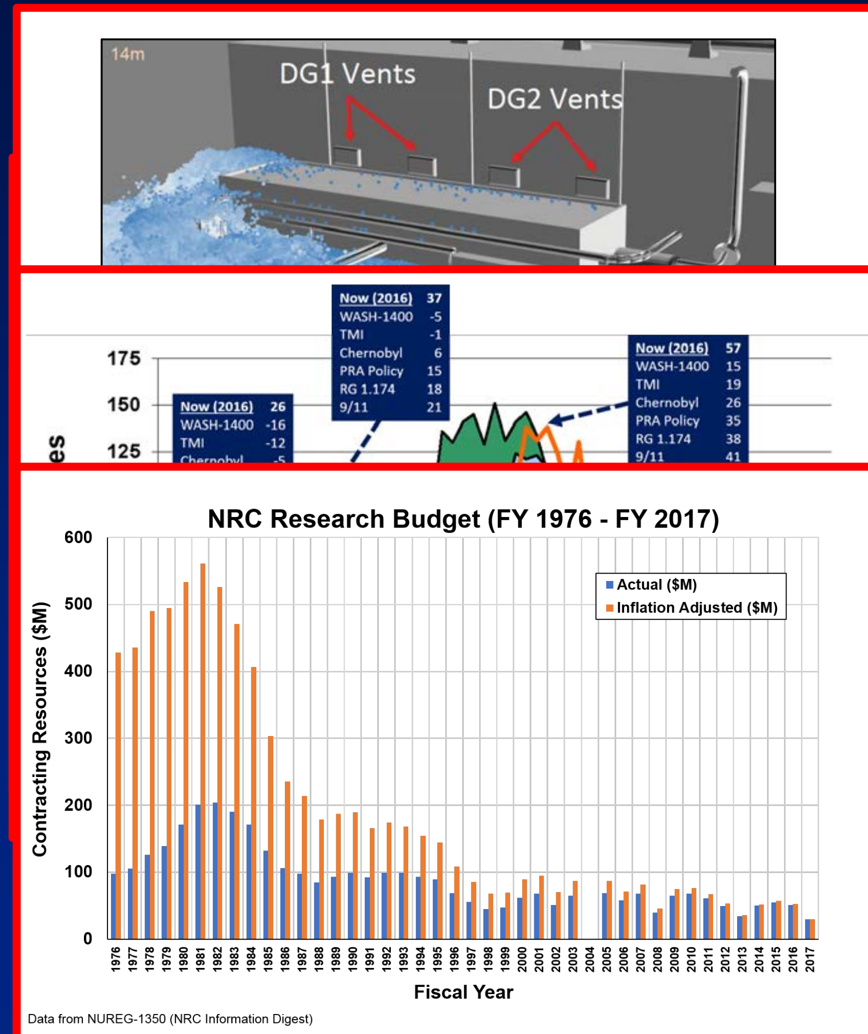
Some key trends

- Increasing economic pressure => increasing drive for RIDM
- Increasing variety of reactor concepts
- Improving analysis technology and expanding data
- Changing staff
- Decreasing R&D budget



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Initiatives and Policies

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"Transformation"

- SECY-18-0060: "Achieving Modern Risk-Informed Regulation," May 23, 2018 (ML18110A187, withdrawn)
- "Applying the Principles of Good Regulation as a Risk-Informed Regulator," October 15, 2019 (ML19260E683)
  - Evolving situation (market forces, new technologies, new professionals)
  - Vision: make safe use of nuclear technology possible
  - Continuing standard: reasonable assurance of adequate protection
  - Potentially different ways of achievement – embrace change

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Single Failure

- 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."

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Potential Future R4&D

- Near term – support operating reactors
- Longer-term
  - Leveraging results
  - Advanced Reactor PRA
  - Completeness uncertainties, e.g.,
    - "Errors of commission"
    - Passive systems
    - Digital I&C
    - External hazards
    - Security
- Forward looking
  - Advanced PRA methods: "dynamic PRA"
  - AI/Big Data: R4&D applications
    - Operational experience mining
    - Model review tools

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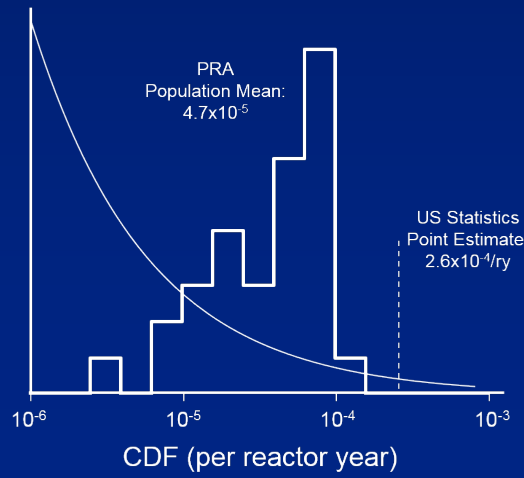
Closing Thoughts

Post-Fukushima critiques, key messages, references

Post-Fukushima PRA Discussions

PRA Critiques

- PRAs did not predict observed scenario – "failure of imagination"
- Global statistics "prove" PRAs underestimate risk



NRC Perspectives

- PRAs
  - identify and quantify possibilities; do not "predict"
  - look beyond the design basis and past operational experience
  - Provide framework to search for failure scenarios
- Global statistical estimates
  - assume exchangeability
  - neglect key information needed for regulatory decisionmaking
  - can spur examination of models

Key Messages

- Risk is the answer to three questions
  - What can go wrong?
  - What are the consequences?
  - How likely is it?
- NRC uses PRA to support regulatory decision making
  - Risk-informed (not risk-based) decisionmaking
  - All regulatory functions
- Technical and implementation challenges are spurring research and other activities

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For Further Reading*

- USNRC, "A Proposed Risk Management Regulatory Framework," NUREG-2150, 2012.
- USNRC, "Use of Probabilistic Risk Assessment Methods in Nuclear Activities: Final Policy Statement," Federal Register, Vol. 60, p. 42622 (60 FR 42622), August 16, 1995.
- USNRC, "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, 2018.
- USNRC, "No Undue Risk: Regulating the Safety of Operating Nuclear Power Plants," NUREG/BR-0518, 2014.
- USNRC, "Probabilistic Risk Assessment and Regulatory Decision Making: Some Frequently Asked Questions," NUREG-2201, 2016.
- Kaplan, S. and B.J. Garrick, "On the quantitative definition of risk," *Risk Analysis*, **1**, 11-37(1981).

*Most of these references can be found at www.nrc.gov

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NRC Information

- Website: www.nrc.gov
- Agencywide Document Access and Management System (ADAMS): https://adams.nrc.gov/wba/
- Jobs (USAJOBS): http://www.nrc.gov/about-nrc/employment/apply.html
- Status of risk-informed activities: https://www.nrc.gov/about-nrc/regulatory/risk-informed/rpp.html

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Additional Slides

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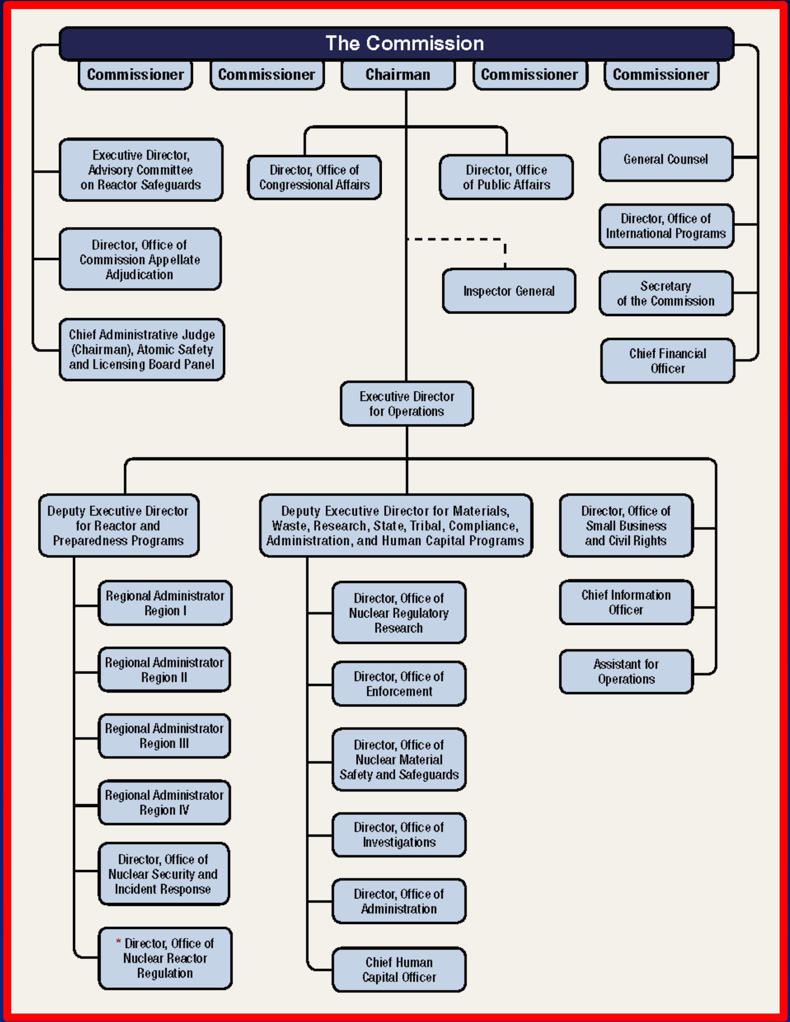
NRC Organization

- Headquarters + 4 Regional Offices
- 5 Commissioners
- ~3100 staff (FY 2019)
- Annual budget ~$910M
- Website: www.nrc.gov
- Information Digest: NUREG-1350 V31



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NRC PRA Work and Interactions

- NRC (HQ and Regions)
  - Analysts
  - Reviewers
  - Policy and decision makers
- National Laboratories
- Private Firms
- Universities
- Cooperating Organizations
  - Other government agencies
  - Industry (licensees, owners groups, R&D)
  - International (IAEA, OECD/NEA)
- Standards Organizations
- Public
  - Industry
  - PRA community
  - General public

NRC Mission

“The U.S. Nuclear Regulatory Commission licenses and regulates the Nation’s civilian use of radioactive materials to protect public health and safety, promote the common defense and security, and protect the environment.”

- NUREG-1614 (NRC Strategic Plan)

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Regulatory Approach

Standard*

"Reasonable assurance of adequate protection"

Principles**

- Independence
- Openness
- Efficiency
- Clarity
- Reliability

* When granting, suspending, revoking, or amending licenses or construction permits. (Atomic Energy Act of 1954, as amended – see NUREG-0980, v1, n7, 2005)

**NRC Strategic Plan (NUREG-1614, v6, 2014)

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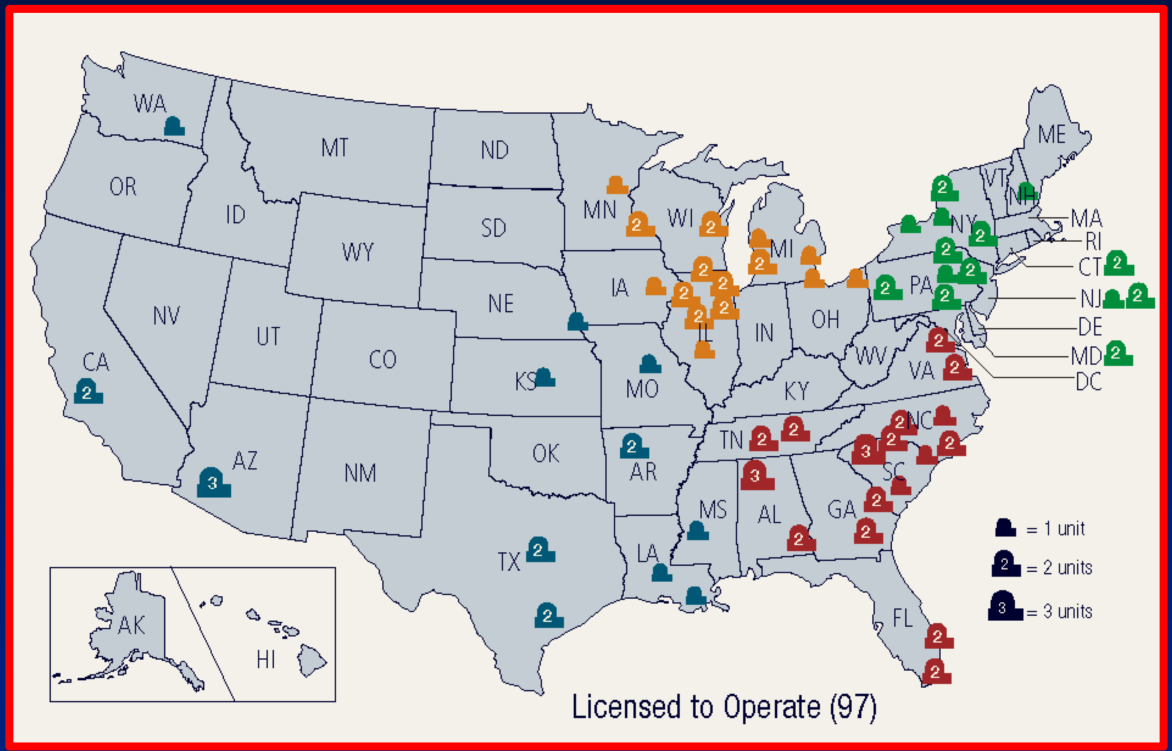
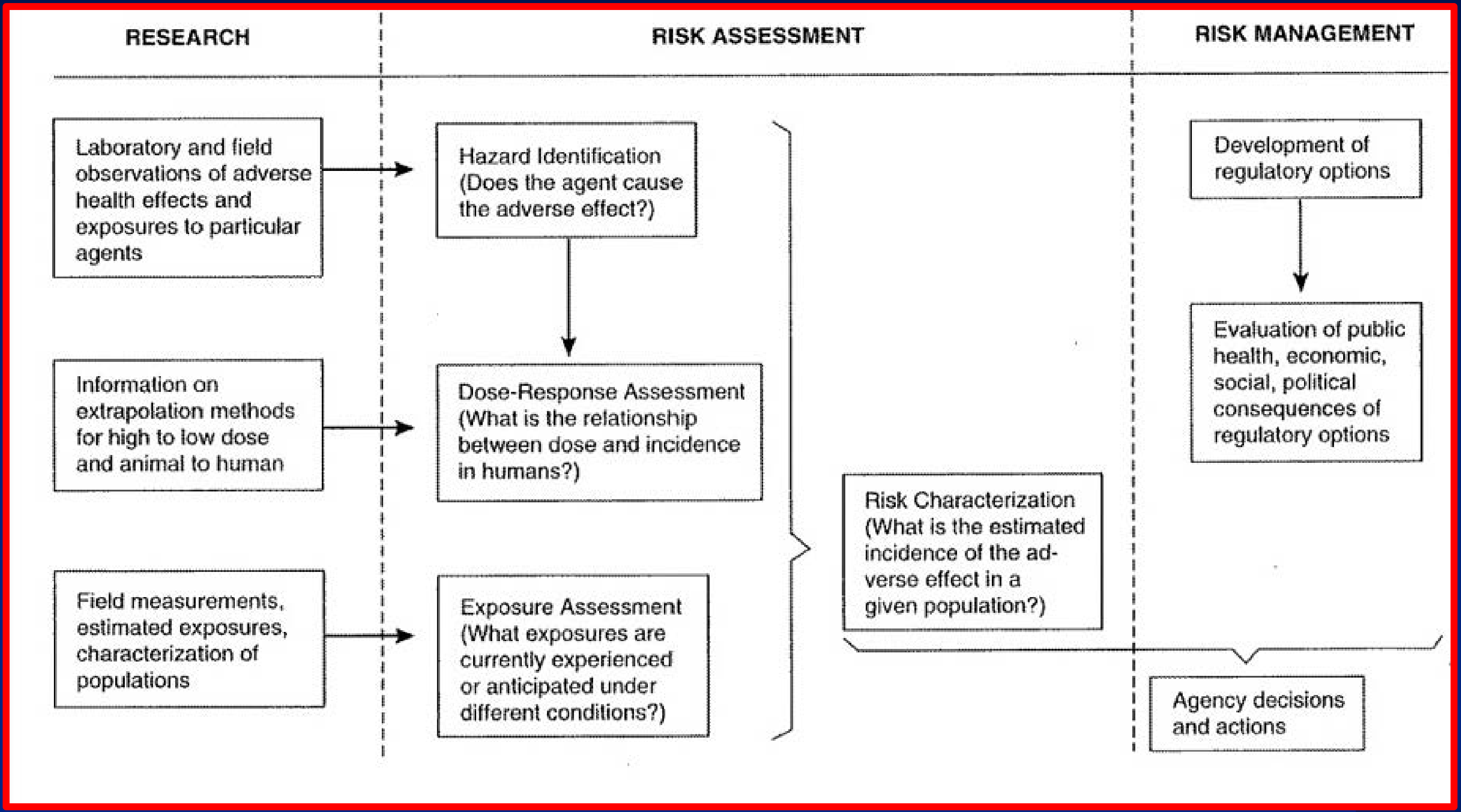
U.S. Nuclear Power Plants (2019)



- 97 plants (58 sites) – 65 PWR, 32 BWR, ~19% U.S. total electricity (2017)
- 12 expected to shut down/not seek license renewal by 2025
- Subsequent License Renewal: 6 applications under review
- Early Site Permits (ESP): 5 issued, 1 (TVA, Clinch River) under review
- Combined Construction and Operating License (COL): 14 issued, 6 terminated
- Design Certification (DC): 6 issued, 2 (US-APWR, NuScale) under review

Risk Assessment vs. Risk Management

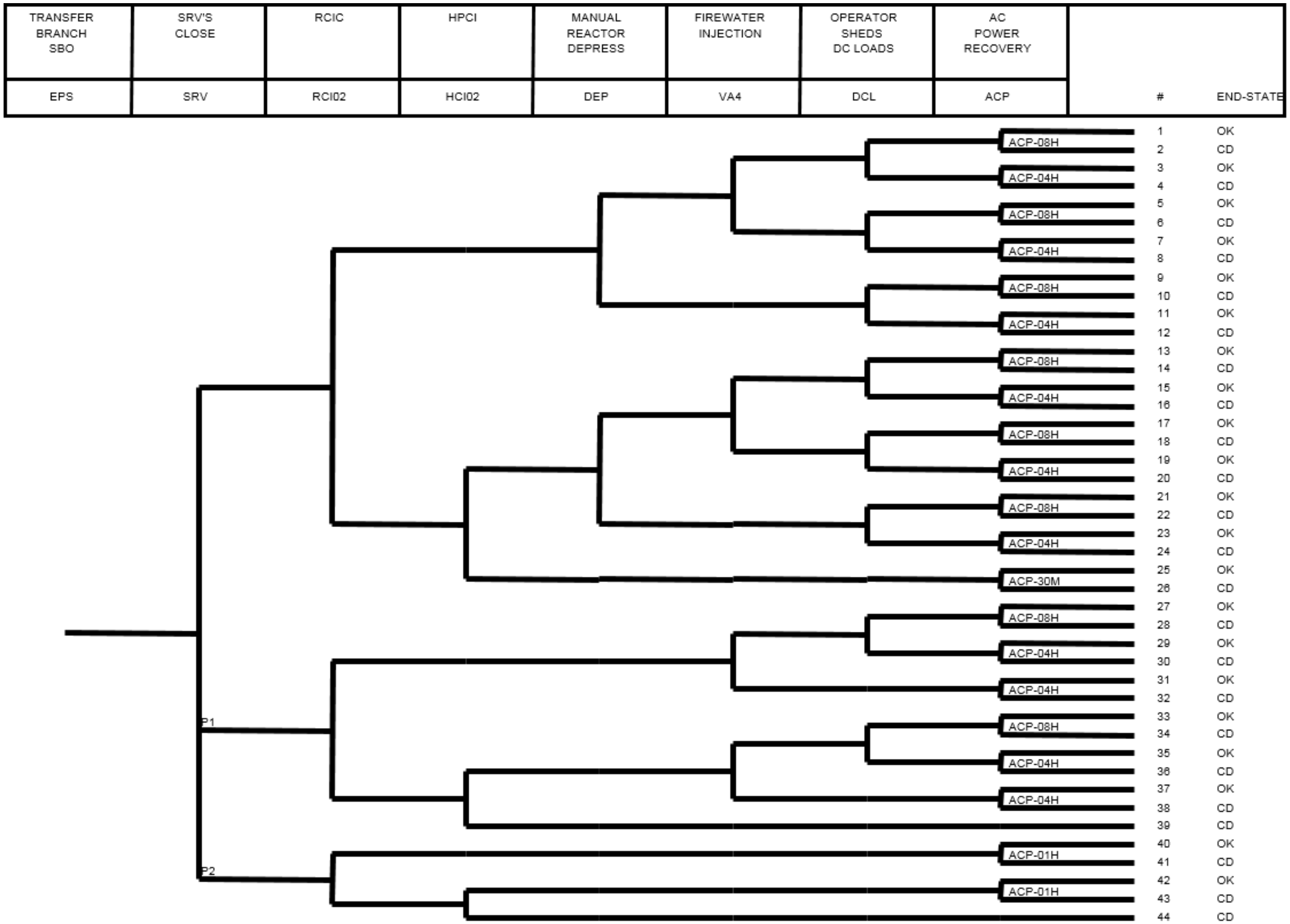


From National Research Council, "Understanding Risk: Informing Decisions in a Democratic Society," National Academy Press, 1996.

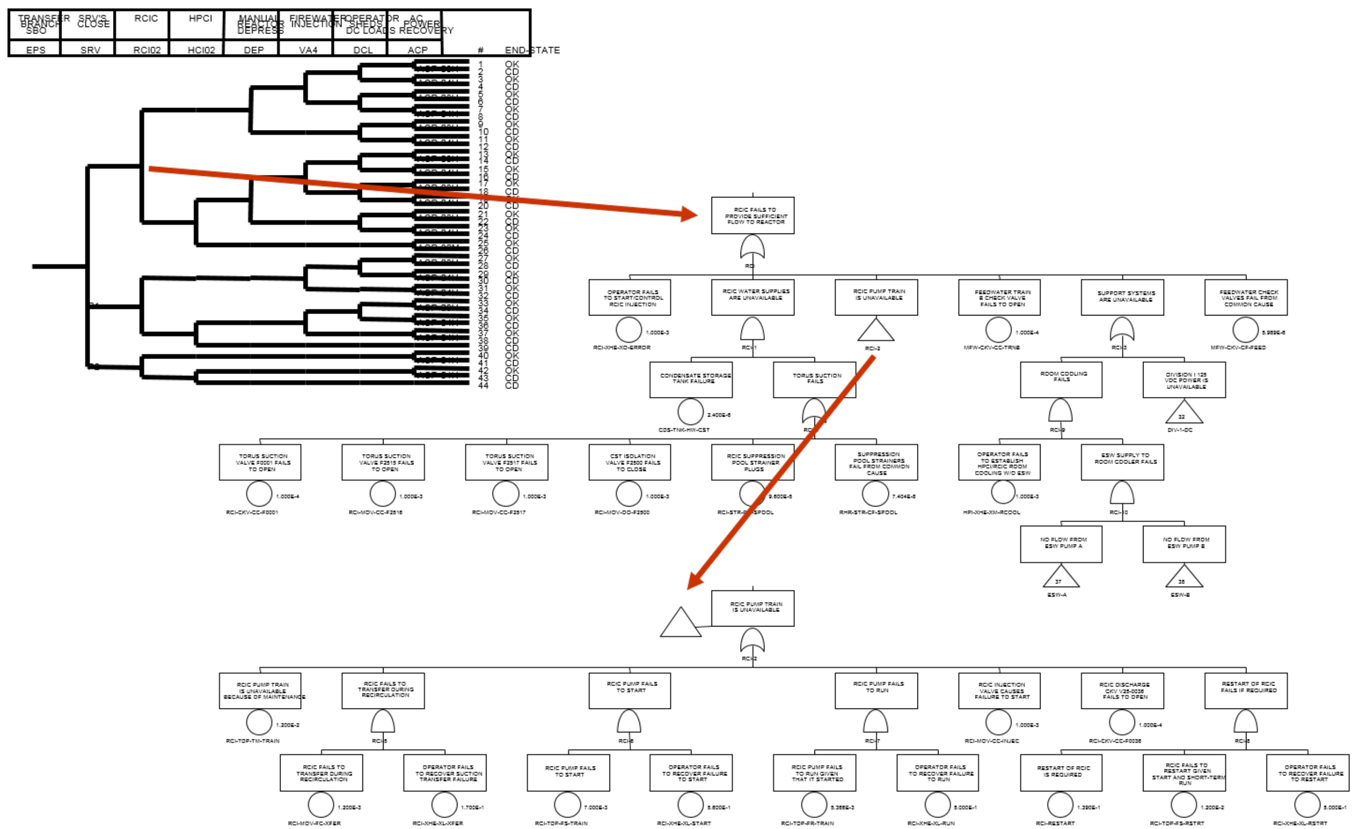
Why PRA: 1995 PRA Policy Statement

- "The use of PRA technology should be increased in all regulatory matters to the extent supported by the state-of-the-art in PRA methods and data and in a manner that complements the NRC's deterministic approach and supports the NRC's traditional defense-in-depth philosophy…"
- A probabilistic approach extends a traditional, deterministic approach to regulation, by:
  (1) Allowing consideration of a **broader set of potential challenges** to safety,
  (2) providing a **logical means for prioritizing** these challenges based on risk significance, and
  (3) Allowing consideration of a **broader set of resources** to defend against these challenges.

Example Event Tree



Example Fault Tree



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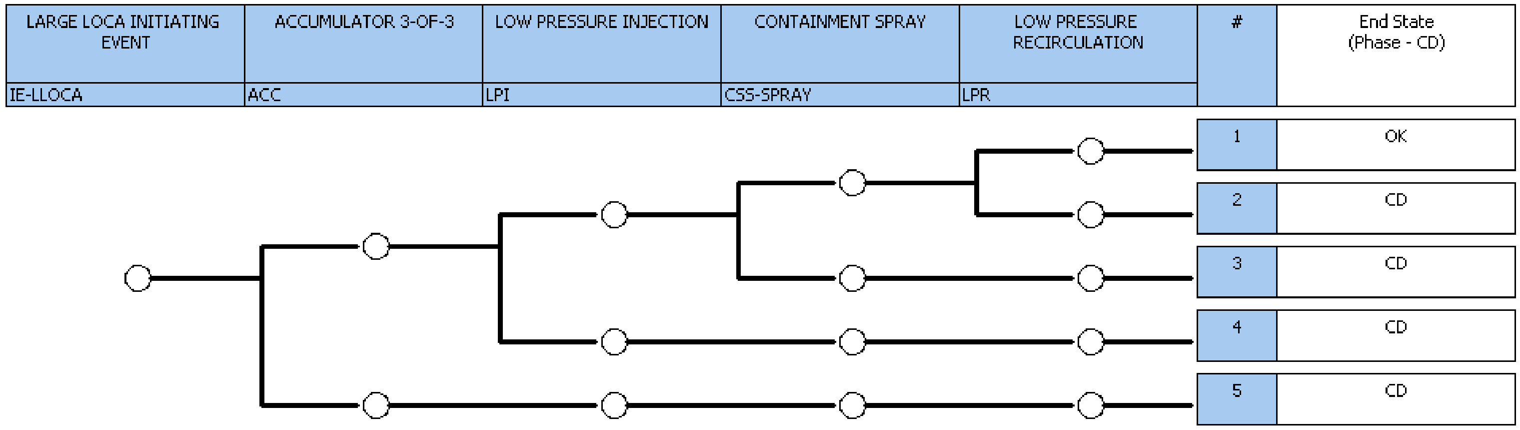
NRC PRA Models and Tools

- SPAR* Models
  - 79 operating plant models (event tree/fault tree)
  - 4 new reactor plant models
- SAPHIRE** code
  - Idaho National Laboratory (NRC-sponsored)
  - Features to support event and condition analysis

*Standardized Plant Analysis Risk

**Systems Analysis Programs for Hands-on Integrated Reliability Evaluation



Risk-Informed Regulations

- Backfitting (10 CFR 50.109)
- Station blackout protection (10 CFR 50.63)
- Maintenance management (10 CFR 50.65)
- Combustible gas control (10 CFR 50.44)
- Fire protection (10 CFR 50.48)
- Reactor pressure vessel protection (10 CFR 50.61a)
- Special treatment of structures, systems, and components (10 CFR 50.69)
- New reactor certification and licensing (10 CFR 52.47)

Risk-Informed Licensing

- Changes in plant licensing basis
- Environmental reviews
- Application of risk-informed regulations

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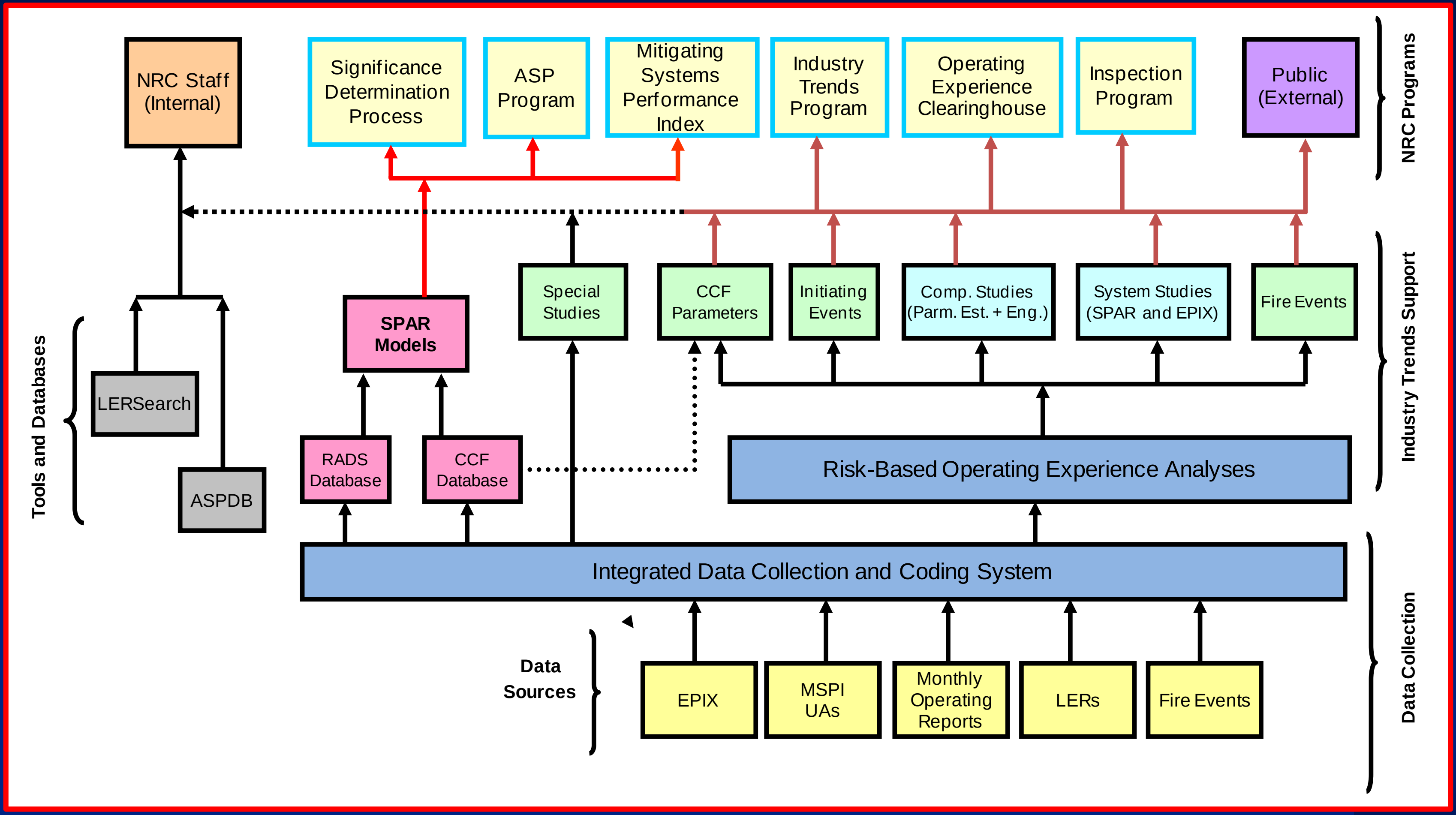
Risk-Informed Oversight

- Reactor oversight process
- Incident investigation
- Enforcement discretion

Risk-Informed Operational Experience

- Accident precursors
- Emergent issues
- Generic issues

Operating Experience Data



Some Fire-Induced "Near Misses"

Event	Summary Description*
Browns Ferry (BWR, 1975)	Multi-unit cable fire; multiple systems lost, spurious component and system operations; makeup from CRD pump
Greifswald (VVER, 1975)	Electrical cable fire; station blackout (SBO), loss of all normal core cooling for 5 hours, loss of coolant through valve; recovered through low pressure pumps and cross-tie with Unit 2
Beloyarsk (LWGR, 1978)	Turbine lube oil fire , collapsed turbine building roof, propagated into control building, main control room (MCR) damage, secondary fires; extinguished in 22 hours; damage to multiple safety systems and instrumentation.
Armenia (VVER, 1982)	Electrical cable fire (multiple locations), smoke spread to Unit 1 MCR, secondary explosions and fire; SBO (hose streams), loss of instrumentation and reactor control; temporary cable from emergency diesel generator to high pressure pump
Chernobyl (RBMK, 1991)	Turbine failure and fire, turbine building roof collapsed; loss of generators, loss of feedwater (direct and indirect causes); makeup from seal water supply
Narora (PHWR, 1993)	Turbine failure, explosion and fire, smoke forced abandonment of shared MCR; SBO, loss of instrumentation; shutdown cooling pump energized 17 hours later

*See NUREG/CR-6738 (2001), IAEA-TECDOC-1421 (2004)

Operational Experience – Blayais

- 12/27/1999 – Storm during high tide in Gironde River estuary
- Overtopping of protective dyke
- Loss of
  - Offsite power (Units 2 and 4) – wind
  - Essential service water (Unit 1, Train A), low head safety injection and containment spray pumps (Units 1 and 2), site access – flooding
  - Site accessibility
- Papers in 2005 IAEA workshop following Indian Ocean tsunami
- Presentation at 2010 USNRC Regulatory Information Conference
- Little notice in PSA community

E. De Fraguier, "Lessons learned from 1999 Blayais flood: overview of EDF flood risk management plan," U.S. NRC Regulatory Information Conference, March 11, 2010.

Potential PRA Technology Challenges Revealed by Fukushima*

- Extending PRA scope
  - Multiple sources
  - Additional systems
  - Additional organizations
  - Post-accident risk
- Treating feedback loops
- Reconsidering intentional conservatism
- Treating long-duration scenarios
  - Severe accident management
  - Offsite resources
  - Aftershocks
  - Success criteria
- Improving human reliability analysis
  - Errors of commission
  - Severe accident management
  - Psychological effects
  - Recovery feasibility and time delays
  - Uncertainty in actual status
  - Cumulative effects over long-duration scenarios
  - Crew-to-crew variability
- Uncertainty in phenomenological codes
- Increasing emphasis on "searching"

*From Siu, N., 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. (ADAMS ML 13099A347 and ML13038A203)