Completion of EPRI Credible Dependent Failure Mechanisms (CDFM) HRA Dependency Methodology

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Presentation Overview

1. Status Of EPRI Credible Dependent Failure Mechanisms (CDFM)
2. Overview of Methodology
3. Example of Dependent Combination Events (DCEs)
   - Identification and Definition
   - Quantification
4. Next Steps for CDFM

Status Of EPRI Credible Dependent Failure Mechanisms (CDFM)

<u>EPRI Technical Report Published 2025</u>

- EPRI CDFM HRA Dependency Methodology and Guidance
  - Initially published in 2024 as a Technical Update
  - Method and Guidance published November 2025
- HRA dependency methodology has not changed from 2024

<u>Newly Developed Method (NDM) peer review</u>

- Review performed in March 2026
- Final report issued July 17, 202 (PWROG-26009-P)
- EPRI is currently working towards F&O Closure of Findings

<u>Pilots</u>

- EPRI lead pilots were performed during development of CDFM (2023-2025)
- 2 Utility lead pilots are being performed in 2026

EPRI 3002032023 (2025)

EPRI 3002029330 (2024)

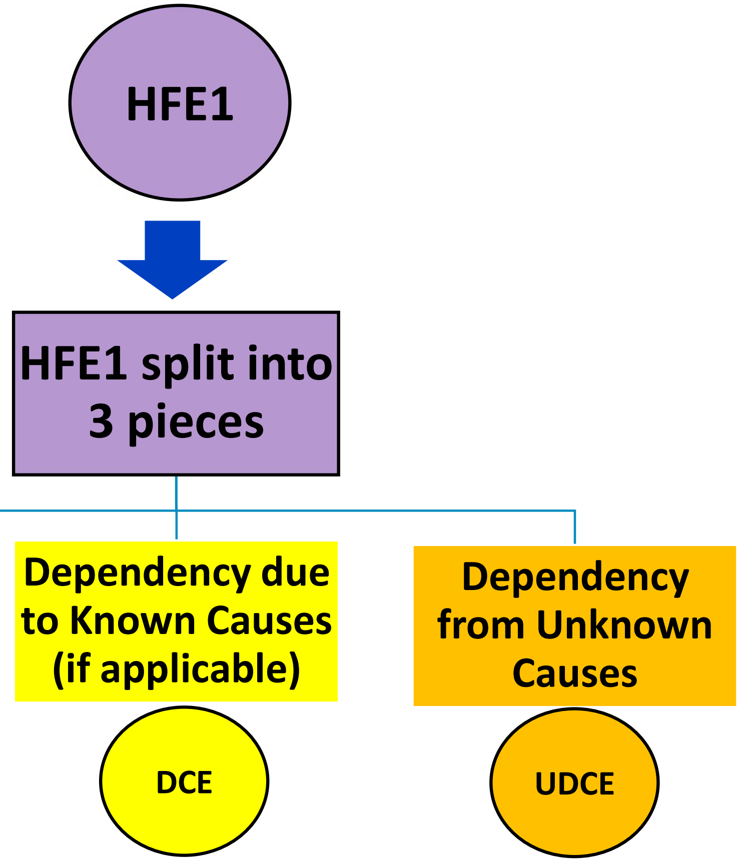
EPRI CDFM NDM Review

- NDM Results
  - Documentation requires more documentation to support the acceptance of the technical basis
  - 11 Findings
- Key Insights Regarding CDFM
  - No technical flaws for the method to be applicable
  - Identification of the dependent combination events is the key novelty
    - Technical basis requires more clarity and documentation
  - CDFM is expected to be applicable for all modes and hazards
    - Additional testing and considerations/guidance for external hazards is needed
- EPRI is working to resolve open F&Os in 2026 with support from industry pilots.

Overview of Methodology - Background

Move from:

Explicitly model contributions:



- Insert a fault tree gate where each HFE is modeled
- Explicitly break out and model two types of dependent contributions
  - Add new events representing "dependency due to the known, credible causes" such as functional similarities or same procedure/goal
  - Add a separate Joint HFE for "dependency due to unknown causes" (joint minimum HEP)
- Revised HFE represents the independent portion
  - For example, Execution actions

New structure is similar to CCF modeling of component fail to start

Overview of Methodology – Process Steps

- **Step 1:** Identify HFE Combinations
  - Dependent Combination Events (DCE) from event tree functions and support systems
  - Combinations of HFEs failed due to unidentified causes (UDCE)
  - DCE should be defined such that they are independent.
- **Step 2: Quantify DCE (2025 change)**
  - 2 Detailed Quantification Approaches
- **Step 3:** Model Incorporation
  - Incorporate DCE into fault tree logic
  - Incorporate UDCE into fault tree logic

Detailed Quantification Approaches

- Approach 1 – use existing cognitive HEP development
  - Used when cognitive HEPs are similar
  - Test for homogeneity
  - Select the lowest Pcog and assign as the DCE probability
- Approach 2 – Develop DCE using existing EPRI HRA methodologies (CBDT, HCR/ORE)
  - Appendix C provides guidance on how to evaluate the CBDT trees for a DCE
  - Add new failure mode of mis-prioritization if CBDTM provides negligible results.

Example of DCE Identification and Definition

Individual HFE Name	Summary of HFE Context
RCPTRIP-LATE - Operators fail to trip of RCP to prevent seal damage (late)	Late RCP trip avoiding significant seal leakage after RCP seal cooling loss.
SWFANSTRT - Operators fail to start of service water cooling tower fan	Increased heat loads require the start of a cooling tower fan to ensure service water maintains appropriate cooling capability. Loss of service water eventually leads to loss of component cooling water (CCW) and of cooling to the charging pumps, leading to the loss of RCP seal injection and thermal barrier cooling.
RCPTRIP-EARLY - Operators fail to trip of RCP to prevent seal damage (early)	Early RCP trip allowing minimum seal leakage after RCP seal cooling loss.
CCWPMPSTRT - Operators fail to start of alternative CCW pump given failure of running pump	Upon loss of the normally operating CCW pump, the standby pump automatically starts. The action here models the manual start of that pump should auto-start fail. Loss of CCW causes loss of thermal barrier cooling and charging pump injection, thereby challenging RCP seal integrity.
ALTCCWPUMPSTRT **Operators fail to start of alternative charging pump given failure of thermal barrier cooling**	The CCW system which cools the thermal barrier also cools the normal charging pump. The loss of the CCW system requires starting another charging pump, cooled by a different system. In absence of both thermal barrier cooling and charging, RCP seal integrity is lost.
RWSTALIGN - Operators fail to transfer charging pump suction from VCT to RWST	During normal operation, a charging pump takes suction from the volume control tank (VCT). Upon low VCT level, suction is transferred to the refueling water storage tank (RWST). The action here ensures that transfer. If failed, charging would be lost, challenging the RCP seal integrity function.
CHGALIGN **Operators fail to align safety grade charging**	Loss of instrument air causes loss of the normal charging path. Safety grade alignment provides an alternative charging path that does not rely on instrument air. Failure of that alignment leads to the loss of charging, challenging the RCP seal integrity function.

DCE – Operators fail to maintain RCP Seal Integrity and Thermal Barrier Cooling

- Group consists of 7 HFEs all supporting the same goal
- All HFEs required within the short time frame of 30 minutes or less.
- Group was identified using bottom-up approach of grouping HFEs based on goal of each HFE, systems and procedures.

Example of DCE Quantification Approach 1

HFE Name And Description	Pcog	Total HEP
RCPTRIP-LATE - Operators fail to trip of RCP to prevent seal damage (late)	**1.4E-04**	5.7E-04
SWFANSTRT - Operators fail to start of service water cooling tower fan	4.4E-04	9.3E-04
RCPTRIP-EARLY - Operators fail to trip of RCP to prevent seal damage (early)	1.4E-03	1.8E-03
CCWPMPSTRT - Operators fail to start of alternative CCW pump given failure of running pump	2.0E-03	3.7E-03
ALTCCWPUMPSTRT - Operators fail to start of alternative charging pump given failure of thermal barrier cooling	2.7E-02	3.5E-02
RWSTALIGN - Operators fail to transfer charging pump suction from VCT to RWST	2.7E-02	3.5E-02
CHGALIGN - Operators fail to align safety grade charging	**2.7E-02**	**3.5E-02**

Pcog HEPs Range from 1.4E-4 to 2.7E-2

This range is > 1 order of magnitude.

The Pcog values are not homogenous without additional review of the development of the individual HFEs.

Move on to Approach 2

Example of DCE Quantification Approach 2 – CBDT and HCR/ORE

- **Pca (data not available) and Pcd (information misleading):** No common set of instrumentation for all HFEs; Both trees are not applicable.
- **Pcb (failure of attention)**: Multiple alarmed and visible indications support RCP seal integrity monitoring; probability of failure to notice is negligible, even under high workload.
- **Pcc (misread/miscommunicate data) and Pch (deliberate violation):** Not applicable for a mature PWR and BWRs (>30 years operation) with robust HMI and communication protocols.
- **Pce (skip a step in procedure) Pcf (misinterpret instruction) and Pcg (misinterpret decision logic):** No single common procedure for step the group of HFEs; trees are not applicable.
- **HCR/ORE** – Average TSW = 17 minutes, Tcog = 1 minute HEP = Negligible

CBDT and HCR/ORE Evaluates to Negligible!

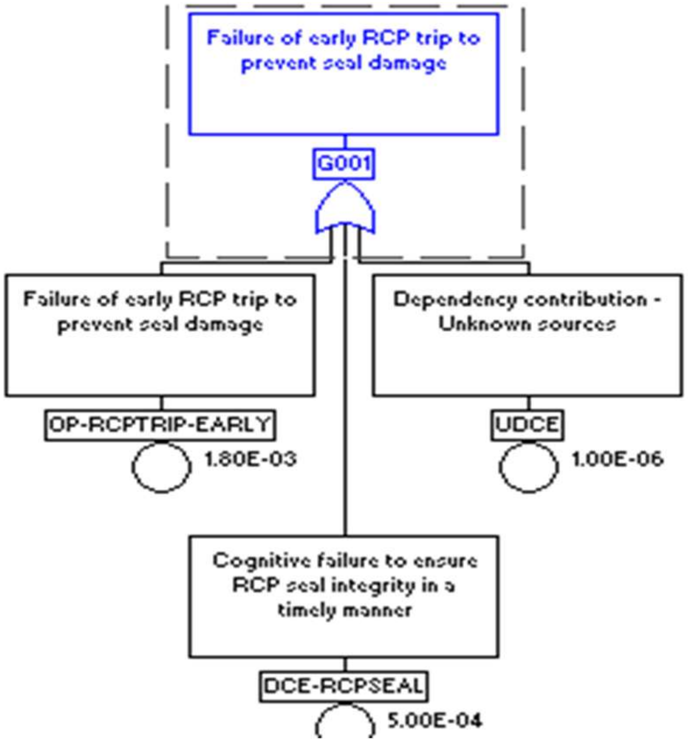
Example of DCE Quantification Approach 2 – Mis-prioritization or incorrect goals

- Additional failure mode not explicitly covered by CBDT.
  - Represents a fundamental failure to properly assess the situation, leading the operators to focus their efforts on tasks or issues that are unrelated to the event of interest.
- For long-term DCEs (time available for recovery greater than 1 hour) a value of 5E-05 is recommended.
- For shorter-term DCEs (time available for recovery less than 1 hour) 5E-04 is recommended.

Mis-prioritization HEP is 5E-4
Time for recovery for all HFEs is less than 1 hour

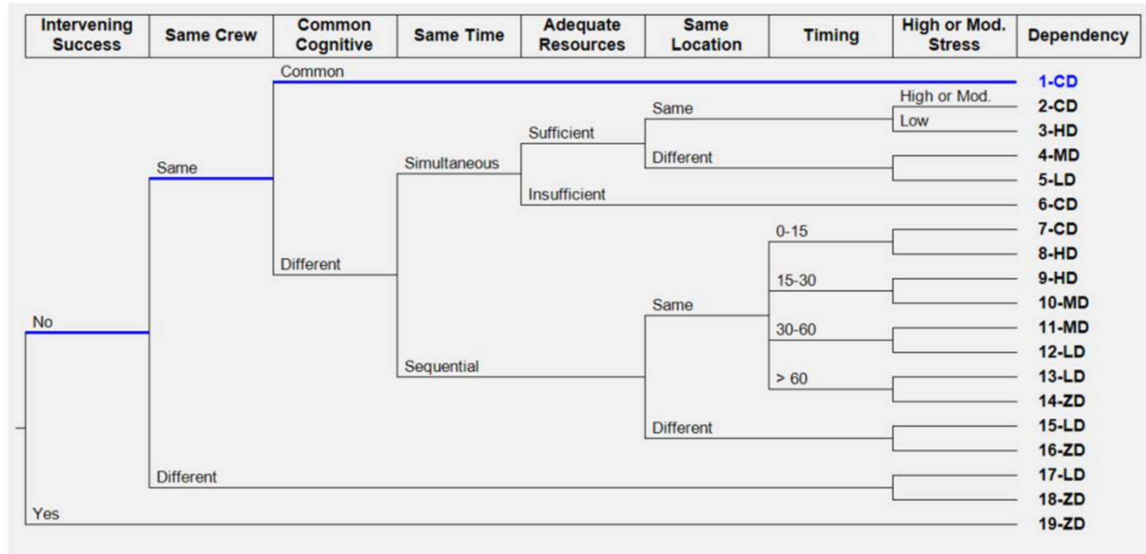
Example of DCE Quantification Conclusions

- DCEP Summary
  - Approach 1 – DCEP - 1.4E-04
  - Approach 2 – DCEP - 5E-04
- Both approaches are on the same order of magnitude. Approach 2 will be used as the final DCEP – 5E-4.
- Final DCEP should be reviewed as part of reasonableness check in ASME/ANS PRA Standard supporting requirement HR-G7.
- The UDCE is incorporated into the PRA model in addition to the DCEP.



Comparison of Example DCE to HRA Calculator JHEP

- THERP uses pairwise comparison approach and when order sequentially the first HFE will dominate the JHEP. The first HFE could range from 9.3E-04 to 3.5E-2
- For the example DCE each action after the first HFE would result in Complete or High Dependency since all HFEs, take place within 15 minutes and same location (MCR)



THERP JHEPs could range **4.65E-4** to **1.7E-2** depending on the specific HFEs in Combinations

CDFM results in 5E-4 for possible combinations

CDFM Next Steps

- CDFM is ready for industry adoption!
- EPRI is working to resolve NDM Peer Review F&Os. F&O's will be resolved by publishing EPRI knowledge base articles
  - Additional guidance on applying CDFM to external hazards
  - Additional documentation on the technical basis
  - Additional examples of identification of DCEs
- Industry pilots are being performed in 2026 and are planning to undergo focused scope peer review in 2027.

CDFM Development Team

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CDFM Overview (Quantification of DCE Prob. cont'd)

- **Step 1:** Identify HFE Combinations
  - Dependent Combination Events (DCE) from event tree functions and support systems
  - Combinations of HFEs failed due to unidentified (UDCE)
- **Step 2: Quantify DCE (2025 change)**
  - Streamlined Approach
  - Detailed Approach
- **Step 3:** Model Incorporation
  - Incorporate DCE into fault tree logic
  - Incorporate UDCE into fault tree logic

Detailed Quantification cont'd

- Approach 2 – use same method as individual HFE development
- Section 5.4.2 and Appendix C
  - Case 1. Given a single, common cue or common procedure for the constituent HFEs (Apply CBDTM to evaluate the common cue or procedure similar to individual HFE)
  - Case 2. Multiple cues or multiple procedures
  - Following quantification, check for an additional failure mode modeling mis-prioritization (Section 5.4.3)
    - Used if Case 1 or Case 2 is too low or if both Approach 1 & 2 are not applicable.

Quantification of DCE – Approach 2 uses Existing Methods for Cognitive HEPs

CDFM Overview (Model Incorporation)

- **Step 1:** Identify HFE Combinations
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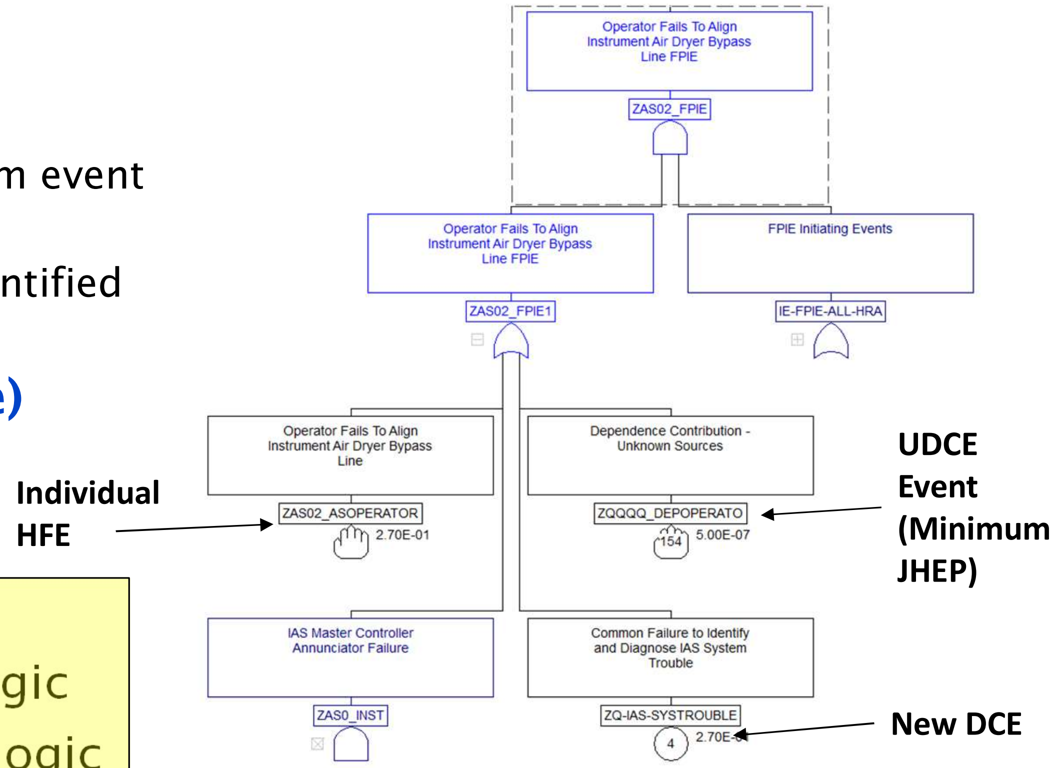

Example of Fault Tree Modeling

CDFM Pilot and Testing Summary

- Testing was conducted using a variety of analysts over 2-years:
  - Model owners
  - External consultant
  - Analysts that were inexperienced and experienced in HRA
- Stress testing of models
  - 1 full model (internal events, internal fire, internal flood)
    - Seismic hazards follows the same approach, will describe in a KB article
  - 1 fire model, and portions of 2 other models
  - Configuration Risk Management sensitivity cases
    - Front line component out of service
    - Support system component out of service

Self-Assessment

- CDFM was assessed against Requirements
  - NDM requirements
  - ASME/ANS requirements in the PRA Standard (2009 and 2024)
- Separate document provides a mapping to the EPRI report
  - High-level requirements
  - Supporting requirements
- Show mapping tables

Table 2-1. Mapping the EPRI CDFM HRA Dependency Approach to the Supporting Requirements of NM-A

Objective of NM-A: the newly developed method has clearly defined scope and limitations.

Attribute ID	Summary of Supporting Requirement	Assessment
NM-A1	The method should include a clear statement of its purpose, and that purpose should align with the documented scope	Section 1 states the purpose.
NM-A2	The method should state the limitations of the method, and these limitations should be consistent with NM-A1.	Section 4 defines the scope, assumptions, and limitations.
NM-A3	Identify which areas of the PRA can apply the method. Also identify which areas of the PRA are not applicable to the method.	Section 4 defines the scope, assumptions, and limitations.

Conclusions: Benefits of implementing CDFM

- Reduced PRA maintenance updates – easier to maintain by focusing on changes
- Reduced PRA quantification times by reducing recovery rules and eliminating seed values
- Tested and no issues seen with PRA model convergence
  - Demonstrated in our pilot models
- Eliminates problems with CRM and applications where the quantified risk decreases when systems removed
- Complies with PRA Standard HR-G and QU-C HRA dependency requirements
- Sets up the PRA for future PRA Standard requirements (e.g., 2024 supporting requirement for a joint minimum HFE)

Conclusions: Benefits of implementing CDFM cont'd

- CDFM applies upfront effort to improve PRA realism
- DCE joint HEP builds upon the human performance characteristics used to develop the cognitive HEPs of the constituent events
- Consolidating unidentified combinations into a single HFE eliminates model "noise"
  - Noise that can mask contributors
  - Thus, improves insights
- Improved communication with operations as CDFM focuses on safety functions and associated systems
  - Improves the credibility of the HRA and PRA