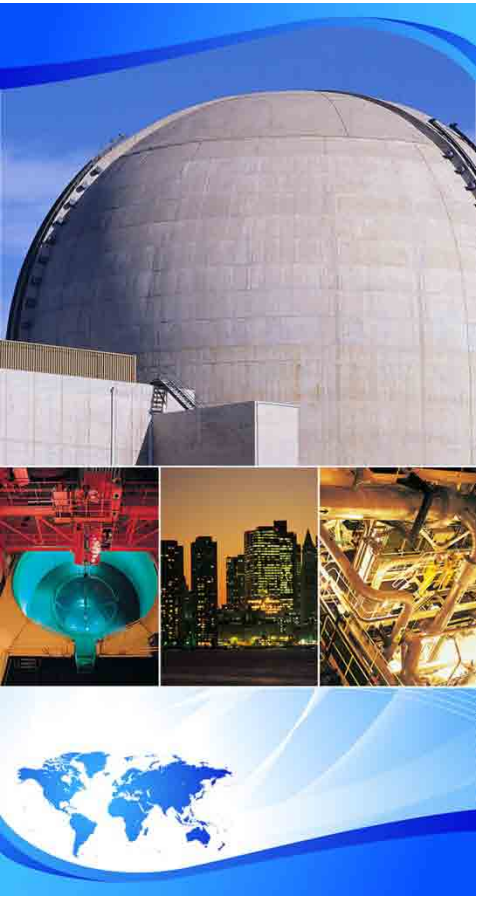


EPRI/NRC-RES FIRE PRA METHODOLOGY
Task 12 – Fire HRA

ATHEANA Approach to Detailed Fire HRA Quantification

Joint NRC-RES/EPRI Fire PRA Workshop 2012

Bethesda, MD

A Collaboration of U.S. NRC Office of Nuclear Regulatory Research (RES) & Electric Power Research Institute (EPRI)

Outline of the Presentation

1. Overview of the EPRI/NRC Fire HRA Guidelines
2. Identification and definition of fire human failure events
3. Qualitative analysis
4. Quantitative analysis
   a) Screening
   b) Scoping
   c) EPRI approach (detailed)
   d) ATHEANA (detailed)
5. Recovery analysis
6. Dependency analysis
7. Uncertainty analysis

ATHEANA - Outline

1. Introduction to ATHEANA
2. ASME/ANS PRA Standards addressed
3. ATHEANA HRA process
4. ATHEANA guidance for facilitating expert elicitation
5. ATHEANA – What's going to be different for fire PRA?
6. Addressing fire-specific issues with ATHEANA
7. Fire HRA exercises using ATHEANA

Introduction to ATHEANA

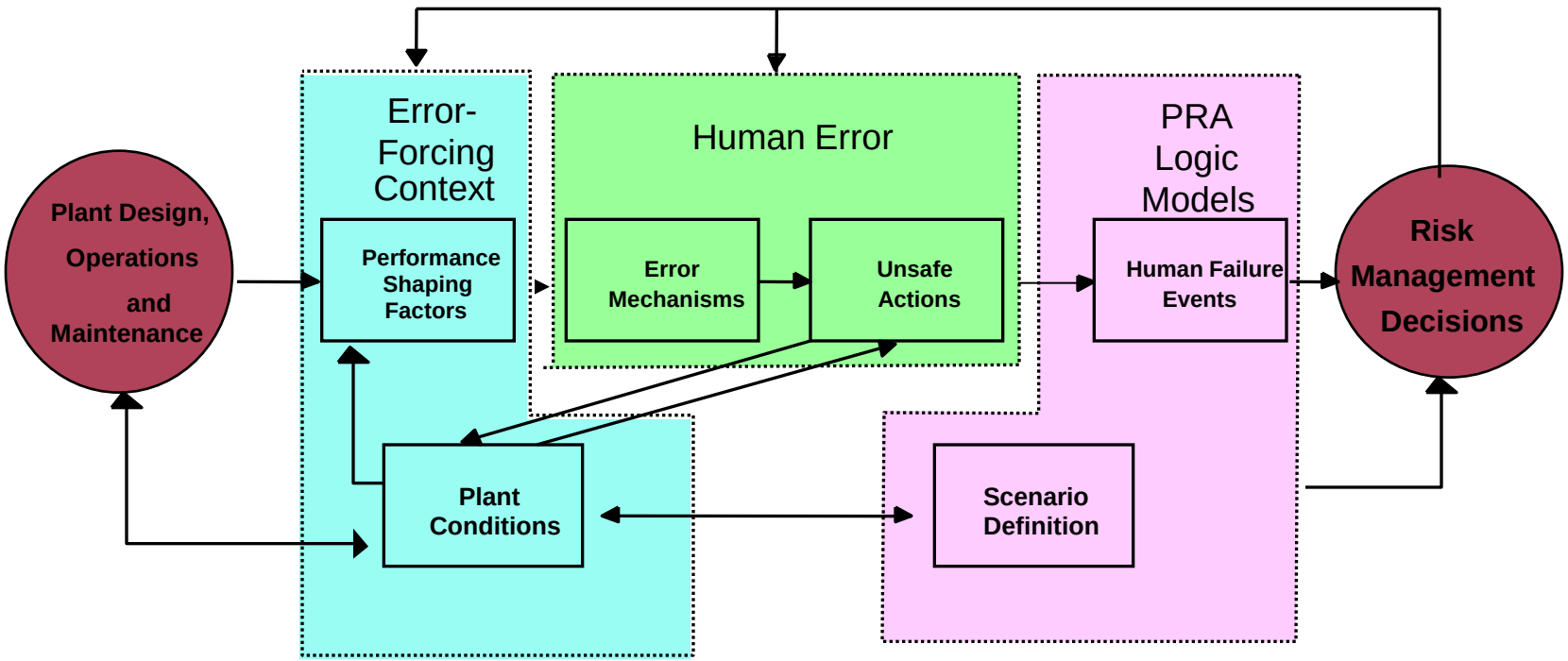
- ATHEANA is…
  - A Technique for Human Event ANAlysis
  - A second-generation HRA method
  - A development of NRC/RES and its contractors
  - An input to NRC's *Good Practices for Implementing Human Reliability Analysis (HRA)*, April 2005
- ATHEANA is documented in:
  - NUREG-1624, Rev. 1, *Technical Basis and Implementation Guidelines for A Technique for Human Event Analysis (ATHEANA)*, May 2000.
  - NUREG-1880, *ATHEANA User's Guide*, June 2007.

Introduction to ATHEANA (continued)

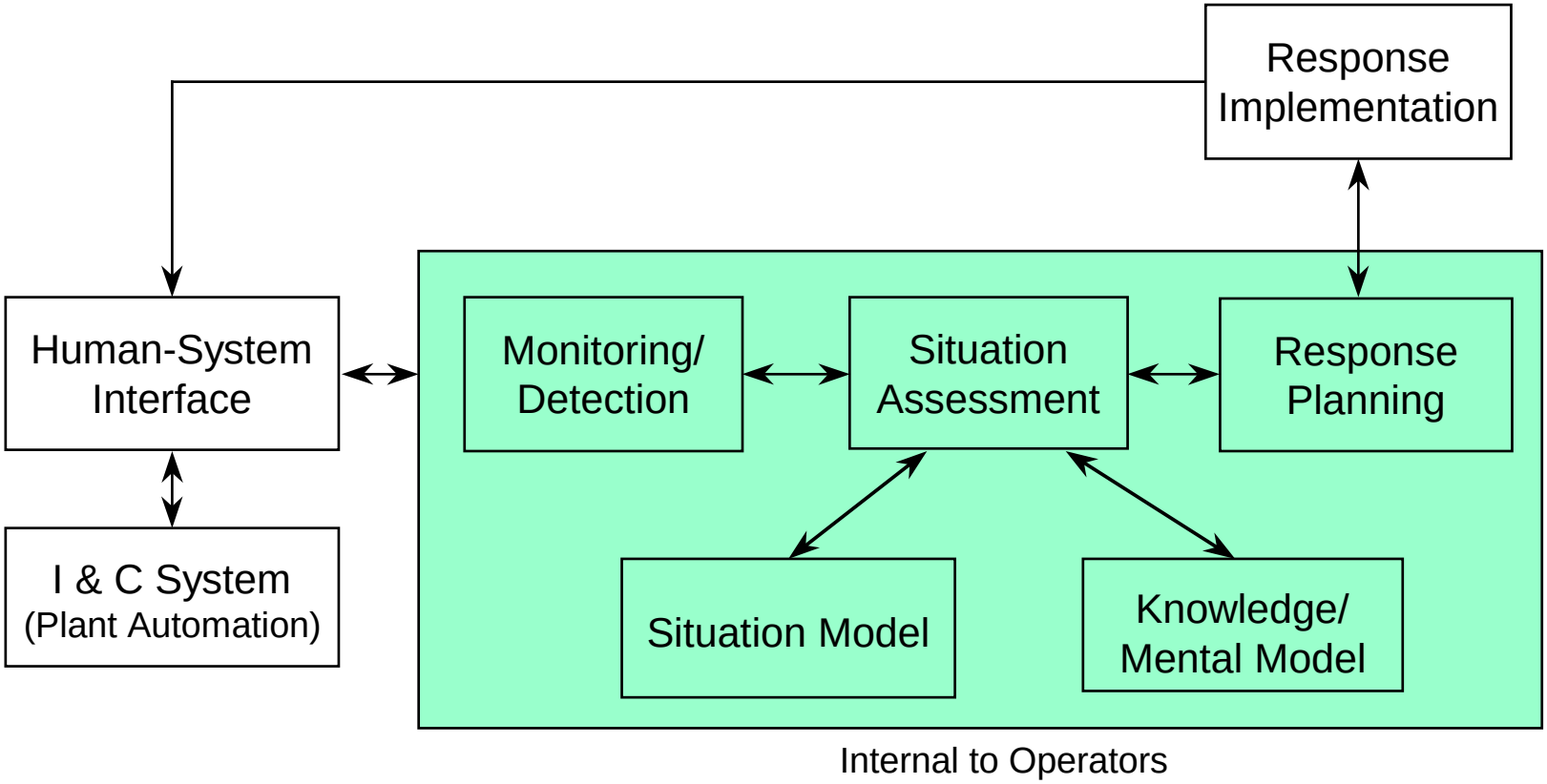
- ATHEANA is…
  - A knowledge-base* for (mostly) at-power, post-initiator HFEs, including:
    - Relevant psychological literature
    - Supporting analyses of historical events
  - A multidisciplinary framework for understanding human error
  - An HRA process (including detailed guidance for performing qualitative analysis)
  - A search scheme for HFEs (including errors of commission)
  - A quantification approach
- Also, ATHEANA provides a basis for performing retrospective analysis of historical events (including example analyses).

But, different knowledge bases* can be used or substituted.

Multidisciplinary framework



Underlying model of operator's behavior



Introduction to ATHEANA (continued)

- The basic premise of ATHEANA:
  - People behave “rationally,” even if reason for an action (or inaction) is wrong.
  - Often, when people make errors, they are “set up.”
  - People can be “set-up” by **contexts** that can create the *appearance* that the wrong response is correct when, in fact, it is not.
- Analyses of operating experience (particularly events with serious consequences) support this view, e.g.:
  - Nuclear power plant events (e.g., TMI 2, Browns Ferry, Chernobyl)
  - Incidents from a variety of other technologies (e.g., aviation, medicine, chemical processing, maritime)

Introduction to ATHEANA (continued)

Across industries, the following **contextual** factors often have been involved in serious events:

1. The plant behavior is outside the expected range (as represented by procedures, training, and traditional safety analyses).
2. The plant's behavior is not understood.
3. Indications of the actual plant state and behavior are not recognized (sometimes due to instrumentation problems).
4. Prepared plans or procedures are not applicable or helpful for the specific plant conditions.

Introduction to ATHEANA (continued)

Consequently, the principal motivators for developing ATHEANA were:

1. HFEs modeled in most HRA/PRAs are not consistent with the roles played by operators in actual operational experience (including errors of commission and dependencies between actions).
2. The accident record and advances in behavior sciences both support a stronger focus on **context**.
3. Recent advances in psychology ought to be used and integrated with the disciplines of engineering, design, operations and training, human factors, and PRA in modeling HFEs.

Introduction to ATHEANA (continued)

- Overall, the goal of ATHEANA quantification approach is to:
  - Develop an "operational story" (including plant conditions, operational aids such as procedures, and other influencing factors) to explain **why** an operator could failure to perform an action
  - Explain and refine the operational story with plant-specific experts
  - Use the expert judgment of plant-specific personnel (especially operator trainers) to develop failure probabilities for HFEs that require detailed HRA quantification (facilitated by the HRA analyst)

Introduction to ATHEANA (continued)

Key characteristics are:

- Focuses on the **error-forcing context** (i.e., the context that sets up operators), but also addressed the nominal context
- Uses a structured search for problem scenarios (i.e., **error-forcing contexts**) and associated unsafe actions (i.e., operator failures)
- Links plant conditions, performance shaping factors (PSFs) and human error mechanisms through the **context**
- Is experience-based, both in its development and application (e.g., uses knowledge of domain experts such as operators, pilots, trainers)
- Uses multidisciplinary approach and underlying cognitive model of operator behavior
- Explicitly considers operator dependencies (including recovery actions) by developing entire accident sequences
- Uses a facilitator-led, expert elicitation approach for quantification (that allows the plant-specific experience and understanding from operators, operator trainers, and other operations experts to be directly reflected)

Introduction to ATHEANA (continued)

Example ATHEANA applications:

- HRA/PRAs in a prospective analysis of regulatory and industry issues such as pressurized thermal shock (PTS) (3 plants – Oconee, Beaver Valley, Palisades)
- International HRA Empirical Study (Steam Generator Tube Rupture and Loss of Feedwater scenarios)
- DOE's license application for Yucca Mountain waste repository (preclosure facility)
- Qualitative analyses of spent fuel handling (misloads and cask drops) (NUREG/CR-7016 and -7017, February 2012)
- Retrospective event analyses and development of a knowledge-base for fire-specific human performance issues (NUREG/CR – to be published)
- HRA/PRA to evaluate design features of a facility to dismantle chemical weapons

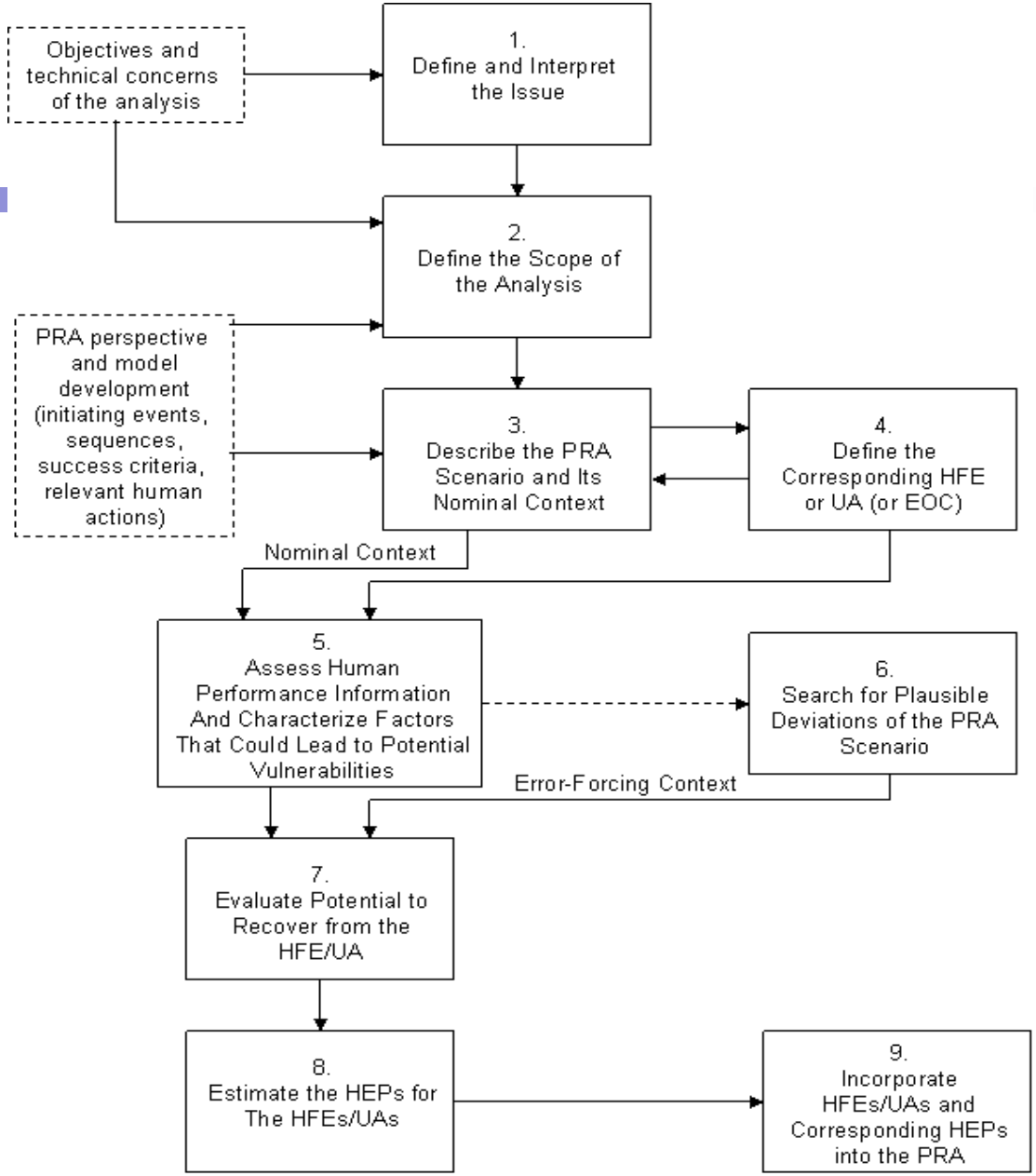
ANS/ASME RA-Sa-2009 Requirements for Fire – At Power High Level Requirements for HEP Quantification

- ATHEANA includes a fully capable detailed HRA quantification approach that satisfies requirements such as:
  - Part 2, HLR-HR-F: Human failure events shall be defined that represent the impact of not properly performing the required responses, in a manner consistent with the structure and level of detail of the accident sequences
  - Part 2, HLR-HR-G: The assessment of the probabilities of the post-initiator HFEs shall be performed using a well-defined and self consistent process that addresses the plant-specific and scenario-specific influences on human performances, and addresses potential dependencies between human failure events in the same accident sequence
  - Part 4, HLR-HRA-B: The Fire PRA shall include events where appropriate in the Fire PRA that represent the impacts of incorrect human responses associated with the identified human actions
  - Part 4, HLR-HRA-C: The Fire PRA shall quantify HEPs associated with incorrect responses accounting for the plant-specific and scenario-specific influences on human performance, particularly including the effects of fire
- …and supporting level requirements such as:
  - Part 2, SRs HR-F1, HR-G3, HR-G7, HR-G8; Part 4 SRs, HRA-B1 [Note 1] and HRA-C1

The ATHEANA HRA Process

- Step 1: Define and interpret issue of concern
- Step 2: Define scope of analysis
- Step 3: Describe base case scenarios
- Step 4: Define HFEs and unsafe actions (UAs)
- Step 5: Identify potential vulnerabilities
- Step 6: Search for deviations from base case
- Step 7: Evaluate recovery potential
- Step 8: Quantification
- Step 9: Incorporation into PRA

Steps in the ATHEANA Process



The ATHEANA HRA Process (continued)

- Not all of these steps are needed for every HRA/PRA job.
- For fire HRA/PRA, certain steps will not need to be performed by ATHEANA, e.g.,
  - NUREG/CR-6850 [EPRI 1011989] and the ANS/ASME PRA Standard already address Steps #1 and #2 (i.e., define and interpret the issue of concern, define the scope of analysis)
  - Deviations from the base case scenario (i.e., Step #6) are **usually** not needed for fire; most fire scenarios are generally challenging enough for operators that we do not have to look for even more unusual conditions
- So, later when we talk about ATHEANA steps, we'll highlight those needed specifically for fire HRA/PRA.

ATHEANA guidance for facilitating expert elicitation

- ATHEANA uses an expert elicitation approach to develop failure probabilities for HFEs:
  - Described in NUREG-1880, ATHEANA's User's Guide
  - Based on previous expert elicitation approaches, especially:
    - NUREG/CR-6372, Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts" (1997) (a.k.a., NRC's "SSHAC report")
  - ...and consists of:
    - A six-step process, leading to quantification of HFE (and its distribution)
    - Description of who the experts should be
    - General guidance for the facilitator
    - Guidance on addressing uncertainty, controlling for unintentional bias in experts, information to discuss, how to lead discussions and build distributions
    - Guidance on how to educate experts on probabilities and context
    - Guidance on how to build a consensus HEP and its distribution, and perform "sanity checks"

ATHEANA – What's going to be different for fire PRA?

1. NUREG/CR-6850 [EPRI 1011989] and supporting documents indicate the need for adjustments for a fire-specific knowledge-base (e.g., fire-specific human performance issues).
2. EOCs are limited to those stated in the ASME/ANS PRA Standard.
3. Many *Fire HRA Guidelines* qualitative analysis tasks overlap; may already be performed or started before detailed quantification is performed.
4. The fire **context** may already be sufficiently challenging for operators; ATHEANA steps and activities related to finding an **error-forcing context** may not be needed.

Mapping ATHEANA process steps to Fire HRA Guidelines process

ATHEANA Process Step	Fire HRA Guideline Process Step
Steps 1 & 2: Define issue & scope of analysis	Defined by fire PRA & its scope of analysis – **no additional work needed**
Step 4: Define HFEs and unsafe actions (UAs)	**Covered*** by Chapter 3: Identification and Definition
Steps 3 & 5: Describe PRA scenario & assess human performance information, etc.	Some additional information needed for detailed HRA; but, **mostly covered** by Chapter 4: Qualitative Analysis
Step 6: Search for deviation scenarios	**Probably not needed**; fire scenarios are already "deviations"
Step 7: Assess potential for recovery	Similar to Chapter 6: Recovery
Step 8: Quantification (explicitly addresses dependencies & develops uncertainty distributions)	Different approach than scoping trees (Chapter 5) or CBDT (Appendix C); different approach to dependency & uncertainty (Chapters 7 & 8)

ATHEANA HRA process – highlighting the needs of Fire HRA

- Step 1: Define and interpret issue of concern
- Step 2: Define scope of analysis
- Step 3: Describe base case scenarios*
- Step 4: Define HFEs and unsafe actions (UAs)*
- Step 5: Identify potential vulnerabilities*
- Step 6: Search for deviations from base case*
- Step 7: Evaluate recovery potential
- Step 8: Quantification
- Step 9: Incorporation into PRA

* Previous fire PRA tasks provide a start on these ATHEANA tasks; for example qualitative analysis is continuous through detailed HRA quantification

Additional ATHEANA needs for Fire HRA

1. Some additional qualitative analysis to support Steps 3, 5, (6), 7, and 8, including:
   - Information collection
   - Interviews of operator trainers
2. ATHEANA approach for quantification and recovery
   - With dependency considerations embedded
   - With uncertainty distribution being explicitly developed as part of quantification
3. Adjustments to knowledge-base (per considerations in NUREG/CR-6850 [EPRI 1011989] and others)

Additional ATHEANA needs for Fire HRA (continued)

- So, in this presentation, we will only discuss the following steps in the ATHEANA process:
  - Step 3: Describe the base case scenario*
  - Step 5: Identify potential vulnerabilities*
  - Step 6: Search for deviations from base case (often not needed)
  - Step 7: Evaluate recovery potential
  - Step 8: Quantification
- As for the entire process in applying the Fire HRA Guidelines, these steps are **iterative**.

Note: If Step 6 is needed, HFEs may need to be redefined (as in any HRA/PRA, if warranted by plant conditions, timing of plant behavior, etc.). But, Fire HRA Guidelines can address this situation without using Step 2 of ATHEANA explicitly.

Step 3: Describe "base case scenario" (i.e., PRA scenario and its nominal context)

- The base case scenario:
  - represents most realistic description of expected plant and operator behavior for selected issue and initiator
  - provides basis to identify and define deviations from such expectations (found in Step 6)
- **Ideally**, base case scenario:
  - has a consensus operator model (COM)
  - is well-defined operationally
  - has well-defined physics
  - is well-documented
  - is realistic
- Scenario description often based on FSAR or other well-documented analyses

  In practice, the available information defining a base case is usually less than ideal - analysts must supplement information deficiencies or simply recognize them.

Step 3: Describe "base case scenario" (continued)

- Initial plant conditions
- Sequence of events and expected timing before and following reactor trip
- Plant system and equipment response
- What the operators will see
  - usually trajectories of key plant parameters and indications
- Key operator actions during the scenario progression

NUREG-1921, Section 4 is good resource for this step

Step 3: Examples of information sources

- Plant-specific FSAR (and other design basis documents)
- Safety analyses (e.g., plant-specific, vendor)
- Procedures (e.g., plant-specific EOPs, vendor, basis documents)
- Operator experience (actual and simulator)
- Operator training material and its background documentation
- Plant staff, especially operators, operator trainers, T-H experts
- Plant-specific and industry generic operating experience

Again, NUREG-1921, Section 4 is a good resource

Step 5: Identify potential vulnerabilities

- Identify and characterize factors (e.g., performance shaping factors (PSFs)) that could contribute to crew performance in responding to the various accident scenarios
  - Factors that might increase the likelihood of the HFEs and UAs of interest
  - Helps focus later deviation searches
- Operators and trainers must play a role in this step
  - directly or through question/answer sessions
  - observation of simulator exercises (with relevant scenarios if possible)

Ways to identify potential vulnerabilities

- Investigation of potential vulnerabilities due to biases in operator expectations (training, experience)
  - review training materials, interview trainers, operators
- Understanding of base-case scenario timeline and any inherent difficulties associated with required response
- Identification of operator-action tendencies based on
  - “standardized” responses to indications of plant conditions
  - informal rules
- Evaluation of formal rules and EOPs
  - critical decision points, ambiguities, sources of confusion, timing mismatches, special cases such as “preemptive actions,” etc.

Ways to identify potential vulnerabilities (continued)

- Guidance given in NUREG-1921, Section 4, is good starting point
- Additional tools or guidance can be found in ATHEANA documentation, e.g.,
  - NUREG-1624, Revision 1 and NUREG-1880:
    - Summary of operator tendencies (for off-normal plant conditions in PWRs and BWRs), e.g.,
      - steam generator pressure too low or decreasing=> operators decrease steam dump (i.e., cooldown) or isolate tube rupture
    - Examples of informal rules (e.g., believe your indications, protect pumps (i.e., stop if no lube oil pressure))
    - Scenario characteristics that are challenging to operators (e.g., missing information, impasses, tradeoffs, double binds)
    - Parameter characteristics that are challenging (e.g., small change in parameter, slow rate of change in parameter, one or more false indications)

Ways to identify potential vulnerabilities (continued)

- Additional tools and guidance…in ATHEANA… (continued)
  - NUREG-1624:
    - Table 9.18, Examples of information problems (e.g., display failures, human factoring issues)
    - Table 9.19, Physics algorithms in instruments that can confuse operators (e.g., drive versus stem position for valve position indication)
    - Table 9.15b and 9.16b, scenario or parameters characteristics and associated error mechanisms, error types, and potential PSFs
    - Appendix A: Retrospective analyses of six events
    - Appendices B - E: ATHEANA example applications (e.g., SLOCA, loss of service water)
  - NUREG-1880:
    - Table 3.5-1, Relevant time frames for large LOCA and Loss of Main Feedwater (MFW) example scenarios
    - Section 3.5.2.2, Descriptions of PSFs (and associated discussion)
    - Appendix A: Example of an EOP flowchart for loss of MFW scenario

Step 6: Search for deviations from base case scenario

- Identify deviations from base case likely to result in risk-significant unsafe acts
- Deviations are plant behaviors or conditions that set up unsafe actions by creating mismatches between the proposed plant behavior and:
  - operators' knowledge, expectations, biases and training
  - procedural guidance and timing
- ATHEANA search schemes guide analysts to find real deviations in plant behavior and conditions
  - not just false perceptions in the operators' minds

Step 6: Four search schemes for deviation scenarios

- Identify deviations from the base case scenario using "HAZOP" guide words to discover troublesome ways that the scenario may differ from base case
  - more, less, quicker, slower, repeat ...
- Identify deviations for vulnerabilities associated with procedures and informal rules
  - e.g., changes in timing, sequencing of decision points, etc.
- Identify deviations caused by subtle failures in support systems
  - cause problems for operators to identify what's happening
- Identify deviations that can set up operator tendencies and error types leading towards HFEs/UAs of interest

Step 7: Evaluate potential for recovery

- Possibility of recovering from UAs is considered in this step; similar to recovery analysis when using other detailed HRA quantification methods
- However, for ATHEANA, recovery **always** considers **both** the complete EFC and the occurrence of other UA(s)
  - in qualitative analysis
  - in quantification (i.e., probability of failed recovery is **conditional** on probabilities of other operator **failures and successes**)
- Deviation description is extended to include the scenario characteristics up to the last opportunity for recovery
- Performance of this step linked with quantification - iteration between these steps is likely

Guidance for recovery analysis

- Define the possible recovery action(s) given the initial error corresponding to the HFE/UA has occurred
- Consider the time available to diagnose the need for and perform the recovery action so as to avoid a serious or otherwise undesired condition
- Identify the existence and timing of cues as well as how compelling the cues are that would alert the operators to the need to recover and provide sufficient information to identify the most applicable recovery action(s)
- Identify the existence and timing of additional resources (e.g., additional staff, special tools), if necessary, to perform the recovery

Step 8: Quantification

- Very structured, facilitator led, expert opinion elicitation process
  - leads to consensus distributions of operator failure probabilities
- Considerations in elicitation process (covered in NUREG-1880):
  - Forming the team of experts (include experts familiar with important relevant factors during fire conditions, operator trainers, etc.)
  - Controlling for biases when performing elicitations
  - Addressing uncertainty

ATHEANA quantification: Asks experts two questions

1. Does the operational story make sense?
   - given the specific PRA scenario or sub-scenario
   - given what is known about operators and operations at this plant

2. What is the likelihood that operators will fail as described in the operational story?

Basic formulation for quantification process

- $P(HFE|S) = \sum_{ij} P(EFC_i|S) \times P(UA_j|EFC_i,S)$
- HFEs are human failure events modeled in PRA
  - Modeled for a given PRA scenario (S)
  - Can include multiple unsafe actions (UAs) and error-forcing contexts (EFCs)
- First determine probability of the EFC (plant conditions and PSFs) being addressed
- Determine probability of UA given the identified EFC
- If multiple EFCs identified, then quantify a UA given each EFC separately

Six steps to quantification process

1. Discuss HFE and possible influences / contexts using a factor “checklist” as an aid
2. Identify “driving” influencing factors and thus most important contexts to consider
3. Compare these contexts to other familiar contexts and each expert independently provide the initial probability distribution for the HEP considering:
   - “Likely” to fail ~ 0.5 (5 out of 10 would fail)
   - “Infrequently” fails ~ 0.1 (1 out of 10 would fail)
   - “Unlikely” to fail ~ 0.01(1 out of 100 would fail)
   - “Extremely unlikely” to fail ~ 0.001 (1 out of 1000 would fail)

Six steps to quantification process (continued)

4. Each expert discusses and justifies his/her HEP estimate
5. Openly discuss opinions and refine the HFE, associated contexts, and/or HEPs (if needed) – each expert independently provides HEP (may be the same as the initial judgment or may be modified)
6. Arrive at a consensus HEP for use in the PRA

Addressing fire-specific issues with ATHEANA

- ATHEANA should be applied in the same way for fire HRA, as for any other HRA/PRA
- However, the fire-specific operator performance issues should be considered in performing ATHEANA steps (e.g., identifying potential vulnerabilities, quantification)
  - Again, Section 4 provides good basis for issues to address and tools for performing qualitative analysis tasks (e.g., how to collect and interpret timing information, fire-specific issues with respect to use of procedures)
- Plus, some of the information needed to apply ATHEANA may be collected and analyzed already in order to have used either the screening values or scoping approach provided in the Fire HRA Guidelines

Addressing fire-specific issues with ATHEANA (continued)

- Additional guidance/discussion on addressing operator response to spurious indications is provided in NUREG-1921, Appendix C, e.g.,
  - Development of uncertainty ranges in timing estimates (as discussed in Section 4.6.2) can (and have) been developed directly with expert elicitation
  - EOCs due to spurious indications (both recovery, as for scoping approach, **and initial failure**)
  - Impact of spurious indications as “distractions” (see Section 4.10)

Example qualitative analysis results - Chapter 4

- In applying the Fire HRA Guidelines, the following are examples of information already collected and/or analyzed:
  - Procedures used in fire scenarios
  - Usage of procedures
  - Potential fire effects and their impacts on human performance
  - Fire PRA scenarios with associated equipment and indication failures
  - Possible crew responses to fire scenarios
    - Errors of Commission
    - Errors of Omission

Examples of additional qualitative analysis to support ATHEANA

1. Identify:
   - important decision points or branching, and other possible places in procedures where operators may make different choices
   - plant-specific “informal rules” and other guidance that may supplement or slightly deviate from relevant procedural guidance
   - tradeoffs (e.g., impromptu choices between alternatives) or other difficult decisions that operators may need to make
   - potential situations where operators may not understand the actual plant conditions (e.g., spurious indications)
   - different ways by which an HFE could occur, starting with the fire PRA scenario description, different procedural paths or choices, and the reasons for these different choices

Examples of additional qualitative analysis to support ATHEANA (continued)

2. Develop:
   - insights from training, experience, or demonstration of fire-related operator actions (in- and ex-MCR), including use of specialized equipment
   - timelines or other ways of representing the time sequencing of events in fire scenarios
3. Objective or final result of ATHEANA qualitative analysis:
   - **A full operational scenario description, or "operational story,"** including accident progression and as many "bells and whistles" as are reasonable, such that operator trainers can "put themselves into" scenario
     - Because, in quantification, you will be asking them, "what would your crews do in this situation?"

Examples of additional qualitative analysis to support ATHEANA (continued)

- The resulting operational scenario description may include:
  - Additional plant conditions that will need to be quantified as part of the HFE (unless accident sequence analyst wants to revise event trees or fault trees).
  - Distinctions on timing of plant behavior (that might need to be addressed as part of the HFE, unless logic is revised).
  - Instrument or indication issues (including failures) that will need to be reflected (for fire, might be explicitly part of PRA model, or may not).
  - Different possible procedure paths or response strategies that operators might rationally take.
  - Reasons why operators might take different procedure paths.
  - Credible **recovery actions**.

Likely to need help from operational experts on the last three elements.

Remember…Basic quantification formula?

First, let's simplify; only one EFC for each scenario, S.

So, we have:

$$P(HFE|S) = \sum_{j} P(UA_j|EFC,S)$$

- S = Full operational story (might not be equivalent to PRA scenario)
- UAs = Different procedure paths leading to undesired outcomes, and associated reasons for taking them
- EFCs = Plant conditions, behavior, PSFs, etc., that are not explicitly modeled in PRA, but needed to represent S

- Probability of each UA is conditional on EFC/S

ATHEANA – Iterating between qualitative analysis and quantification

- Development of operational scenario descriptions should be both for and by operational experts (e.g., trainers).
- Even "during quantification," the analyst should be alert to the need to modify, refine, and/or add details to the operational description of the scenario. For example:
  - During quantification, very different failure probabilities are provided by the expert panel of trainers.
  - When explaining answers, one trainer brings up a possible influence (e.g., a specific plant condition or equipment failure) that no one else has considered.
  - Because everyone agrees to the validity and importance of this factor, the analyst either:
    - Has everyone include this factor in their quantification, or
    - Defines a new HFE to address this newly defined scenario

ATHEANA – Iterating between qualitative analysis and quantification (continued)

- Based on experience in applying ATHEANA, most of the effort is in identifying and developing the elements of an "operational story" that represents what the experts think is important to operator behavior.
- Once this agreement is reached, reaching a consensus in final quantification by the operational experts is usually not difficult (if using the tools and techniques for facilitating expert elicitation, such as that given in the ATHEANA User's Guide.)

ATHEANA – Addressing uncertainty in fire HRA/PRA

- Performed as usually would, i.e.,
  - Expert elicitation process for quantification includes:
    - Detailed qualitative discussions to ensure all the available information (evidence) is brought to the table, shared, and agreed upon to the extent possible
    - Detailed identification of the key factors contributing to aleatory and epistemic uncertainty
  - The HEP developed for an HFE in a fire scenario (as for any other scenario) may be made up of combinations of distributions of multiple unsafe actions that have been evaluated separately.
  - Individual distributions combined mathematically into a single distribution.

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