# COMMON CAUSE FAILURE MODELLING IN UK PSAs

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# Contents – First Session

Presented by **Nadim Choudhary**

- Introduction to Common Cause Failure (CCF)
- CCFs modelling in UK PSAs for Nuclear Power Plants
- Importance of including CCFs in PSAs
- Overview of β-factor/ UPM approach
- Advantages and disadvantages of the current method
- List of components included in AGR PSAs.

# Contents – Second Session

Presented by **Dr Charles Shepherd**

- Other available options for modelling CCFs
- CCFs modelling in current PSAs in other countries
- Strengths/weaknesses of the CCF modelling approaches
- Available sources of data
- CCF modelling facilities in PSA software
- Applicability of generic data to other PSAs.

**Much of the work described in this presentation was carried out under contract to EDF Energy.**

# What is a CCF?

**COMMON CAUSE FAILURE**

**Failure of a set similar components due to a common cause**

**COMMON CAUSES**

| | |
|---|---|
| **Component inadequacies** | - design, fabrication, installation |
| **Maintenance errors** | - omission, commission |
| **Hazardous environment** | - temperature, humidity, etc. |
| **Hazardous events** | - fire, flood, earthquake, etc. |
| **Common support systems** | - electrical power, cooling water, etc. |

# Protection Against CCFs

- **Redundancy:**

  Providing more identical 'trains' or plant items, each of which can perform the safety function.

- **Segregation:**

  Physically separating systems or components to reduce vulnerability to single events e.g. install pumps in different rooms in different parts of the site.

- **Diversity:**

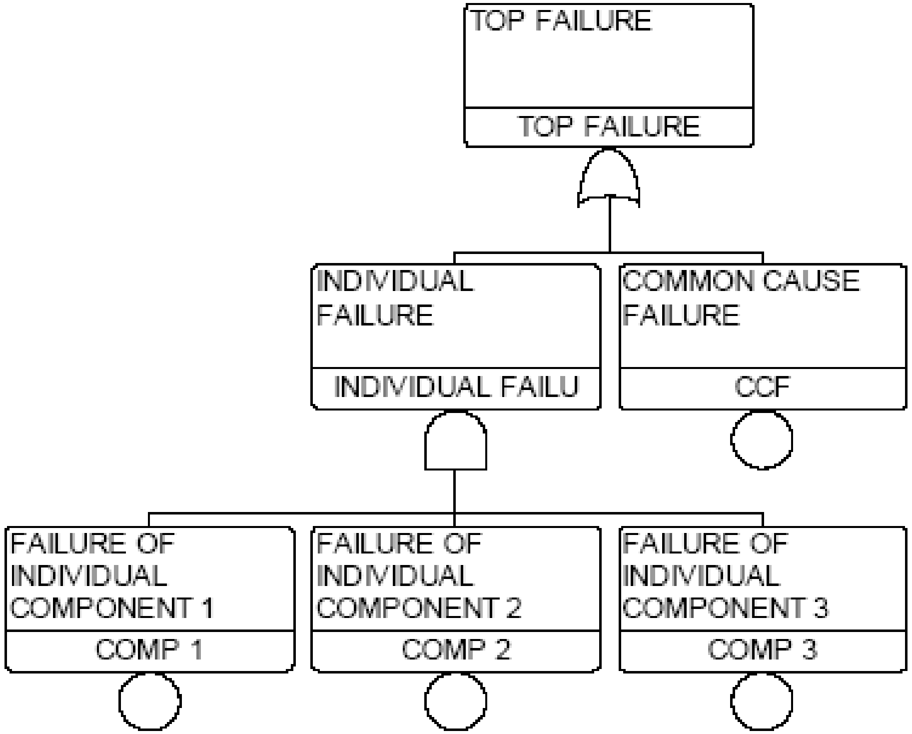
  Providing different types of systems or components to improve the reliability of a safety function e.g. installation of one electrically driven and one diesel driven pump.

# Why do CCFs need to be included in PSAs?

- CCF analysis is important in reliability and safety studies as CCFs often dominate random failures.
- The CCF events can significantly affect the availability of Nuclear Power Plant safety systems.
- General conclusion from PSA assessments of commercial Nuclear Power Plants is that CCFs are significant contributors to the unavailability of the safety systems.
- Important to capture this risk in all reliability studies.

# How are CCFs Currently Modelled in UK PSAs for NPPs?

- β-factor/ Unified Partial Method (UPM) approach is used
- Single Basic Event is used in the PSA model to represent a system failure, half system failure or a component failure.



# What is the Unified Partial Method (UPM)?

- The UPM assesses the effectiveness of system defences against a number of significant root cause factors including:
  1. Inadequate system redundancy (and diversity)
  2. Inadequate separation
  3. Understanding (Experience, Novelty, Complexity & Misfit)
  4. Analysis
  5. Man Machine Interface (MMI)
  6. Safety Culture
  7. Environmental Control, and
  8. Environmental Testing.

# Example of UPM in Practice

- Active redundant components are recorded for system.
- Component failure mode with the highest failure probability is selected to determine contributors.

| System | Status | | |
|---|---|---|---|
| Essential Circulating Water System (ECW) | Operational Pre-Trip | | |
| **Redundant Components Modelled in the PSA** | | | |
| **Active Redundant Components** | | | |
| Running Components (1 Pump per Reactor Pit and Strainer per Train) | Failure Mode | Basic Event ID | Failure Probability |
| Duty ECW Pump | Fails to Run | ECP1------PCFR | 3.02E-04 |
| Duty ECW Pump Contactor | Spuriously Opens | ECP1------EXSO | 3.36E-06 |
| ECW Strainer | Blocked | ECSTRAINA-FSAL | 5.64E-05 |
| Discharge Main Flood Valve | Spurious Closure | EC-CW/90A-VMSC | 1.08E-05 |

| **Selected CCF Events and Justifications** | | | |
|---|---|---|---|
| **CCF Code Input to PSA Model** | **Description** | **Basic Event ID** | **Component(s) and Failure Mode(s) Considered for CCF Probability** |
| EC-ECWSYS--CCF | CCF OF THE ECW SYSTEM | ECP1------PCFR | ECW PUMP 1 FAILS TO RUN FOR 24 HOURS |
| | | ECSTRAINA-FSAL | ECW STRAINER A BLOCKS WITHIN 24 HOURS |

# Example of UPM in Practice

| Assessment Factors | Judgment/Discussion | Category | Value |
|---|---|---|---|
| DESIGN: | | | |
| Redundancy | The essential circulating water (ECW) system consists of four pumps separated into two pairs, with each pair operating on a duty/automatic standby arrangement and serving one circuit of the ECW system. The ECW system provides cooling sea water to the heat exchangers of RACW, PVCW and THACW systems. As there are 2 ECW circuits in operation, redundancy is 1oo2. | A | 1750 |
| ENVIRONMENTAL: | | | |
| Control | The ECW system is located within the CW pumphouse where there is no access control. All equipment and services are subject to design control. | B | 425 |
| Tests | The ECW system is required to have the integrity and functionality to withstand a 1.0E-04 pry seismic event, and the system has been assessed against this. Mods relating to seismic qualification have been carried out. | B | 290 |
| | UPM beta factor | 7.31E-02 | |
| | Standby/Running: | R | |
| | Basic Event: | EC-ECWSYS--CCF | |

- In assessing the β-factor, the UPM approach assigns a category A-E against each root cause factor (8) assessed.
- E.g. for redundancy Category A as defined by UPM is 'minimum identical redundancy (e.g. 1oo2, 2oo3 for success), whilst a Category E is two entirely diverse independent redundant systems.

# Example of UPM in Practice

| Common Cause Factor | A | A+ | B | B+ | C | D | E |
|---|---|---|---|---|---|---|---|
| Design | | | | | | | |
| Redundancy (& diversity) | 1750 | 875 | 425 | 213 | 100 | 25 | 6 |
| Separation | 2400 | | 580 | | 140 | 35 | 8 |
| Understanding | 1750 | | 425 | | 100 | 25 | 6 |
| Analysis | 1750 | | 425 | | 100 | 25 | 6 |
| **Operation** | | | | | | | |
| MMI | 3000 | | 720 | | 175 | 40 | 10 |
| Safety culture | 1500 | | 360 | | 90 | 20 | 5 |
| **Environment** | | | | | | | |
| Control | 1750 | | 425 | | 100 | 25 | 6 |
| Tests | 1200 | | 290 | | 70 | 15 | 4 |

- A numerical value is provided for each category.
- The β-factor is calculated by summating the numerical values assigned against each category and then dividing by 50,000.

# Example of UPM in Practice

- For multiple component failure modes, the failure probability for each BE is summed in order to calculate the overall CCF event failure probability.
- Value of each CCF is multiplied by the β-factor.

| Table Ref. No. | Basic Event ID | Description | HRA PSR2 RSP PSA MODEL DATA | | | ß Factor | | CCF |
|---|---|---|---|---|---|---|---|---|
| | | | Basic Event ID | Description | Failure Probability | Standby | Running | CCF Probability |
| B37 | EC-ECWSYS--CCF | CCF OF THE ECW SYSTEM | ECP1------PCFR | ECW PUMP 1 FAILS TO RUN FOR 24 HOURS | 3.02E-04 | - | - | - |
| | | | ECSTRAINA-FSAL | ECW STRAINER A BLOCKS WITHIN 24 HOURS | 5.64E-05 | - | - | - |
| | | | | | 3.58E-04 | - | 7.31E-02 | 2.62E-05 |

- Overall CCF probability derived for this specific system is 2.62E-05.
- Inserted as a probability into the Basic Event within the PSA model.

# Advantages of β-factor/UPM Approach

- Very simple
- Conservative; all CCF events are assumed to fail all redundant components
- Small number of basic events in PSA model
- Additional basic events can be included at a lower level to model specific CCFs
- β-factors derived using UPM approach
- Provides an auditable trail.

# Disadvantages of $\beta$-factor/UPM Approach

- UPM requires judgements to be made on CCF influencing factors
- Numerical values provided by UPM have not been calibrated
- Level of conservatism is not known but could be very large
- Cannot be used to model for example the event that 2 out of 3 components fail.

# Example of Components for which there are CCFs in AGR PSAs

- Air Circuit Breakers
- Bulk Fuel Oil System
- Turbine Generators
- Electrical Systems (11kV, 3.3kV, etc.)
- Pumps
- Various types of Valves
- $CO_2$ System
- Batteries
- Pressure Switches
- Control Timers
- Gas Circulators and its IGVs
- Relays
- Instrument Air Systems

# Other Ways of Modelling CCF in PSAs

## Parametric models

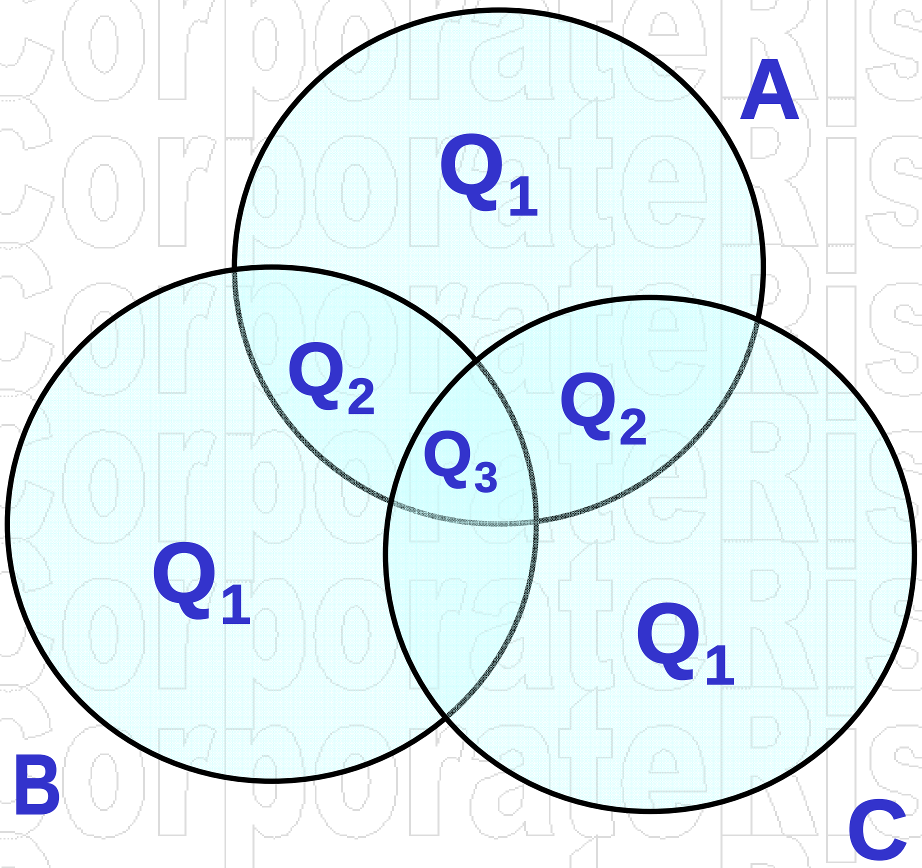
- Basic parameter model
- Multiple Greek Letter (MGL) method
- α-factor method.

# Basic Parameter Model

$Q_k$ = P (k specific components fail in a group of m components)

k = 1 to m

m = level of redundancy




**$P(A) = P(B) = P(C) = Q_1$**

**$P(AB) = P(AC) = P(BC) = Q_2$**

**$P(ABC) = Q_3$**

**$Q_k = n_k / N_k$**

**$n_k$ = number of events where k components have failed**

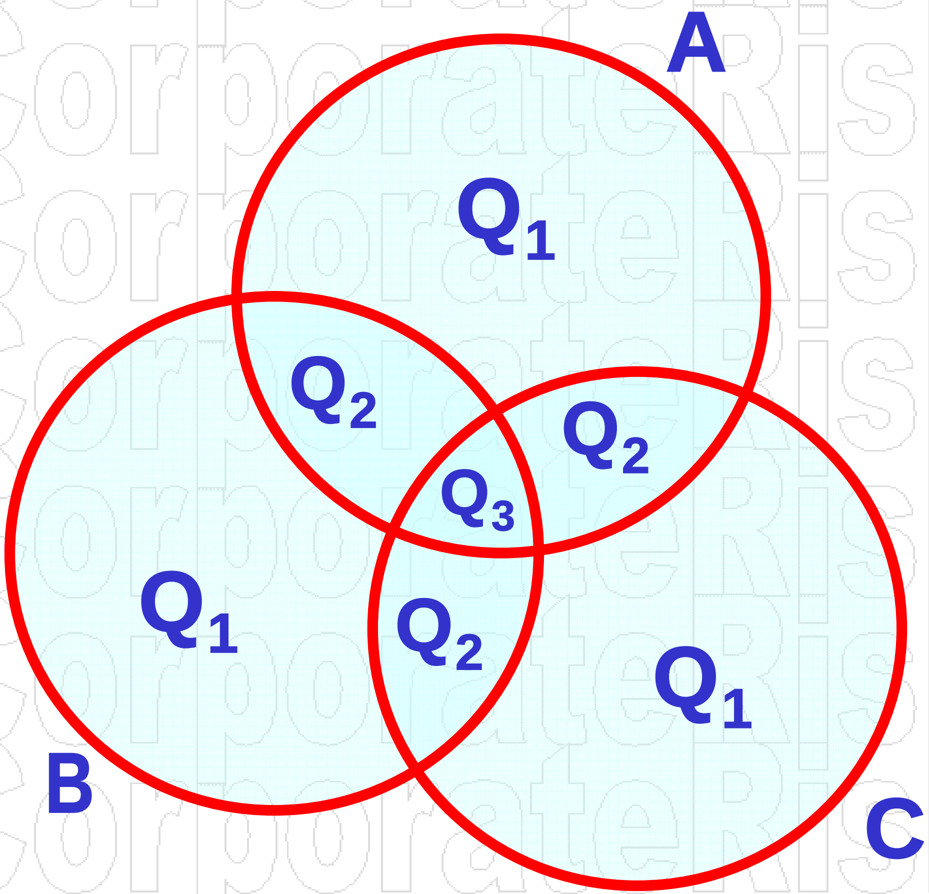
**$N_k$ = number of demands on any k components**

# α-factor Method

$\alpha_k$ = P (exactly k components fail | failure event occurs)

k = 1 to m

m = level of redundancy




$$\alpha_1 = 3Q_1 / (3Q_1 + 3Q_2 + Q_3)$$

$$\alpha_2 = 3Q_2 / (3Q_1 + 3Q_2 + Q_3)$$

$$\alpha_3 = Q_3 / (3Q_1 + 3Q_2 + Q_3)$$

$$\alpha_1 + \alpha_2 + \alpha_3 = 1$$

$$\alpha_k = n_k / \Sigma n_{k\ \{all\ k\}}$$

**for k = 1 to m**

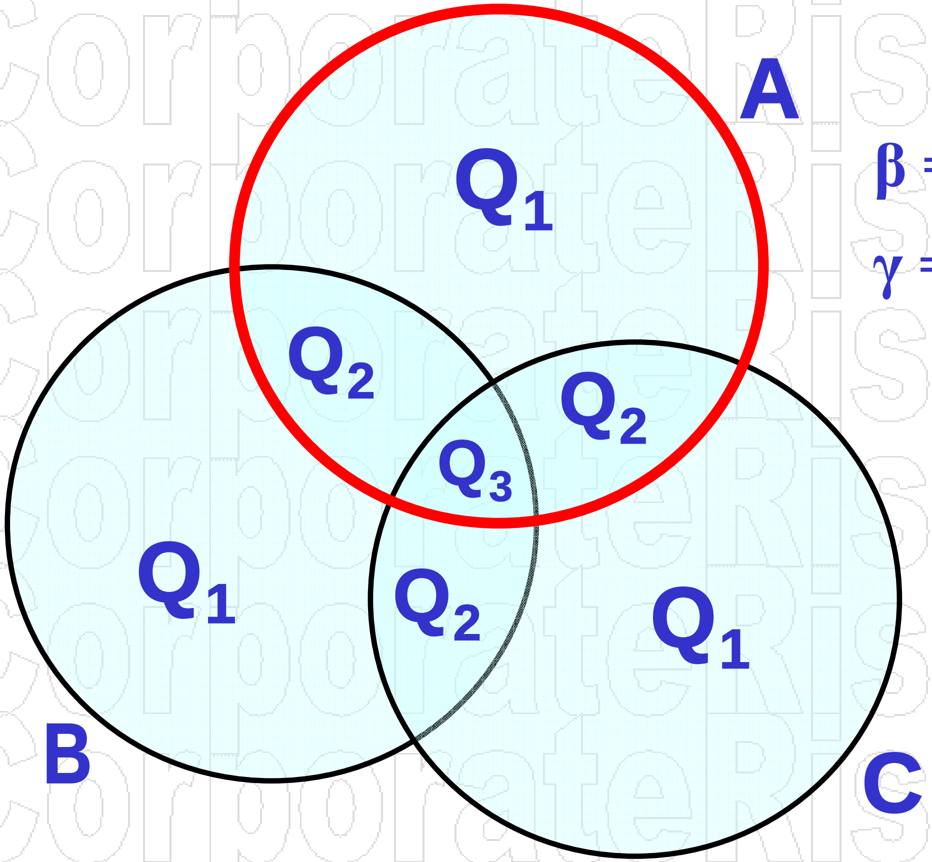
**$n_k$ = number of events where k components have failed**

# MGL Method

$\rho_k$ = P (a specific component fails dependently with another k-1 or more components | it fails dependently with another k-2 or more components)

k = 2 to m

m = level of redundancy




$\beta = (2Q_2 + Q_3) / (Q_1 + 2Q_2 + Q_3)$

$\gamma = Q_3 / (2Q_2 + Q_3)$

$\rho_2 \rightarrow \beta \quad \rho_3 \rightarrow \gamma$

$$\rho_k = \Sigma n_{k\{\geq k\}} / \Sigma n_{k\{>(k-1)\}}$$

**for k = 2 to m**

**$n_k$ = number of events where k components have failed**

# Comparison of Methods

| | β-factor | MGL | α-factor |
|---|---|---|---|
| Parameters | $\beta$ | $\beta\ \gamma$ | $\alpha_1\ \alpha_2\ \alpha_3$ |
| $Q_1$ | $(1-\beta)\ Q_T$ | $(1-\beta)\ Q_T$ | $\frac{1}{3}\ \alpha_1\ Q_T$ |
| $Q_2$ | 0 | $\frac{1}{2}\ \beta\ (1-\gamma)\ Q_T$ | $\frac{1}{3}\ \alpha_2\ Q_T$ |
| $Q_3$ | $\beta\ Q_T$ | $\beta\ \gamma\ Q_T$ | $\alpha_3\ Q_T$ |
| | $Q_T = Q_1 + 2Q_2 + Q_3$ | $Q_T = Q_1 + 2Q_2 + Q_3$ | $Q_T = 3Q_1 + 3Q_2 + Q_3$ |

# Strengths of α-factor/ MGL Methods

## Strengths

- Provides a more realistic model of CCF that reflects operating experience
- Addresses complete and partial CCFs
- Removes the conservatisms in the β-factor/ system cut-off approach
- Can be included in PSA model using the CCF facility in PSA software; this makes the CCF model easy to update
- Can be used to address uncertainties (for the α-factor approach using INL data).

# Weaknesses of α-factor/ MGL Methods

## Weaknesses

- Data only available for some component types; not available for some of the risk-significant AGR components.
- Makes PSA model larger; increases solution times; makes cut-sets more complicated.
- Assumptions made in deriving the CCF parameters not known.

# Review of PSA Modelling in other Countries

- **Information gathered in a number of ways:**
  - Questionnaire/ supplementary information/ difficulties encountered
  - Information from IAEA Workshops and IPSART missions
  - Literature search (NRC, EPRI, IAEA, WGRisk, conferences, internet)
  - Discussions with PSA analysts (RiskSpectrum User Group meeting, IAEA meetings, emails/ telephone calls to PSA analysts).
- **Information collected for 27 sources which included:**
  - Single plants (Bulgaria/ Belene)
  - More than one plant (Finland/ Olkiluoto 1 and 2)
  - All the plants in a series/ country (France/ all PWRs)
  - Different types of plants (AGR, PWR, BWR, VVER, Candu, etc.).

# Insights from the Review (1)

- **Approach to modelling CCF in the current PSAs**
  - Current practice is to use the α-factor or MGL approach to model CCF
  - α-factor approach used most often in USA/ method supported by NRC
  - MGL approach used for French plants and EPR
  - Some PSAs being changed from MGL to α-factor approach to provide a better way of handling uncertainties.
- **CCF modelling in the PSA model**
  - Usual way is to use the CCF modelling facility in PSA software
  - Seen as a relatively simple way of modelling CCF in a large, complex PSA
  - Analysts consider that this approach makes the fault tree logic much clearer than if CCF basic events included explicitly.

# Insights from the Review (2)

- **More detailed modelling for the important CCF groups**
  - Initial (screening) analysis often done using β-factor approach to identify the important CCF groups which are then modelled using a more detailed/ less conservative model (α-factor or MGL)
  - α-factor or MGL approach often used for systems with low levels or redundancy (3 or 4-fold) and the β-factor approach for systems with high redundancy
  - Use of two different CCF models in the same PSA not seen as a problem; better to have an accurate/ realistic/ less conservative model for risk-significant CCFs.
- **Data used in quantifying the CCF parameters**
  - α-factor and MGL parameters quantified using generic operating experience data
  - Many plants have used relatively old generic data
  - Move towards using more recent data (INL 2007)
  - CCF data collection going on internationally (OECD ICDE) and nationally (France, Germany, Finland).

# Insights from the Review (3)

- **Data analysis – factors taken into account**
  - Impact vector approach to take account of partial CCFs
  - Bayesian updating (where prior is generic data that is updated using national/ plant specific data)
  - Testing regime (sequential or staggered testing)
  - Data may be derived from systems with a different level of redundancy; scaling required.
- **Quantification of the PSA model**
  - Solution times not significantly longer/ convergent solution can be obtained
  - Greater number of cut-sets; no difficulty in understanding or using PSA results
  - In comparing the results of an analysis using the β-factor and MGL approaches, care needs to be taken that (1-β) factor is included in both
  - Updating of the PSA can be done easily if the facility in the CCF software is used; much more difficult if CCF basic events are included in the model.

# Insights from the Review (4)

- **Uncertainties**
  - α-factor approach usually used when an uncertainty analysis is required
  - Issues relating to uncertainty analysis:
    - **Sampling scheme:** Needs to take account of the correlations between the basic events for independent failure and CCF; some of the PSA software doesn't do this correctly
    - **Truncation of distributions:** CCF parameters may be close to zero or unity (e.g., (1-β), (1-δ), etc. in MGL approach) so that the uncertainty distributions need to be truncated.

# Insights from the Review (5)

- **Difficulties encountered in CCF modelling**
  - No specific difficulties identified in the use of the α-factor or MGL approaches; general difficulties include:
    - Data not available for all components in PSA model; data for similar components used
    - Components may belong to more than one CCF group
    - Difficulties in scaling data to take account of different levels of redundancy.
- **Analysis effort required**
  - Substantial experience required in moving from β-factor approach to α-factor/ MGL approach.

# CCF Modelling Facilities in PSA Software

- **Most of the current PSA codes have a CCF modelling facility**
- **Analyst defines**
  - CCF component groups; CCF modelling approach (α-factor, MGL, etc.); CCF parameters.
- **CCF software defines**
  - Generates CCF basic events; CCF fault trees for each of the component groups; calculates the CCF basic event probabilities; solves the overall PSA model which includes the CCF fault trees.
- **Feedback from analysts**
  - Seen as a relatively simple way of modelling CCF in a large, complex PSA
  - Analysts consider this approach makes the fault tree logic much clearer than if CCF basic events included explicitly
  - It is easier to update the model (compared to including CCF basic events explicitly in the PSA model).

# CCF Modelling in RiskSpectrum

- RiskSpectrum has CCF modelling facilities
- Care needs to be taken in using these facilities with INL data
- Putting equivalent data into RS for the α-factor and MGL methods produced different results
- The INL data relates to staggered testing
- However, the formula used in RS for the α-factor method are for non-staggered testing
- The RS Theory Manual states that staggered testing needs to be modelled using the time dependent facility in RS.

# Sources of CCF Data (1)

- **Idaho National Laboratory (INL)/ Nuclear Regulatory Commission (NRC)**
  - Data from LWRs operating in the USA; data produced originally in 1998; updated 2003, 2005, 2007, 2009; next update 2011
  - Uses data from: Nuclear Plant Reliability Data System (NPRDS), Equipment Performance Information Exchange (EPIX), Licensee Event Reports (LERs); LER reporting is mandatory for all nuclear power plants
  - Databases searched to identify CCF events – multiple failures in same CCF group due to the same cause that occurred within a specified timescale
  - Data included for a range of different types of pumps and valves, diesel generators, circuit breakers, strainers/ filters and heat exchangers
  - CCF events characterised in terms of their proximate cause and coupling factors
  - Data analysed using Impact Vector approach to take account of partial CCFs; scaling to take account of different CCF group sizes
  - Gives α-factors (full uncertainty analysis) and MGL parameters (MLE only); results are pooled in different ways (all components, BWR/PWR, systems)
  - INL data indicates that the incidence of CCF is decreasing.

# Sources of CCF Data (2)

- **International CCF Data Exchange (ICDE)**
  - Database organised by OECD/ participating member countries
  - Data collection campaigns organised for different types of components and includes: centrifugal pumps, diesel generators, motor operated valves, safety and relief valves, non-return valves/ check valves, batteries, switching devices/ circuit breakers, level measurement, main steam isolation valves
  - Contains CCF event data where an ICDE Event is defines as "impairment of two or more components (with respect to performing a specific function) that exists over a relevant time interval and is the direct result of a common cause"
  - The ICDE events are characterised in terms of root cause, coupling factor and shared cause factor
  - ICDE have not carried out a statistical analysis to derive CCF parameters for use in PSAs.

# Sources of CCF Data (3)

- **Generic CCF Data Sources**
  - NUREGs give guidance on CCF modelling in PSA and generic data
  - Data included for a range of different types of pumps and valves, diesel generators, circuit breakers, strainers/ filters, heat exchangers, condensers, batteries/ chargers.
- **National CCF Data collection**
  - CCF data collected and analysed in some countries: France, Germany, Finland
  - Some countries use as Bayesian updating process with generic data as the prior updated with national/ plant specific data.
- **Availability of data for AGR PSAs**
  - Data available from INL/ICDE/ generic sources for major components (pumps, valves, etc.)
  - Many unique components that are risk-significant where data is not available.

# Applicability of Generic CCF Data (1)

- **Needs to consider a number of factors including:**
  - Suitability of the generic data
  - Factors affecting the degree of dependency.
- **Suitability of the generic data**
  - Completeness of the database
  - Definition of component boundaries
  - Design differences
  - Component CCF modes
  - Pooling of component types
  - Testing regime
  - Assumptions made in the analysis of the CCF data.

# Applicability of Generic CCF Data (2)

- **Factors affecting the degree of dependency**
  - Likelihood of occurrence of root causes/ proximate causes
    - Design/ construction/ installation/ manufacturing inadequacy
    - Operational/ human error
    - Internal environmental causes
    - External environmental causes.
  - Magnitude of CCF coupling factors
    - Hardware quality based coupling factors
    - Design based coupling factors
    - Maintenance coupling factors
    - Operational coupling factors.

# Applicability of Generic CCF Data - Conclusions

- The INL and ICDE databases provide information that can be used for the quantification of PSAs
- The databases are expected to contain all the significant CCF events that would influence the magnitude of the CCF parameters
- It would be reasonable to assume that the root causes/ proximate causes and coupling factors would be broadly similar for nuclear power plants
- No overriding reason why generic data should not be used in the quantification of a PSA
- Care needs to be taken in the definition of the component boundaries and the pooling of components.