Treatment of Common-Cause Failures in SPAR Models

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Outline of Presentation

- CCF modeling
  - Approach
  - Implementation
- CCF data
- ICDE observations

Dependent Failures in PSA

- Mechanistic modeling
  - Functional requirement dependencies (e.g., sequence-dependent success criteria)
  - Functional input dependencies (e.g., support system dependencies)
  - Cascade failures (e.g., pump "dead head")
  - Physical/environmental (e.g., fires, external events)
  - Human interactions (e.g., maintenance errors)
- Parametric modeling ≈ Common Cause Failure (CCF) modeling
  - Beta factor (c. 1975)
  - Multiple Greek Letter (MGL) (c. 1983)
  - Alpha factor (c. 1987)

CCF in Standardized Plant Analysis Risk (SPAR) Models

- Basic events represent CCFs
- Quantification uses parameters Q_k (Basic Parameter Model)
  - $Q_k \equiv$ probability of failure of exactly k components due to common cause
- Q_k estimated using α-factor re-parameterization
- Example: 2/3 system
  - CCF event probability = $3Q_2 + Q_3$
  - $Q_2 = \dfrac{\alpha_2}{\alpha_1 + 2\alpha_2 + 3\alpha_3} Q_c \qquad Q_3 = \dfrac{3\alpha_3}{\alpha_1 + 2\alpha_2 + 3\alpha_3} Q_c$
  - Maximum likelihood estimators: $\hat{\alpha}_2 = \dfrac{n_2}{n_1 + n_2 + n_3} \qquad \hat{\alpha}_3 = \dfrac{n_3}{n_1 + n_2 + n_3}$
- Assumptions:
  - Failure events represented by Q_k are mutually exclusive
  - Q_k is constant (symmetry)
  - Component failure events are statistically independent
  - Total component failure probability (Q_c) is constant

Relationship Between α-factor and MGL (3 component example)

- CCF probability
  - $Q_{CCF} = \frac{3}{2}\beta(1-\gamma)Q_c + \beta\gamma Q_c$
- Relationship with α-factors

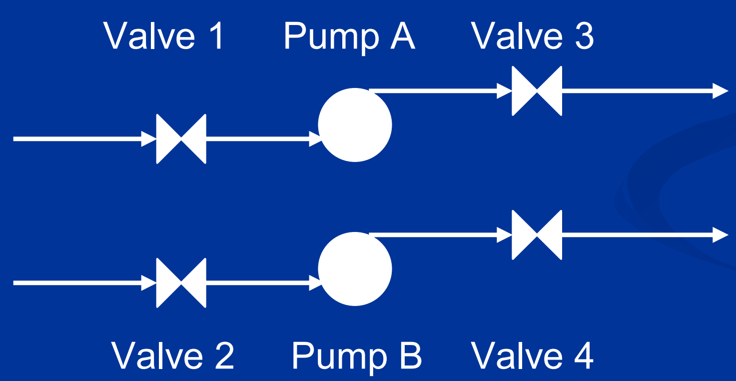
$$\beta = \frac{2\alpha_2 + 3\alpha_3}{\alpha_1 + 2\alpha_2 + 3\alpha_3} \qquad \gamma = \frac{3\alpha_3}{2\alpha_2 + 3\alpha_3}$$

- Joint distribution for MGL parameters can be derived from joint distribution for α-factors
  - MGL parameters are correlated
  - Rigorous estimation requires numerical analysis

Common-Cause Component Groups - 1

- CCCG ≡ A group of components, usually similar in design, mission, maintenance, environment, etc., that are considered to have a high potential of failing due to the same cause or causes

- Example:



  - CCCG 1: {Pump A, Pump B}
  - CCCG 2: {Valve 1, Value 2, Valve 3, Valve 4}

Common-Cause Component Groups - 2

- In principle, CCCGs can be broad enough to model CCFs involving:
  - Large numbers of components
  - Similar components used by different systems
  - Similar components used by different units
- Current SPAR or licensee models provide some level of treatment
  - High-redundancy situations (e.g., SRVs)
  - Cross-systems CCFs (e.g., HPCI/RCIC pumps)
  - Shared component/cross-unit CCFs (e.g., EPS, SWS)

CCF Data: Key Challenge and Approach

Plant-specific data for CCF events are more sparse than data for individual component failures

⇒ Use data from other plants; "impact vectors" quantify uncertainty in applicability

- ⇒ Adjustments ("mapping") for differences in size of exposed population
- ⇒ Adjustments to reflect uncertainties in applicability of observed event due to:
  - degree of observed degradation
  - degree to which failure cause is shared
  - Degree to which failures are close in time

Impact Vector Example (group size = 3)

- If, for a given event in the database, it is not clear whether 2 or 3 components were affected by a shared cause, the two possible impact vectors for Hypotheses A and B are:

1 in this position indicates failure of 2 components

$$I_A = [0, 0, 1, 0] \text{ and } I_B = [0, 0, 0, 1]$$

Indicates failure of 3 components

- If the analyst believes that Hypothesis A is true with probability of p_A, then Hypothesis B is true with probability $1-p_A$, and the average impact vector is

$$p_A \times I_A + (1 - p_A) \times I_B = [0, 0, p_A, 1-p_A]$$

- Bayesian methods can be used to estimate α-factors

Quantifying Impact Vectors: Example (group size = 2)

- Notation
  - P_1: degradation value for component 1
  - P_2: degradation value for component 2
  - t: value of the timing factor ($0 \leq t \leq 1$)
  - c: value of the shared cause factor ($0 \leq c \leq 1$)
- Assignment of impact vector values

$$I = [F_0, F_1, F_2]$$

where

$$F_0 = (1-P_1)(1-P_2)$$

$$F_1 = [P_1(1-P_2)+P_2(1-P_1)] + (1- ct)(P_1+ P_2)$$

$$F_2 = ct\ P_1P_2$$

Guidance for Impact Factors

- Component Degradation Value (P_i)
  - P = 0 if component is working
  - P = 0.1 if component is slightly degraded
  - P = 0.5 if component is degraded
  - P = 1.0 if component is failed

- Timing Factor (t)
  - t = 0.0 if times are really different
  - t = 0.1 if times are quite different
  - t = 0.5 if times are about the same
  - t = 1.0 if times are the same

- Shared Cause Factor (c)
  - c= 0 if causes are different
  - c = 0.1 if causes might be the same
  - c = 0.5 if similar cause
  - c = 1.0 if same cause

CCF Database

- Information obtained from LERs, NPRDS, and EPIX
- Data collection period from 1980 – 2003
- Loading data for 2004 and 2005
- Data collected by component type and system
- Database contains ~1700 CCF events of which 224 events are complete CCF events

CCF Event Information

- Qualitative Information
  - Plant name and event date
  - System and component type
  - Cause of failure (proximate cause)
  - Coupling factor
  - Event narrative
- Quantitative Information
  - Number of exposed components
  - Degree of degradation or failure of each component (component degradation value)
  - Timing among failures or degradations (timing factor)
  - A measure of the shared cause among the components (shared cause factor)

CCF Systems and Components

SYSTEMS

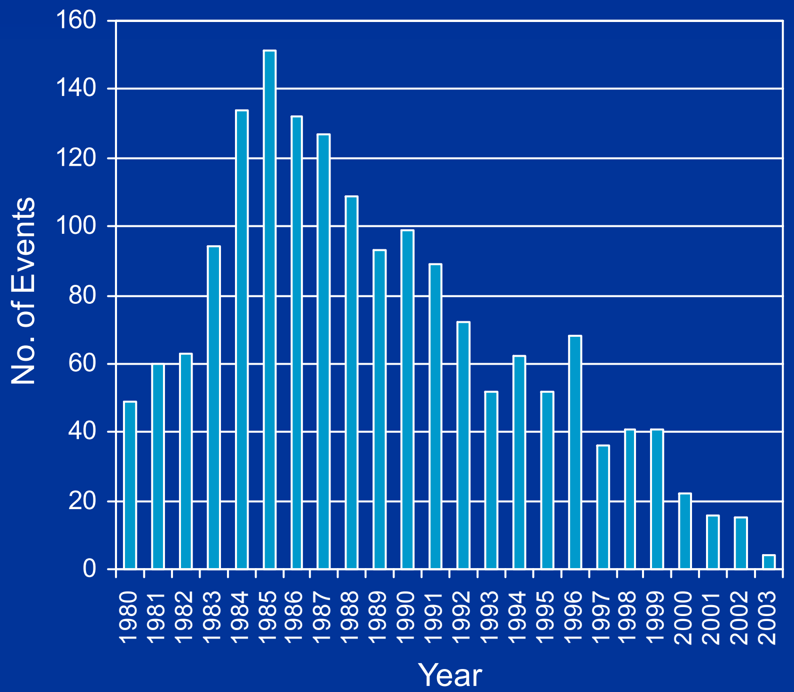
- DC Power
- AC Emergency Power
- Containment Spray
- Residual Heat Removal
- Emergency Power
- Auxiliary Feedwater
- Service Water
- PWR High Pressure Safety Injection
- PWR Low Pressure Safety Injection
- BWR Low Pressure Coolant Injection
- BWR High Pressure Coolant Injection
- BWR Reactor Core Isolation Cooling
- Reactor Protection
- Shutdown Cooling
- Standby Liquid Control
- Main Steam
- Low Pressure Core Spray
- Isolation Condenser
- Reactor Coolant
- Component Cooling Water

COMPONENTS

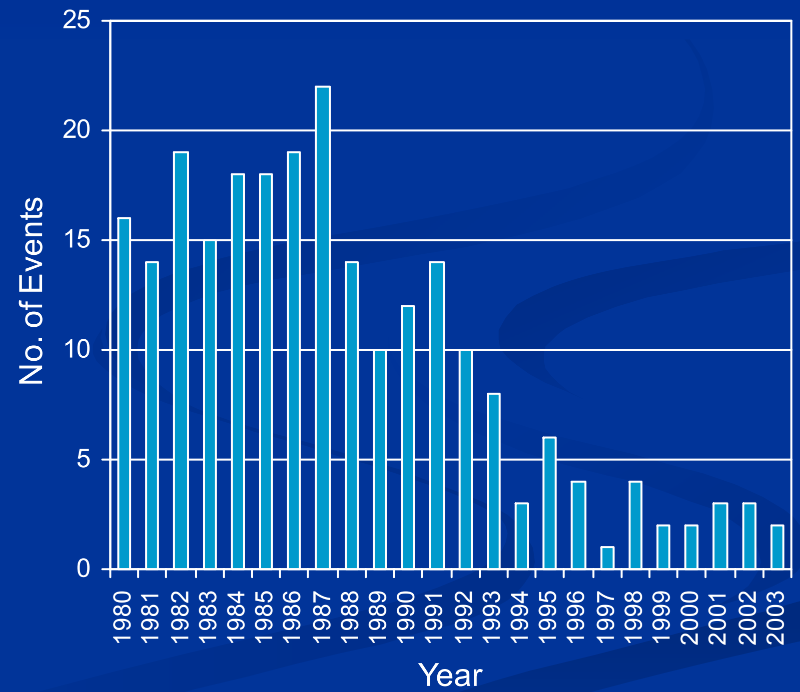
- Batteries
- Battery Chargers
- Circuit Breakers
- Reactor Trip Breakers
- Emergency Diesel Generators
- Heat Exchangers
- Strainers
- Motor-Driven Pumps
- Turbine-Driven Pumps
- Motor-Operated Valves
- Air-Operated Valves
- Check Valves
- Safety and Relief Valves
- Main Steam Isolation Valves
- Relays
- Logic Modules
- Control Rod Drive Assemblies
- Detectors
- Transmitters

USA CCF Event Trends

All Common Cause-Failure Events



Complete Common-Cause Failure Events



ICDE Observations

- NRC has participated in all component data exchanges
- Information collected in ICDE Project can be used in CCF quantification methods used in US
- NRC uses the ICDE CCF data for qualitative information
- NRC issued a report in 2006 summarizing insights from ICDE data for pumps, MOVs, EDGs, and breakers for use in the inspection program

Selected References

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- A. Mosleh and N. Siu, "A multi-parameter common cause failure model," *Proceedings of 9th International Conference on Sructural Mechanics in Reactor Technology (SMiRT-9)*, 1987.
- Updated Common-Cause Failure Parameter Estimates are available at http://nrcoe.inel.gov/results/ under Common-Cause Failures