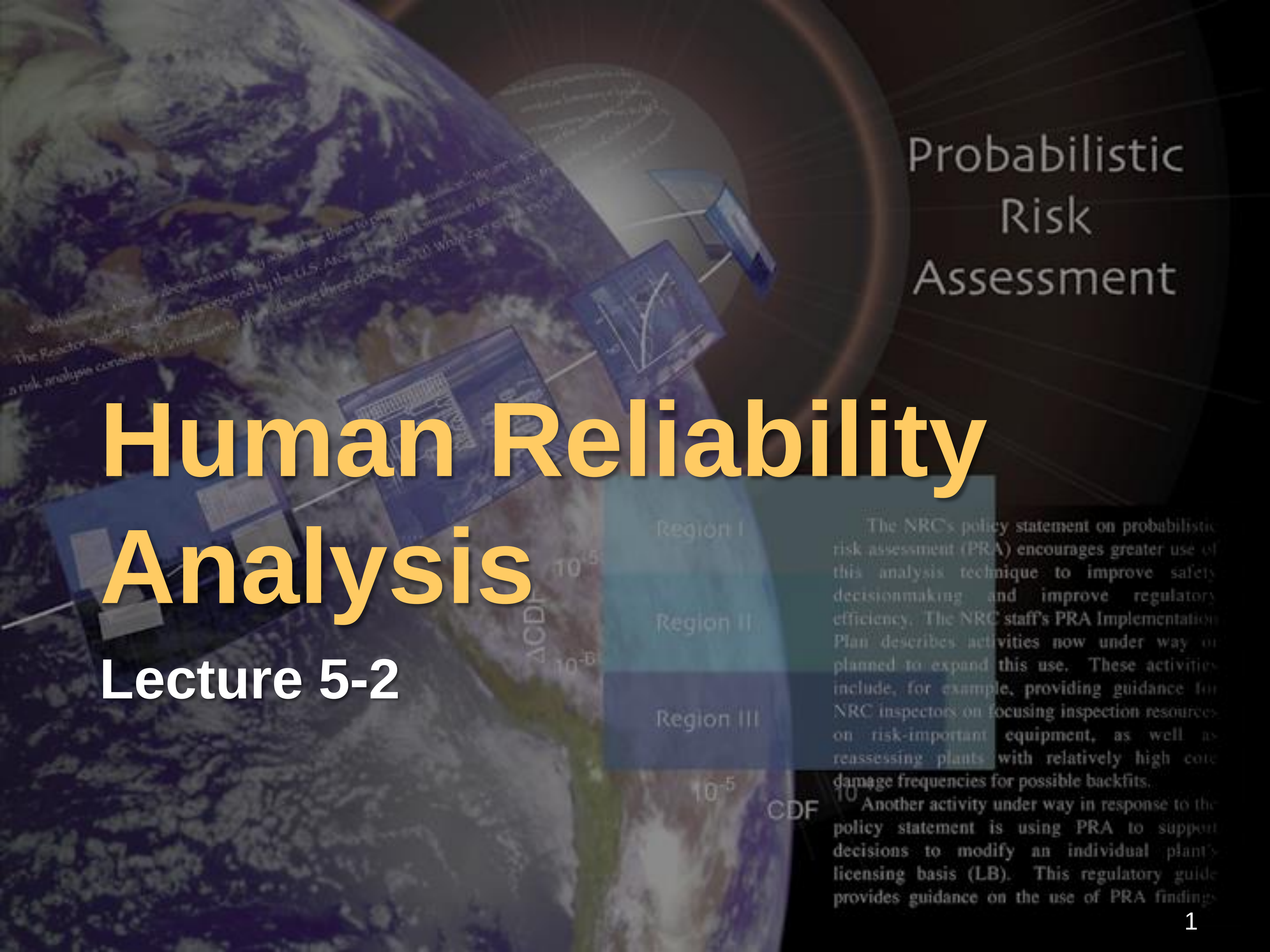

Human Reliability Analysis

Lecture 5-2

Key Topics

- HRA importance
- General description
- Fundamental model
- Methods
- Validation
- Challenges

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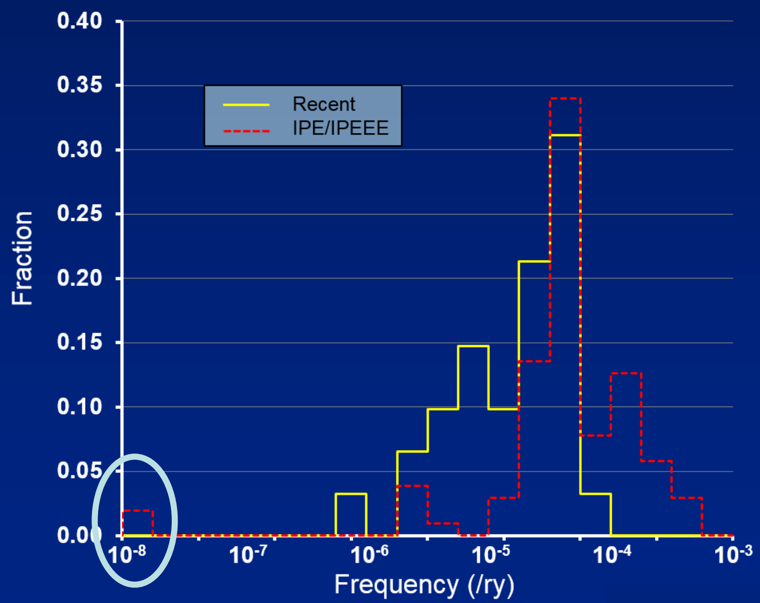
Human Actions and NPP PRA

Operational decisions and actions have played an important role in every major NPP accident and incident

- Occurrence and progression
- Successes and failures

PRAs that don't account for human contributions are not useful (for most applications)



Example Events

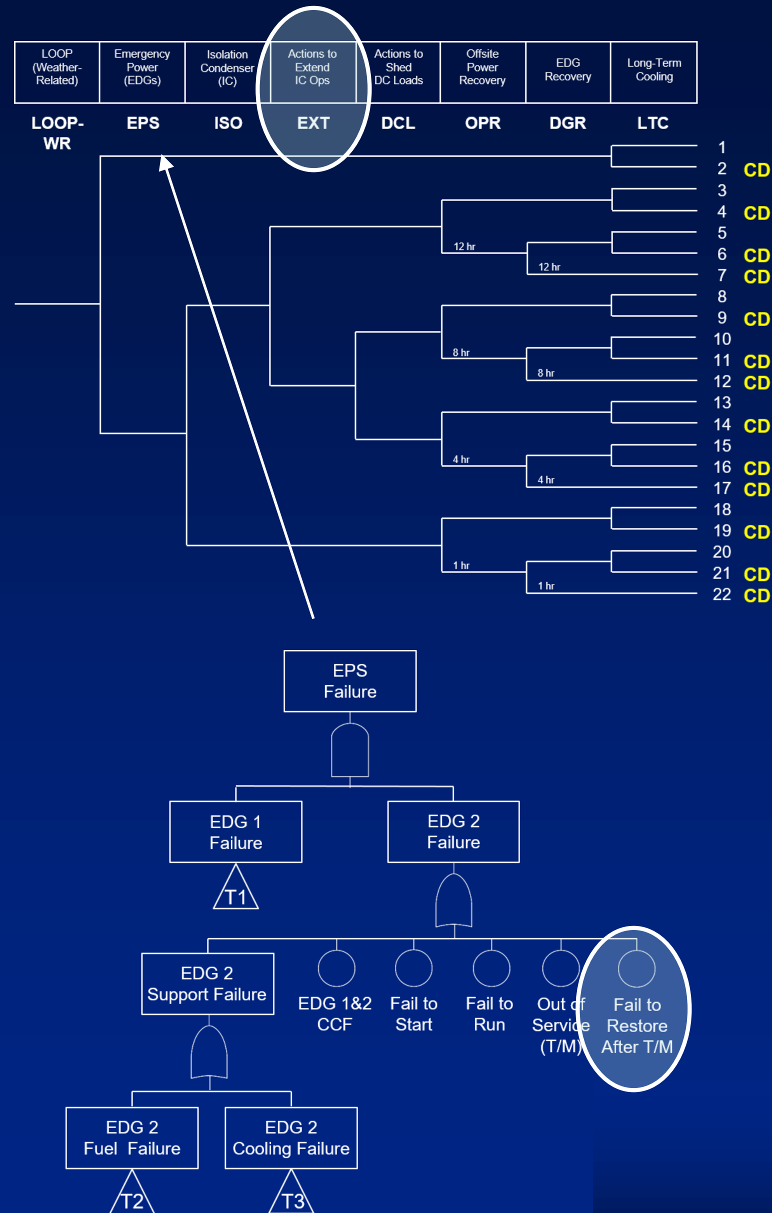
- Browns Ferry 1 & 2 cable fire (1975)
  - Worker ignites polyurethane foam, starts cable fire
  - Fire suppression delayed 7+ hours (reluctant to use water)
  - Operators achieve safe shutdown using non-safety system
- Davis-Besse loss of feedwater (1985)
  - Operator error causes loss of feedwater
  - Multiple malfunctions => feed and bleed cooling directed by procedures, would have major economic consequences
  - Shift supervisor chooses to wait for recovery of AFW (which is successful)
- Fukushima Dai-ichi Unit 1 (2011)
  - Operators close isolation condenser (little effect given accident conditions)
  - Operators perform numerous non-proceduralized actions (e.g., scavenge car batteries to supply power) in attempts to save plant
  - Ex-control room actions hampered by site conditions (tsunami alerts, aftershocks, damage, dark, radiation, …)

What is HRA?

- In the context of NPP PRA: "A structured approach used to identify potential human failure events and to systematically estimate the probability of those events using data, models, or expert judgment" (NUREG-2122)
- "Human Failure Event:" interface with rest of PRA model:
  - Terminology used to emphasize connection with NPP PRA model ("basic events"), avoid connotation of blame (e.g., when time available is insufficient)
  - Includes "errors of omission," "errors of commission"
  - Can be included at scenario level (event trees) or system level (fault trees)

HRA General Process

- Activities
  - Qualitative analysis
  - Modeling
  - Quantification
- Supports overall model construction
  - Initiating event identification
  - Accident scenario modeling
  - Systems modeling
- Not just a quantification activity



HRA Dimensions and Descriptors

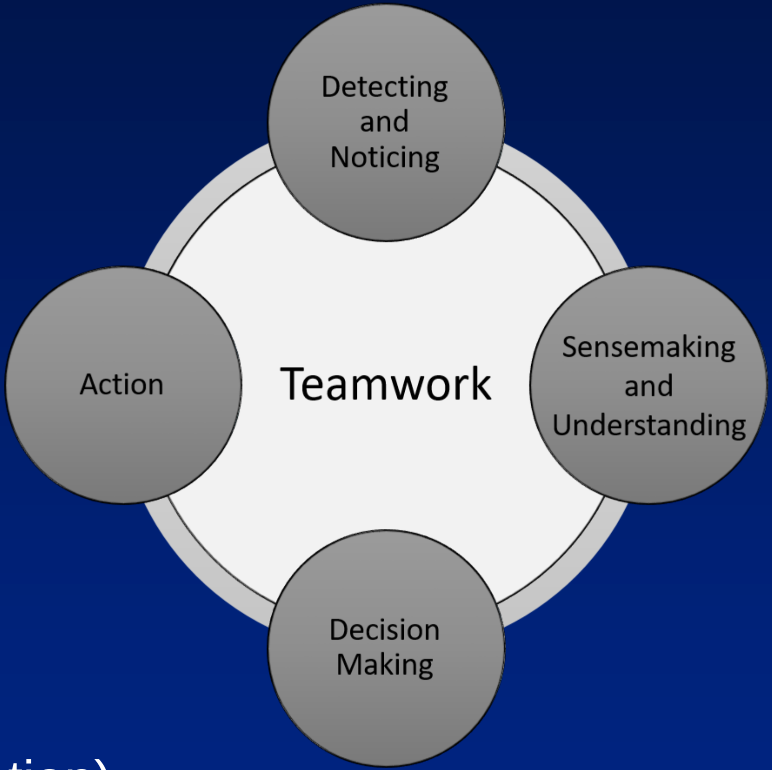
- Time
  - Pre-initiator
  - Initiator
  - Post-initiator
- Space
  - Within control room
  - Outside control room
- Organization
  - Control room crew
  - Field operators
  - Emergency response organization
- Implicit
  - Actions addressed by other PRA model elements (e.g., initiating event frequencies, loss of offsite power recovery, common cause failure probabilities)
  - Pre-initiator decisions affecting fundamental plant design (e.g., flood barrier height) and operations (e.g., resources for training)
- Out-of-scope for NPP PRA
  - Sabotage
  - Terrorism

Typical HFE Level of Detail

- Macro-level crew actions, e.g.,
  - Isolate faulted steam generator
  - Initiate bleed and feed cooling
  - Recover a failed pump
- Micro-level modeling (e.g., put control switch X in pull-to-lock position) can support HFE; need to consider micro-level recoveries as well as failures

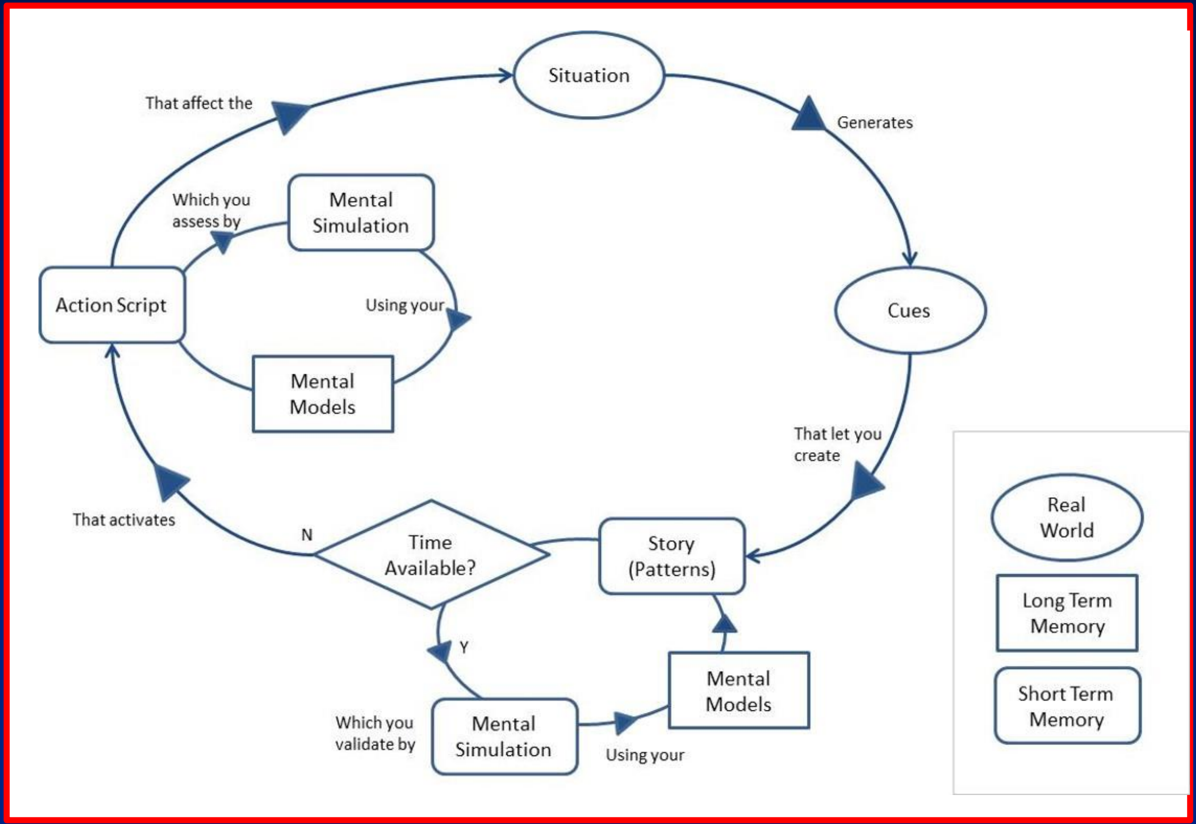
"How Things Work"

- Task-oriented view
  - Diagnosis and Planning
  - Action
- Cognitive view
  - Detecting/Noticing
  - Sensemaking/Understanding
  - Decision Making
  - Action Execution
  - Teamwork (communication/coordination)



Macrocognitive functions
(NUREG-2114)

Naturalistic Decision Making



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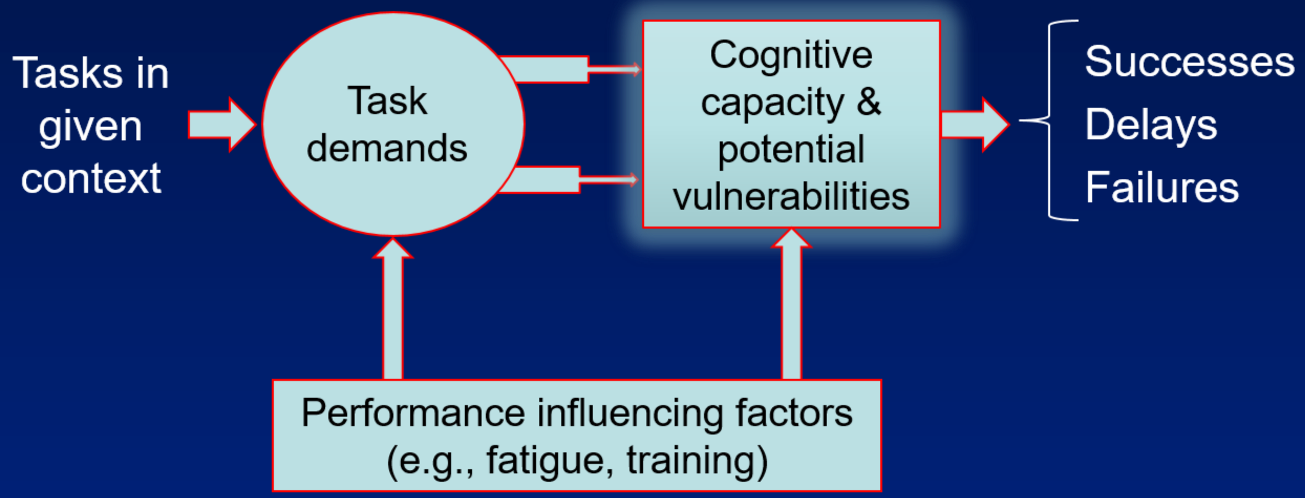
How Things Can Fail



Real-world contextual elements and PIFs* can include:

- Specific conditions (e.g., problematic components, mixed crews)
- Scenario dynamics (e.g., shift changes, multiple system shocks)
- Economic concerns
- Social behaviors and relationships

*Usually referred to as "Performance Shaping Factors" (PSFs)

Fundamental Probabilistic Model

- Human Error Probability (HEP)
  - Quantifies aleatory uncertainty
  - Is subject to epistemic uncertainties
  - Is a function of the task, the scenario context leading up to the task, and the relevant PIFs

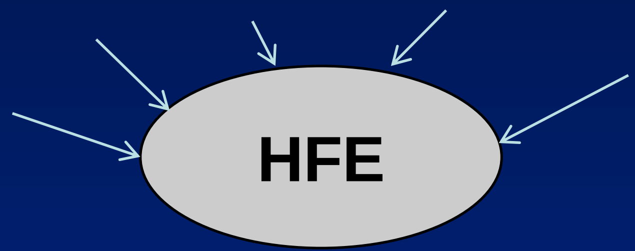
$$HEP \equiv P\{HFE\} = f\left(task, scenario\ context, \underline{PIF}\right)$$

- Underlying assertion: human actions are predictable (in a probabilistic sense)
  - Performance of specific tasks, often with specific procedures and training
  - Bounded rationality: operators/staff are trying to do the right thing
- Note: HEP functional behavior on PIFs is usually assumed to be multiplicative, but other data might support additivity

HRA Approaches

Holistic Analysis (ATHEANA, MERMOS)

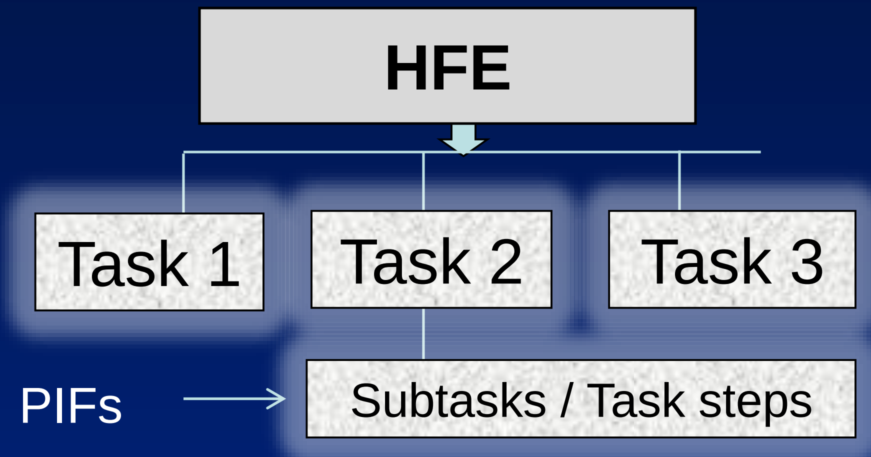
Tasks + Context (plant situation, scenario, and crew factors)



- Analyze context and develop operational story / narrative
- Identify situations deviating from the base story that lead to undesired actions
- Estimate the HEPs of the deviations

Strengths – Preserves context; uses expert ability to integrate complex information
Limitations – Level of effort; subjectivity and variability

Decomposition-Based Analysis (THERP, SPAR-H, CBDT, etc.)



- Decompose HFE into tasks, possibly subtasks / steps
- Analyze PIFs for the lowest decomposition level
- Calculate HEP of every part, combine HEPs for the event

Strengths – Transparency; consistency
Limitations – Formulaic; loss of context, interactions, non-linearities

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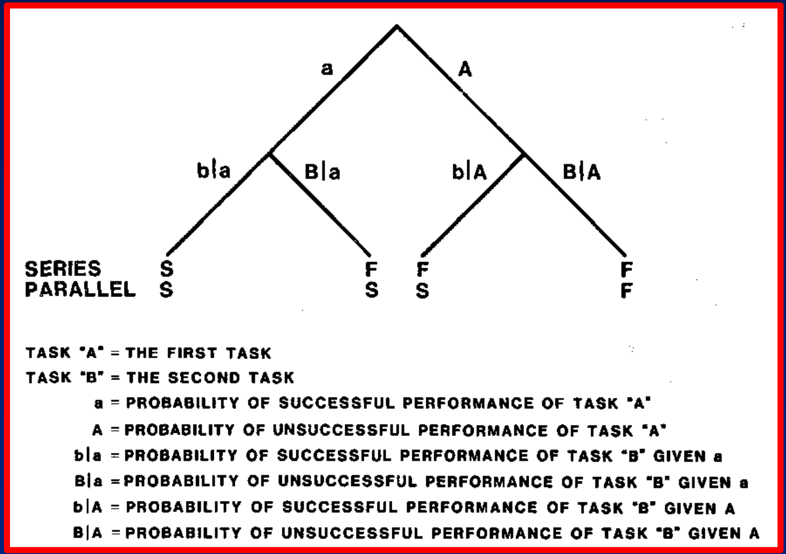
Technique for Human Error Rate Prediction (THERP)

- Widely-used HRA method, based on research started in 1976
- Task-oriented, focus on rule-based behavior (but also includes a time-reliability correlation for diagnosis)
- Task successes and failures represented with HRA event tree
- Tables used to quantify task success/failure probabilities
  - Some empirical basis
  - Considerable expert judgment
- Provides modifiers for dependent actions



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Human Cognitive Reliability/Operator Reliability Experiment (HCR/ORE)

- Extension of HCR method (which was based on skill/rule/knowledge base categorization of actions)
- Focused on probability of non-response
  - Non-response = failure to diagnose OR failure to initiate response in a timely manner
  - Normalized correlations for groups of HFEs (“human interactions”) categorized by cue-response characteristics.
  - Analyst estimates median response time and time window; model provides non-response probability.
  - Has no “floor” for very large time margins
- Included in EPRI HRA Calculator

Cause-Based Decision Tree (CBDT)

- Originally a supplement to HCR/ORE, now a standalone method in the EPRI HRA Calculator
- Eight decision trees used to develop non-response probabilities, considering multiple PIFs (e.g., training quality, procedures, human-machine interface)

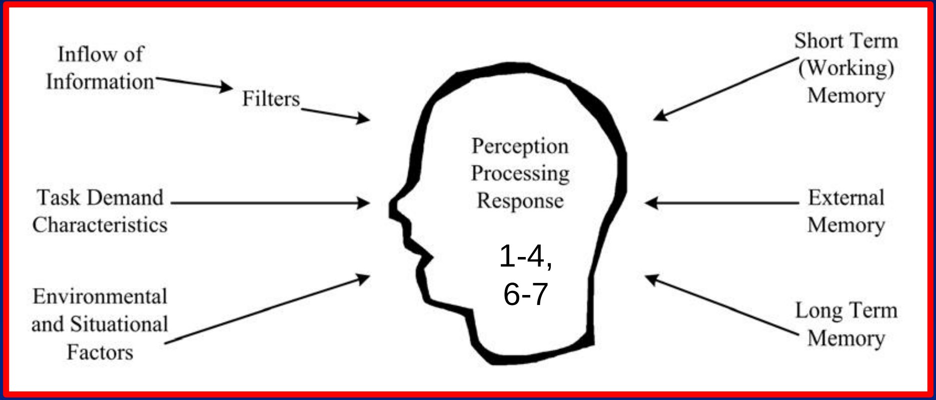
1) Relevant data not available
2) Data not attended to
3) Data errors
4) Data misleading
5) Procedure steps missed
6) Misinterpretation of instructions
7) Errors in interpreting logic
8) Deliberate violations

- Initial non-response probabilities modified by a time-based recovery factor and added to the probabilities of execution failure

Standardized Plant Analysis Risk – HRA (SPAR-H)

- Developed to support SPAR models, event and condition assessments
- Derived from THERP, multiple PIFs (PSFs) aggregated into eight groups based on information processing model

2-7



2-5,7

2-7

1) Available time
2) Stress and stressors
3) Complexity
4) Experience and training
5) Procedures (including job aids)
6) Ergonomics and human-machine interface
7) Fitness for duty
8) Work processes

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SPAR-H Worksheets

A. Evaluate PSFs for the Diagnosis Portion of the Task, If Any.

PSFs	PSF Levels	Multiplier for Diagnosis	Please note specific reasons for PSF level selection in this column.
Available Time	Inadequate time	P(failure) = 1.0	
	Barely adequate time (≈2/3 x nominal)	10	
	Nominal time	1	
	Extra time (between 1 and 2 x nominal and > than 30 min)	0.1	
	Expansive time (> 2 x nominal and > 30 min)	0.01	
	Insufficient information	1	
Stress/ Stressors	Extreme	5	
	High	2	
	Nominal	1	
	Insufficient Information	1	
Complexity	Highly complex	5	
	Moderately complex	2	
	Nominal	1	
	Obvious diagnosis	0.1	
	Insufficient Information	1	
Experience/ Training	Low	10	
	Nominal	1	
	High	0.5	
	Insufficient Information	1	
Procedures	Not available	50	
	Incomplete	20	
	Available, but poor	5	
	Nominal	1	
	Diagnostic/symptom oriented	0.5	
	Insufficient Information	1	
Ergonomics/ HMI	Missing/Misleading	50	
	Poor	10	
	Nominal	1	
	Good	0.5	
	Insufficient Information	1	
Fitness for Duty	Unfit	P(failure) = 1.0	
	Degraded Fitness	5	
	Nominal	1	
	Insufficient Information	1	
Work Processes	Poor	2	
	Nominal	1	
	Good	0.8	
	Insufficient Information	1	

Rev 1 (1/20/04)

A. Evaluate PSFs for the Action Portion of the Task, If Any.

PSFs	PSF Levels	Multiplier for Action	Please note specific reasons for PSF level selection in this column.
Available Time	Inadequate time	P(failure) = 1.0	
	Time available is ≈ the time required	10	
	Nominal time	1	
	Time available ≥ 5x the time required	0.1	
	Time available is ≥ 50x the time required	0.01	
	Insufficient Information	1	
Stress/ Stressors	Extreme	5	
	High	2	
	Nominal	1	
	Insufficient Information	1	
Complexity	Highly complex	5	
	Moderately complex	2	
	Nominal	1	
	Insufficient Information	1	
Experience/ Training	Low	3	
	Nominal	1	
	High	0.5	
	Insufficient Information	1	
Procedures	Not available	50	
	Incomplete	20	
	Available, but poor	5	
	Nominal	1	
	Insufficient Information	1	
Ergonomics/ HMI	Missing/Misleading	50	
	Poor	10	
	Nominal	1	
	Good	0.5	
	Insufficient Information	1	
Fitness for Duty	Unfit	P(failure) = 1.0	
	Degraded Fitness	5	
	Nominal	1	
	Insufficient Information	1	
Work Processes	Poor	5	
	Nominal	1	
	Good	0.5	
	Insufficient Information	1	

A Technique for Human Event Analysis (ATHEANA)

- Development started in support of low power and shutdown PRA (different conditions from at-power); evolved into general method
- Focuses on HFE context, identification of error-forcing conditions (EFCs)
- Does not use pre-established list of PIFs (PSFs)
- Holistic quantification via expert judgment; emphasizes involvement of knowledgeable plant staff (operations and training)

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Integrated Human Event Analysis System (IDHEAS)

- Staff response to Commission direction “to evaluate the different human reliability models in an effort to propose a single model for the agency to use or guidance on which model(s) should be used in specific circumstances”
- General methodology + application modules
  - At-power
  - Event and condition assessment
- Decomposition-based, cognitive focus
- Supported by extensive review of human cognition literature (psychology, cognition, behavioral science, human factors) to identify relevant functions, mechanisms, and factors

IDHEAS At-Power

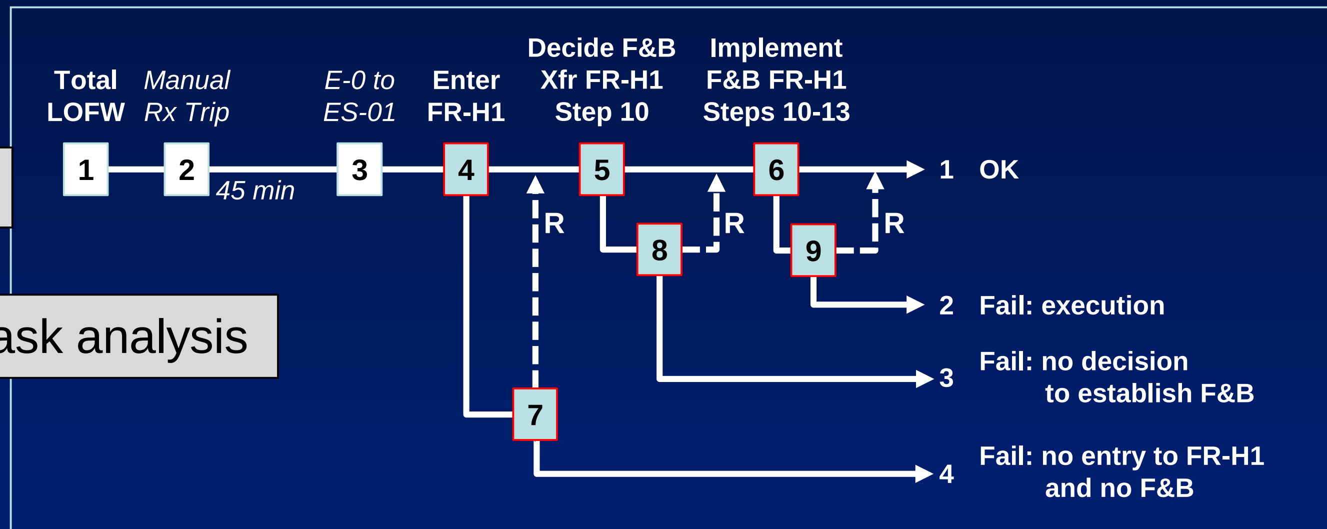
Qualitative analysis

PRA scenario

Define HFE: fail F&B

HFE Feasible?

Task analysis



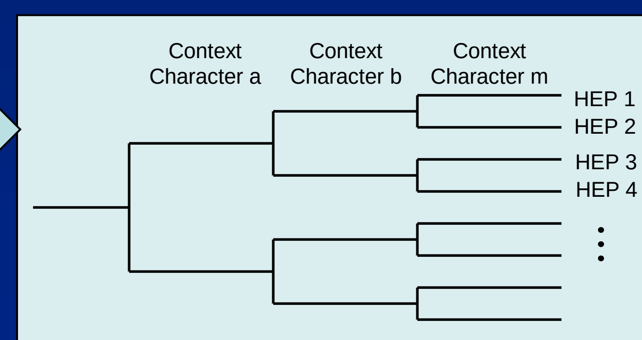
HEP quantification

Tasks

- Enter FR-H1
- Critical Task 2
- ⋮
- Critical Task K

Failure Modes

- Failure Mode 1
- Data Misleading
- ⋮
- Failure Mode N



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IDHEAS-G

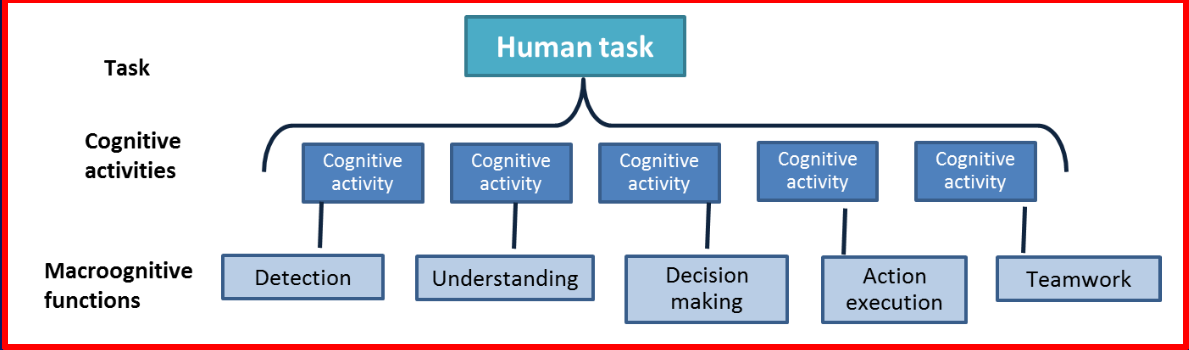
Tasks are accomplished through the performance of various cognitive activities. These cognitive activities exercise general macrocognitive functions.

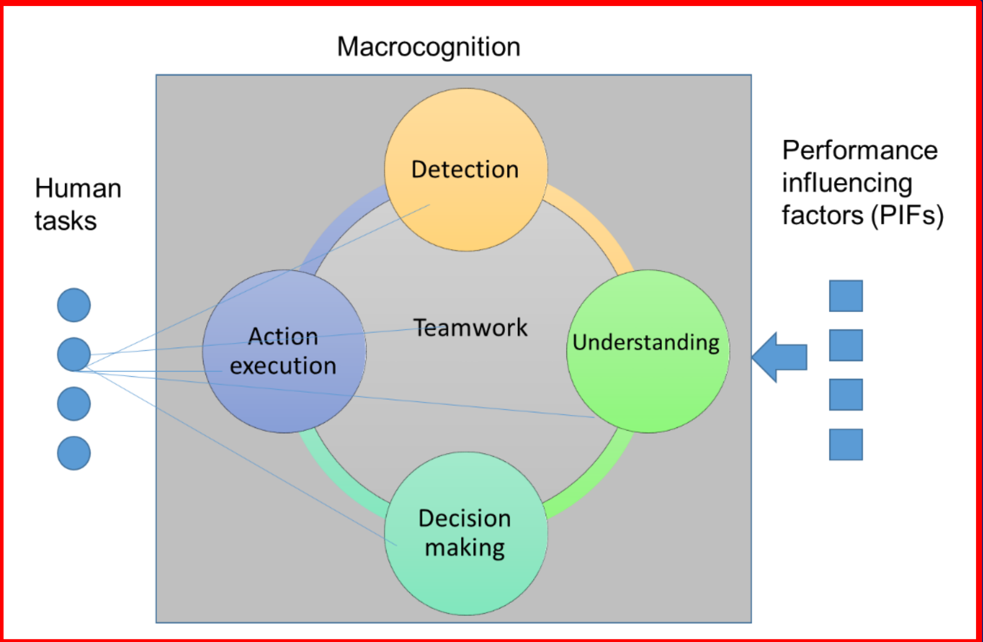
Example

Task:
Identify Ruptured SG (as part of an action to isolate the ruptured SG)

Cognitive Activities:
- Detect any one of:
  - unexpected rise in any SG NR level
  - high radiation level from any SG sample
  - high radiation from any SG steamline
  - high radiation from any SG blowdown
- Understand that any one signal provides indication of the faulted SG. Note:
  - The HRA-specified context includes successful reactor and turbine trip, energization of all AC buses, SI actuated, AFW available.
  - The specified context does not explicitly address the possibility of confounding signals and demands (e.g., alarms from unrelated SSCs not modeled in the PRA but demanding operator response.)

Macrocognitive Functions:
- Detection
- Understanding





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IDHEAS-G

Example

Macrocognitive Function:
- Detection

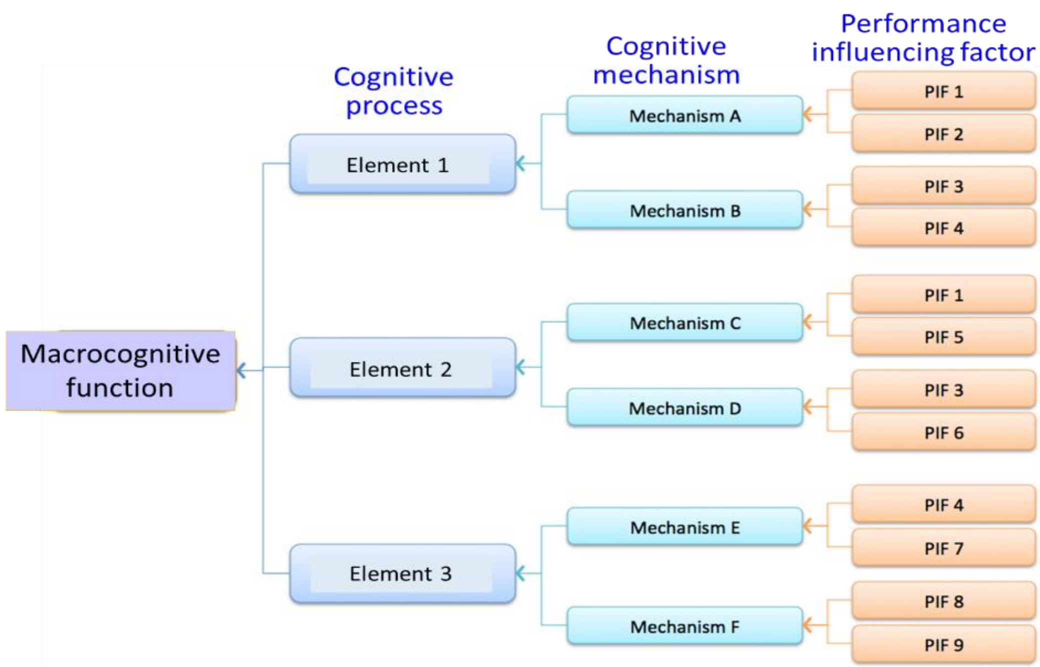
Cognitive Process Elements:
- Establish mental model
- Select, identify, attend to information sources
- Perceive, recognize, classify information
- Verify, modify detection outcomes
- Retain, document/record, communicate outcomes

Cognitive Mechanisms:
- Sensing
- Perception of sensing stimuli
- Vigilance maintenance
- …

"Capacity Limits":
- Mismatch between sensory system and signal
- Weak signal
- Reduced vigilance due to sustained cognitive activities

Performance Influencing Factors:
- Human-system interface
- Environmental factors
- Stress, time pressure, and anxiety
- Mental fatigue
- …

Macrocognitive functions are accomplished through a set of cognitive processes ("elements") and cognitive processes are accomplished by cognitive mechanisms. Performance influencing factors affect how well the cognitive mechanisms are executed by challenging "capacity limits" for these mechanisms.



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IDHEAS-G

Example

Task:
Identify Ruptured SG (as part of an action to isolate the ruptured SG)

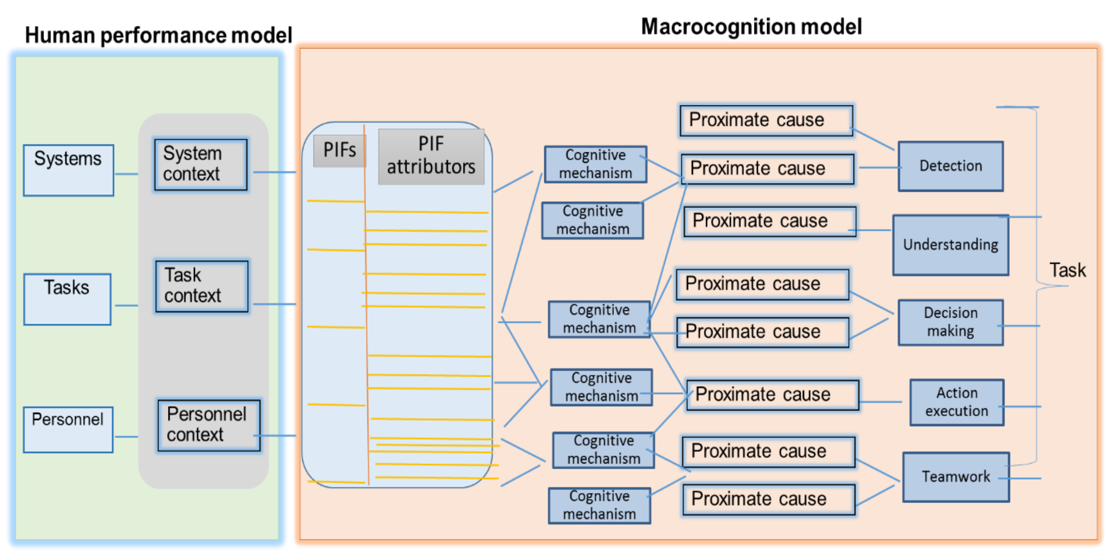
Macrocognitive Function:
- Detection
- Understanding

Proximate Causes:
- Failure to perceive information
- Failure to attend to source of information
- …

Cognitive Mechanisms:
- Sensing
- Perception of sensing stimuli
- Vigilance maintenance
- …

Performance Influencing Factors:
- Human-system interface
- Environmental factors
- Stress, time pressure, and anxiety
- Mental fatigue
- …

Task failure can be caused by failure of any single cognitive mechanism (which propagates through the cognitive process/macrocognitive function/cognitive activity causality chain).* Each potential failure of a cognitive process is a potential "proximate cause" for macrocognitive function failure.



*Note: from a systems point of view, a task is modeled as a series system with a very large number of potential single-point failures.

HRA Guidance

- Many methods and viewpoints, but general agreement on high-level model and "good practices"
- NUREG-1792: high-level guidance, e.g.,
  - Perform field observations and discussions
  - Use screening values during initial quantification
  - Account for dependencies among HEPs
  - Evaluate the reasonableness of the HEPs
- NUREG-1842: evaluation of several methods against these good practices
- Various documents for specific applications, e.g., NUREG-1921 (fire HRA) and NUREG-1921 Supplement 1 (fire HRA, main control room abandonment)

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Ispra Benchmark Exercises (1986-1988)

- European Commission Joint Research Centre
- Comparison of methods and modeling
- 15 teams, multiple methods
- Test and maintenance
  - Failure to detect check valve failure, failure to restore system
  - Good agreement on qualitative characterization (key human error interactions and failure mechanisms), divergence on modeling and quantification
  - Some variance reduction when using a common model
- Complicated transient
  - LOOP, 2/4 EDGs fail to start, partial CCF of EFW valves
  - Differences in modeling (scope of analysis, aggregation) and quantification
  - Large method-to-method and team-to-team differences

Validation

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International HRA Empirical Studies

- OECD/NEA Halden Reactor Project
- Comparisons of analysis results with data from HAMMLAB simulator to identify strengths and weaknesses
- 14 operator crews, 13 HRA teams, “blind” study
- Operational transients:
  - Steam generator tube rupture (SGTR), loss of feedwater (LOFW)
  - Base case and complex, multiple HFEs with varying difficulty
- Findings include:
  - Large variations in how crews followed procedures
  - Large variations in HEPs; many rankings don’t reflect difficulty
  - Some analyses don’t strongly differentiate across HFEs
  - Methods that emphasize mechanisms and contextual factors provide richer (and often predictive) narratives, but not necessarily better HEPs

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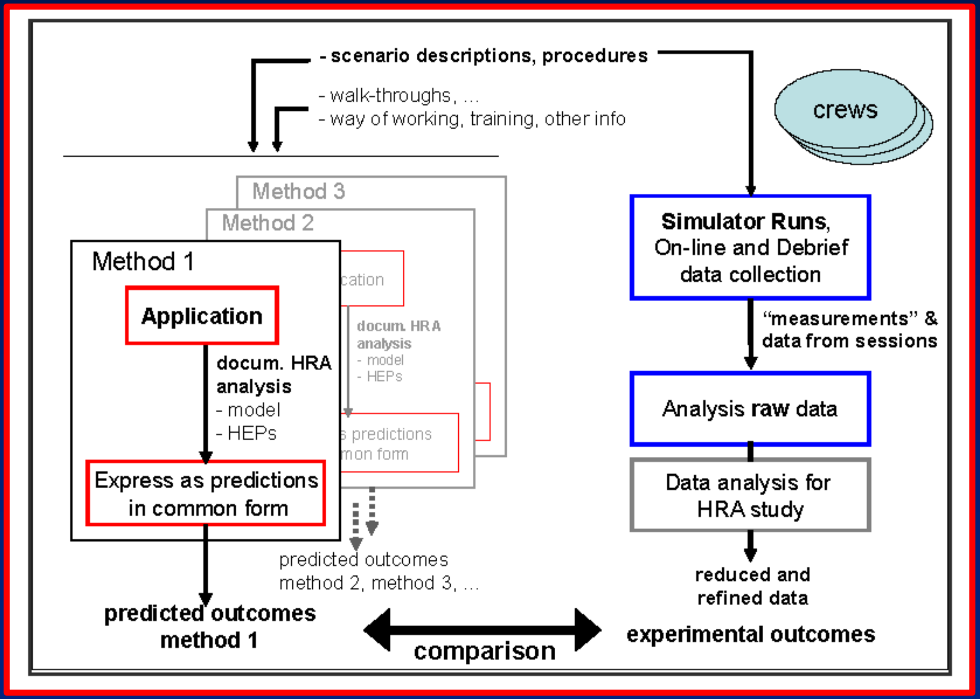
Study Process



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Challenges Include:

- Differences between HAMMLAB simulator and home plant
- Characterizing crew behaviors (e.g., drivers for performance)
- Statistically small sample
- Defining "failure" for intermediate HFEs

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US HRA Empirical Studies

- Similar to international study but using a US PWR (simulator and crews). Also addressed concerns regarding
  - Lack of testing of team-to-team variability in using the same method
  - Inability of analysis teams to visit simulator, interview crews
- 4 crews, 9 HRA teams
- Operational transients:
  - LOFW followed by SGTR
  - Loss of component cooling water and RCP seal water
  - SGTR
- Findings include:
  - Less variability vs. HAMMLAB study and Ispra: HRA team learning? Better practiced with US crews? Plant visit?
  - Qualitative analyses can be improved
  - HRA improvements should focus on aiding analysts finding and characterizing contextual factors and mechanisms causing cognitive failures

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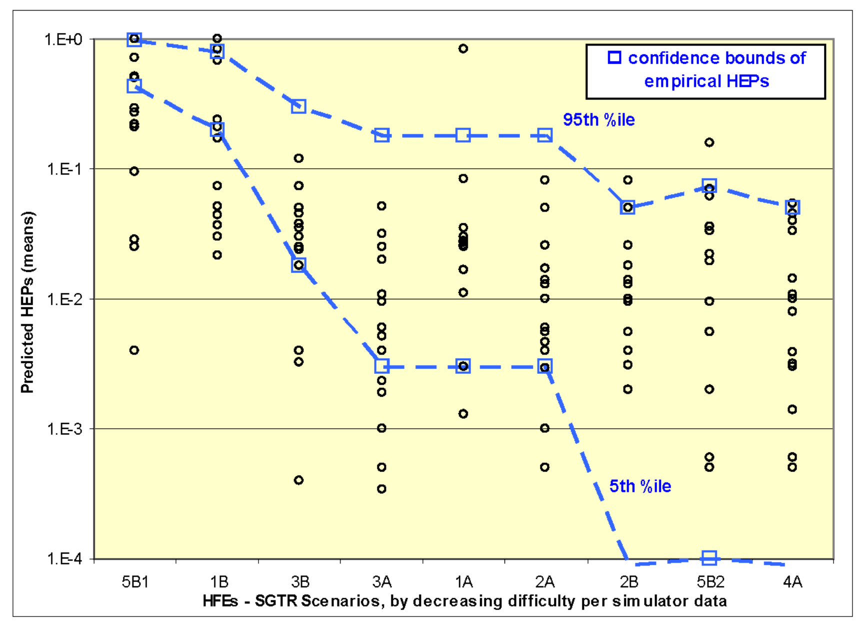
Comparing Predictions with Performance



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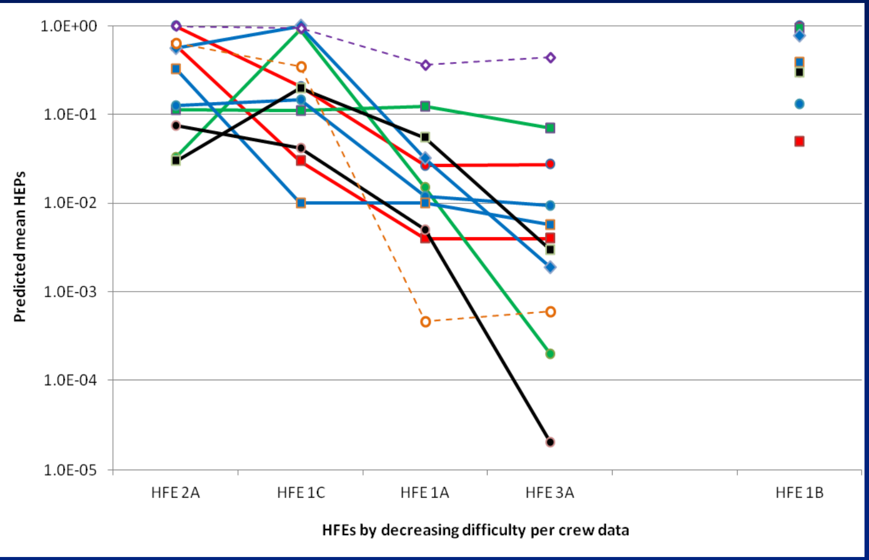

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Technical Challenges

- Complicating factors
  - Specific conditions (e.g., pre-accident conditions including problematic components; specific crew on shift including makeup crews)
  - Scenario dynamics (e.g., mindset established by specific evolution, shift changes, multiple system shocks, changes in local environment, external directions)
  - Additional crew concerns (e.g., economic impact of action, offsite environment)
  - Social behaviors and relationships (e.g., trust within crew, between organizational elements, group behavior)

Technical Challenges (cont.)

- Data from actual incidents
  - Statistically sparse, arguably unique characteristics for each event
  - Extremely rich qualitative information for a few events
- Data from other simulator exercises: transferability to HRA/PRA
  - Design and operational differences
  - Data collection protocols
- Technology advances affecting human performance
  - Advanced control rooms
  - Smart/distributed technology
  - Remote operations
  - …

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Socio-Organizational Challenges

- Multiple technical disciplines with varying goals, views on the meaningfulness of a PRA-oriented HRA, views on needed rigor
- Interdisciplinary trust
  - HRA developers: academic/professional reward system => proliferation of HRA methods
  - PRA analysts: need for “now” answers => development of “good enough” methods, resistance to change
  - PRA users: discomfort with large uncertainties => dismissal/discounting of results and insights
  - Science critics: weaknesses in current methods/models => “house of cards” view on PRA and RIDM affecting willingness to help

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Grand Challenge – Incorporating Organizational Factors

- Long-recognized as an important influence
  - Culture and climate
  - Resources
  - Direct involvement in events
- Scope >> current PRA scope
  - Time
  - Organizations (functions and structure)
  - Space
  - Technical disciplines
- Data
  - Availability
  - Quality
- Non-monotonic effects

Non-Monotonic Effects: Examples

- Good safety culture can reduce worker risk but increase plant-level risk
  - Pre-emptive reactor trip on loss of communications with diver
  - Reluctance to send workers to hazardous areas
- “Forceful leadership” can overcome organizational inertia but can also stifle important views