Dependent Failures

Lecture 6-1

Key Topics

- Importance of dependent failures
- Types of dependencies
- Common cause failure analysis

Resources

- American Nuclear Society and the Institute of Electrical and Electronics Engineers, "PRA Procedures Guide," *NUREG/CR-2300*, January 1983.
- A. Mosleh, et al., "Procedures for Treating Common Cause Failures in Safety and Reliability Studies," *NUREG/CR-4780*, Vols. 1 and 2, January 1988 and January 1989.
- D. Rasmuson and N. Siu, "Treatment of Common-Cause Failures in SPAR Models," presented at Annual Meeting of NEA Working Group on Risk Assessment (WGRISK), Paris, France, April 20, 2007. (ADAMS ML070990049)
- "CCF Parameter Estimates:" https://nrcoe.inl.gov/resultsdb/ParamEstSpar/

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Other References

- K.N. Fleming, "A reliability model for common mode failure in redundant safety systems," *Proceedings Sixth Annual Pittsburgh Conference on Modeling and Simulation*, Pittsburgh, April 23-25, 1975.
- K.N. Fleming and A.M. Kalinowski, "An Extension of the Beta Factor Method to Systems with High Levels of Redundancy," Pickard, Lowe and Garrick, Inc., *PLG-0289*, June 1983.
- C.L. Atwood, "Common Cause Failure Rates for Pumps," *NUREG/CR-2098*, February 1983.
- A. Mosleh and N. Siu, "A multi-parameter common cause failure model," *Proceedings 9th International Conference on Structural Mechanics in Reactor Technology*, Lausanne, Switzerland, August 17-21, 1987.
- N. Siu, "A Monte Carlo method for multiple parameter estimation in the presence of uncertain data," *Reliability Engineering and System Safety*, **28**, No. 1, 59-98, 1990.

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Other References (cont.)

- T.E. Wierman, et al., "Common-Cause Failure Database and Analysis System: Event Data Collection, Classification, and Coding," *NUREG/CR-6268, Rev. 1*, September 2007.
- T.E. Wierman, D.M. Rasmuson, and N.B. Stockton, "Common-Cause Failure Event Insights: Emergency Diesel Generators," NUREG/CR-6819, Vol. 1, May 2003.
- T.E. Wierman, D.M. Rasmuson, and N.B. Stockton, "Common-Cause Failure Event Insights: Motor-Operated Valves," NUREG/CR-6819, Vol. 2, May 2003.
- T.E. Wierman, D.M. Rasmuson, and N.B. Stockton, "Common-Cause Failure Event Insights: Pumps," NUREG/CR-6819, Vol. 3, May 2003.
- T.E. Wierman, D.M. Rasmuson, and N.B. Stockton, "Common-Cause Failure Event Insights: Circuit Breakers," NUREG/CR-6819, Vol. 4, May 2003.

Dependence – Concept and Importance

- The propositions (events) A and B are (probabilistically) dependent if

$$P\{A \cap B\} \neq P\{A\}P\{B\}$$

- For typical PRA elements, P{•} ~ o(10^{-4}) to o(10^{-2}) so if P{A|B} ~ o(10^{-1}), this could be very important to the qualitative as well as quantitative results and insights

> The identification and appropriate treatment of important dependencies is arguably the most significant part of an NPP PRA

Definitions of "Dependency"

- In these lectures, a "dependency" is a source of probabilistic dependence.
- Some more restricted definitions tied to requirements on addressing and documenting key dependencies:
  - "Reliance of a function, system, component, or human action on another part of the system or another human action to accomplish its function." (PRA Glossary, NUREG-2122)
  - "Requirement external to an item and upon which its function depends and is associated with dependent events that are determined by, influenced by, or correlated to other events or occurrences." (ASME/ANS RA-Sa-2009)
  - "Requirement external to a structure, system, or component (SSC), and upon which the SSC's function depends." (NUREG-1742)

Sources of Probabilistic Dependencies

- Aleatory
  - Causal links: A directly influences the occurrence of B
  - Correlational: A and B are subject to common influence

$$P\{A \cap B\} = P\{A|C\}P\{B|C\}P\{C\}$$

- Epistemic
  - Common information
  - In terms of density functions

$$\pi_{X,Y}(x,y) \neq \pi_X(x)\pi_Y(y)$$

Aleatory Classifications – Examples

A classification scheme:
- Can prompt imagination (useful)
- Is a model (not unique or "right")

- PRA Procedures Guide (NUREG/CR-2300, 1983)
  - Common Cause Initiating Events (Type 1)
  - Intersystem Dependencies (Type 2)
    - Functional Dependencies (Type 2A)
    - Shared Equipment Dependencies (Type 2B)
    - Physical Interactions (Type 2C)
    - Human-Interaction Dependencies (Type 2D)
  - Intercomponent Dependencies (Type 3)

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Common-Cause Initiators

- Generally involve spatial dependencies due to exposure to a common environmental (“spatial”) hazard (Lecture 6-2)
  - Fire
  - Flood
  - Earthquake
  - …
- Also includes support system losses, e.g., loss of offsite power (LOOP, LOSP), loss of ultimate heat sink (LOUHS), loss of specific power buses, loss of instrument air (LOIA)

Functional Dependencies

- Failure of System A directly affects likelihood of failure of System B
- Examples
  - System A provides support function, e.g.,
    - Power
    - Cooling
    - Control
    - Structural
  - System A performs enabling function, e.g.,
    - Reactor scram enables decay heat removal by engineered systems
    - Depressurization enables low pressure injection
    - Pressure boundary integrity prevents exposure to hazardous environment
  - System B is not needed unless A has failed (e.g., use of HPCI if RCIC fails)

Shared Equipment Dependencies

- Systems A and B share components (e.g., low-pressure injection and residual heat removal)
- System A supports Systems B, C, … (and so is "shared" with these systems) [Better viewed as a functional dependency?]

Physical Interactions

- Similar to common-cause initiators, but don't necessarily cause an initiating event
- Typically involve environmental stresses caused by failure of a component. Examples:
  - Jet, missiles, and steam from high energy line break
  - Blast, heat, smoke, and conductive particles from high-energy arc fault (HEAF)
  - High temperature from failure of room cooling
- Can also involve direct contact (e.g., pipe whip)

Human Interaction Dependencies

- Includes “errors of omission” (failure to perform needed action) and “errors of commission” (incorrect action); both can affect subsequent actions as well as system behavior.
- See Lecture 5-2.

Intercomponent Dependence

- Has same sub-categories as intersystem dependencies (functional, shared equipment, physical interaction, human interaction).
- Common cause failure (CCF) parametric models used to treat dependencies that are not modeled explicitly.

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CCF Modeling Approaches

- Parametric Models
  - “Catch all” treatment of the wide variety of dependent failures not modeled explicitly*
  - Quantified using simple probability models and operational experience
  - Includes human-induced CCFs
  - Narrow scope: do not address effect of underling causes on other parts of the scenario
- Mechanistic Models

*Example: fire can be the common cause of multiple component failures, but typically is treated separately

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CCFs – Engineering Considerations

- Event examples:
  - All emergency diesel generators fail to start during a test due to an improper modification to load sequencers.
  - Multiple motor-operated valves fail due to wrong shaft coupling pins
  - Auxiliary feedwater pumps failed due to steam binding (due to leakage past downstream check valves)
  - Poor maintenance leads to low lubrication and wear of reactor trip breakers, which fail then fail to meet trip time requirements
- Engineering analysis of CCF event data (including identification of proximate causes and coupling factors):'
  - Helps identify fixes/defenses
  - Supports assessment of impact vectors

Beta Factor and Other Models

- Beta factor model (Fleming, 1975)
  - Define m = number of redundant components in system, Q_n = probability of failure of exactly n components, Q_c = total failure probability for a component
  - Then

$$Q_1 = (1 - \beta)Q_c \quad \text{Independent failure}$$

$$Q_m = \beta Q_c \quad \text{Common cause failure}$$

- Multiple Greek Letter (MGL) model (Fleming and Kalinowski, 1983): extension of beta factor
- Binomial Failure Rate (BFR) model (Atwood, 1983): treats CCFs as responses to “shocks”

Other Models (cont.)

- Alpha factor (Mosleh and Siu, 1987)

$$Q_k = \frac{m\alpha_k}{\binom{m}{k}\alpha_t} Q_c$$

where

$\alpha_k \equiv$ fraction of failures involving k components due to common cause

$$\alpha_t \equiv \sum_{k=1}^{m} k\alpha_k$$

- Note: Sparse data and differing plant designs and operational characteristics => use “impact vectors” to translate event into plant-specific terms => practical application of uncertain (“fuzzy”) data

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Epistemic Dependencies*

- General case

$$\pi_{X,Y}(x, y) \neq \pi_X(x)\pi_Y(y)$$

- Special case where it matters: identical components in series (see next)
- Other applications
  - Parameter uncertainty propagation through phenomenological models
  - Sensitivity analyses for common modeling assumptions

*Typically referred to as "state-of-knowledge dependencies" in the literature.

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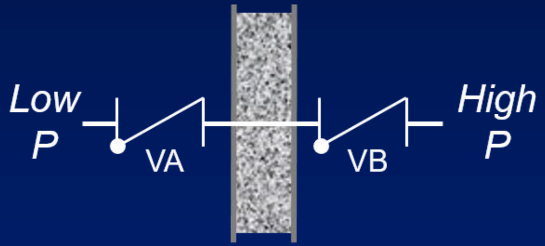
Thought Exercise



Consider a system of two check valves at a high/low pressure interface. Denote their aleatory failure probabilities as ϕ_A and ϕ_B. What is the mean system failure probability if:

- The failure probabilities are epistemically independent, i.e., knowing the value of one tells us nothing about the value of the other:

$$\pi_{\phi_A,\phi_B}(x,y) = \pi_{\phi_A}(x)\pi_{\phi_B}(y)$$

- The failure probabilities are completely epistemically dependent, i.e., knowing the value of one tells us the value of the other:

$$\pi_{\phi_A,\phi_B}(x,y) = \begin{cases} \pi_{\phi}(x) & \text{if } x = y \\ 0 & \text{otherwise} \end{cases}$$

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Thought Exercise – Categorize These Events

Event (March, 2011)

- Earthquake-induced HEAF causes heavy smoke in Turbine Building
- Tsunami damages service water pumps
- Operators delay containment venting due to delays in offsite evacuation
- Loss of air pressure prevents use of AOV to depressurize RCS to enable low pressure injection (fire water)
- Operators delay using saltwater for cooling due to instructions from company HQ

Dependency Type

- Common-Cause Initiating Event
- Intersystem
  - Functional
  - Shared equipment
  - Physical
  - Human
- Intercomponent
  - Functional
  - Shared equipment
  - Physical
  - Human