Update of the Common Cause Failure Reliability Data Book

Mattias Håkansson[a] and Gunnar Johanson[b]

[a] Risk Pilot AB, Stockholm, Sweden, *Mattias.hakansson@riskpilot.se*

[b] AFRY AB, Stockholm, Sweden, *Gunnar.johanson@afry.com*

Abstract: Common Cause Failure (CCF) events can significantly impact the availability of safety systems of nuclear power plants. In 2016, the first version of the CCF data book (C-book) was published by the Nordic PSA Group (NPSAG). The C-book provides the Nordic PSA practitioners with CCF reliability data for the dependency analysis that is considered in the compulsory, probabilistic safety assessment (PSA) of nuclear power plants. The C-Book should be considered as an important step in the continuous effort to collect and analyse data on CCF of safety components at NPPs, and to improve quality of data in PSA. In 2021, a second version of the C-book was published by NPSAG, and it considers that the collected data has doubled since the first version. This second version of the C-book presents the methodology for quantification of CCF rates, CCF probabilities and alpha factors for k-out-of-n failures. Generic CCF reliability data tables, supported by sensitivity cases, general trends, and comparisons with other CCF data sources. The C-book includes a comprehensive procedure including all steps from CCF event input data, via event impact vectors, to final CCF parameters, which has been developed and validated. The procedure provides a common basis for methods and guidelines for data classification and assessment, and by establishing a format to allow data to be shared for quantifications and provide interpretation of raw data for exchange and use in quantification models. The sensitivity cases address important aspects of data subsets, especially by separating design and human error related events. In conclusion, the updated CCF data book, which contains generic and plant specific CCF rates, probabilities, and alpha factors, will improve the quality of data for the dependency analysis in the PSA of nuclear power plants.

1. INTRODUCTION

Common Cause Failure (CCF) events can significantly impact the availability of safety systems of nuclear power plants. In recognition of this, CCF data are systematically being collected and analysed in several countries under the framework of the ICDE (International Common cause failure Data Exchange) project, [1]. The data collection and qualitative analysis results in qualitative CCF information that can be used for the assessment of the effectiveness of defences against CCF events and of the importance of CCF events in the PSA framework.

A comprehensive procedure including all steps from CCF event input data as provided in ICDE, via event impact vectors, to final CCF parameters has been developed and validated within a Nordic/German working group on common cause failure analysis, [2].

In 2016, the first version of the CCF data book (C-book) was published by the Nordic PSA Group (NPSAG) [3]. The C-book provides the Nordic PSA practitioners with CCF reliability data for the dependency analysis that is considered in the compulsory, probabilistic safety assessment (PSA) of nuclear power plants. The C-Book should be considered as an important step in the continuous effort to collect and analyse data on CCF of safety components at NPPs, and to improve quality of data in PSA. In 2021, a second version of the C-book [4] was published by NPSAG, and it considers that the collected data has doubled since the first version.

1.1 Challenges when Quantifying CCF

To achieve quality assurance of the data input to the analyses in a transparent way, several challenges exist and must be considered. For the quantitative analysis, component groups and events need to be assessed, divided, and grouped to assure that the quantification is made on a homogenous and applicable set of data. The main challenges to consider are summarized in Table 1.

Table 1: Challenges when Quantifying CCF.

Challenge	Description
Event set	Answer whether the completeness of CCF event set covers the available national CCF experience.
Observation time	Answer whether the completeness of group observation data correctly estimates the group years in relation to the reported event data set.
Applicability of data	Decide via individual specific assessment whether to take events and groups into account or not in the CCF reliability data to assure a homogenous set of data.
Event interpretation with respect to CCF combinations	Independent of the used quantification model, probabilities for different CCF combinations must be calculated through transformation of component impairment vector to event impact vector.
Parameter estimation and transformation of rates	Determine method for estimating failure rates (frequencies), when failure or degradation event data is available from one or more units (components, systems or plants). For further treatment (to obtain other parameters such as probabilities, alpha factors, etc.) consideration of test policy, test interval, success criterion for the target plant and system must be made.

1.2 Objective and Scope

The overall objective was to create a CCF data book similar to the Nordic T-book (reliability data book for independent failures). The amount of available CCF data (from the ICDE project) allows estimating and presenting k-out-of-n specific CCF rates as presented in the component reports. The CCF failure rates and their percentiles forms the resulting data of the CCF data book.

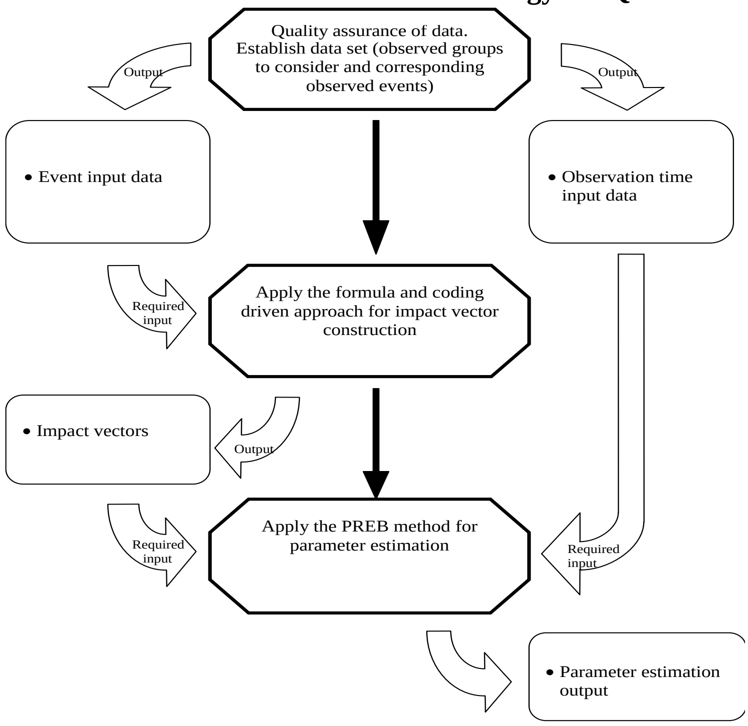
The C-book includes CCF reliability data for Centrifugal Pumps, Emergency Diesel Generators, Check Valves, Motor Operated Valves, Level measurements, Breakers, and Batteries. The C-book presents essentially CCF rates. To complement the data, reliability data for CCF probabilities and alpha factors are provided through a basis for transformation of rates into probabilities or alpha factors. In addition, it includes sensitivity cases that address important aspects of data subsets, especially by separating design and human error related events.

2. QUANTIFICATION METHODOLOGY

2.1 Introduction

The methodology for quantification is the procedure described in SSM report 2009:07 [2]. The overall procedure is illustrated in Figure 1.

Figure 1: Overall Procedure of the Methodology for Quantification.



A comprehensive procedure including all steps from CCF event input data, via event impact vectors, to final CCF parameters has been developed and validated. The main objective was to establish a common procedure and model of quantification of CCF events. This was done by:

- Providing a common basis for methods and guidelines for data classification and assessment.
- Establishing format to allow data to be shared for quantifications and to provide interpretation of raw data for exchange and use in quantification models.

In the following sections are the steps described briefly and for further details see [2].

2.2 Quality Assurance of Data

The quality assurance of the input to any data analysis is of great importance. The following gives guidance on issues for review. The data needs to be evaluated concerning internal symmetry and homogeneity. In general, CCF events of a Common Cause Component Group (CCCG) belonging to a certain component type are supposed to be fully applicable to other component groups of this component type, i.e., internal symmetry. The data needs to be screened concerning homogeneity and once it is defined what groups at different plants that are to be included in the assessment (or rather how the data should be split up), the evaluation of events to be included can be performed. It cannot be stressed too strongly, that the quality of input data is a critical issue for any automatic treatment of this input data. It must be assured, that the input data is of high quality.

The quality procedures of CCF data generation follows a QA review form for each event to ensure this. The review process within the NAFCS project follows this form. The input data to the analyses represents homogenous subsets of data reported to the ICDE.

2.3 Impact Vector Construction Method

The formula and coding driven (FCD) impact vector construction method has been developed using various approaches to select a suitable approach taking into account existing cases for diesels and pumps. For the agreed approach, there have been two basic requirements, i.e., it shall be defendable, and it shall result in realistic modelling. The formula and coding driven approach is a systematic approach to interpret the component impairment vector into an event impact vector.

- **Component Impairment vector** expresses the degradation of the individual components in a CCF group. The degradation scale ranges from; complete – degraded – incipient – working.
- **Event impact vector** expresses the conditional (on symptoms) failure probability, given an observed CCF, that different numbers of components would fail if an actual demand should occur during the presence of the CCF impact.

The approach can be applied for quantitative analysis of CCF events, and it fulfils the above basic requirements. It can be properly described with the following arguments:

- It takes the most conservative approach possible given the data when stronger impairment is seen.
- It takes a less conservative approach when weak impairment as dominant observation is seen, because this is, what experts have been observed to do.
- On an average, the approach is still conservative in comparison with expert assessments.

The model is summarized in Table 2. The High Bound approach is adopted for cases with indication of stronger impairment or no clear pattern. Otherwise, the less conservative approach is used to represent scenario based expert judgments for cases with indication of weak impairment as dominant observation.

Table 2: Applied Approach for Impact Vector Construction.

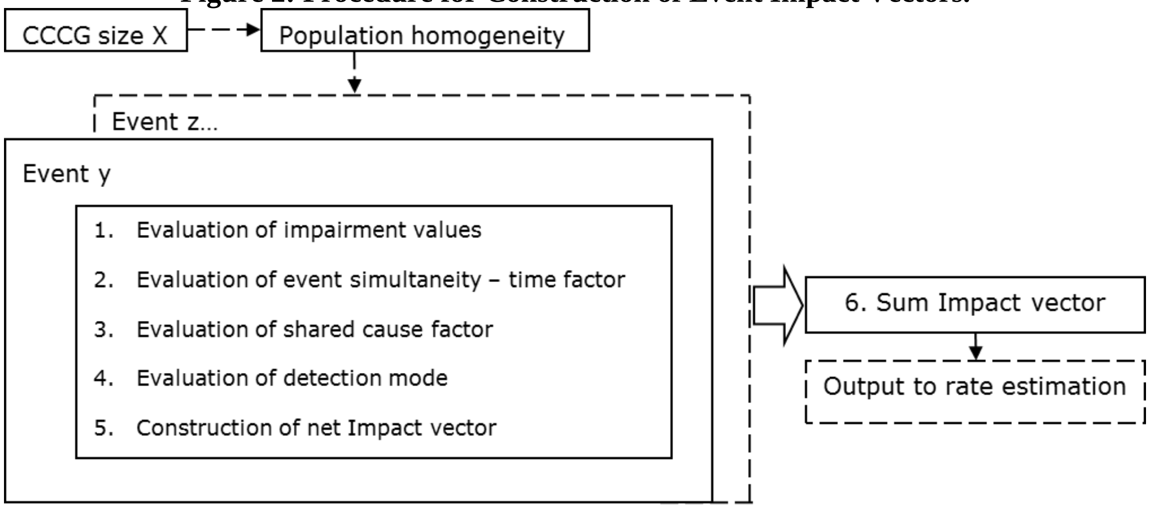
	More than one C	**At most one C**
More than one D, I	High Bound applied	Scenario based approach
At most one D, I	High Bound applied	High Bound applied

2.3.1 Construction of Impact Vectors

The general flow in the impact vector construction is presented in Figure 2. Steps 1-4 are concerned with the basic evaluation of CCF parameters for a defined component group, failure mode and observation period. In practice, the data of identical or closely similar CCF groups of the same size are often pooled together. In a general case, the analysis may include CCCGs of varying size from different systems and/or plants. Steps 5-6 concern the actual impact vector construction and the integration of the impact vectors for the estimation of reliability and dependence parameters.

The impact vector presentation is related to failure modes in a way similar to component and CCF models. Different functional failure modes each require a specific way of treatment. Especially, latent and monitored failure modes should be kept strictly separated because they differ significantly both regarding qualitative analysis and quantitative treatment.

Figure 2: Procedure for Construction of Event Impact Vectors.



2.3.2 Merging of Impact Vectors

Before any of the impact vectors are used, it must be concluded which component groups and which events to be grouped for the purpose of quantification. It must be assured that the quantification is made on a homogenous set of data. This means that the data set should be divided based on homogeneity issues, but only to such extent that the data set do not become too scarce. Potential characteristics for grouping are group size, failure modes (e.g., failure to start or failure to run), operating modes (e.g., operational, or standby components), and system types (e.g., clean or raw water centrifugal pumps).

2.4 Parameter estimation

Based on the outcome of the impact vector construction the CCF parameter can be estimated. The estimation procedure used here is “direct estimation” of the failure rate. An algorithm for Empirical Bayesian parameter estimation is applied. The Algorithm has been shown to be an applicable method for CCF parameter estimation application. The algorithm has been applied to derive the uncertainty bounds with parameters representing quantitative uncertainties.

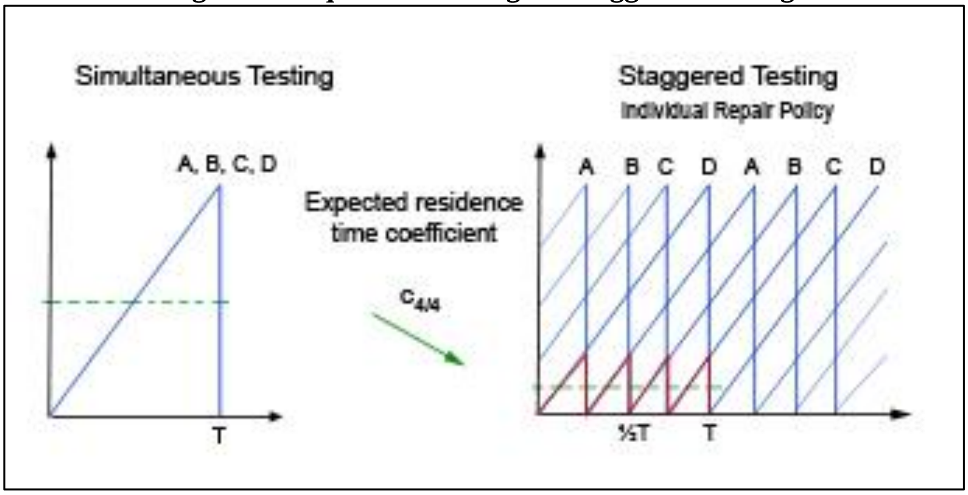
The PREB (Parametric Robust Empirical Bayes) estimation method is designed for estimating failure rates (frequencies), initiating event rates and failure probabilities per demand (opportunity), when failure or degradation event data is available from one or more units (components, systems, or plants). The output of the estimation is k out of n specific CCF rates. The CCF rates, *Reg(k|n)*, represents the basic CCF event, *“failing exactly specific k components i, j… out of n similar components”*.

2.5 Transformation of rates into probabilities and alpha factors

For further treatment of the quantification results (to obtain other parameters such as probabilities, alpha factors, etc.) consideration of test policy, test interval, success criterion for the target plant and system must be made.
The estimated CCF rates can be transformed into probabilities. The probabilities *Peg(k|n)*, representing the basic CCF event; “*failing exactly specific k components i, j… out of n similar components*”. For standby safety components, tested with test interval T, the probabilities are:

$Peg(k|n) = \lambda_{(s)\ k/n}\ [c_{k/n}T/2] = Reg(k|n) \times [c_{k/n}T/2]$, where $c_{k/n}$ is the expected residence time coefficient and Reg(k|n) or $\lambda_{(s)\ k/n}$ is the estimated CCF rate. The expected residence time coefficients $c_{k/n}$ are based on the expected residence times of a CCF in a system [5. The coefficients $c_{k/n}$ depend on k, n, test policy, repair policy and the system success criterion. The impact of the difference between simultaneous and staggered testing on the expected residence time coefficient is illustrated in Figure 3.

Figure 3: Sequential Testing vs. Staggered Testing.



The alpha factors represent the fraction of multiple failure events of order k with respect to the total number of failure events. To obtain alpha factors that consider test and repair policies, different test intervals and success criteria, a different formalism is required. For standby components with non-staggered testing scheme, the alpha factors are approximated with Eq. 1:

$$\alpha(m|n) = \frac{\binom{n}{m}Q(m|n)}{\sum_{k=1}^{n}\binom{n}{k}Q(k|n)} = \frac{\binom{n}{m}Peg(m|n)}{\sum_{k=1}^{n}\binom{n}{k}Peg(k|n)} \quad (1)$$

If the testing model is staggered, this must be considered either by modifying the Common Cause Basic Event probability, Q(m|n), as is done here by choice of $c_{k/n}$, or otherwise by modifying the way the alpha factors are calculated.

It is important to note that when deriving the alpha factors, is either the generic single failure rate or the plant-specific single failure rate used as denominator. Thus, the use of alpha factors is dependent on the single failure rate and the CCF rates.

3. GENERIC CCF RELIABILITY DATA

The scope of the generic CCF reliability data tables (include CCF rates, probabilities for a given test interval, and alpha factors) in the C-book is presented in Table 3. The components diesels, centrifugal pumps, check valves, motor operated valves and level measurements include data from the Nordic countries (Sweden and Finland) and Germany. Due to the scarcity of data for the component's batteries and breakers, the Nordic and German data is supplemented with data from other ICDE member countries. As seen in the table, different conditions of grouping have been used to create as homogenous sets as possible. For instance, the centrifugal pumps are divided depending on system type and operational mode for different group sizes and failure modes. For level measurements and breakers, the formulas for mapping down in [6] have been applied for mapping down event impact vectors from group size 6 to size 4. An example of the data tables in the C-book is presented in Table 4.

Table 3: Scope of generic CCF reliability tables in the C-book

Component type	Group Size	Failure mode*	System type
Diesels	2, 4	FS, FR	-
Centrifugal pumps	2, 4	FR	Operational/Intermittent systems

* The abbreviations are: FS=Failure to Start, FR=Failure to Run, FC= Failure to Close, FF=Failure to Function, FCP=Failure to Change Position, RC&IL= Failure to remain closed and internal leakage.

Component type	Group Size	Failure mode*	System type
	2, 3, 4	FS	All system types
	2, 3, 4	FS&FR	All system types with FS and standby systems with FR
Check valves	2, 3, 4	FC&RC/IL	-
Motor operated valves	2, 4	FO, FC	-
Level measurements	Pooled 4 & 4*†	FF	-
Batteries	2, 4	FS&FR	-
Breakers	Pooled 4 & 4*	FCP	-

Table 4: Emergency Diesel Generators, CCF Rates, Failure Mode: Failure to Start (FS), Single Failure Rate (T-Book 8: 7.3.2)

Group size	C-book ID*	Mean	5th%	50th%	95th%	Dist. Par. 1	Dist. Par. 2
N	Reg(1|N)	1,31E-05	5,00E-07	8,62E-06	3,00E-05	-	-
2	Reg(2|2)	1,32E-06	8,77E-12	1,94E-07	6,52E-06	2,31E-01	5,70E-06
4	Reg(2|4)	1,27E-07	2,97E-15	6,36E-09	6,89E-07	1,58E-01	8,00E-07
	Reg(3|4)	3,07E-08	2,33E-11	1,06E-08	1,30E-07	3,82E-01	8,04E-08
	Reg(4|4)	1,33E-07	1,33E-11	3,19E-08	6,08E-07	2,98E-01	4,45E-07

*Reg(k|n) represents "*failing exactly specific k components i, j... out of n similar components*".

4. DATA TRENDS AND SENSITIVITY ANALYSIS

4.1 Component-Specific Data Trends

Version 2 of the C-book include additional observation times and events. This has resulted in various changes of the CCF reliability parameters, especially when assessing the homogeneity in the new data sets.

For emergency diesel generators (EDGs), version 2 of the C-book no longer includes CCF parameters for group size 3, only present data for group size 2 and 4. The 4-out-of-4 failure rates have decreased about 20%.

For centrifugal pumps, major changes have been introduced. The first version quantification grouped the data based on system type (i.e., clean or raw water system). In version 2 the grouping is based on the operating modes (i.e., standby system or operational/intermittent system). Consequently, no data trends could be compared.

For motor operated valves (MOVs), most of the CCF rates for the k-out-of-n failures are reduced by a factor of 2, but for failure to close the 2-out-of-4 failures rates increased by 50% and for failure to open the 4-ot-of-4 failures increased by 25%.

For check valves, the rates are significantly reduced by 50-70%. No changes in the grouping of events were needed.

† Mapped down from group size 6

The results for level measurements only include the case with pooled group sizes (size 4 and 6) where events with group size 6 have been mapped down to size 4. This interpretation of the data resulted in the most reliable results in the quantification. The 4-out-of-4 failures remain almost the same, but the failure combination of 2 and 3-out-of-4 failures were reduced by 30%.

For batteries, the rates are reduced by 30-45%. The quantification still use data from all countries in the ICDE project. The reason is the low event impact seen among the Swedish/Finnish/German events.

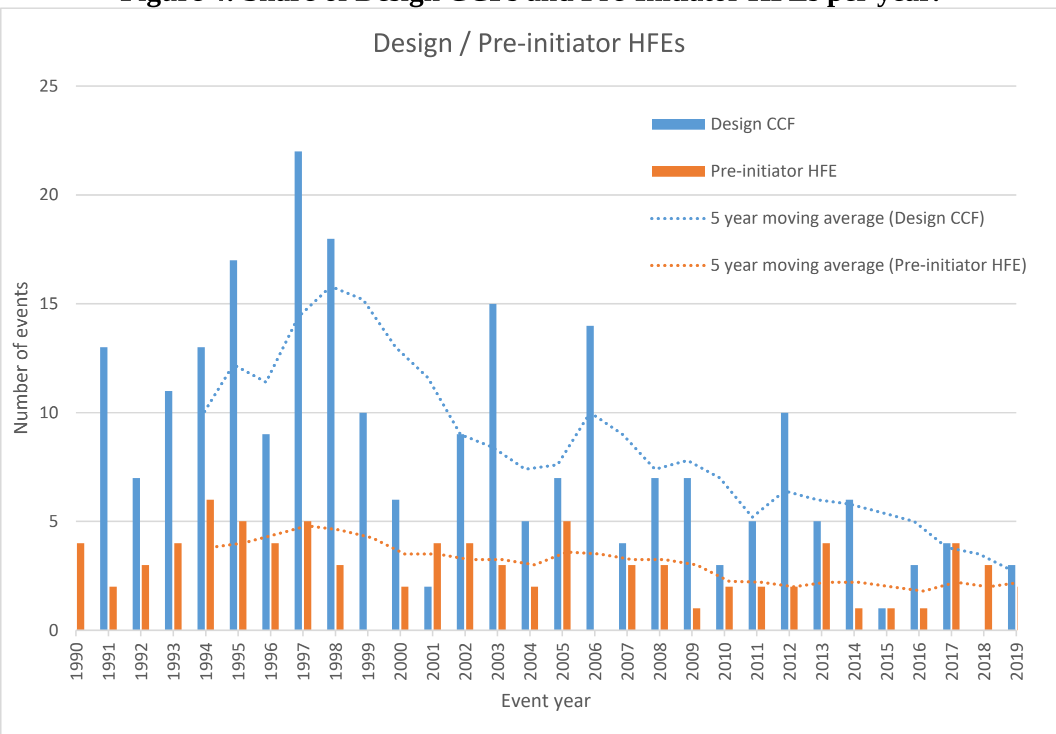
For breakers, the second version only considers data from Sweden, Finland, and Germany, whereas the first version used data from several other countries. The results for breakers only include the case with pooled group sizes (size 4 and 6) where events with group size 6 have been mapped down to size 4. This interpretation of the data gave the most reliable results in the quantification. The 4-out-of-4 failures remain almost the same (increased by about 10%), but the 2-out-of-4 failures are reduced by 50% and the 3-out-of-4 are increased by 50%.

4.2 Share of Design and Pre-Initiator HFEs

The CCF events can be classified as either design related CCFs or as potential pre-initiator human failure events (HFEs). An HFE is an event caused by a human action or procedures linked with an organizational coupling factor. The criteria applied to classify an event as a pre-initiator HFE are events with coupling factors “Operation” combined with event cause “Human actions, plant staff (H), Maintenance (M) and Procedure inadequacy (P)”.

Figure 4 presents the share of design CCFs and pre-initiator HFEs per year and their 5-year moving averages. Here we can see that the design CCFs are significantly decreasing, but the pre-initiator HFEs remains almost constant.

Figure 4: Share of Design CCFs and Pre-Initiator HFEs per year.



As a sensitivity analysis, the impact vector sums and parameter estimations (rates) were analyzed for the emergency diesel generators (EDGs), by splitting the data into design CCFs and pre-initiator HFEs. One interesting question that arise from this sensitivity case concern how the pre-initiator HFE values compares to the HFE values in the corresponding HRA analysis, in cases where pre-initiator HFEs are modelled separately, see Table 5. This would be interesting to study further but requires benchmarking against PSA-studies and evaluation of the HFE dependency values from, e.g., THERP‡ or ASEP§.

Table 5: Pre-initiator HFE Probability Values, Peg(4|4).

Failure mode	Normal case	Pre-initiator HFE	Design CCF	Design CCF+HFE	THERP/ASEP
Failure to run	5,93E-04	3,50E-04	4,00E-04	7,50E-04	1,00E-05
Failure to start	4,46E-05	2,83E-05	3,17E-05	6,00E-05	1,00E-05

5. APPLICATION OF GENERIC AND PLANT-SPECIFIC DATA

Application of the C-book CCF direct estimates is always a correct use of the presented CCF estimates. The reason alfa factor is presented is because the commonly used software for PSA is “Risk Spectrum”, which requires alfa factors as input for its built-in function. The C-book provides appropriate input for this. However, when using plant specific data together with generic alfa-factors the analyst must be cautious to avoid underestimation of the CCF shock rate, i.e., events affecting all components (e.g., complete CCFs).

Generic/Generic: Application of the generic C-book CCF alfa factor estimates requires that generic T-book data is used. The generic CCF alfa factors presented in the C-book is a correct application under the condition that the generic T-book data as given is applied. This is necessary since the alfa factor is derived from the direct estimate using the single failure rate.

Specific/Specific: Application of plant specific T-book data with plant specific alfa factors estimates requires that the computation tools, which is included the proprietary part of the C-book is used.

Specific/Generic: Application of plant specific single failure data with generic alfa factors estimates should be avoided since the CCF shock rate can be seriously underestimated. The alfa factor model assumes a direct correlation between the CCF shock rate and the single failure rate, and this is not the case.

The built-in function to create CCF fault trees in Risk Spectrum should be possible to use without alpha factors. It would be more desirable to only use failure rates combined with test and repair policies as basic parameters. The effect of individual repair policy should be included in the CCF-logic.

In the case of application of generic CCF data it is important to use direct estimates of the CCF rate. This since the single failure rate applied to derive alfa factor can vary and is usually not known. The single failure rate can also vary completely independent of the CCF rate, i.e., the HFE portion of the CCF rate is independent of the single failure rate.

6. COMPARISON OF CCF PARAMETER ESTIMATES

There exist a few other data sources for CCF parameters. In the US, NUREG parameter estimates (NUREG 2015 update [7]) are used, and in Germany, the “Leitfaden” by BfS (Leitfaden 2015 update [8]) is available.

In [7], the CCF parameters are presented with only alpha factors. In [8], the CCF parameters are presented with only probabilities. Both probabilities and alpha factors are dependent on the single failure rate and/or system parameters (such as test interval and test policy). Consequently, it is very difficult to compare the CCF parameter values in the available data sources.

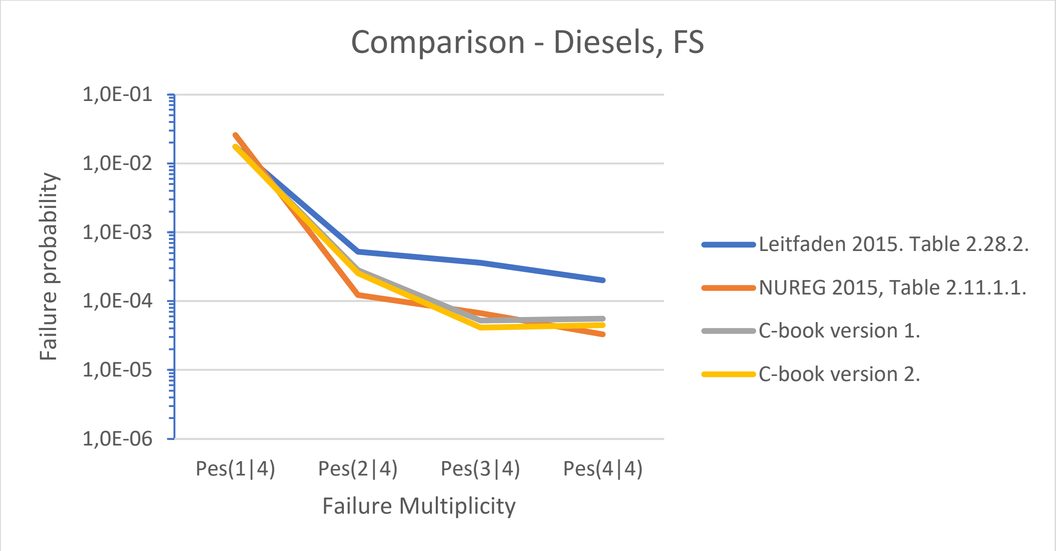
‡ Technique for Human Error Rate Prediction (THERP)

§ Accident Sequence Evaluation Program (ASEP)

A comparison case for diesels is presented with some assumptions. The test interval is assumed to be four weeks (672 hours) with sequential testing. The single failure rate is the generic failure rate for the failure mode failure to start from the T-book [9]. To perform the comparison, this single failure rate is used to transform the alpha factors in [7] to probabilities. Then, the C-book probability parameters are converted from the entity "Peg[**]" to "Pes[††]" to reflect the same entity given in [8].

The result of the comparison is given in Figure 5. The updated C-book parameters have a slightly lower failure probability compared to the first version. The updated parameters also lies in between the other two data sources for Pes(2|4) and Pes(4|4), but are slightly lower than the other two for Pes(3|4). The results are within one order of magnitude.

Figure 5: Comparison of Data Sources – Diesels – Failure to Start.



7. CONCLUSION

The C-book presents CCF rates for k out of n failures. The reliability data is complemented with CCF probabilities and alpha factors through a basis for transformation of rates into probabilities and/or alpha factors. The quantification methodology comprises of a comprehensive procedure including all steps from CCF event input data, via event impact vectors, to final CCF parameters, which has been developed and validated. The basis for transformation of the quantification results (to obtain other parameters such as probabilities, alpha factors, etc.) allows consideration of test policy, repair policy, test interval, success criterion for the target plant and system.

The development of a CCF data book, which contains generic and plant specific CCF rates, probabilities and alpha factors, will improve the quality of data for the dependency analysis in the PSA for nuclear power plants.

Acknowledgements

This research was supported by the Nordic PSA Group, who provided insight and expertise that greatly assisted the research.

[**] Peg(k|n) = Probability for just the specific k components i, j,… out of n components fail, while the other n-k survive.

[††] Pes(k|n) = P{Exactly some k out of n components fail, while the other n-k survive}, which denotes failure Probability of an Exclusive groups of components Summed over given multiplicity.

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