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Developing Generic Prior Distributions for Common Cause Failure Alpha Factors and Causal Alpha Factors

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ABSTRACT

This report is a revision of the original report, INL/LTD-17-43723. Distribution of the original report was to the Nuclear Regulatory Commission (NRC) only, and the report was not made available to the public. The original report was revised as this report for public distribution.

This report presents the latest update of generic prior distributions for common cause failure (CCF) alpha factors, as well as the development of new generic prior distributions for CCF causal alpha factors. The history of CCF treatment and parameter estimations is reviewed. The existing process for developing generic prior distributions is reviewed and used to develop new priors for CCF alpha factors and causal alpha factors. For causal alpha factors, different priors are developed for the five different CCF cause groups: Component (GC), Design (GD), Environment (GE), Human (GH), and Other (GO). These generic prior distributions could be used in the Standardized Plant Analysis Risk (SPAR) models for CCF parameter estimation. The issues and preliminary thoughts regarding prior distribution development are documented. Potential future work is then proposed for improving the process of developing priors.

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ACRONYMS

AFM	alpha factor model
BFR	binomial failure rate
BPM	basic parameter model
CAFM	causal alpha factor model
CCBE	common cause basic event
CCCG	common cause component group
CC	common cause
CCF	common cause failure
ECA	event and condition assessment
EDG	emergency diesel generator
EPIX	equipment performance and information exchange
FTR	fail to run
FTS	fail to start
INL	Idaho National Laboratory
LER	licensee event report
MLE	maximum likelihood estimate
MM	method of moments
NPRDS	nuclear plant reliability data system
NRC	Nuclear Regulatory Commission
NUREG	Nuclear Regulatory Commission Regulation
PAFM	partial alpha factor model
PRA	probabilistic risk assessment
PWROG	pressurized water reactor owner group
SAPHIRE	Systems Analysis Programs for Hands on Integrated Reliability Evaluations
SCSS	sequence coding and search system
SPAR	Standardized Plant Analysis Risk
SQL	structured query language
U.S.	United States
WUG	Westinghouse user group

Developing Generic Prior Distributions for Common Cause Failure Alpha Factors and Causal Alpha Factors

1. INTRODUCTION

Common cause failures (CCFs) have been recognized as significant risk contributors, ever since the early launching of probabilistic risk assessments (PRAs) for commercial nuclear power plants (NPPs). Since the 1980s, a series of U.S. Nuclear Regulatory Commission (NRC) reports have been published to provide guidelines for performing CCF modeling using PRA and performing CCF event data analysis. A CCF database system was developed and is maintained by the NRC and Idaho National Laboratory (INL) for the U.S. commercial nuclear power industry. The CCF database system includes a CCF database that stores coded CCF events, and a CCF software that uses an impact vector and mapping method to estimate CCF parameters for the events stored in the CCF database. Generic prior distributions (or simply "prior distributions" or "priors") were developed and included in the CCF software for CCF Alpha Factor Model (AFM) parameter estimations. However, while the CCF database has been maintained ever since its development in late 1990s, and the CCF parameter estimations have been updated and published on a yearly basis, the process of developing prior distributions has not been published, and the prior distributions themselves have not been updated since the early 2000s. This report intends to uncover and review the existing process of developing prior distributions for CCF parameters, use recent data to update the prior distributions for CCF alpha factors, develop the prior distributions for causal alpha factors for use in the Causal Alpha Factor Model (CAFM), and document any issues and thoughts that arise regarding the CCF priors during this study.

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1.1 History of CCF Treatment and Parameter Estimations

First, let us review the history of CCF treatment and parameter estimations in PRA. The following is a summary of the key reports on the development of CCF modeling guidelines and the NRC CCF database system.

NUREG/CR-4780 (also EPRI NP-5613), *Procedures for Treating Common Cause Failures in Safety and Reliability Studies, Volumes 1 and 2* [1,2], was published in January 1988 to present the framework for including CCFs in risk and reliability evaluations. It provides procedures for performing and documenting CCF analysis via a practical, systematic approach. The framework includes the following four major stages: (1) system logic model development, (2) identification of common cause component groups, (3) common cause modeling and data analysis, and (4) system quantification and the interpretation of results. While it is not the purpose of the report "to advance or promote a particular method or technique," it does introduce the concept of impact vector for CCF event classification and representation, along with the mapping method that adjusts the original impact vectors to account for common cause group size differences in common cause parameter estimation. Appendix D of the report provides a detailed discussion on the background and justification of using the mapping method for parameter estimation. Although some doubts existed as regards the mapping method, especially the mapping up technique (when the component group size in the original system is smaller than in the system being analyzed) [3], use of the impact vector and mapping method was adopted in subsequent NRC CCF studies, becoming the state-of-the-practice in CCF parameter estimation.

NUREG/CR-6268, *Common-Cause Failure Database and Analysis System* (Volumes 1–4) [4,5,6,7], published in June 1998, extended previous CCF studies by introducing a method of collecting industry failure data, identifying and characterizing CCF events, and estimating CCF parameters and uncertainties using a computer software. The report relied on two data sources for CCF event identification: the

Nuclear Plant Reliability Data System (NPRDS), which contains component failure information, and the Sequence Coding and Search System (SCSS), which contains Licensee Event Reports (LERs). Data from the years 1980–1995 were analyzed. The report describes a process by which analysts can consistently code CCF events. A CCF database system was developed, with a searchable CCF database for retrieving the CCF events of interest, and a CCF software for estimating CCF parameters. The CCF software stores CCF events and independent failure counts, and it estimates CCF parameters for the Alpha Factor and Multiple Greek Letter Models, based on the CCF event impact vector and mapping method.

NUREG/CR-5497, *Common-Cause Failure Parameter Estimations* [8], published in October 1998, documented the quantitative results of the CCF data collection effort described in Volumes 1–4 of NUREG/CR-6268 [4,5,6,7], as well as the insights from the CCF data analysis. It contains the CCF parameter estimates for most of the risk-important safety systems and components in commercial NPPs.

NUREG/CR-5485, *Guidelines on Modeling Common-Cause Failures in Probabilistic Risk Assessment* [9], published in November 1998, provided a set of guidelines to help PRA analysts model CCF events in commercial NPPs. The report combines the key aspects of the procedural guidelines presented in previous NRC CCF reports, provides additional insights from the CCF applications, and describes the CCF software capabilities and how to apply the CCF database information to PRA studies.

NUREG/CR-6268, Revision 1, *Common-Cause Failure Database and Analysis System, Event Data Collection, Classification, and Coding* [10], published in September 2007, updated the previous version's guidance on collecting, classifying, and coding CCF events. Three data sources are used for selecting equipment failure reports to be reviewed for CCF event identification: (1) the NPRDS, which contains component failure information from the years 1980–1996; (2) the Equipment Performance and Information Exchange (EPIX), which contains component failure information from the years since 1997; and (3) LER Search, which contains LERs. The updated CCF data analysis includes the following steps: collection of source data, identification of CCF events, coding of CCF events, database quality assurance, data analysis, and parameter estimation. The CCF event information and the independent event count are entered into the CCF database along with the quality assurance verification. The CCF software system uses the impact vector and mapping method to estimate CCF parameters. The impact vector method used in the process is based on the event's physical characteristics, including component degradation factor, timing factor, and shared cause factor. The software enables analysts to modify generic event impact factors for plant-specific applications, including using the mapping method to account for differences in common cause component group (CCCG) size.

A Series of NRC CCF Parameter Estimation Update Reports, published on the NRC website (http://nrcoe.inl.gov/ParamEstSpar/) starting in 2003, updated the CCF parameter estimations in NUREG/CR-5497 [8] on a yearly basis. Below is a list of these update reports, including the date range of the data used for the update.

CCF Parameter Estimation 2003 Update [11] reflects the version of the CCF database that contains data from 1980 to 2003. However, it uses a starting date of 1/1/1985 so as to avoid the large number of CCF events in the 1980–1984 period, as the trend decreases significantly between 1980 and 1985. The analysis also found that the previously recommended maximum value of 0.85 for the mapping up factor, rho, was very conservative. A recommended maximum value of 0.50 for rho was used in the 2003 Update.

CCF Parameter Estimation 2005 Update [12] reflects the version of the CCF database that contains data from 1980 to 2005. It uses a starting date of 1/1/1991 so as to avoid the large number of CCF events in the 1980–1990 period, as the trend decreases significantly from 1980 to 1991.

CCF Parameter Estimation 2007 Update [13] reflects the version of the CCF database that contains data from 1980 to 2007. It uses a starting date of 1/1/1991 so as to avoid the large number of CCF events in the 1980–1990 period, as the trend decreases significantly from 1980 to 1991.

CCF Parameter Estimation 2009 Update [14] reflects the version of the CCF database that contains data from 1997 to 2009. The starting date is 1/1/1997. The large number of CCF events in the 1980–1996 period are excluded from the analysis (and subsequent analyses), as the trend decreases significantly from 1980 to 1997.

CCF Parameter Estimation 2010 Update [15] reflects the version of the CCF database that contains data from 1997 to 2010. The starting date is 1/1/1997.

CCF Parameter Estimation 2012 Update [16] reflects the version of the CCF database that contains data from 1997 to 2012. The starting date is 1/1/1997.

CCF Parameter Estimation 2015 Update [17] reflects the CCF data contained within the CCF database by having executed the query rules in the folder *SPAR Rules 2015A* on October 26, 2016. It contains data from 1/1/1997 to 12/31/2015.

It is worthwhile to note that, during the development and maintenance of the CCF database system, the whole process of data classification, loading, and parameter estimation underwent several levels of quality control. For example, all events are reviewed by two data analysts to ensure they are classified as CCF events and coded correctly. Then, a PRA analyst reviews the CCF events and results for consistency and compares them with PRA experience. A final review is performed by independent CCF experts (external to INL) who maintain the CCF database system for NRC. The independent review is usually conducted by CCF experts from industry organizations such as the Pressurized Water Reactor Owner Group (PWROG), formerly the Westinghouse User Group (WUG).

Nonetheless, CCF event identification and characterization remain subject to engineering judgement, as analysts could interpret the events in different ways and make various assumptions about the mission information, based on both the event reports and the physical and operational descriptions of the NPPs involved. The uncertainty caused by the data, as well as other uncertainties such as statistical uncertainty and modeling uncertainty, should be identified and properly addressed in CCF studies and applications.

1.2 Prior Distributions in CCF Parameter Estimations

NUREG/CR-5485 [9] discusses the data uncertainty inherent in developing a statistical database using CCF event reports. To develop an uncertainty distribution of CCF parameters, if one employs the Bayesian estimation procedure, the choice of prior distribution becomes critical. The prior distribution could reflect the analyst's subjective judgement or be based on observed ranges of variation in the parameters. Several different approaches are mentioned in NUREG/CR-5485:

1. Using the hierarchical Bayes method to develop a plant-to-plant variability distribution of various alpha factors (or other CCF model parameters) across all components and failure modes
2. Obtaining the maximum likelihood estimate (MLE) for a given alpha factor, then using a constrained noninformative prior as its uncertainty distribution in order to maximize the uncertainty given a constraint on the mean value; this distribution is usually broader than the corresponding hierarchical Bayes distribution
3. Using information from the constrained noninformative prior distributions to estimate the parameters of Dirichlet distributions for the CCCG. These estimates can be combined to obtain an effective estimate for the Dirichlet distribution parameter.
4. Using the mapping method to develop prior distributions for alpha factors pertaining to each CCCG size so as to utilize all CCF events in the CCF database. In this approach, all CCF events are mapped to a given CCCG size. The MLE for each alpha factor is obtained and fit using a constrained noninformative distribution. The estimates of the Dirichlet distribution parameters are calculated and combined to obtain an effective estimate.

Using this final approach, NUREG/CR-5485 developed the prior distributions used for CCF parameter estimations in NUREG/CR-5497 [8]. However, the details of the process were not documented in the NUREG report or otherwise published. Instead, a white paper entitled "Estimation of Industry-Wide Common-Cause Failure Prior Distributions" [18], dated January 2010, may be the best documentation so far that describes the process of estimating CCF generic prior distributions. This 2010 paper used the CCF data from the years 1995–2005 to develop the prior distributions and create step-by-step instructions.

Apart from the prior distribution results found in the 2010 paper [18] and in NUREG/CR-5485 [9], three other formal prior distributions are documented in the NRC CCF Parameter Estimation Update Reports: 2003 version, as per the 2003 update [11]; 2005 version, as per the 2005 update [12]; and 2007 version, as per the 2007 and subsequent updates [13–17]. Table 1 shows the date range of the data, along with the mean α values in each of these prior distributions. A copy of the prior distributions in NUREG/CR-5485 and the annual update reports is provided in Appendix A, while the prior distributions calculated in the 2010 paper is included in Section 2.

Table 1. Date ranges of the data and some of mean alpha values for existing prior distributions.

Parameter	NUREG/CR-5485 NUREG/CR-5497	2003 CCF Update	2005 CCF Update	2007 CCF Update	2010 Paper	2009/2010/2012/2015 CCF Update
Date Range of Failure Data	1980–1995	1985–2003	1991–2005	1991–2007	1995–2005	1997–2009 /2010/2012/2015
Version of Priors in the Report	NUREG/CR-5485 Version	2003 Version	2005 Version	2007 Version	2010 Version	2007 Version
α2 (CCCG=2)	4.70E-02	3.09E-02	4.06E-02	2.57E-02	1.75E-02	2.57E-02
α3 (CCCG=3)	2.58E-02	7.17E-03	8.71E-03	5.79E-03	5.94E-03	5.79E-03
α4 (CCCG=4)	1.86E-02	3.72E-03	4.64E-03	2.98E-03	3.81E-03	2.98E-03
α5 (CCCG=5)	1.46E-02	6.26E-04	7.25E-04	5.33E-04	9.32E-04	5.33E-04
α6 (CCCG=6)	1.23E-02	6.15E-04	6.86E-04	4.07E-04	5.06E-04	4.07E-04
α7 (CCCG=7)	1.03E-02	1.29E-04	1.52E-04	1.17E-04	2.22E-04	1.17E-04
α8 (CCCG=8)	9.06E-03	1.38E-04	1.46E-04	1.25E-04	1.88E-04	1.25E-04
Version of Priors Used in Parameter Estimate	Unclear	2003 Version	2005 Version	2005 Version	2010 Version	2005 Version

On the other hand, the prior distributions used for CCF parameter estimates are embedded in the CCF software as a hardcopy table. They were compared with the 2003, 2005, and 2007 versions of the prior distributions, revealing that the software/database uses the 2005 version of prior distributions instead of the 2007 version. This means that although the 2007 version of prior distributions was published in the 2007 and subsequent updates [13–17], the 2005 version of prior distributions was actually used in those CCF parameter estimate updates.

1.3 Outline

The remainder of the report is organized as follows. Section 2 reviews the existing process of developing prior distributions, as described in the 2010 paper. Section 3 updates the prior distributions for alpha factors with data from the years 1997–2015. Section 4 develops prior distributions for causal alpha factors via a similar process and using the failure data from the years 1997–2015. Section 5 presents the issues encountered during the prior distribution development, as well as preliminary thoughts on these issues. Section 6 suggests potential future work for improving the CCF prior development process. Appendix A lists the CCF prior distributions as published in NUREG/CR-5485 and previous CCF parameter updates. Appendix B provides an example of how to perform a Bayesian update on CCF parameters using the prior distributions. Appendix C presents a new process that could be used to estimate the mapping up factor ρ. Appendix D provides explicit justification and an explicit general formula for the mapping up method in NUREG/CR-5485 [9].

2. EXISTING PROCESS TO DEVELOP GENERIC PRIOR DISTRIBUTIONS

To develop an uncertainty distribution of CCF parameters, one can employ the Bayesian estimation procedure, which makes the choice of prior distribution critical. The prior distribution could reflect the analyst's subjective judgement or be based on observed ranges of variation in the parameters. As discussed in Section 1.2, NUREG/CR-5485 [9] presents several methods to develop CCF prior distributions. The mapping method was used to develop prior distributions for alpha factors pertaining to each CCCG size, which utilizes all CCF events in the CCF database. In this method, all CCF events are mapped to a given CCCG size. The MLE for each alpha factor is obtained, then fit via a constrained noninformative distribution. The estimates of the Dirichlet distribution parameters for the CCCG are calculated and combined to obtain an effective estimate. However, the details of the process were not documented in NUREG/CR-5485 or other documents. Instead, a white paper titled "Estimation of Industry-Wide Common-Cause Failure Prior Distributions" [18], dated January 2010, may be the best documentation so far that describes the existing process of estimating CCF generic prior distributions. The 2010 white paper provides step-by-step instructions for developing a CCF prior distribution using an industry-wide dataset:

Step 1. For each CCCG size, tabulate the number of CCF events and complete CCF events. A complete CCF is defined as a CCF in which all redundant components are failed simultaneously as a direct result of a shared cause (i.e., the component degradation value equals 1.0 for all components and both the timing factor and the shared cause factor are equal to 1.0 .

Step 2. Calculate the n_k's for each group size (2–16), using all partial (i.e., incomplete) CCF events. This involves mapping up and mapping down. A partial CCF is a CCF with at least one of the CCF character parameters (component degradation value, timing factor, and shared cause factor) not being equal to 1.0).

Step 3. Using the information obtained in Step 1, perform a binomial regression to obtain the probability of CCF events in a given group size.

Step 4. Using the results from Step 3, obtain the estimated number of complete CCF events. Add this number to the final n_k for each group size. For example, for group size 2, add the number to n_2; for group size 4, add it to n_4.

Step 5. Using the final n_k values, estimate the mean value alpha factors for each group size.

Step 6. Using these final n_i values, estimate the beta prior distributions for each group size. The parameters of the beta distribution are α and β. The beta distribution is denoted by Beta(α, β). A computer code, CalcPrior, was developed by INL to estimate the distributions via a procedure to calculate Dirichlet distribution parameters with noninformative prior distributions.

Step 7. As a check, calculate the mean of each prior distribution and compare them with the values obtained in Step 5. The mean value is obtained through the formula $\mu = \alpha / (\alpha+\beta)$.

The main difference between this process and the short descriptions in NUREG/CR-5485 seems to be that the process in the 2010 white paper separates the complete CCF events from the partial ones. While the impact vector and the mapping methods are used for partial CCF events, the binomial regression method is used to curve fit the complete CCF events. This is probably due to the concern that the mapping method might be adding too many pseudo-complete CCF events to other group sizes from the observed complete CCF events with the mapping method.

To explain the process, the 2010 white paper uses the CCF data from the years 1995–2005 as an example. This range was chosen because it was the most recent and reflected more current plant conditions and practices. For 1995–2005, there are 289 partial and 32 complete CCF events, with an average group size of 6.41. Table 2 shows the CCF data used in the white paper for Step 1.

Table 2. CCF data (1995–2005) used in the 2010 white paper [18].

Group Size	No. Partial CCF Events	No. Complete CCF Events	Total No. CCF Events	Probability of Complete CCF Event	Estimated No. Complete CCF Events
2	55	25	80	0.22631	18.1048
3	37	3	40	0.15199	6.0796
4	57	2	59	0.09896	5.83864
5	9	0	9	0.06305	0.56745
6	15	0	15	0.0396	0.594
7	3	0	3	0.02464	0.07392
8	41	1	42	0.01525	0.6405
9	3	0	3	0.0094	0.0282
10	1	0	1	0.00578	0.00578
11	9	0	9	0.00355	0.03195
12	5	0	5	0.00218	0.0109
13	4	0	4	0.00134	0.00536
14	6	0	6	0.00082	0.00492
15	1	0	1	0.0005	0.0005
16	43	1	44	0.00031	0.01364
Total	289	32	321		32.00016

In Step 2, the impact factors of 289 partial CCF events are mapped up or down to obtain the values of n_k (the number of events involving failure of k similar components) for each group sized 2–16 (refer to [9] and [10] for the CCF event impact vector and mapping method). The number of independent events, n_I, for a given group size m is estimated via the following equation:

$$n_I = \frac{N*m}{AVG} \quad \text{(Eq. 1)}$$

where n_I = adjusted number of independent events for group size m

N = total number of independent events

m = group size

AVG = average group size

Table 3 shows the n_k values for the 289 partial CCF events obtained in the white paper.

In Step 3, the binomial regression method (see Ref. [19] and NUREG/CR-6823 [20]) rather than the mapping method is used to curve fit the fraction of complete CCF events over the total number of CCF events. Assuming the fraction of complete CCF events over the total number of CCF events to be *P*, the values in Table 2 (i.e., the columns for Group Size, No. Complete CCF Events, and Total No. CCF Events) are curve fitted via binomial regression. The results (i.e., Probability of Complete CCF Event and Estimated No. Complete CCF Events for each group size) are listed in the last two columns of Table 2.

In Step 4, Estimated No. Complete CCF Events in Table 2 is added to the final n_k in Table 3 for each group size (e.g., n_2 for group size 2 and n_3 for group size 3). For example, in Table 2, the estimated number of complete CCF events for group size 2 is 18.1048. This number is added to n_2 for group size 2 in Table 2 (i.e., 19.7694) in order to obtain the adjusted n_2 value for group size 2 (i.e., 37.8742). The total number of failures, n_t, for each group size m is also calculated via the following equation:

$$n_t = n_I + \sum_{k=1}^{m} n_k \quad \text{(Eq. 2)}$$

Table 3. n_k values for the partial CCF events for years 1995–2005, as per the 2010 white paper [18].

Group Size	n_I	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9	n_{10}	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}	n_{16}
2	2023.0900	106.3113	19.7694														
3	1077.0168	116.5278	42.9392	13.0124													
4	1436.0224	121.2871	55.2676	16.2645	10.3760												
5	1795.0280	131.1944	54.4966	25.7099	8.8633	4.3541											
6	2154.0336	139.4990	54.8839	29.7565	14.9416	5.0185	2.6030										
7	2513.0391	145.8261	57.1983	30.9931	18.9744	9.3164	2.9235	1.5594									
8	2872.0447	150.8235	60.1519	31.7431	20.8969	12.9359	5.9814	1.7075	0.9370								
9	3231.0503	156.5314	61.8792	32.0043	22.1217	15.2958	9.0293	3.8507	1.0019	0.5645							
10	3590.0559	161.3800	64.1529	32.3025	22.6214	16.5976	11.4885	6.2910	2.4705	0.5913	0.3410						
11	3949.0615	165.4662	66.6130	33.3967	22.1117	17.3671	13.1500	8.5764	4.3481	1.5805	0.3519	0.2068					
12	4308.0671	169.3230	68.5994	34.9270	21.7793	17.3869	14.1415	10.3999	6.3261	2.9791	1.0108	0.2117	0.1258				
13	4667.0727	172.8500	70.2772	36.7663	21.7364	17.0610	14.5053	11.6616	8.1210	4.6048	2.0271	0.6482	0.1289	0.0768			
14	5026.0783	175.9892	71.8040	38.7455	22.0010	16.6733	14.4171	12.3592	9.5469	6.2428	3.3119	1.3742	0.4181	0.0796	0.0469		
15	5385.0839	178.8299	73.1061	40.8249	22.5243	16.3906	14.0766	12.5782	10.5183	7.7011	4.7246	2.3597	0.9311	0.2718	0.0498	0.0286	
16	5744.0895	181.4401	74.1467	42.9721	23.2403	16.2910	13.6529	12.4509	11.0399	8.8463	6.1077	3.5267	1.6712	0.6326	0.1783	0.0316	0.0177

Table 4 shows the adjusted n_k values (including n_t) for group sizes 2–16, and these can be used to calculate the parameter of the AFM or the industry-wide prior distribution mean values via the following MLE (Step 5):

$$\alpha_1 = \frac{n_I + n_1}{n_t} \quad \text{(Eq. 3)}$$

$$\alpha_i = \frac{n_i}{n_t}, \text{ for i = 2, …, m} \quad \text{(Eq. 4)}$$

The values in Table 4 are used as input to CalcPrior, an INL-developed computer code, to estimate the industry-wide prior distributions with parameters α and β (Step 6).

Table 5 and Table 6 show the results of the calculated industry-wide alpha factor mean values and prior distributions, respectively.

The 2010 white paper ends with the following caution regarding the use of industry-wide prior distributions: "A sufficient number of CCF and independent events is needed to obtain meaningful results when using the prior distributions. If sufficient events do not exist, then the data should not be binned so finely. Similar bins should be grouped based on engineering and environmental considerations."

Table 4. Adjusted n_k values for the prior distribution calculation, as per the 2010 white paper [18].

Group Size	n_t	n_I	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9	n_{10}	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}	n_{16}
2	2167.2755	2023.09	106.3113	37.8742														
3	3213.1890	3034.63	116.5278	42.9392	19.0920													
4	4255.2138	4046.18	121.2871	55.2676	16.2645	16.2146												
5	5282.9058	5057.72	131.1944	54.4966	25.7099	8.8633	4.9216											
6	6316.5665	6069.27	139.4990	54.8839	29.7565	14.9416	5.0185	3.1970										
7	7347.6751	7080.81	145.8261	57.1983	30.9931	18.9744	9.3164	2.9235	1.6333									
8	8378.1777	8092.36	150.8235	60.1519	31.7431	20.8969	12.9359	5.9814	1.7075	1.5775								
9	9406.2070	9103.9	156.5314	61.8792	32.0043	22.1217	15.2958	9.0293	3.8507	1.0019	0.5927							
10	10433.6767	10115.44	161.3800	64.1529	32.3025	22.6214	16.5976	11.4885	6.2910	2.4705	0.5913	0.3410						
11	11460.1904	11126.99	165.4662	66.6130	33.3967	22.1117	17.3671	13.1500	8.5764	4.3481	1.5805	0.3519	0.2388					
12	12485.7514	12138.53	169.3230	68.5994	34.9270	21.7793	17.3869	14.1415	10.3999	6.3261	2.9791	1.0108	0.2117	0.1367				

Group Size	n_t	n_I	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9	n_{10}	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}	n_{16}
13	13510.5500	13150.08	172.8500	70.2772	36.7663	21.7364	17.0610	14.5053	11.6616	8.1210	4.6048	2.0271	0.6482	0.1289	0.0822			
14	14534.6346	14161.62	175.9892	71.8040	38.7455	22.0010	16.6733	14.4171	12.3592	9.5469	6.2428	3.3119	1.3742	0.4181	0.0796	0.0518		
15	15558.0861	15173.17	178.8299	73.1061	40.8249	22.5243	16.3906	14.0766	12.5782	10.5183	7.7011	4.7246	2.3597	0.9311	0.2718	0.0498	0.0291	
16	16580.9696	16184.71	181.4401	74.1467	42.9721	23.2403	16.2910	13.6529	12.4509	11.0399	8.8463	6.1077	3.5267	1.6712	0.6326	0.1783	0.0316	0.0313

Table 5. Calculated alpha factor mean values in the 2010 white paper [18].

Group Size	α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8
2	0.982525	1.7475E-02						
3	0.980694	1.3363E-02	5.9417E-03					
4	0.979379	1.2988E-02	3.8222E-03	3.8106E-03				
5	0.982209	1.0316E-02	4.8666E-03	1.6777E-03	9.3161E-04			
6	0.982934	8.6891E-03	4.7108E-03	2.3656E-03	7.9450E-04	5.0614E-04		
7	0.983527	7.7846E-03	4.2179E-03	2.5823E-03	1.2679E-03	3.9787E-04	2.2229E-04	
8	0.983887	7.1796E-03	3.7888E-03	2.4943E-03	1.5440E-03	7.1394E-04	2.0380E-04	1.8829E-04
9	0.984502	6.5785E-03	3.4025E-03	2.3519E-03	1.6262E-03	9.5992E-04	4.0938E-04	1.0652E-04
10	0.984966	6.1487E-03	3.0960E-03	2.1681E-03	1.5908E-03	1.1011E-03	6.0296E-04	2.3678E-04
11	0.985364	5.8125E-03	2.9141E-03	1.9295E-03	1.5154E-03	1.1474E-03	7.4836E-04	3.7941E-04
12	0.985753	5.4944E-03	2.7973E-03	1.7444E-03	1.3925 E-03	1.1326E-03	8.3297E-04	5.0667E-04
13	0.986113	5.2017E-03	2.7212E-03	1.6088E-03	1.2628E-03	1.0736E-03	8.6317E-04	6.0108E-04
14	0.986444	4.9401E-03	2.6658E-03	1.5136E-03	1.1471E-03	9.9192E-04	8.5031E-04	6.5686E-04
15	0.986754	4.6989E-03	2.6241E-03	1.4477E-03	1.0535E-03	9.0482E-04	8.0849E-04	6.7606E-04
16	0.987044	4.4720E-03	2.5917E-03	1.4016E-03	9.8249E-04	8.2340E-04	7.5091E-04	6.6582E-04
Group Size	α_9	α_{10}	α_{11}	α_{12}	α_{13}	α_{14}	α_{15}	α_{16}
9	6.3011E-05							
10	5.6672E-05	3.2682E-05						
11	1.3791E-04	3.0706E-05	2.0838E-05					
12	2.3861E-04	8.0958E-05	1.6955E-05	1.0949E-05				
13	3.4082E-04	1.5003E-04	4.7978E-05	9.5404E-06	6.0840E-06			
14	4.2951E-04	2.2787E-04	9.4548E-05	2.8766E-05	5.4767E-06	3.5640E-06		
15	4.9500E-04	3.0368E-04	1.5167E-04	5.9844E-05	1.7470E-05	3.2009E-06	1.8704E-06	
16	5.3351E-04	3.6836E-04	2.1269E-04	1.0079E-04	3.8152E-05	1.0753E-05	1.9058E-06	1.8877E-06

Table 6. Estimated CCF industry-wide prior distributions in the 2010 white paper [18].

Group Size	α_1	b_1	α_2	b_2	α_3	b_3	α_4	b_4	α_5	b_5	α_6	b_6	α_7	b_7	α_8	b_8
2	2.661E+1	4.732E-1	4.732E-1	2.661E+1												
3	5.341E+1	1.051E+0	7.278E-1	5.373E+1	3.236E-1	5.414E+1										
4	8.352E+1	1.759E+0	1.108E+0	8.417E+1	3.259E-1	8.495E+1	3.250E-1	8.495E+1								
5	1.628E+2	2.949E+0	1.710E+0	1.640E+2	8.065E-1	1.649E+2	2.780E-1	1.655E+2	1.544E-1	1.656E+2						
6	2.338E+2	4.060E+0	2.067E+0	2.358E+2	1.121E+0	2.368E+2	5.628E-1	2.373E+2	1.890E-1	2.377E+2	1.204E-1	2.378E+2				
7	3.351E+2	5.612E+0	2.652E+0	3.380E+2	1.437E+0	3.392E+2	8.797E-1	3.398E+2	4.319E-1	3.402E+2	1.355E-1	3.405E+2	7.573E-2	3.406E+2		
8	4.202E+2	6.882E+0	3.066E+0	4.240E+2	1.618E+0	4.255E+2	1.065E+0	4.260E+2	6.595E-1	4.264E+2	3.049E-1	4.268E+2	8.704E-2	4.270E+2	8.042E-2	4.270E+2
9	5.894E+2	9.279E+0	3.939E+0	5.948E+2	2.037E+0	5.967E+2	1.408E+0	5.973E+2	9.736E-1	5.977E+2	5.747E-1	5.981E+2	2.451E-1	5.985E+2	6.377E-2	5.986E+2
10	7.606E+2	1.161E+1	4.748E+0	7.675E+2	2.391E+0	7.698E+2	1.674E+0	7.705E+2	1.228E+0	7.710E+2	8.503E-1	7.714E+2	4.656E-1	7.717E+2	1.828E-1	7.720E+2
11	9.447E+2	1.403E+1	5.573E+0	9.532E+2	2.794E+0	9.560E+2	1.850E+0	9.569E+2	1.453E+0	9.573E+2	1.100E+0	9.576E+2	7.175E-1	9.580E+2	3.638E-1	9.584E+2
12	1.181E+3	1.707E+1	6.583E+0	1.192E+3	3.352E+0	1.195E+3	2.090E+0	1.196E+3	1.669E+0	1.197E+3	1.357E+0	1.197E+3	9.981E-1	1.197E+3	6.071E-1	1.198E+3
13	1.451E+3	2.043E+1	7.652E+0	1.463E+3	4.003E+0	1.467E+3	2.367E+0	1.469E+3	1.858E+0	1.469E+3	1.579E+0	1.469E+3	1.270E+0	1.470E+3	8.842E-1	1.470E+3
14	1.754E+3	2.411E+1	8.786E+0	1.770E+3	4.741E+0	1.774E+3	2.692E+0	1.776E+3	2.040E+0	1.776E+3	1.764E+0	1.777E+3	1.512E+0	1.777E+3	1.168E+0	1.777E+3
15	2.118E+3	2.844E+1	1.009E+1	2.137E+3	5.634E+0	2.141E+3	3.108E+0	2.144E+3	2.262E+0	2.145E+3	1.943E+0	2.145E+3	1.736E+0	2.145E+3	1.451E+0	2.145E+3
16	2.425E+3	3.183E+1	1.099E+1	2.446E+3	6.368E+0	2.451E+3	3.444E+0	2.454E+3	2.414E+0	2.455E+3	2.023E+0	2.455E+3	1.845E+0	2.455E+3	1.636E+0	2.456E+3

Group Size	α_9	b_9	α_{10}	b_{10}	α_{11}	b_{11}	α_{12}	b_{12}	α_{13}	b_{13}	α_{14}	b_{14}	α_{15}	b_{15}	α_{16}	b_{16}
9	3.773E-2	5.987E+2														
10	4.376E-2	7.722E+2	2.524E-2	7.722E+2												
11	1.322E-1	9.586E+2	2.944E-2	9.587E+2	1.998E-2	9.587E+2										
12	2.859E-1	1.198E+3	9.700E-2	1.198E+3	2.032E-2	1.198E+3	1.312E-2	1.20E+3								
13	5.014E-1	1.471E+3	2.207E-1	1.471E+3	7.057E-2	1.471E+3	1.403E-2	1.47E+3	8.95E-3	1.47E+3						
14	7.639E-1	1.778E+3	4.052E-1	1.778E+3	1.682E-1	1.778E+3	5.116E-2	1.78E+3	9.74E-3	1.78E+3	6.34E-3	1.78E+3				
15	1.063E+0	2.146E+3	6.520E-1	2.146E+3	3.256E-1	2.147E+3	1.285E-1	2.15E+3	3.75E-2	2.15E+3	6.87E-3	2.15E+3	4.02E-3	2.15E+3		
16	1.311E+0	2.456E+3	9.051E-1	2.456E+3	5.226E-1	2.457E+3	2.477E-1	2.46E+3	9.37E-2	2.46E+3	2.64E-2	2.46E+3	4.68E-3	2.46E+3	4.64E-3	2.46E+3

3. UPDATING GENERIC PRIOR DISTRIBUTIONS FOR ALPHA FACTORS

This section updates the generic prior distributions for alpha factors, using CCF data for the years 1997–2015 in addition to the existing process described in Section 2, with changes applied as deemed necessary. The 1997–2015 period was the most recent date range of the CCF data available when the analysis was performed for the original report INL/LTD-17-43723, reflecting more current plant conditions and practices at the time. Furthermore, 1997 is the earliest year selectable on the CCF Database website.

3.1 Accessing CCF Data

CCF data stored in the NRC CCF Database system (https://rads.inl.gov/Pages/CCF.aspx) can be accessed and used for CCF analysis.[a] The CCF Database website includes various CCF rules for selecting the CCF date range and other CCF event characteristics, such as component types of interest, failure modes, and failure causes. Through the CCF Database website, CCF events of interest can be obtained by selecting the proper CCF event characteristics. It can generate both the number of CCF events and the effective independent event count that satisfy the selection criteria. In addition, the CCF Database website can provide the original (or unmapped) impact vector for each selected CCF event, the mapped impact vector, and adjusted independent counts for different group sizes. The impact vector results can be output for further analysis. Table 7 shows examples of CCF events whose unmapped impact vectors were obtained from the CCF Database website.

Table 7. CCF events with unmapped impact vectors obtained from the CCF Database website.

CCF Event	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
219-1997-0278	0	1	0	0	--	--	--	--	--	--	--	--	--	--	--	--
219-1998-0207	1.8	0.1	--	--	--	--	--	--	--	--	--	--	--	--	--	--
219-1999-0248	0	1	0	0	--	--	--	--	--	--	--	--	--	--	--	--
219-2000-0051	0	1	0	0	0	0	0	0	--	--	--	--	--	--	--	--
219-2003-0369	0	0	1	0	0	0	--	--	--	--	--	--	--	--	--	--
219-2005-0341	0	0	1	0	0	0	--	--	--	--	--	--	--	--	--	--
219-2014-0488	0	1	0	0	0	--	--	--	--	--	--	--	--	--	--	--
220-2001-0398	0	0	0	1	--	--	--	--	--	--	--	--	--	--	--	--
220-2007-0144	0	0	0	1	0	0	0	0	--	--	--	--	--	--	--	--
220-2010-0412	0	1	0	0	--	--	--	--	--	--	--	--	--	--	--	--
237-1998-0219	1.45	0.025	--	--	--	--	--	--	--	--	--	--	--	--	--	--
237-2004-0336	0	1	0	0	0	0	--	--	--	--	--	--	--	--	--	--

CCF data from 1997–2015 were chosen for this study, as this period represents more recent plant conditions and practices that were in place when the analysis was performed. On the CCF Database website, the following selection criteria are defined:

- Type of CCF Event Level: All Level CCF Events
- CCF Event Type: CCF Events Only
- Date Range: 1997–2015

[a] The NRC CCF Database system includes proprietary information and is not available to the public.

- Filter Independent Events by Selected Cause(s): True
- Shock Criteria: All Events
- Redundancy Range: Minimum = 2, Maximum = 16
- Bayesian Update Method: Mean Method
- Failure Modes: select all failure modes except Setpoint
- Plants/Systems/Components/CCF Categories: No Selection on These CCF Event Characteristics

A total of 268 CCF events and 7,492.8 effective independent failure events correspond to the above selection criteria. Figure 3-1, Figure 3-2, and Figure 3-3 show screenshots of the CCF Database website to illustrate the CCF selection criteria and results.

Additional criterion on CCF Categories → Degree → Almost/Partial or Complete is used to obtain the partial CCF events and complete CCF events, as required in the existing process. The unmapped/mapped impact vectors are also acquired from the CCF Database website. The mapped impact vectors for partial CCF events for each group size, as obtained from the website, are used directly in this study.

Table 8 shows the number of partial CCF events, the number of complete CCF events, and the total number of CCF events. Table 9 shows the mapped impact vectors for partial CCF events pertaining to each group size (2–16), as obtained from the CCF Database website.

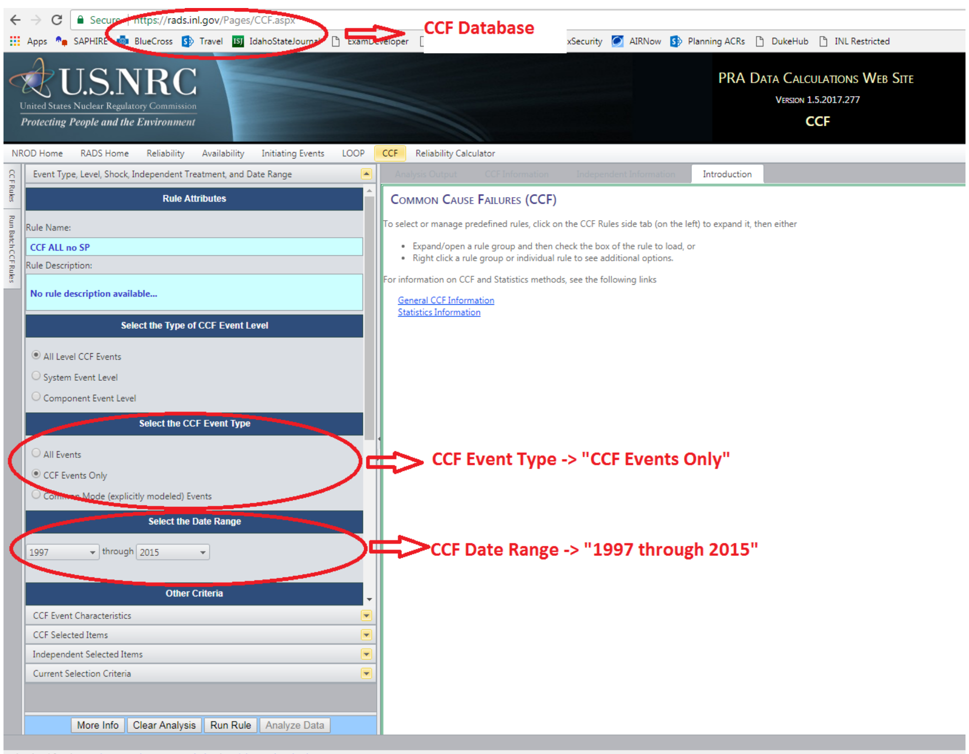


Figure 3-1. Selecting CCF event types and date ranges in the CCF Database.

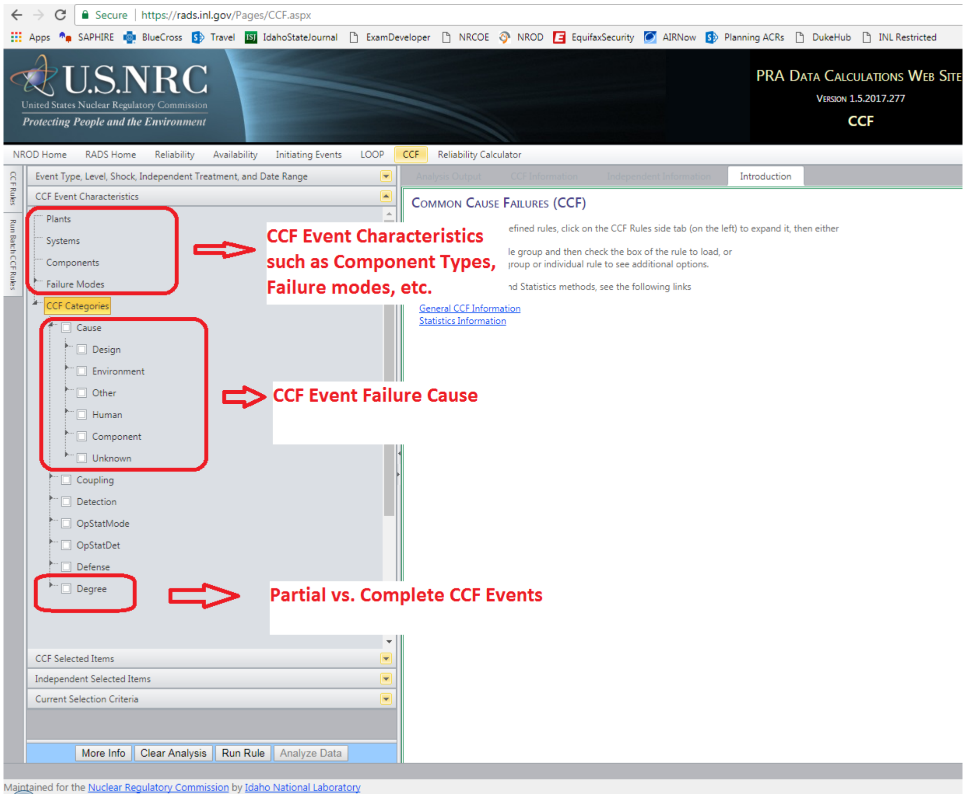


Figure 3-2. Defining CCF event characteristics in the CCF Database.

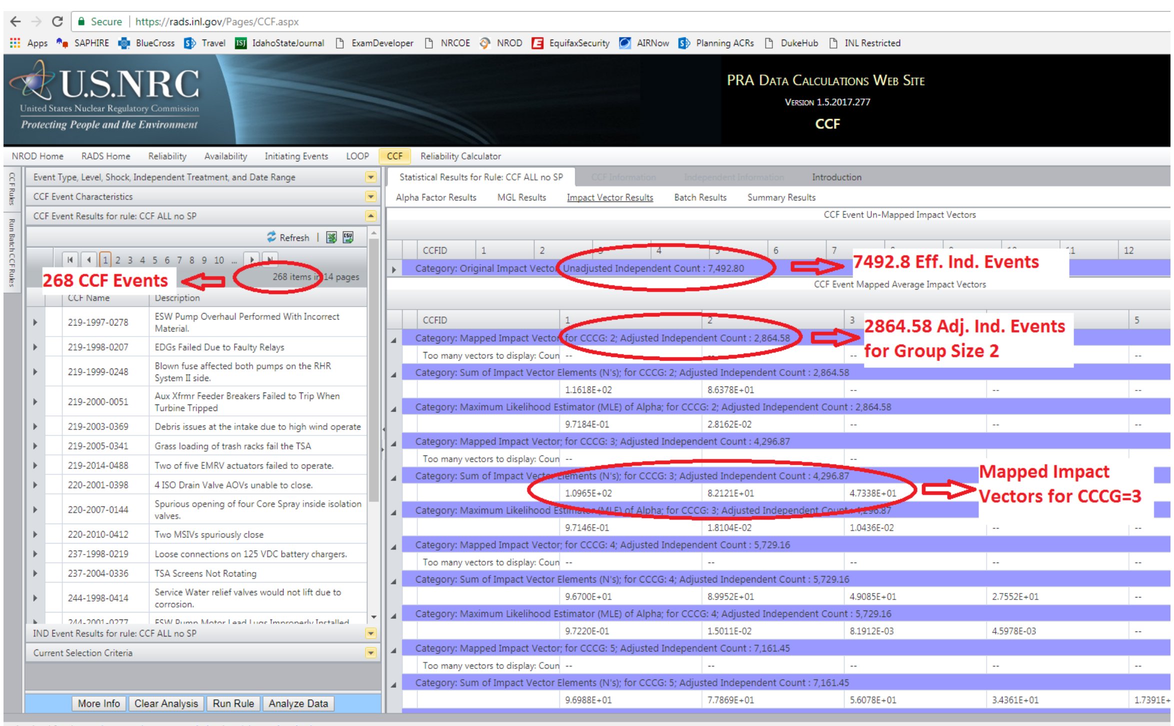


Figure 3-3. CCF data, including CCF impact vectors that satisfy the selection criteria.

Table 8. CCF data (1997–2015).

Group Size	No. Partial CCF Events	No. Complete CCF Events	Total No. CCF Events
2	27	34	61
3	27	12	39
4	61	2	63
5	7	0	7
6	30	5	35
7	3	0	3
8	30	2	32
9	0	0	0
10	0	0	0
11	5	0	5
12	7	1	8
13	0	0	0
14	1	0	1
15	0	0	0
16	14	0	14
Total	212	56	268

Table 9. n_k values for the partial CCF events from 1997 through 2015.

Group Size	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9	n_{10}	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}	n_{16}
2	115.61	31.164														
3	109.23	64.693	9.267													
4	96.47	80.938	25.857	4.038												
5	96.92	73.190	39.900	14.539	2.141											
6	98.05	65.654	46.584	23.001	8.533	1.209										
7	101.15	61.106	44.388	29.499	15.401	5.219	0.716									
8	102.97	59.825	41.221	31.486	20.828	10.368	3.197	0.453								
9	104.47	59.373	38.811	31.849	23.262	14.602	7.206	2.091	0.298							
10	105.31	59.671	37.235	31.000	24.661	17.351	10.623	5.043	1.393	0.2028						
11	105.59	60.457	36.289	29.832	25.016	19.214	13.174	7.876	3.546	0.9485	0.1428					
12	105.79	61.357	35.385	29.051	24.559	20.390	15.020	10.190	5.885	2.5054	0.6629	0.1033				
13	106.59	61.096	35.601	27.950	23.941	20.846	16.489	11.834	8.027	4.3833	1.7881	0.4762	0.0763			
14	107.17	61.004	35.911	27.231	23.266	20.412	17.884	12.950	9.655	6.3242	3.2457	1.2993	0.3508	0.0573		
15	107.54	61.048	36.226	26.865	22.526	20.158	17.903	14.461	10.562	8.0560	4.8995	2.4070	0.9672	0.2632	0.0435	
16	107.74	61.214	36.481	26.799	21.847	19.709	17.795	15.214	11.863	8.6598	6.9238	3.6040	1.8474	0.7303	0.2008	0.0334

3.2 Treating Complete CCF Events

As described in Section 2, the existing process uses the binomial regression method rather than the mapping technique to curve fit the fraction of complete CCF events over the total number of CCF events. This is probably due to concerns that the mapping technique might be adding too many pseudo-complete CCF events to other group sizes when mapping the observed complete CCF events from one group size to other group sizes. For example, Table 8 shows 34 complete CCF events for group size 2, 12 for group size 3, and 56 for all group sizes combined. Using the mapping technique, all complete CCF events in group sizes 3–16 (i.e., 56 – 34 = 22) would be mapped down with 22 pseudo-complete CCF events added to group size 2. For group size 3, all complete CCF events in group sizes 4–16 (i.e., 56 – 34 – 12 = 10) would be mapped down, and the complete CCF events in group size 2 (which is 34) would be mapped up and added to group size 3. Assuming 0.5 to be the conditional probability of failure for each component, given a nonlethal shock, ρ, 10 + 34 * 0.5 = 27 pseudo-complete CCF events would be added to group size 3.

The binomial regression used in Section 2 defines *P(m)* as the probability of a CCF event being a complete failure in a particular group size, m. It then uses the observed fractions of complete CCF failures in all group sizes and fits the data using a pre-defined function. In this study, MATLAB [21] was used for curve fitting. However, the curve fitting results for the data in Table 2 could not be reproduced using MATLAB in conjunction with the general logit function $\ln\left(\frac{P(m)}{1-P(m)}\right) = a + bm,$ as per [20], or with any other pre-defined functions in MATLAB. Instead, the following function (suggested by Cory Atwood, the primary author of NUREG/CR-6823) was used to fit the curve:

$$\ln\left(\frac{P(m)}{1-P(m)}\right) = a + b(1 - e^{-m}) \quad \text{(Eq. 5)}$$

The results (i.e., the probability of a complete CCF event and the estimated number of complete CCF events for each group size) are listed in the last two columns of Table 10. Note that the binomial regression treatment of complete CCF events in Table 10 (and in Section 2) does not distinguish lethal shock events from nonlethal shock but complete CCF events. For lethal shocks, the impact vector is supposed to map directly (i.e., the probability of all x components in a system of x components having failed due to lethal shock is mapped directly and equals the probability of failing all y components in a system of y components). The correct process should treat lethal shock events differently from nonlethal shock but complete CCF events, i.e., the lethal shock events should be removed from the curve fitting process (do not include the lethal shock events in the No. Complete CCF Events column in Table 10), instead, the total number of lethal shock events, disregarding their group sizes, should be added to the final n_k value in Section 3.3 and Table 11.

A review of the CCF data used in this study (1997–2015) found only three CCF events coded as lethal shock: 244-2005-0142, 263-1999-0046, and 423-2012-0501—all corresponding to a group size of 2. While the results in Table 10 are used in the following sections to estimate prior distributions, sensitivity analysis could be conducted to estimate the prior distributions via different treatment of complete CCF events (i.e., using the mapping or binomial regression methods but distinguishing lethal shocks from nonlethal ones).

Table 10. CCF data (1997–2015) with curve-fitted complete CCF events.

Group Size	No. Partial CCF Events	No. Complete CCF Events	Total No. CCF Events	Prob. of Complete CCF Event - Data	Prob. of Complete CCF Event - Curve Fitting	Estimated No. Complete CCF Events
2	27	34	61	0.55738	0.51050	31.14031
3	27	12	39	0.30769	0.30184	11.77164

Group Size	No. Partial CCF Events	No. Complete CCF Events	Total No. CCF Events	Prob. of Complete CCF Event - Data	Prob. of Complete CCF Event - Curve Fitting	Estimated No. Complete CCF Events
4	61	2	63	0.03175	0.17199	10.83554
5	7	0	7	0.00000	0.11118	0.77827
6	30	5	35	0.14286	0.08650	3.02750
7	3	0	3	0.00000	0.07707	0.23122
8	30	2	32	0.06250	0.07355	2.35374
9	0	0	0	NA	0.07225	0.00000
10	0	0	0	NA	0.07177	0.00000
11	5	0	5	0.00000	0.07160	0.35799
12	7	1	8	0.12500	0.07153	0.57226
13	0	0	0	NA	0.07151	0.00000
14	1	0	1	0.00000	0.07150	0.07150
15	0	0	0	NA	0.07150	0.00000
16	14	0	14	0.00000	0.07150	1.00094
Total	212	56	268			62.14091

3.3 Estimating Prior Distributions

Adjusted n_k Values

Adjusted n_k values for CCF events from 1997 through 2015 are obtained for each group size by adding the estimated number of complete CCF events in Table 10 to the final n_k value for the partial CCF events in Table 9. For example, the estimated number of complete CCF events for a group size of 2 is 31.140 in Table 10; the n_2 value for partial CCF events for a group size of 2 in Table 9 is 31.164; the adjusted n_2 value for a group size of 2 will be 31.164 + 31.140 = 62.304. Table 11 shows the adjusted n_k results for group sizes 2–16, with CCF data for 1997–2015. The number of effective independent failure events (n_I), as obtained from the CCF database website query results (see Figure 3-3), and the total number of failures (n_t) (i.e., n_I and n_k) for each group size are also presented in the table.

Table 11. Adjusted n_k values for CCF events from 1997 through 2015.

Group Size	n_t	n_I	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9	n_{10}	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}	n_{16}
2	3042.49	2864.58	115.61	62.304														
3	4491.83	4296.87	109.23	64.693	21.038													
4	5947.30	5729.16	96.47	80.938	25.857	14.873												
5	7388.92	7161.45	96.92	73.190	39.900	14.539	2.919											
6	8839.80	8593.74	98.05	65.654	46.584	23.001	8.533	4.237										
7	10283.74	10026.03	101.15	61.106	44.388	29.499	15.401	5.219	0.948									
8	11731.02	11458.32	102.97	59.825	41.221	31.486	20.828	10.368	3.197	2.807								
9	13172.57	12890.61	104.47	59.373	38.811	31.849	23.262	14.602	7.206	2.091	0.298							
10	14615.39	14322.90	105.31	59.671	37.235	31.000	24.661	17.351	10.623	5.043	1.393	0.2028						
11	16057.63	15755.19	105.59	60.457	36.289	29.832	25.016	19.214	13.174	7.876	3.546	0.9485	0.5007					
12	17498.95	17187.48	105.79	61.357	35.385	29.051	24.559	20.390	15.020	10.190	5.885	2.5054	0.6629	0.6755				

Group Size	n_t	n_I	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9	n_{10}	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}	n_{16}
13	18938.87	18619.77	106.59	61.096	35.601	27.950	23.941	20.846	16.489	11.834	8.027	4.3833	1.7881	0.4762	0.0763			
14	20378.89	20052.06	107.17	61.004	35.911	27.231	23.266	20.412	17.884	12.950	9.655	6.3242	3.2457	1.2993	0.3508	0.1288		
15	21818.28	21484.35	107.54	61.048	36.226	26.865	22.526	20.158	17.903	14.461	10.562	8.0560	4.8995	2.4070	0.9672	0.2632	0.0435	
16	23258.30	22916.64	107.74	61.214	36.481	26.799	21.847	19.709	17.795	15.214	11.863	8.6598	6.9238	3.6040	1.8474	0.7303	0.2008	1.0343

Alpha Factor Mean Values

The MLEs or mean values of alpha factors for each group size can then be calculated using Eqs. 3 and 4. Table 12 presents the results.

Table 12. Calculated alpha factor mean values for CCF events from 1997 through 2015.

Group Size	α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8	α_9	α_{10}	α_{11}	α_{12}	α_{13}	α_{14}	α_{15}	α_{16}
2	0.9795	2.048E-02														
3	0.9809	1.440E-02	4.684E-03													
4	0.9795	1.361E-02	4.348E-03	2.501E-03												
5	0.9823	9.905E-03	5.400E-03	1.968E-03	3.951E-04											
6	0.9833	7.427E-03	5.270E-03	2.602E-03	9.653E-04	4.793E-04										
7	0.9848	5.942E-03	4.316E-03	2.869E-03	1.498E-03	5.075E-04	9.214E-05									
8	0.9855	5.100E-03	3.514E-03	2.684E-03	1.775E-03	8.838E-04	2.725E-04	2.393E-04								
9	0.9865	4.507E-03	2.946E-03	2.418E-03	1.766E-03	1.109E-03	5.470E-04	1.587E-04	2.261E-05							
10	0.9872	4.083E-03	2.548E-03	2.121E-03	1.687E-03	1.187E-03	7.268E-04	3.450E-04	9.530E-05	1.388E-05						
11	0.9877	3.765E-03	2.260E-03	1.858E-03	1.558E-03	1.197E-03	8.204E-04	4.905E-04	2.208E-04	5.907E-05	3.118E-05					
12	0.9882	3.506E-03	2.022E-03	1.660E-03	1.403E-03	1.165E-03	8.583E-04	5.823E-04	3.363E-04	1.432E-04	3.788E-05	3.860E-05				
13	0.9888	3.226E-03	1.880E-03	1.476E-03	1.264E-03	1.101E-03	8.706E-04	6.249E-04	4.238E-04	2.314E-04	9.441E-05	2.515E-05	4.030E-06			
14	0.9892	2.993E-03	1.762E-03	1.336E-03	1.142E-03	1.002E-03	8.776E-04	6.355E-04	4.738E-04	3.103E-04	1.593E-04	6.376E-05	1.721E-05	6.319E-06		
15	0.9896	2.798E-03	1.660E-03	1.231E-03	1.032E-03	9.239E-04	8.206E-04	6.628E-04	4.841E-04	3.692E-04	2.246E-04	1.103E-04	4.433E-05	1.207E-05	1.995E-06	
16	0.9899	2.632E-03	1.569E-03	1.152E-03	9.393E-04	8.474E-04	7.651E-04	6.541E-04	5.101E-04	3.723E-04	2.977E-04	1.550E-04	7.943E-05	3.140E-05	8.633E-06	4.447E-05

CalcPrior Code and Prior Distributions

Adjusted n_k values, including the number of effective independent failure events (n_I) in Table 11, are used as input to the computer code CalcPrior to estimate the industry-wide prior distributions with parameters α and β. The CalcPrior code was first developed in early 2000, then re-coded with modern computer language for this study. Figure 3-4 shows the CalcPrior code homepage. Figure 3-5 shows the needed input to the code to calculate the prior distributions. Such input includes the prior name, independent event count, average CCCG size, description of the prior, and n_k values for each group size.

The total independent event count (called the effective independent event count or unadjusted independent count in the CCF Database website), adjusted independent event count, and unadjusted n_k values for each group size are included in the CCF Database website querying results. The average CCCG size can be calculated from Eq. 1. The n_k values for each group size can be adjusted after the proper treatment of complete CCF events. These values can be input to the CalcPrior code via the following *.csv* file format:

PriorName, PriorDescription,,,,,,,,,,,,,

TotalIndependentEventCount, AverageGroupSize,,,,,,,,,,,,,

n_1, n_2,,,,,,,,,,,,,,

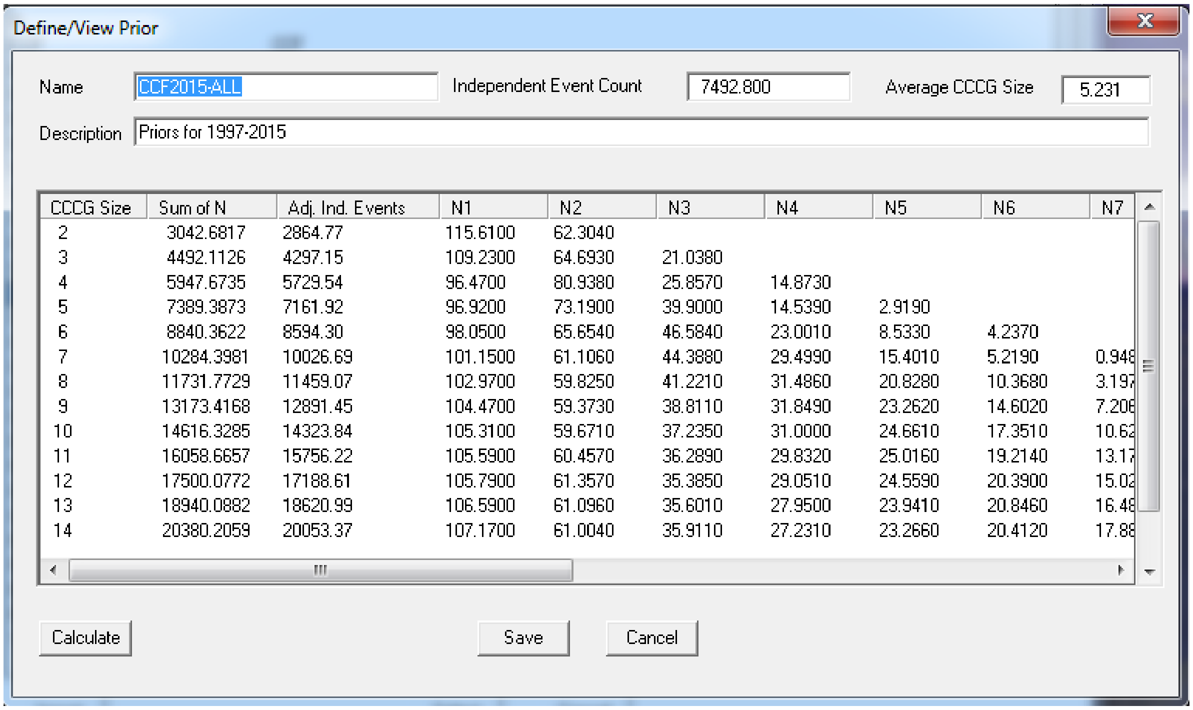
n_1, n_2, n_3,,,,,,,,,,,,

n_1, n_2, n_3, n_4,,,,,,,,,,,

......

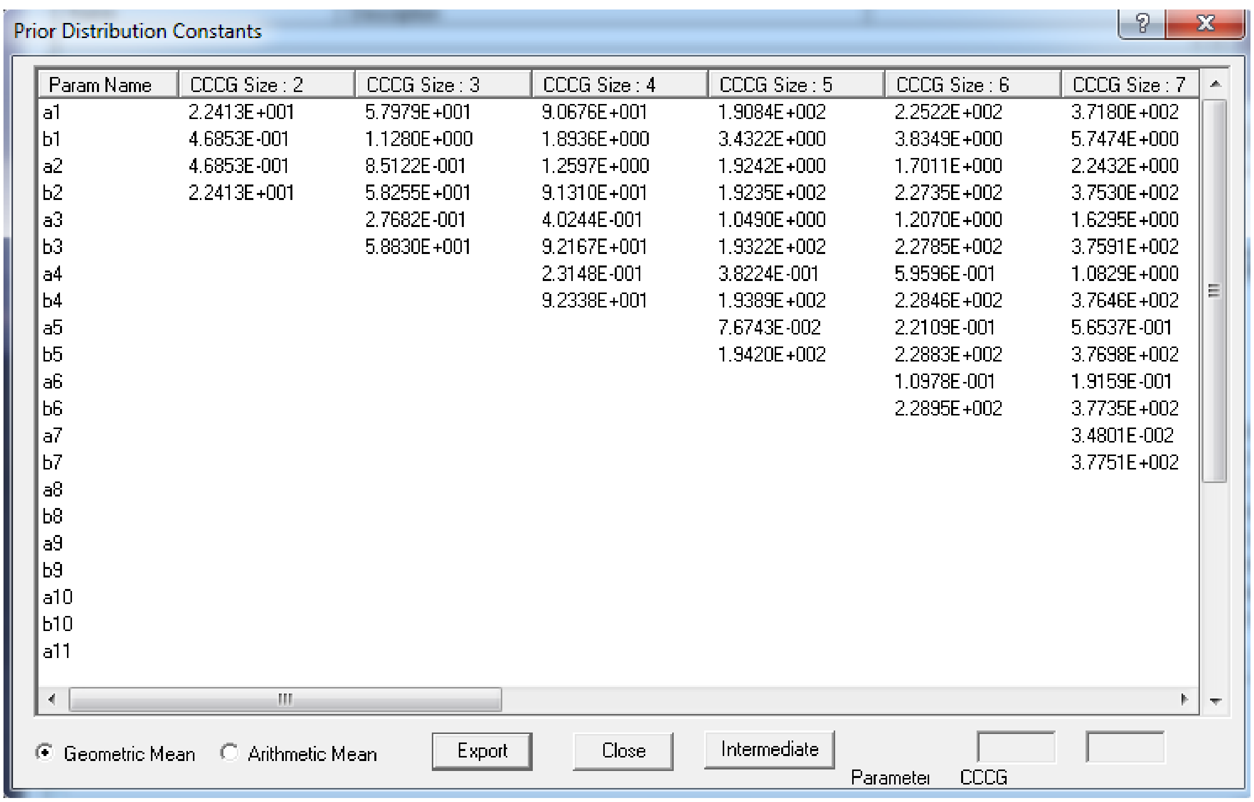
The n_I values and n_t values for each group size will be automatically calculated by the code in accordance with the input values. The code can then estimate prior distributions, based on the constrained noninformative and Dirichlet methodology (refer to [20]). Figure 3-6 shows the CalcPrior code results for the prior distribution parameters, which can be output to Table 13.

Figure 3-4. Homepage of the CalcPrior code for estimating alpha factor prior distributions.



CCCG Size	Sum of N	Adj. Ind. Events	N1	N2	N3	N4	N5	N6	N7
2	3042.6817	2864.77	115.6100	62.3040					
3	4492.1126	4297.15	109.2300	64.6930	21.0380				
4	5947.6735	5729.54	96.4700	80.9380	25.8570	14.8730			
5	7389.3873	7161.92	96.9200	73.1900	39.9000	14.5390	2.9190		
6	8840.3622	8594.30	98.0500	65.6540	46.5840	23.0010	8.5330	4.2370	
7	10284.3981	10026.69	101.1500	61.1060	44.3880	29.4990	15.4010	5.2190	0.948
8	11731.7729	11459.07	102.9700	59.8250	41.2210	31.4860	20.8280	10.3680	3.197
9	13173.4168	12891.45	104.4700	59.3730	38.8110	31.8490	23.2620	14.6020	7.206
10	14616.3285	14323.84	105.3100	59.6710	37.2350	31.0000	24.6610	17.3510	10.62
11	16058.6657	15756.22	105.5900	60.4570	36.2890	29.8320	25.0160	19.2140	13.17
12	17500.0772	17188.61	105.7900	61.3570	35.3850	29.0510	24.5590	20.3900	15.02
13	18940.0882	18620.99	106.5900	61.0960	35.6010	27.9500	23.9410	20.8460	16.48
14	20380.2059	20053.37	107.1700	61.0040	35.9110	27.2310	23.2660	20.4120	17.88

Figure 3-5. Input to the CalcPrior code for estimating alpha factor prior distributions.



Param Name	CCCG Size : 2	CCCG Size : 3	CCCG Size : 4	CCCG Size : 5	CCCG Size : 6	CCCG Size : 7
a1	2.2413E+001	5.7979E+001	9.0676E+001	1.9084E+002	2.2522E+002	3.7180E+002
b1	4.6853E-001	1.1280E+000	1.8936E+000	3.4322E+000	3.8349E+000	5.7474E+000
a2	4.6853E-001	8.5122E-001	1.2597E+000	1.9242E+000	1.7011E+000	2.2432E+000
b2	2.2413E+001	5.8255E+001	9.1310E+001	1.9235E+002	2.2735E+002	3.7530E+002
a3		2.7682E-001	4.0244E-001	1.0490E+000	1.2070E+000	1.6295E+000
b3		5.8830E+001	9.2167E+001	1.9322E+002	2.2785E+002	3.7591E+002
a4			2.3148E-001	3.8224E-001	5.9596E-001	1.0829E+000
b4			9.2338E+001	1.9389E+002	2.2846E+002	3.7646E+002
a5				7.6743E-002	2.2109E-001	5.6537E-001
b5				1.9420E+002	2.2883E+002	3.7698E+002
a6					1.0978E-001	1.9159E-001
b6					2.2895E+002	3.7735E+002
a7						3.4801E-002
b7						3.7751E+002
a8						
b8						
a9						
b9						
a10						
b10						
a11						

Figure 3-6. Prior distribution parameters calculated by the CalcPrior code.

Table 13. Estimated CCF industry-wide prior distributions with CCF events from 1997 through 2015.

Group Size	α_1	b_1	α_2	b_2	α_3	b_3	α_4	b_4	α_5	b_5	α_6	b_6	α_7	b_7	α_8	b_8
2	2.2413E+01	4.6853E-01	4.6853E-01	2.2413E+01												
3	5.7979E+01	1.1280E+00	8.5122E-01	5.8255E+01	2.7682E-01	5.8830E+01										
4	9.0676E+01	1.8936E+00	1.2597E+00	9.1310E+01	4.0244E-01	9.2167E+01	2.3148E-01	9.2338E+01								
5	1.9084E+02	3.4322E+00	1.9242E+00	1.9235E+02	1.0490E+00	1.9322E+02	3.8224E-01	1.9389E+02	7.6743E-02	1.9420E+02						
6	2.2522E+02	3.8349E+00	1.7011E+00	2.2735E+02	1.2070E+00	2.2785E+02	5.9596E-01	2.2846E+02	2.2109E-01	2.2883E+02	1.0978E-01	2.2895E+02				
7	3.7180E+02	5.7474E+00	2.2432E+00	3.7530E+02	1.6295E+00	3.7591E+02	1.0829E+00	3.7646E+02	5.6537E-01	3.7698E+02	1.9159E-01	3.7735E+02	3.4801E-02	3.7751E+02		
8	3.9002E+02	5.7256E+00	2.0181E+00	3.9373E+02	1.3905E+00	3.9436E+02	1.0621E+00	3.9469E+02	7.0259E-01	3.9505E+02	3.4974E-01	3.9540E+02	1.0784E-01	3.9564E+02	9.4689E-02	3.9565E+02
9	6.3746E+02	8.7061E+00	2.9123E+00	6.4325E+02	1.9037E+00	6.4426E+02	1.5622E+00	6.4460E+02	1.1410E+00	6.4502E+02	7.1624E-01	6.4545E+02	3.5346E-01	6.4581E+02	1.0257E-01	6.4606E+02
10	7.8579E+02	1.0194E+01	3.2496E+00	7.9274E+02	2.0278E+00	7.9396E+02	1.6882E+00	7.9430E+02	1.3430E+00	7.9465E+02	9.4492E-01	7.9504E+02	5.7852E-01	7.9541E+02	2.7464E-01	7.9571E+02
11	8.3890E+02	1.0411E+01	3.1974E+00	8.4611E+02	1.9192E+00	8.4739E+02	1.5777E+00	8.4773E+02	1.3230E+00	8.4799E+02	1.0162E+00	8.4829E+02	6.9674E-01	8.4861E+02	4.1654E-01	8.4889E+02
12	9.5624E+02	1.1373E+01	3.3926E+00	9.6422E+02	1.9565E+00	9.6566E+02	1.6063E+00	9.6601E+02	1.3579E+00	9.6626E+02	1.1274E+00	9.6649E+02	8.3049E-01	9.6679E+02	5.6343E-01	9.6705E+02
13	1.3364E+03	1.5165E+01	4.3599E+00	1.3472E+03	2.5405E+00	1.3491E+03	1.9946E+00	1.3496E+03	1.7085E+00	1.3499E+03	1.4876E+00	1.3501E+03	1.1767E+00	1.3504E+03	8.4449E-01	1.3508E+03
14	1.4630E+03	1.5941E+01	4.4270E+00	1.4746E+03	2.6060E+00	1.4764E+03	1.9761E+00	1.4770E+03	1.6884E+00	1.4773E+03	1.4813E+00	1.4775E+03	1.2978E+00	1.4777E+03	9.3977E-01	1.4780E+03
15	1.7967E+03	1.8836E+01	5.0795E+00	1.8104E+03	3.0142E+00	1.8125E+03	2.2353E+00	1.8133E+03	1.8743E+00	1.8136E+03	1.6773E+00	1.8138E+03	1.4896E+00	1.8140E+03	1.2032E+00	1.8143E+03
16	1.6355E+03	1.6615E+01	4.3479E+00	1.6478E+03	2.5912E+00	1.6495E+03	1.9035E+00	1.6502E+03	1.5518E+00	1.6506E+03	1.3999E+00	1.6507E+03	1.2640E+00	1.6508E+03	1.0806E+00	1.6510E+03

Group Size	α_9	b_9	α_{10}	b_{10}	α_{11}	b_{11}	α_{12}	b_{12}	α_{13}	b_{13}	α_{14}	b_{14}	α_{15}	b_{15}	α_{16}	b_{16}
9	1.4617E-02	6.4615E+02														
10	7.5861E-02	7.9591E+02	1.1044E-02	7.9598E+02												
11	1.8754E-01	8.4912E+02	5.0164E-02	8.4926E+02	2.6481E-02	8.4928E+02										
12	3.2539E-01	9.6729E+02	1.3853E-01	9.6748E+02	3.6653E-02	9.6758E+02	3.7350E-02	9.6758E+02								
13	5.7282E-01	1.3510E+03	3.1280E-01	1.3513E+03	1.2760E-01	1.3515E+03	3.3982E-02	1.3516E+03	5.4449E-03	1.3516E+03						
14	7.0066E-01	1.4783E+03	4.5894E-01	1.4785E+03	2.3554E-01	1.4787E+03	9.4289E-02	1.4789E+03	2.5457E-02	1.4790E+03	9.3469E-03	1.4790E+03				
15	8.7881E-01	1.8146E+03	6.7030E-01	1.8148E+03	4.0766E-01	1.8151E+03	2.0028E-01	1.8153E+03	8.0476E-02	1.8154E+03	2.1900E-02	1.8155E+03	3.6194E-03	1.8155E+03		
16	8.4261E-01	1.6513E+03	6.1509E-01	1.6515E+03	4.9179E-01	1.6516E+03	2.5599E-01	1.6519E+03	1.3122E-01	1.6520E+03	5.1872E-02	1.6521E+03	1.4263E-02	1.6521E+03	7.3465E-02	1.6520E+03

4. DEVELOPING GENERIC PRIOR DISTRIBUTIONS FOR CAUSAL ALPHA FACTORS

While the AFM is widely utilized in PRAs, including the Standardized Plant Analysis Risk (SPAR) models, industry has expressed some concerns over applying the AFM in event and condition assessments (ECAs). For example, the AFM is not causal-based, as the methodology does not explicitly incorporate causes of failure. So, when using the AFM in ECA, the conditional CCF probabilities in the AFM do not acknowledge other causes that may be included in the CCF probabilities but not affect the component that fails, and as such would bias the risk evaluation for the event or condition. To address this concern, NRC asked INL to conduct a feasibility study in 2014 to aid NRC in investigating alternative CCF models potentially usable for event assessment in the SPAR models. The feasibility study suggests that the CAFM—or Partial Alpha Factor Model (PAFM), as referred to in the study report [22]—could be used in the SPAR models to replace the current AFM for ECA. To implement the CAFM in the SPAR models, new generic causal prior distributions must be developed for the different CCF cause groups defined in the feasibility study. The feasibility study recommends using five CCF cause groups in the CAFM: Component (GC), Design (GD), Environment (GE), Human (GH), and Other (GO). Table 14 shows the five recommended CCF cause groups, along with the CCF failure causes (failure cause codes, descriptions, and meaning) for each group. These CCF cause groups and failure causes align with the current CCF database categorization. The same process described in Section 3 for alpha factor prior distribution updating is used to access CCF data based on a specific CCF cause, treat complete CCF events separately, and estimate prior distributions using adjusted n_k values and the CalcPrior program.

4.1 Prior Distributions for the “Component” Cause Group (GC)

To estimate prior distributions for the GC (i.e., Component) CCF cause group, the following selection criteria are defined in the CCF Database website:

- Type of CCF Event Level: All Level CCF Events
- CCF Event Type: CCF Events Only
- Date Range: 1997–2015
- Filter Independent Events by Selected Cause(s): True
- Shock Criteria: All Events
- Redundancy Range: Minimum = 2, Maximum = 16
- Bayesian Update Method: Mean Method
- Failure Modes: select all failure modes except Setpoint
- CCF Categories: Cause → Component

A total of 61 CCF events and 2,855.2 effective independent failure events related to the above selection criteria.

Additional criterion on CCF Categories → Degree → Almost/Partial or Complete is used to obtain the partial/complete CCF events, as required in the existing process. The unmapped/mapped impact vectors are also acquired from the CCF Database website. The mapped impact vectors for partial CCF events for each group size obtained from the website are used directly in the study.

Table 14. CCF cause groups recommended in the alternative CCF model feasibility study.

CCF Cause Group	CCF Cause Code	Failure Cause Description	Failure Cause Meaning
Component (GC)	IC	Internal to component, piece-part	Used when the cause of a failure is a non-specific result of a failure internal to the component that failed, other than aging or wear.
	IQ	Setpoint drift	Used when the cause of a failure is the result of setpoint drift or adjustment.
	IW	Age/wear	Used when the cause of a failure is a non-specific aging or wear issue.
Design (GD)	DC	Construction installation error or inadequacy	Used when a construction or installation error is made during the original or modification installation. This includes specification of an incorrect component or material.
	DE	Design error or inadequacy	Used when a design error is made.
	DM	Manufacturing error or inadequacy	Used when a manufacturing error is made during component manufacture.
Environment (GE)	EA	Ambient environmental stress	Used when the cause of a failure is the result of an environmental condition from the location of the component.
	EE	Extreme environmental stress	Used when the cause of a failure is the result of an environmental condition that places a higher-than-expected load on the equipment and is transitory in nature.
	IE	Internal environment	Internal environment led to the failure. Debris/foreign material as well as an operating medium chemistry issue.
Human (GH)	HA	Accidental human action	Used when a human error (during the performance of an activity) results in an unintentional or undesired action.
	HM	Inadequate maintenance	Used when a human error (during the performance of maintenance) results in an unintentional or undesired action.
	HP	Human action procedure	Used when the procedure is not followed or is incorrect. For example, when a missed or incorrect step in a surveillance procedure results in component failure.
	PA	Inadequate procedure	Used when a failure results from an inadequate operating or maintenance procedure.

CCF Cause Group	CCF Cause Code	Failure Cause Description	Failure Cause Meaning
Other (GO)	EC	State of other component	Used when a failure results from a component state not associated with the component that failed. For example, diesel failure due to no fuel in the fuel storage tanks.
	OT	Other	Used when the cause of a failure is provided but does not meet any of the descriptions.
	OK	Unknown	Used when the cause of the failure is unknown.

Table 15 shows the number of partial CCF events, the number of complete CCF events, and the total number of CCF events for the GC cause group. The same binomial regression treatment used for complete CCF events was conducted. The estimated number of complete CCF events for each group size is listed in Table 15, as well.

Table 15. CCF data for GC cause group from 1997 through 2015.

Group Size	No. Partial CCF Events	No. Complete CCF Events	Total No. CCF Events	Prob. of Complete CCF Event - Data	Prob. of Complete CCF Event - Curve Fitting	Estimated No. of Complete CCF Events
2	11	5	16	0.31250	0.39631	6.34089
3	3	2	5	0.40000	0.21374	1.06870
4	14	0	14	0.00000	0.11532	1.61442
5	1	0	1	0.00000	0.07261	0.07261
6	8	3	11	0.27273	0.05584	0.61426
7	0	0	0	NA	0.04952	0.00000
8	11	0	11	0.00000	0.04717	0.51890
9	0	0	0	NA	0.04631	0.00000
10	0	0	0	NA	0.04599	0.00000
11	2	0	2	0.00000	0.04587	0.09174
12	0	0	0	NA	0.04583	0.00000
13	0	0	0	NA	0.04581	0.00000
14	0	0	0	NA	0.04580	0.00000
15	0	0	0	NA	0.04580	0.00000
16	1	0	1	0.00000	0.04580	0.04580
Total	51	10	61			10.36732

Table 16 shows the mapped impact vectors for the partial CCF events in the GC cause groups sized 2–16, as obtained from the CCF Database website. Table 17 shows the adjusted n_k results for CCF events in GC cause groups sized 2–16, after adding the estimated number of complete CCF events. The MLEs or mean values of alpha factors for GC cause groups of each size are then calculated, while the CalcPrior code is used to estimate the prior distributions for causal alpha factors pertaining to the GC cause group. Table 18 and Table 19 show the mean values and the distributions results, respectively.

Table 16. nk values for the partial CCF events in the GC cause group from 1997 through 2015.

Group Size	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9	n_{10}	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}	n_{16}
2	28.952	6.780														
3	30.077	13.350	2.330													
4	27.723	18.633	5.316	1.017												
5	27.477	18.744	8.284	3.147	0.532											
6	26.998	18.665	9.944	4.852	1.938	0.286										
7	28.048	17.059	10.491	6.515	3.230	1.189	0.160									
8	28.880	16.218	10.375	7.248	4.628	2.111	0.750	0.091								
9	28.939	16.431	9.947	7.683	5.404	3.115	1.469	0.475	0.053							
10	28.924	16.622	9.761	7.681	5.918	3.932	2.216	1.021	0.303	0.0312						
11	28.839	16.814	9.719	7.530	6.145	4.542	2.907	1.612	0.710	0.1946	0.0189					
12	28.931	16.687	9.861	7.373	6.165	4.928	3.495	2.186	1.182	0.4938	0.1262	0.0116				
13	28.998	16.574	10.010	7.279	6.076	5.114	3.944	2.712	1.661	0.8692	0.3445	0.0826	0.0072			
14	29.042	16.483	10.140	7.251	5.954	5.150	4.237	3.159	2.120	1.2684	0.6406	0.2412	0.0546	0.0046		
15	29.063	16.418	10.240	7.276	5.849	5.094	4.387	3.502	2.537	1.6642	0.9715	0.4730	0.1695	0.0363	0.0029	
16	29.062	16.379	10.309	7.333	5.781	4.999	4.425	3.730	2.889	2.0406	1.3103	0.7457	0.3501	0.1196	0.0243	0.0019

Table 17. Adjusted nk values for CCF events in the GC cause group from 1997 through 2015.

Group Size	n_t	n_I	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9	n_{10}	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}	n_{16}
2	1203.19	1161.12	28.952	13.121														
3	1788.50	1741.67	30.077	13.350	3.399													
4	2376.53	2322.23	27.723	18.633	5.316	2.631												
5	2961.05	2902.79	27.477	18.744	8.284	3.147	0.605											
6	3546.64	3483.34	26.998	18.665	9.944	4.852	1.938	0.901										
7	4130.59	4063.90	28.048	17.059	10.491	6.515	3.230	1.189	0.160									
8	4715.28	4644.46	28.880	16.218	10.375	7.248	4.628	2.111	0.750	0.610								
9	5298.54	5225.02	28.939	16.431	9.947	7.683	5.404	3.115	1.469	0.475	0.053							
10	5881.98	5805.57	28.924	16.622	9.761	7.681	5.918	3.932	2.216	1.021	0.303	0.031						
11	6465.25	6386.13	28.839	16.814	9.719	7.530	6.145	4.542	2.907	1.612	0.710	0.195	0.111					
12	7048.13	6966.69	28.931	16.687	9.861	7.373	6.165	4.928	3.495	2.186	1.182	0.494	0.126	0.012				
13	7630.92	7547.25	28.998	16.574	10.010	7.279	6.076	5.114	3.944	2.712	1.661	0.869	0.344	0.083	0.007			
14	8213.55	8127.80	29.042	16.483	10.140	7.251	5.954	5.150	4.237	3.159	2.120	1.268	0.641	0.241	0.055	0.005		
15	8796.04	8708.36	29.063	16.418	10.240	7.276	5.849	5.094	4.387	3.502	2.537	1.664	0.971	0.473	0.170	0.036	0.003	
16	9378.47	9288.92	29.062	16.379	10.309	7.333	5.781	4.999	4.425	3.730	2.889	2.041	1.310	0.746	0.350	0.120	0.024	0.048

Table 18. Calculated alpha factor mean values for CCF events in the GC cause group from 1997 through 2015.

Group Size	α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8	α_9	α_{10}	α_{11}	α_{12}	α_{13}	α_{14}	α_{15}	α_{16}
2	0.9891	1.091E-02														
3	0.9906	7.464E-03	1.900E-03													
4	0.9888	7.840E-03	2.237E-03	1.107E-03												
5	0.9896	6.330E-03	2.798E-03	1.063E-03	2.043E-04											
6	0.9898	5.263E-03	2.804E-03	1.368E-03	5.464E-04	2.539E-04										
7	0.9906	4.130E-03	2.540E-03	1.577E-03	7.818E-04	2.878E-04	3.864E-05									
8	0.9911	3.439E-03	2.200E-03	1.537E-03	9.815E-04	4.477E-04	1.590E-04	1.293E-04								
9	0.9916	3.101E-03	1.877E-03	1.450E-03	1.020E-03	5.880E-04	2.773E-04	8.963E-05	9.946E-06							
10	0.9919	2.826E-03	1.659E-03	1.306E-03	1.006E-03	6.685E-04	3.767E-04	1.736E-04	5.146E-05	5.309E-06						
11	0.9922	2.601E-03	1.503E-03	1.165E-03	9.505E-04	7.024E-04	4.496E-04	2.493E-04	1.098E-04	3.010E-05	1.711E-05					
12	0.9925	2.368E-03	1.399E-03	1.046E-03	8.748E-04	6.992E-04	4.959E-04	3.102E-04	1.677E-04	7.006E-05	1.791E-05	1.646E-06				
13	0.9928	2.172E-03	1.312E-03	9.538E-04	7.962E-04	6.702E-04	5.168E-04	3.554E-04	2.177E-04	1.139E-04	4.514E-05	1.083E-05	9.495E-07			
14	0.9931	2.007E-03	1.235E-03	8.829E-04	7.249E-04	6.270E-04	5.159E-04	3.846E-04	2.581E-04	1.544E-04	7.799E-05	2.936E-05	6.644E-06	5.584E-07		
15	0.9933	1.867E-03	1.164E-03	8.272E-04	6.649E-04	5.791E-04	4.988E-04	3.981E-04	2.884E-04	1.892E-04	1.104E-04	5.378E-05	1.927E-05	4.129E-06	3.337E-07	
16	0.9936	1.746E-03	1.099E-03	7.819E-04	6.164E-04	5.331E-04	4.718E-04	3.977E-04	3.081E-04	2.176E-04	1.397E-04	7.951E-05	3.733E-05	1.275E-05	2.595E-06	5.086E-06

Table 19. Estimated CCF industry-wide prior distributions with CCF events in the GC cause group from 1997 through 2015.

Group Size	α_1	b_1	α_2	b_2	α_3	b_3	α_4	b_4	α_5	b_5	α_6	b_6	α_7	b_7	α_8	b_8
2	4.384E+01	4.834E-01	4.834E-01	4.384E+01												
3	1.297E+02	1.226E+00	9.769E-01	1.299E+02	2.487E-01	1.306E+02										
4	1.819E+02	2.057E+00	1.442E+00	1.825E+02	4.114E-01	1.835E+02	2.036E-01	1.837E+02								
5	3.506E+02	3.683E+00	2.243E+00	3.521E+02	9.912E-01	3.533E+02	3.765E-01	3.539E+02	7.237E-02	3.542E+02						
6	4.003E+02	4.139E+00	2.128E+00	4.023E+02	1.134E+00	4.033E+02	5.533E-01	4.039E+02	2.210E-01	4.042E+02	1.027E-01	4.043E+02				
7	6.811E+02	6.432E+00	2.840E+00	6.847E+02	1.746E+00	6.858E+02	1.084E+00	6.865E+02	5.376E-01	6.870E+02	1.979E-01	6.874E+02	2.656E-02	6.875E+02		
8	6.811E+02	6.112E+00	2.364E+00	6.848E+02	1.512E+00	6.857E+02	1.056E+00	6.861E+02	6.745E-01	6.865E+02	3.076E-01	6.869E+02	1.093E-01	6.871E+02	8.885E-02	6.871E+02
9	1.140E+03	9.669E+00	3.564E+00	1.146E+03	2.158E+00	1.147E+03	1.666E+00	1.148E+03	1.172E+00	1.148E+03	6.758E-01	1.149E+03	3.187E-01	1.149E+03	1.030E-01	1.149E+03

Group Size	α_1	b_1	α_2	b_2	α_3	b_3	α_4	b_4	α_5	b_5	α_6	b_6	α_7	b_7	α_8	b_8
10	1.424E+03	1.159E+01	4.057E+00	1.432E+03	2.382E+00	1.433E+03	1.875E+00	1.434E+03	1.444E+00	1.434E+03	9.597E-01	1.435E+03	5.408E-01	1.435E+03	2.493E-01	1.435E+03
11	1.466E+03	1.149E+01	3.842E+00	1.474E+03	2.221E+00	1.475E+03	1.721E+00	1.476E+03	1.404E+00	1.476E+03	1.038E+00	1.476E+03	6.643E-01	1.477E+03	3.683E-01	1.477E+03
12	2.120E+03	1.592E+01	5.058E+00	2.131E+03	2.989E+00	2.133E+03	2.235E+00	2.134E+03	1.869E+00	2.134E+03	1.494E+00	2.135E+03	1.060E+00	2.135E+03	6.626E-01	2.136E+03
13	2.538E+03	1.832E+01	5.553E+00	2.551E+03	3.354E+00	2.553E+03	2.439E+00	2.554E+03	2.036E+00	2.555E+03	1.713E+00	2.555E+03	1.321E+00	2.555E+03	9.086E-01	2.556E+03
14	3.006E+03	2.090E+01	6.074E+00	3.021E+03	3.737E+00	3.023E+03	2.672E+00	3.024E+03	2.194E+00	3.025E+03	1.898E+00	3.025E+03	1.562E+00	3.025E+03	1.164E+00	3.026E+03
15	3.527E+03	2.366E+01	6.627E+00	3.544E+03	4.133E+00	3.546E+03	2.937E+00	3.548E+03	2.361E+00	3.548E+03	2.056E+00	3.548E+03	1.771E+00	3.549E+03	1.413E+00	3.549E+03
16	3.310E+03	2.149E+01	5.818E+00	3.326E+03	3.662E+00	3.328E+03	2.605E+00	3.329E+03	2.054E+00	3.330E+03	1.776E+00	3.330E+03	1.572E+00	3.330E+03	1.325E+00	3.330E+03

Group Size	α_9	b_9	α_{10}	b_{10}	α_{11}	b_{11}	α_{12}	b_{12}	α_{13}	b_{13}	α_{14}	b_{14}	α_{15}	b_{15}	α_{16}	b_{16}
9	1.143E-02	1.149E+03														
10	7.388E-02	1.436E+03	7.622E-03	1.436E+03												
11	1.622E-01	1.477E+03	4.446E-02	1.477E+03	2.528E-02	1.477E+03										
12	3.582E-01	2.136E+03	1.497E-01	2.136E+03	3.826E-02	2.136E+03	3.516E-03	2.136E+03								
13	5.564E-01	2.556E+03	2.912E-01	2.556E+03	1.154E-01	2.557E+03	2.769E-02	2.557E+03	2.427E-03	2.557E+03						
14	7.811E-01	3.026E+03	4.674E-01	3.026E+03	2.361E-01	3.027E+03	8.888E-02	3.027E+03	2.011E-02	3.027E+03	1.690E-03	3.027E+03				
15	1.024E+00	3.549E+03	6.717E-01	3.550E+03	3.921E-01	3.550E+03	1.909E-01	3.550E+03	6.843E-02	3.550E+03	1.466E-02	3.551E+03	1.185E-03	3.551E+03		
16	1.026E+00	3.331E+03	7.249E-01	3.331E+03	4.655E-01	3.331E+03	2.649E-01	3.331E+03	1.244E-01	3.331E+03	4.249E-02	3.332E+03	8.646E-03	3.332E+03		

4.2 Prior Distributions for the "Design" Cause Group (GD)

To estimate prior distributions for GD (i.e., Design) CCF cause group, the following selection criteria are defined on the CCF Database website:

- Type of CCF Event Level: All Level CCF Events
- CCF Event Type: CCF Events Only
- Date Range: 1997–2015
- Filter Independent Events by Selected Cause(s): True
- Shock Criteria: All Events
- Redundancy Range: Minimum = 2, Maximum = 16
- Bayesian Update Method: Mean Method
- Failure Modes: select all failure modes except Setpoint
- CCF Categories: Cause → Design

A total of 74 CCF events and 1,128.0 effective independent failure events related to the above selection criteria.

Additional criterion on CCF Categories → Degree → Almost/Partial or Complete is used to obtain the partial CCF events and complete CCF events, as required in the existing process. The unmapped/mapped impact vectors are also acquired from the CCF Database website. The mapped impact vectors for partial CCF events for each group size obtained from the website are used directly in the study.

Table 20 shows the number of partial CCF events, the number of complete CCF events, and the total number of CCF events for the GD cause group. The same binomial regression treatment used for complete CCF events was conducted. The estimated number of complete CCF events for each group size is listed in Table 20.

Table 21 shows the mapped impact vectors for partial CCF events for the GD cause groups sized 2–16, as obtained from the CCF Database website. Table 22 shows the adjusted n_k results for CCF events in GD cause groups sized 2–16, after adding the estimated number of complete CCF events. The MLEs or mean values of alpha factors for the GD cause groups of each size are then calculated, while the CalcPrior code is used to estimate the prior distributions for causal alpha factors pertaining to the GD cause group. Table 23 and Table 24 show the mean values and the distributions results, respectively.

Table 20. CCF data for the GD cause group from 1997 through 2015.

Group Size	No. Partial CCF Events	No. Complete CCF Events	Total No. CCF Events	Prob. of Complete CCF Event - Data	Prob. of Complete CCF Event - Curve Fitting	Estimated No. of Complete CCF Events
2	7	7	14	0.50000	0.44260	6.19640
3	7	2	9	0.22222	0.24527	2.20746
4	18	1	19	0.05263	0.13226	2.51302
5	2	0	2	0.00000	0.08168	0.16336
6	7	0	7	0.00000	0.06155	0.43088
7	1	0	1	0.00000	0.05393	0.05393
8	11	0	11	0.00000	0.05109	0.56198

Group Size	No. Partial CCF Events	No. Complete CCF Events	Total No. CCF Events	Prob. of Complete CCF Event - Data	Prob. of Complete CCF Event - Curve Fitting	Estimated No. of Complete CCF Events
9	0	0	0	NA	0.05004	0.00000
10	0	0	0	NA	0.04965	0.00000
11	2	0	2	0.00000	0.04951	0.09902
12	1	1	2	0.50000	0.04946	0.09892
13	0	0	0	NA	0.04944	0.00000
14	1	0	1	0.00000	0.04943	0.04943
15	0	0	0	NA	0.04943	0.00000
16	6	0	6	0.00000	0.04943	0.29658
Total	63	11	74			12.67097

Table 21. nk values for the partial CCF events in the GD cause group from 1997 through 2015.

Group Size	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9	n_{10}	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}	n_{16}
2	30.924	7.492														
3	29.907	16.480	1.999													
4	27.738	20.373	6.224	0.985												
5	28.283	18.667	10.107	3.404	0.516											
6	28.558	17.382	11.932	5.535	2.072	0.257										
7	28.906	17.494	10.841	7.348	3.977	1.173	0.126									
8	28.741	18.152	10.287	7.446	5.320	2.882	0.558	0.072								
9	29.056	17.918	10.391	7.472	5.706	3.798	1.968	0.337	0.042							
10	29.205	17.784	10.680	7.285	5.906	4.375	2.803	1.342	0.202	0.0248						
11	29.245	17.640	11.130	7.102	5.881	4.740	3.377	2.110	0.906	0.1213	0.0152					
12	29.171	17.825	11.134	7.245	5.652	4.984	3.742	2.669	1.591	0.6000	0.0743	0.0096				
13	29.033	17.986	11.172	7.514	5.356	5.011	4.126	2.922	2.200	1.1635	0.3942	0.0478	0.0063			
14	28.807	18.184	11.174	7.836	5.319	4.480	4.794	2.954	2.540	1.7880	0.8132	0.2644	0.0324	0.0041		
15	28.502	18.429	11.100	8.218	5.328	4.404	4.391	3.646	2.404	2.3444	1.3564	0.5534	0.1869	0.0221	0.0027	
16	28.123	18.741	10.914	8.659	5.388	4.324	4.122	3.818	2.876	1.9570	2.3277	0.8259	0.4211	0.1328	0.0152	0.0018

Table 22. Adjusted nk values for CCF events in the GD cause group from 1997 through 2015.

Group Size	n_t	n_I	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9	n_{10}	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}	n_{16}
2	429.27	384.66	30.924	13.689														
3	627.59	577.00	29.907	16.480	4.207													
4	827.16	769.33	27.738	20.373	6.224	3.498												
5	1022.80	961.66	28.283	18.667	10.107	3.404	0.679											
6	1220.16	1153.99	28.558	17.382	11.932	5.535	2.072	0.688										
7	1416.24	1346.32	28.906	17.494	10.841	7.348	3.977	1.173	0.180									
8	1612.67	1538.65	28.741	18.152	10.287	7.446	5.320	2.882	0.558	0.634								

Group Size	n_t	n_I	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9	n_{10}	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}	n_{16}
9	1807.68	1730.99	29.056	17.918	10.391	7.472	5.706	3.798	1.968	0.337	0.042							
10	2002.93	1923.32	29.205	17.784	10.680	7.285	5.906	4.375	2.803	1.342	0.202	0.0248						
11	2198.02	2115.65	29.245	17.640	11.130	7.102	5.881	4.740	3.377	2.110	0.906	0.121	0.1142					
12	2392.78	2307.98	29.171	17.825	11.134	7.245	5.652	4.984	3.742	2.669	1.591	0.600	0.074	0.1086				
13	2587.24	2500.31	29.033	17.986	11.172	7.514	5.356	5.011	4.126	2.922	2.200	1.164	0.394	0.048	0.0063			
14	2781.69	2692.65	28.807	18.184	11.174	7.836	5.319	4.480	4.794	2.954	2.540	1.788	0.813	0.264	0.032	0.0535		
15	2975.87	2884.98	28.502	18.429	11.100	8.218	5.328	4.404	4.391	3.646	2.404	2.344	1.356	0.553	0.187	0.022	0.0027	
16	3170.25	3077.31	28.123	18.741	10.914	8.659	5.388	4.324	4.122	3.818	2.876	1.957	2.328	0.826	0.421	0.133	0.015	0.2984

Table 23. Calculated alpha factor mean values for CCF events in the GD cause group from 1997 through 2015.

Group Size	α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8	α_9	α_{10}	α_{11}	α_{12}	α_{13}	α_{14}	α_{15}	α_{16}
2	0.9681	3.189E-02														
3	0.9670	2.626E-02	6.703E-03													
4	0.9636	2.463E-02	7.525E-03	4.229E-03												
5	0.9679	1.825E-02	9.882E-03	3.328E-03	6.641E-04											
6	0.9692	1.425E-02	9.779E-03	4.536E-03	1.698E-03	5.640E-04										
7	0.9710	1.235E-02	7.655E-03	5.188E-03	2.808E-03	8.283E-04	1.272E-04									
8	0.9719	1.126E-02	6.379E-03	4.617E-03	3.299E-03	1.787E-03	3.463E-04	3.933E-04								
9	0.9737	9.912E-03	5.748E-03	4.133E-03	3.156E-03	2.101E-03	1.089E-03	1.866E-04	2.317E-05							
10	0.9748	8.879E-03	5.332E-03	3.637E-03	2.949E-03	2.185E-03	1.400E-03	6.702E-04	1.011E-04	1.238E-05						
11	0.9758	8.025E-03	5.064E-03	3.231E-03	2.675E-03	2.157E-03	1.536E-03	9.599E-04	4.121E-04	5.519E-05	5.196E-05					
12	0.9768	7.450E-03	4.653E-03	3.028E-03	2.362E-03	2.083E-03	1.564E-03	1.115E-03	6.650E-04	2.508E-04	3.106E-05	4.537E-05				
13	0.9776	6.952E-03	4.318E-03	2.904E-03	2.070E-03	1.937E-03	1.595E-03	1.129E-03	8.501E-04	4.497E-04	1.523E-04	1.849E-05	2.423E-06			
14	0.9783	6.537E-03	4.017E-03	2.817E-03	1.912E-03	1.610E-03	1.723E-03	1.062E-03	9.130E-04	6.428E-04	2.923E-04	9.503E-05	1.163E-05	1.924E-05		
15	0.9790	6.193E-03	3.730E-03	2.762E-03	1.790E-03	1.480E-03	1.476E-03	1.225E-03	8.079E-04	7.878E-04	4.558E-04	1.860E-04	6.281E-05	7.419E-06	9.043E-07	
16	0.9796	5.912E-03	3.443E-03	2.731E-03	1.700E-03	1.364E-03	1.300E-03	1.204E-03	9.071E-04	6.173E-04	7.342E-04	2.605E-04	1.328E-04	4.190E-05	4.784E-06	9.411E-05

Table 24. Estimated CCF industry-wide prior distributions with CCF events in the GD cause group from 1997 through 2015.

Group Size	α_1	b_1	α_2	b_2	α_3	b_3	α_4	b_4	α_5	b_5	α_6	b_6	α_7	b_7	α_8	b_8
2	1.366E+01	4.498E-01	4.498E-01	1.366E+01												
3	3.457E+01	1.178E+00	9.387E-01	3.481E+01	2.396E-01	3.551E+01										
4	5.029E+01	1.899E+00	1.285E+00	5.090E+01	3.927E-01	5.179E+01	2.207E-01	5.197E+01								
5	1.056E+02	3.506E+00	1.992E+00	1.071E+02	1.078E+00	1.081E+02	3.632E-01	1.088E+02	7.248E-02	1.091E+02						
6	1.321E+02	4.200E+00	1.941E+00	1.343E+02	1.332E+00	1.349E+02	6.181E-01	1.356E+02	2.313E-01	1.360E+02	7.684E-02	1.362E+02				
7	2.087E+02	6.223E+00	2.654E+00	2.122E+02	1.645E+00	2.132E+02	1.115E+00	2.138E+02	6.034E-01	2.143E+02	1.780E-01	2.147E+02	2.734E-02	2.149E+02		
8	2.162E+02	6.245E+00	2.504E+00	2.199E+02	1.419E+00	2.210E+02	1.027E+00	2.214E+02	7.337E-01	2.217E+02	3.975E-01	2.220E+02	7.703E-02	2.223E+02	8.749E-02	2.223E+02
9	3.756E+02	1.016E+01	3.824E+00	3.819E+02	2.217E+00	3.835E+02	1.594E+00	3.842E+02	1.218E+00	3.845E+02	8.105E-01	3.849E+02	4.200E-01	3.853E+02	7.199E-02	3.857E+02
10	4.693E+02	1.212E+01	4.275E+00	4.772E+02	2.567E+00	4.789E+02	1.751E+00	4.797E+02	1.420E+00	4.800E+02	1.052E+00	4.804E+02	6.739E-01	4.808E+02	3.227E-01	4.811E+02
11	4.711E+02	1.167E+01	3.874E+00	4.789E+02	2.445E+00	4.803E+02	1.560E+00	4.812E+02	1.292E+00	4.815E+02	1.041E+00	4.817E+02	7.416E-01	4.820E+02	4.634E-01	4.823E+02
12	5.588E+02	1.330E+01	4.262E+00	5.679E+02	2.662E+00	5.695E+02	1.732E+00	5.704E+02	1.351E+00	5.708E+02	1.192E+00	5.709E+02	8.946E-01	5.712E+02	6.382E-01	5.715E+02
13	8.293E+02	1.898E+01	5.897E+00	8.424E+02	3.663E+00	8.446E+02	2.464E+00	8.458E+02	1.756E+00	8.466E+02	1.643E+00	8.467E+02	1.353E+00	8.470E+02	9.581E-01	8.474E+02
14	8.017E+02	1.774E+01	5.357E+00	8.141E+02	3.292E+00	8.162E+02	2.309E+00	8.172E+02	1.567E+00	8.179E+02	1.320E+00	8.182E+02	1.412E+00	8.181E+02	8.703E-01	8.186E+02
15	1.138E+03	2.437E+01	7.200E+00	1.155E+03	4.337E+00	1.158E+03	3.211E+00	1.159E+03	2.081E+00	1.161E+03	1.721E+00	1.161E+03	1.716E+00	1.161E+03	1.425E+00	1.161E+03
16	9.389E+02	1.960E+01	5.667E+00	9.529E+02	3.300E+00	9.552E+02	2.618E+00	9.559E+02	1.629E+00	9.569E+02	1.308E+00	9.572E+02	1.246E+00	9.573E+02	1.154E+00	9.574E+02

Group Size	α_9	b_9	α_{10}	b_{10}	α_{11}	b_{11}	α_{12}	b_{12}	α_{13}	b_{13}	α_{14}	b_{14}	α_{15}	b_{15}	α_{16}	b_{16}
9	8.938E-03	3.857E+02														
10	4.866E-02	4.814E+02	5.959E-03	4.815E+02												
11	1.989E-01	4.825E+02	2.664E-02	4.827E+02	2.509E-02	4.827E+02										
12	3.805E-01	5.717E+02	1.435E-01	5.720E+02	1.777E-02	5.721E+02	2.596E-02	5.721E+02								
13	7.212E-01	8.476E+02	3.815E-01	8.479E+02	1.292E-01	8.482E+02	1.569E-02	8.483E+02	2.056E-03	8.483E+02						
14	7.482E-01	8.187E+02	5.268E-01	8.189E+02	2.396E-01	8.192E+02	7.788E-02	8.194E+02	9.530E-03	8.195E+02	1.577E-02	8.195E+02				
15	9.393E-01	1.162E+03	9.159E-01	1.162E+03	5.299E-01	1.162E+03	2.162E-01	1.162E+03	7.302E-02	1.163E+03	8.625E-03	1.163E+03	1.051E-03	1.163E+03		
16	8.695E-01	9.577E+02	5.917E-01	9.579E+02	7.038E-01	9.578E+02	2.497E-01	9.583E+02	1.273E-01	9.584E+02	4.016E-02	9.585E+02	4.586E-03	9.585E+02	9.021E-02	9.584E+02

4.3 Prior Distributions for the "Environment" Cause Group (GE)

To estimate prior distributions for the GE (i.e., Environment) CCF cause group, the following selection criteria are defined in the CCF Database website:

- Type of CCF Event Level: All Level CCF Events
- CCF Event Type: CCF Events Only
- Date Range: 1997–2015
- Filter Independent Events by Selected Cause(s): True
- Shock Criteria: All Events
- Redundancy Range: Minimum = 2, Maximum = 16
- Bayesian Update Method: Mean Method
- Failure Modes: select all failure modes except Setpoint
- CCF Categories: Cause → Environment

A total of 57 CCF events and 467.9 effective independent failure events related to the above selection criteria.

Additional criterion on CCF Categories → Degree → Almost/Partial or Complete is used to obtain the partial CCF events and complete CCF events, as required in the existing process. The unmapped/mapped impact vectors are also acquired from the CCF Database website. The mapped impact vectors for partial CCF events for each group size obtained from the website are used directly in the study.

Table 25 shows the number of partial CCF events, the number of complete CCF events, and the total number of CCF events for the GE cause group. The same binomial regression treatment used for complete CCF events was conducted. The estimated number of complete CCF events for each group size is listed in Table 25[b].

Table 26 shows the mapped impact vectors for partial CCF events for the GE cause groups sized 2–16, as obtained from the CCF Database website. Table 27 shows the adjusted n_k results for CCF events in the GE cause groups sized 2–16, after adding the estimated number of complete CCF events. The MLEs or mean values of alpha factors for the GE cause groups of each size are then calculated, while the CalcPrior code is used to estimate the prior distributions for causal alpha factors pertaining to the GE cause group. Table 28 and Table 29 show the mean values and the distributions results, respectively.

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[b] Note that the curve-fitting parameter value calculated by MatLab using Eq. 5 would lead to negative values for higher group sizes. Thus, the curve parameter value was adjusted manually to avoid negative values for the probability of complete CCF events.

Table 25. CCF data for the GE cause group from 1997 through 2015.

Group Size	No. Partial CCF Events	No. Complete CCF Events	Total No. CCF Events	Prob. of Complete CCF Event - Data	Prob. of Complete CCF Event - Curve Fitting	Estimated No. of Complete CCF Events
2	2	11	13	0.84615	0.72767	9.45974
3	5	6	11	0.54545	0.49731	5.47045
4	15	1	16	0.06250	0.27022	4.32346
5	2	0	2	0.00000	0.12475	0.24951
6	9	0	9	0.00000	0.05550	0.49947
7	1	0	1	0.00000	0.02718	0.02718
8	0	0	0	NA	0.01633	0.00000
9	0	0	0	NA	0.01227	0.00000
10	0	0	0	NA	0.01078	0.00000
11	0	0	0	NA	0.01022	0.00000
12	5	0	5	0.00000	0.01002	0.05010
13	0	0	0	NA	0.00994	0.00000
14	0	0	0	NA	0.00992	0.00000
15	0	0	0	NA	0.00991	0.00000
16	0	0	0	NA	0.00990	0.00000
Total	39	18	57			20.07989

Table 26. nk values for the partial CCF events in the GE cause group from 1997 through 2015.

Group Size	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9	n_{10}	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}	n_{16}
2	23.211	8.115														
3	17.219	17.597	2.249													
4	9.728	21.221	7.941	0.608												
5	7.219	17.451	11.757	4.228	0.286											
6	6.310	12.373	14.186	6.664	2.286	0.175										
7	5.790	9.950	12.775	8.263	4.440	1.495	0.108									
8	5.204	8.635	10.833	9.116	5.515	3.114	0.986	0.068								
9	4.562	7.792	9.217	9.160	6.296	4.025	2.229	0.655	0.043							
10	3.863	7.303	7.835	8.822	6.781	4.611	3.077	1.608	0.437	0.0273						
11	3.097	7.117	6.580	8.367	6.965	5.076	3.573	2.398	1.162	0.2925	0.0175					
12	2.243	7.230	5.347	7.952	6.894	5.439	3.923	2.882	1.875	0.8397	0.1964	0.0113				
13	2.086	6.419	4.969	6.954	6.912	5.672	4.234	3.171	2.370	1.4618	0.6056	0.1321	0.0073			
14	1.956	5.723	4.649	6.119	6.666	5.835	4.516	3.394	2.655	1.9578	1.1329	0.4359	0.0890	0.0047		
15	1.849	5.120	4.370	5.427	6.278	5.879	4.764	3.615	2.828	2.2662	1.6114	0.8724	0.3131	0.0600	0.0031	
16	1.763	4.596	4.119	4.857	5.827	5.802	4.949	3.845	2.977	2.4338	1.9458	1.3170	0.6676	0.2244	0.0406	0.0020

Table 27. Adjusted nk values for CCF events in the GE cause group from 1997 through 2015.

Group Size	n_t	n_I	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9	n_{10}	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}	n_{16}
2	250.79	210.00	23.211	17.574														
3	357.54	315.00	17.219	17.597	7.719													
4	463.82	420.00	9.728	21.221	7.941	4.931												
5	566.20	525.01	7.219	17.451	11.757	4.228	0.535											
6	672.50	630.01	6.310	12.373	14.186	6.664	2.286	0.674										
7	777.86	735.01	5.790	9.950	12.775	8.263	4.440	1.495	0.136									
8	883.48	840.01	5.204	8.635	10.833	9.116	5.515	3.114	0.986	0.068								
9	988.99	945.01	4.562	7.792	9.217	9.160	6.296	4.025	2.229	0.655	0.043							
10	1094.37	1050.01	3.863	7.303	7.835	8.822	6.781	4.611	3.077	1.608	0.437	0.0273						
11	1199.66	1155.01	3.097	7.117	6.580	8.367	6.965	5.076	3.573	2.398	1.162	0.293	0.0175					
12	1304.89	1260.01	2.243	7.230	5.347	7.952	6.894	5.439	3.923	2.882	1.875	0.840	0.196	0.0614				
13	1410.01	1365.02	2.086	6.419	4.969	6.954	6.912	5.672	4.234	3.171	2.370	1.462	0.606	0.132	0.0073			
14	1515.15	1470.02	1.956	5.723	4.649	6.119	6.666	5.835	4.516	3.394	2.655	1.958	1.133	0.436	0.089	0.0047		
15	1620.28	1575.02	1.849	5.120	4.370	5.427	6.278	5.879	4.764	3.615	2.828	2.266	1.611	0.872	0.313	0.060	0.0031	
16	1725.39	1680.02	1.763	4.596	4.119	4.857	5.827	5.802	4.949	3.845	2.977	2.434	1.946	1.317	0.668	0.224	0.041	0.0020

Table 28. Calculated alpha factor mean values for CCF events in the GE cause group from 1997 through 2015.

Group Size	α_1	b_1	α_2	b_2	α_3	b_3	α_4	b_4	α_5	b_5	α_6	b_6	α_7	b_7	α_8	b_8
2	0.9299	7.008E-02														
3	0.9292	4.922E-02	2.159E-02													
4	0.9265	4.575E-02	1.712E-02	1.063E-02												
5	0.9400	3.082E-02	2.076E-02	7.468E-03	9.452E-04											
6	0.9462	1.840E-02	2.109E-02	9.909E-03	3.399E-03	1.003E-03										
7	0.9524	1.279E-02	1.642E-02	1.062E-02	5.708E-03	1.921E-03	1.744E-04									
8	0.9567	9.774E-03	1.226E-02	1.032E-02	6.242E-03	3.524E-03	1.117E-03	7.686E-05								
9	0.9601	7.878E-03	9.320E-03	9.262E-03	6.366E-03	4.070E-03	2.254E-03	6.624E-04	4.337E-05							
10	0.9630	6.673E-03	7.159E-03	8.061E-03	6.196E-03	4.213E-03	2.812E-03	1.470E-03	3.993E-04	2.494E-05						
11	0.9654	5.933E-03	5.485E-03	6.974E-03	5.806E-03	4.231E-03	2.978E-03	1.999E-03	9.689E-04	2.438E-04	1.457E-05					
12	0.9673	5.541E-03	4.098E-03	6.094E-03	5.283E-03	4.168E-03	3.006E-03	2.209E-03	1.437E-03	6.435E-04	1.505E-04	4.702E-05				
13	0.9696	4.552E-03	3.524E-03	4.932E-03	4.902E-03	4.023E-03	3.003E-03	2.249E-03	1.681E-03	1.037E-03	4.295E-04	9.367E-05	5.166E-06			
14	0.9715	3.777E-03	3.068E-03	4.038E-03	4.400E-03	3.851E-03	2.981E-03	2.240E-03	1.752E-03	1.292E-03	7.477E-04	2.877E-04	5.874E-05	3.123E-06		
15	0.9732	3.160E-03	2.697E-03	3.349E-03	3.875E-03	3.628E-03	2.940E-03	2.231E-03	1.746E-03	1.399E-03	9.945E-04	5.384E-04	1.932E-04	3.706E-05	1.903E-06	
16	0.9747	2.664E-03	2.387E-03	2.815E-03	3.377E-03	3.363E-03	2.869E-03	2.229E-03	1.725E-03	1.411E-03	1.128E-03	7.633E-04	3.870E-04	1.301E-04	2.350E-05	1.168E-06

Table 29. Estimated CCF industry-wide prior distributions with CCF events in the GE cause group from 1997 through 2015.

Group Size	α_1	b_1	α_2	b_2	α_3	b_3	α_4	b_4	α_5	b_5	α_6	b_6	α_7	b_7	α_8	b_8
2	5.044E+00	3.801E-01	3.801E-01	5.044E+00												
3	1.260E+01	9.601E-01	6.673E-01	1.289E+01	2.927E-01	1.327E+01										
4	2.103E+01	1.669E+00	1.039E+00	2.166E+01	3.887E-01	2.231E+01	2.414E-01	2.246E+01								
5	5.463E+01	3.487E+00	1.791E+00	5.632E+01	1.207E+00	5.691E+01	4.340E-01	5.768E+01	5.493E-02	5.806E+01						
6	6.867E+01	3.905E+00	1.335E+00	7.124E+01	1.531E+00	7.104E+01	7.191E-01	7.186E+01	2.467E-01	7.233E+01	7.279E-02	7.250E+01				
7	1.154E+02	5.770E+00	1.549E+00	1.196E+02	1.989E+00	1.191E+02	1.287E+00	1.198E+02	6.913E-01	1.204E+02	2.327E-01	1.209E+02	2.112E-02	1.211E+02		
8	1.550E+02	7.017E+00	1.583E+00	1.604E+02	1.986E+00	1.600E+02	1.672E+00	1.603E+02	1.011E+00	1.610E+02	5.709E-01	1.614E+02	1.809E-01	1.618E+02	1.245E-02	1.620E+02
9	1.961E+02	8.141E+00	1.609E+00	2.027E+02	1.904E+00	2.024E+02	1.892E+00	2.024E+02	1.300E+00	2.030E+02	8.313E-01	2.035E+02	4.604E-01	2.038E+02	1.353E-01	2.041E+02
10	2.435E+02	9.356E+00	1.687E+00	2.511E+02	1.810E+00	2.510E+02	2.038E+00	2.508E+02	1.567E+00	2.513E+02	1.065E+00	2.518E+02	7.108E-01	2.521E+02	3.715E-01	2.524E+02

Group Size	α_1	b_1	α_2	b_2	α_3	b_3	α_4	b_4	α_5	b_5	α_6	b_6	α_7	b_7	α_8	b_8
11	2.974E+02	1.067E+01	1.828E+00	3.062E+02	1.690E+00	3.064E+02	2.148E+00	3.059E+02	1.789E+00	3.063E+02	1.303E+00	3.068E+02	9.174E-01	3.071E+02	6.157E-01	3.074E+02
12	3.074E+02	1.039E+01	1.761E+00	3.161E+02	1.302E+00	3.165E+02	1.937E+00	3.159E+02	1.679E+00	3.162E+02	1.325E+00	3.165E+02	9.554E-01	3.169E+02	7.019E-01	3.171E+02
13	4.303E+02	1.351E+01	2.020E+00	4.418E+02	1.564E+00	4.422E+02	2.189E+00	4.416E+02	2.175E+00	4.416E+02	1.785E+00	4.420E+02	1.333E+00	4.425E+02	9.979E-01	4.428E+02
14	5.112E+02	1.499E+01	1.987E+00	5.242E+02	1.615E+00	5.246E+02	2.125E+00	5.240E+02	2.315E+00	5.239E+02	2.026E+00	5.241E+02	1.568E+00	5.246E+02	1.179E+00	5.250E+02
15	6.020E+02	1.657E+01	1.955E+00	6.166E+02	1.668E+00	6.169E+02	2.072E+00	6.165E+02	2.397E+00	6.162E+02	2.244E+00	6.163E+02	1.819E+00	6.168E+02	1.380E+00	6.172E+02
16	7.036E+02	1.824E+01	1.923E+00	7.199E+02	1.723E+00	7.201E+02	2.032E+00	7.198E+02	2.438E+00	7.194E+02	2.427E+00	7.194E+02	2.071E+00	7.197E+02	1.609E+00	7.202E+02

Group Size	α_9	b_9	α_{10}	b_{10}	α_{11}	b_{11}	α_{12}	b_{12}	α_{13}	b_{13}	α_{14}	b_{14}	α_{15}	b_{15}	α_{16}	b_{16}
9	8.859E-03	2.043E+02														
10	1.010E-01	2.527E+02	6.305E-03	2.528E+02												
11	2.985E-01	3.078E+02	7.511E-02	3.080E+02	4.489E-03	3.081E+02										
12	4.567E-01	3.174E+02	2.045E-01	3.176E+02	4.782E-02	3.178E+02	1.494E-02	3.178E+02								
13	7.460E-01	4.431E+02	4.601E-01	4.434E+02	1.906E-01	4.436E+02	4.157E-02	4.438E+02	2.293E-03	4.438E+02						
14	9.219E-01	5.253E+02	6.799E-01	5.255E+02	3.934E-01	5.258E+02	1.514E-01	5.260E+02	3.090E-02	5.261E+02	1.643E-03	5.262E+02				
15	1.080E+00	6.175E+02	8.652E-01	6.177E+02	6.152E-01	6.180E+02	3.331E-01	6.183E+02	1.195E-01	6.185E+02	2.292E-02	6.186E+02	1.177E-03	6.186E+02		
16	1.245E+00	7.206E+02	1.018E+00	7.208E+02	8.140E-01	7.210E+02	5.510E-01	7.213E+02	2.793E-01	7.215E+02	9.387E-02	7.217E+02	1.696E-02	7.218E+02	8.431E-04	7.218E+02

4.4 Prior Distributions for the "Human" Cause Group (GH)

To estimate prior distributions for the GH (i.e., Human) CCF cause group, the following selection criteria are defined in the CCF Database website:

- Type of CCF Event Level: All Level CCF Events
- CCF Event Type: CCF Events Only
- Date Range: 1997–2015
- Filter Independent Events by Selected Cause(s): True
- Shock Criteria: All Events
- Redundancy Range: Minimum = 2, Maximum = 16
- Bayesian Update Method: Mean Method
- Failure Modes: select all failure modes except Setpoint
- CCF Categories: Cause → Human

A total of 67 CCF events and 2,120.9 effective independent failure events related to the above selection criteria.

Additional criterion on CCF Categories → Degree → Almost/Partial or Complete is used to obtain the partial CCF events and complete CCF events, as required in the existing process. The unmapped/mapped impact vectors are also acquired from the CCF Database website. The mapped impact vectors for partial CCF events for each group size obtained from the website are used directly in the study.

Table 30 shows the number of partial CCF events, the number of complete CCF events, and the total number of CCF events for the GH cause group. The same binomial regression treatment used for complete CCF events was conducted. The estimated number of complete CCF events for each group size is listed in Table 30.

Table 31 shows the mapped impact vectors for partial CCF events for the GH cause groups sized 2–16 obtained from the CCF Database website. Table 32 shows the adjusted n_k results for CCF events in the GH cause groups sized 2–16, after adding the estimated number of complete CCF events. The MLEs or mean values of alpha factors for the GC cause groups of each size are then calculated, while the CalcPrior code is used to estimate the prior distributions for causal alpha factors pertaining to the GH cause group. Table 33 and Table 34 show the mean values and the distributions results, respectively.

Table 30. CCF data for the GH cause group from 1997 through 2015.

Group Size	No. Partial CCF Events	No. Complete CCF Events	Total No. CCF Events	Prob. of Complete CCF Event - Data	Prob. of Complete CCF Event - Curve Fitting	Estimated No. of Complete CCF Events
2	7	9	16	0.56250	0.46086	7.37377
3	10	2	12	0.16667	0.25147	3.01769
4	12	0	12	0.00000	0.12670	1.52042
5	2	0	2	0.00000	0.06965	0.13930
6	5	2	7	0.28571	0.04674	0.32719
7	1	0	1	0.00000	0.03803	0.03803

Group Size	No. Partial CCF Events	No. Complete CCF Events	Total No. CCF Events	Prob. of Complete CCF Event - Data	Prob. of Complete CCF Event - Curve Fitting	Estimated No. of Complete CCF Events
8	7	1	8	0.12500	0.03478	0.27825
9	0	0	0	NA	0.03358	0.00000
10	0	0	0	NA	0.03314	0.00000
11	1	0	1	0.00000	0.03298	0.03298
12	1	0	1	0.00000	0.03292	0.03292
13	0	0	0	NA	0.03289	0.00000
14	0	0	0	NA	0.03289	0.00000
15	0	0	0	NA	0.03288	0.00000
16	7	0	7	0.00000	0.03288	0.23018
Total	53	14	67			12.99072

Table 31. nk values for the partial CCF events in the GH cause group from 1997 through 2015.

Group Size	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9	n_{10}	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}	n_{16}
2	29.035	8.039														
3	28.595	15.457	2.553													
4	28.377	18.039	5.919	1.364												
5	31.267	15.626	8.745	3.540	0.776											
6	33.916	14.356	9.281	5.454	2.124	0.475										
7	36.243	14.012	8.785	6.634	3.494	1.302	0.314									
8	38.114	14.417	8.145	6.736	4.931	2.115	0.869	0.219								
9	39.948	15.045	7.649	6.459	5.260	3.406	1.456	0.605	0.158							
10	41.428	15.943	7.375	6.056	5.324	4.052	2.370	1.022	0.441	0.1185						
11	42.595	16.998	7.320	5.640	5.193	4.359	3.072	1.660	0.739	0.3347	0.0907					
12	43.705	17.835	7.554	5.277	4.949	4.443	3.523	2.293	1.176	0.5552	0.2630	0.0705				
13	44.805	18.423	8.015	5.008	4.658	4.376	3.761	2.799	1.692	0.8513	0.4341	0.2121	0.0554			
14	45.757	18.996	8.564	4.849	4.368	4.218	3.836	3.141	2.183	1.2414	0.6358	0.3522	0.1740	0.0438		
15	46.587	19.527	9.179	4.793	4.107	4.013	3.798	3.328	2.577	1.6727	0.9154	0.4938	0.2945	0.1443	0.0348	
16	47.317	19.999	9.844	4.826	3.890	3.793	3.688	3.390	2.847	2.0741	1.2657	0.6864	0.3999	0.2516	0.1205	0.0277

Table 32. Adjusted nk values for CCF events in the GH cause group from 1997 through 2015.

Group Size	n_t	n_I	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9	n_{10}	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}	n_{16}
2	804.338	759.890	29.035	15.413														
3	1189.463	1139.840	28.595	15.457	5.571													
4	1575.010	1519.790	28.377	18.039	5.919	2.885												
5	1959.833	1899.740	31.267	15.626	8.745	3.540	0.915											
6	2345.613	2279.680	33.916	14.356	9.281	5.454	2.124	0.802										

Group Size	n_t	n_I	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9	n_{10}	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}	n_{16}
7	2730.451	2659.630	36.243	14.012	8.785	6.634	3.494	1.302	0.352									
8	3115.405	3039.580	38.114	14.417	8.145	6.736	4.931	2.115	0.869	0.497								
9	3499.516	3419.530	39.948	15.045	7.649	6.459	5.260	3.406	1.456	0.605	0.158							
10	3883.599	3799.470	41.428	15.943	7.375	6.056	5.324	4.052	2.370	1.022	0.441	0.119						
11	4267.455	4179.420	42.595	16.998	7.320	5.640	5.193	4.359	3.072	1.660	0.739	0.335	0.124					
12	4651.047	4559.370	43.705	17.835	7.554	5.277	4.949	4.443	3.523	2.293	1.176	0.555	0.263	0.103				
13	5034.399	4939.310	44.805	18.423	8.015	5.008	4.658	4.376	3.761	2.799	1.692	0.851	0.434	0.212	0.055			
14	5417.618	5319.260	45.757	18.996	8.564	4.849	4.368	4.218	3.836	3.141	2.183	1.241	0.636	0.352	0.174	0.044		
15	5800.674	5699.210	46.587	19.527	9.179	4.793	4.107	4.013	3.798	3.328	2.577	1.673	0.915	0.494	0.294	0.144	0.035	
16	6183.811	6079.160	47.317	19.999	9.844	4.826	3.890	3.793	3.688	3.390	2.847	2.074	1.266	0.686	0.400	0.252	0.120	0.258

Table 33. Calculated alpha factor mean values for CCF events in the GH cause group from 1997 through 2015.

Group Size	α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8	α_9	α_{10}	α_{11}	α_{12}	α_{13}	α_{14}	α_{15}	α_{16}
2	0.9808	1.916E-02														
3	0.9823	1.299E-02	4.684E-03													
4	0.9830	1.145E-02	3.758E-03	1.832E-03												
5	0.9853	7.973E-03	4.462E-03	1.806E-03	4.669E-04											
6	0.9864	6.120E-03	3.957E-03	2.325E-03	9.056E-04	3.419E-04										
7	0.9873	5.132E-03	3.217E-03	2.430E-03	1.279E-03	4.767E-04	1.290E-04									
8	0.9879	4.628E-03	2.615E-03	2.162E-03	1.583E-03	6.790E-04	2.789E-04	1.595E-04								
9	0.9886	4.299E-03	2.186E-03	1.846E-03	1.503E-03	9.732E-04	4.159E-04	1.729E-04	4.527E-05							
10	0.9890	4.105E-03	1.899E-03	1.559E-03	1.371E-03	1.043E-03	6.103E-04	2.632E-04	1.135E-04	3.052E-05						
11	0.9894	3.983E-03	1.715E-03	1.322E-03	1.217E-03	1.022E-03	7.199E-04	3.890E-04	1.732E-04	7.842E-05	2.899E-05					
12	0.9897	3.835E-03	1.624E-03	1.135E-03	1.064E-03	9.552E-04	7.575E-04	4.931E-04	2.529E-04	1.194E-04	5.655E-05	2.224E-05				
13	0.9900	3.659E-03	1.592E-03	9.948E-04	9.253E-04	8.691E-04	7.471E-04	5.560E-04	3.360E-04	1.691E-04	8.622E-05	4.212E-05	1.100E-05			
14	0.9903	3.506E-03	1.581E-03	8.951E-04	8.062E-04	7.785E-04	7.081E-04	5.797E-04	4.029E-04	2.291E-04	1.174E-04	6.501E-05	3.212E-05	8.085E-06		
15	0.9905	3.366E-03	1.582E-03	8.262E-04	7.079E-04	6.919E-04	6.548E-04	5.737E-04	4.443E-04	2.884E-04	1.578E-04	8.513E-05	5.077E-05	2.488E-05	5.997E-06	
16	0.9907	3.234E-03	1.592E-03	7.804E-04	6.291E-04	6.134E-04	5.965E-04	5.483E-04	4.604E-04	3.354E-04	2.047E-04	1.110E-04	6.467E-05	4.069E-05	1.948E-05	4.170E-05

Table 34. Estimated CCF industry-wide prior distributions with CCF events in the GH cause group from 1997 through 2015.

Group Size	α_1	b_1	α_2	b_2	α_3	b_3	α_4	b_4	α_5	b_5	α_6	b_6	α_7	b_7	α_8	b_8
2	2.409E+01	4.706E-01	4.706E-01	2.409E+01												
3	6.126E+01	1.103E+00	8.104E-01	6.155E+01	2.921E-01	6.207E+01										
4	1.126E+02	1.953E+00	1.312E+00	1.133E+02	4.307E-01	1.142E+02	2.099E-01	1.144E+02								
5	2.082E+02	3.107E+00	1.684E+00	2.096E+02	9.426E-01	2.103E+02	3.816E-01	2.109E+02	9.865E-02	2.112E+02						
6	2.761E+02	3.821E+00	1.714E+00	2.783E+02	1.108E+00	2.789E+02	6.509E-01	2.793E+02	2.536E-01	2.797E+02	9.572E-02	2.799E+02				
7	4.050E+02	5.195E+00	2.105E+00	4.081E+02	1.320E+00	4.089E+02	9.967E-01	4.092E+02	5.249E-01	4.097E+02	1.956E-01	4.100E+02	5.291E-02	4.102E+02		
8	4.759E+02	5.832E+00	2.229E+00	4.795E+02	1.260E+00	4.805E+02	1.042E+00	4.807E+02	7.626E-01	4.810E+02	3.271E-01	4.814E+02	1.344E-01	4.816E+02	7.682E-02	4.817E+02
9	6.722E+02	7.779E+00	2.923E+00	6.770E+02	1.486E+00	6.785E+02	1.255E+00	6.787E+02	1.022E+00	6.789E+02	6.617E-01	6.793E+02	2.828E-01	6.797E+02	1.176E-01	6.798E+02
10	8.249E+02	9.171E+00	3.424E+00	8.307E+02	1.584E+00	8.325E+02	1.301E+00	8.328E+02	1.143E+00	8.330E+02	8.702E-01	8.332E+02	5.090E-01	8.336E+02	2.195E-01	8.339E+02
11	9.631E+02	1.037E+01	3.878E+00	9.696E+02	1.670E+00	9.718E+02	1.287E+00	9.722E+02	1.185E+00	9.723E+02	9.944E-01	9.725E+02	7.008E-01	9.728E+02	3.786E-01	9.731E+02
12	1.138E+03	1.186E+01	4.409E+00	1.146E+03	1.868E+00	1.148E+03	1.305E+00	1.149E+03	1.224E+00	1.149E+03	1.098E+00	1.149E+03	8.711E-01	1.149E+03	5.670E-01	1.149E+03
13	1.380E+03	1.393E+01	5.102E+00	1.389E+03	2.219E+00	1.392E+03	1.387E+00	1.393E+03	1.290E+00	1.393E+03	1.212E+00	1.393E+03	1.042E+00	1.393E+03	7.751E-01	1.393E+03
14	1.599E+03	1.568E+01	5.662E+00	1.609E+03	2.552E+00	1.612E+03	1.445E+00	1.613E+03	1.302E+00	1.613E+03	1.257E+00	1.613E+03	1.143E+00	1.614E+03	9.361E-01	1.614E+03
15	1.835E+03	1.753E+01	6.237E+00	1.847E+03	2.932E+00	1.850E+03	1.531E+00	1.851E+03	1.312E+00	1.852E+03	1.282E+00	1.852E+03	1.213E+00	1.852E+03	1.063E+00	1.852E+03
16	1.801E+03	1.685E+01	5.878E+00	1.812E+03	2.893E+00	1.815E+03	1.418E+00	1.816E+03	1.144E+00	1.816E+03	1.115E+00	1.816E+03	1.084E+00	1.817E+03	9.965E-01	1.817E+03

Group Size	α_9	b_9	α_{10}	b_{10}	α_{11}	b_{11}	α_{12}	b_{12}	α_{13}	b_{13}	α_{14}	b_{14}	α_{15}	b_{15}	α_{16}	b_{16}
9	3.078E-02	6.799E+02														
10	9.465E-02	8.340E+02	2.546E-02	8.341E+02												
11	1.686E-01	9.733E+02	7.634E-02	9.734E+02	2.822E-02	9.735E+02										
12	2.908E-01	1.150E+03	1.373E-01	1.150E+03	6.503E-02	1.150E+03	2.558E-02	1.150E+03								
13	4.684E-01	1.394E+03	2.357E-01	1.394E+03	1.202E-01	1.394E+03	5.873E-02	1.394E+03	1.534E-02	1.394E+03						
14	6.505E-01	1.614E+03	3.700E-01	1.614E+03	1.895E-01	1.615E+03	1.050E-01	1.615E+03	5.186E-02	1.615E+03	1.306E-02	1.615E+03				
15	8.233E-01	1.852E+03	5.343E-01	1.852E+03	2.924E-01	1.853E+03	1.577E-01	1.853E+03	9.406E-02	1.853E+03	4.610E-02	1.853E+03	1.111E-02	1.853E+03		
16	8.368E-01	1.817E+03	6.096E-01	1.817E+03	3.720E-01	1.817E+03	2.017E-01	1.817E+03	1.175E-01	1.817E+03	7.395E-02	1.818E+03	3.541E-02	1.818E+03	7.580E-02	1.818E+03

4.5 Prior Distributions for the "Other" Cause Group (GO)

To estimate prior distributions for the GO (i.e., Other or unknown) CCF cause group, the following selection criteria are defined in the CCF Database website:

- Type of CCF Event Level: All Level CCF Events
- CCF Event Type: CCF Events Only
- Date Range: 1997–2015
- Filter Independent Events by Selected Cause(s): True
- Shock Criteria: All Events
- Redundancy Range: Minimum = 2, Maximum = 16
- Bayesian Update Method: Mean Method
- Failure Modes: select all failure modes except Setpoint
- CCF Categories: Cause → Other & Unknown

A total of nine CCF events and 921.8 effective independent failure events related to the above selection criteria.

Additional criterion on CCF Categories → Degree → Almost/Partial or Complete is used to obtain the partial CCF events and complete CCF events, as required in the existing process. The unmapped/mapped impact vectors are also acquired from the CCF Database website. The mapped impact vectors for partial CCF events for each group size obtained from the website are used directly in the study.

Table 35 shows the number of partial CCF events, the number of complete CCF events, and the total number of CCF events for the GO cause group. The same binomial regression treatment used for complete CCF events was conducted. The estimated number of complete CCF events for each group size is listed in Table 35.

Table 36 shows the mapped impact vectors for partial CCF events for the GO cause groups sized 2–16 obtained from the CCF Database website. Table 37 shows the adjusted n_k results for CCF events in the GO cause groups sized 2–16, after adding the estimated number of complete CCF events. The MLEs or mean values of alpha factors for the GC cause groups of each size are then calculated, while the CalcPrior code is used to estimate the prior distributions for causal alpha factors pertaining to the GO cause group. Table 38 and Table 39 show the mean values and the distributions results, respectively.

Table 35. CCF data for the GO cause group from 1997 through 2015.

Group Size	No. Partial CCF Events	No. Complete CCF Events	Total No. CCF Events	Prob. of Complete CCF Event - Data	Prob. of Complete CCF Event - Curve Fitting	Estimated No. of Complete CCF Events
2	0	2	2	1.00000	0.58154	1.16309
3	2	0	2	0.00000	0.37068	0.74135
4	2	0	2	0.00000	0.22746	0.45492
5	0	0	0	NA	0.15688	0.00000
6	1	0	1	0.00000	0.12755	0.12755
7	0	0	0	NA	0.11624	0.00000

Group Size	No. Partial CCF Events	No. Complete CCF Events	Total No. CCF Events	Prob. of Complete CCF Event - Data	Prob. of Complete CCF Event - Curve Fitting	Estimated No. of Complete CCF Events
8	1	1	2	0.50000	0.11201	0.22402
9	0	0	0	NA	0.11044	0.00000
10	0	0	0	NA	0.10986	0.00000
11	0	0	0	NA	0.10965	0.00000
12	0	0	0	NA	0.10957	0.00000
13	0	0	0	NA	0.10954	0.00000
14	0	0	0	NA	0.10953	0.00000
15	0	0	0	NA	0.10953	0.00000
16	0	0	0	NA	0.10953	0.00000
Total	6	3	9			2.71094

Table 36. nk values for the partial CCF events in the GO cause group from 1997 through 2015.

Group Size	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9	n_{10}	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}	n_{16}
2	3.491	0.738														
3	3.428	1.809	0.135													
4	2.905	2.672	0.456	0.064												
5	2.672	2.701	1.007	0.220	0.032											
6	2.264	2.878	1.241	0.497	0.114	0.016										
7	2.161	2.591	1.496	0.739	0.262	0.061	0.008									
8	2.032	2.403	1.580	0.940	0.433	0.146	0.033	0.004								
9	1.960	2.188	1.607	1.076	0.597	0.258	0.084	0.018	0.002							
10	1.887	2.020	1.585	1.157	0.732	0.381	0.157	0.049	0.010	0.0010						
11	1.815	1.888	1.541	1.195	0.832	0.497	0.245	0.097	0.029	0.0054	0.0005					
12	1.744	1.781	1.488	1.204	0.899	0.596	0.337	0.159	0.060	0.0168	0.0030	0.0002				
13	1.674	1.693	1.435	1.195	0.940	0.673	0.425	0.230	0.104	0.0375	0.0098	0.0016	0.0001			
14	1.605	1.619	1.385	1.176	0.959	0.730	0.501	0.302	0.158	0.0686	0.0232	0.0056	0.0009	0.0001		
15	1.539	1.555	1.338	1.151	0.965	0.767	0.563	0.370	0.216	0.1085	0.0448	0.0143	0.0032	0.0005	0.0000	
16	1.474	1.499	1.296	1.124	0.961	0.790	0.610	0.431	0.274	0.1543	0.0744	0.0291	0.0087	0.0018	0.0002	0.0000

Table 37. Adjusted nk values for CCF events in the GO cause group from 1997 through 2015.

Group Size	n_t	n_I	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9	n_{10}	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}	n_{16}
2	420.20	414.81	3.491	1.901														
3	628.32	622.21	3.428	1.809	0.876													
4	836.17	829.62	2.905	2.672	0.456	0.519												
5	1043.66	1037.03	2.672	2.701	1.007	0.220	0.032											
6	1251.57	1244.43	2.264	2.878	1.241	0.497	0.114	0.143										

Group Size	n_t	n_I	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9	n_{10}	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}	n_{16}
7	1459.16	1451.84	2.161	2.591	1.496	0.739	0.262	0.061	0.008									
8	1667.04	1659.24	2.032	2.403	1.580	0.940	0.433	0.146	0.033	0.228								
9	1874.44	1866.65	1.960	2.188	1.607	1.076	0.597	0.258	0.084	0.018	0.002							
10	2082.03	2074.05	1.887	2.020	1.585	1.157	0.732	0.381	0.157	0.049	0.010	0.001						
11	2289.60	2281.46	1.815	1.888	1.541	1.195	0.832	0.497	0.245	0.097	0.029	0.005	0.000					
12	2497.15	2488.86	1.744	1.781	1.488	1.204	0.899	0.596	0.337	0.159	0.060	0.017	0.003	0.000				
13	2704.68	2696.26	1.674	1.693	1.435	1.195	0.940	0.673	0.425	0.230	0.104	0.038	0.010	0.002	0.000			
14	2912.20	2903.67	1.605	1.619	1.385	1.176	0.959	0.730	0.501	0.302	0.158	0.069	0.023	0.006	0.001	0.000		
15	3119.70	3111.07	1.539	1.555	1.338	1.151	0.965	0.767	0.563	0.370	0.216	0.108	0.045	0.014	0.003	0.000	0.000	
16	3327.21	3318.48	1.474	1.499	1.296	1.124	0.961	0.790	0.610	0.431	0.274	0.154	0.074	0.029	0.009	0.002	0.000	0.000

Table 38. Calculated alpha factor mean values for CCF events in the GO cause group from 1997 through 2015.

Group Size	α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8	α_9	α_{10}	α_{11}	α_{12}	α_{13}	α_{14}	α_{15}	α_{16}
2	0.9955	4.524E-03														
3	0.9957	2.878E-03	1.395E-03													
4	0.9956	3.196E-03	5.458E-04	6.209E-04												
5	0.9962	2.588E-03	9.651E-04	2.110E-04	3.024E-05											
6	0.9961	2.300E-03	9.914E-04	3.968E-04	9.108E-05	1.144E-04										
7	0.9965	1.776E-03	1.025E-03	5.066E-04	1.795E-04	4.195E-05	5.361E-06									
8	0.9965	1.442E-03	9.480E-04	5.638E-04	2.600E-04	8.731E-05	2.002E-05	1.367E-04								
9	0.9969	1.167E-03	8.572E-04	5.743E-04	3.184E-04	1.377E-04	4.460E-05	9.751E-06	1.042E-06							
10	0.9971	9.702E-04	7.612E-04	5.556E-04	3.516E-04	1.828E-04	7.538E-05	2.344E-05	4.801E-06	4.691E-07						
11	0.9972	8.244E-04	6.728E-04	5.217E-04	3.635E-04	2.169E-04	1.070E-04	4.234E-05	1.250E-05	2.379E-06	2.133E-07					
12	0.9974	7.132E-04	5.960E-04	4.820E-04	3.602E-04	2.386E-04	1.351E-04	6.386E-05	2.416E-05	6.708E-06	1.183E-06	9.777E-08				
13	0.9975	6.260E-04	5.306E-04	4.418E-04	3.474E-04	2.489E-04	1.570E-04	8.510E-05	3.863E-05	1.388E-05	3.605E-06	5.899E-07	4.513E-08			
14	0.9976	5.560E-04	4.754E-04	4.036E-04	3.294E-04	2.506E-04	1.719E-04	1.038E-04	5.420E-05	2.354E-05	7.981E-06	1.935E-06	2.944E-07	2.096E-08		
15	0.9977	4.986E-04	4.288E-04	3.689E-04	3.093E-04	2.460E-04	1.803E-04	1.187E-04	6.917E-05	3.477E-05	1.437E-05	4.578E-06	1.036E-06	1.470E-07	0.000E+00	
16	0.9978	4.506E-04	3.894E-04	3.378E-04	2.888E-04	2.375E-04	1.834E-04	1.294E-04	8.230E-05	4.638E-05	2.235E-05	8.743E-06	2.614E-06	5.534E-07	7.347E-08	0.000E+00

Table 39. Estimated CCF industry-wide prior distributions with CCF events in the GO cause group from 1997 through 2015.

Group Size	α_1	b_1	α_2	b_2	α_3	b_3	α_4	b_4	α_5	b_5	α_6	b_6	α_7	b_7	α_8	b_8
2	1.085E+02	4.932E-01	4.932E-01	1.085E+02												
3	2.469E+02	1.060E+00	7.137E-01	2.473E+02	3.458E-01	2.476E+02										
4	4.827E+02	2.115E+00	1.549E+00	4.832E+02	2.646E-01	4.845E+02	3.010E-01	4.845E+02								
5	1.398E+03	5.325E+00	3.632E+00	1.400E+03	1.354E+00	1.402E+03	2.961E-01	1.403E+03	4.243E-02	1.403E+03						
6	1.263E+03	4.936E+00	2.915E+00	1.265E+03	1.257E+00	1.267E+03	5.031E-01	1.267E+03	1.155E-01	1.268E+03	1.451E-01	1.268E+03				
7	2.722E+03	9.655E+00	4.851E+00	2.727E+03	2.800E+00	2.729E+03	1.384E+00	2.731E+03	4.902E-01	2.731E+03	1.146E-01	2.732E+03	1.464E-02	2.732E+03		
8	2.061E+03	7.148E+00	2.980E+00	2.065E+03	1.960E+00	2.066E+03	1.166E+00	2.067E+03	5.375E-01	2.067E+03	1.805E-01	2.068E+03	4.139E-02	2.068E+03	2.827E-01	2.068E+03
9	4.897E+03	1.528E+01	5.733E+00	4.907E+03	4.211E+00	4.909E+03	2.821E+00	4.910E+03	1.564E+00	4.911E+03	6.763E-01	4.912E+03	2.191E-01	4.913E+03	4.790E-02	4.913E+03
10	6.399E+03	1.877E+01	6.226E+00	6.411E+03	4.884E+00	6.413E+03	3.565E+00	6.414E+03	2.256E+00	6.415E+03	1.173E+00	6.416E+03	4.837E-01	6.417E+03	1.504E-01	6.417E+03

Group Size	α_1	b_1	α_2	b_2	α_3	b_3	α_4	b_4	α_5	b_5	α_6	b_6	α_7	b_7	α_8	b_8
11	8.237E+03	2.283E+01	6.809E+00	8.253E+03	5.557E+00	8.254E+03	4.309E+00	8.255E+03	3.002E+00	8.257E+03	1.792E+00	8.258E+03	8.840E-01	8.259E+03	3.497E-01	8.259E+03
12	1.047E+04	2.751E+01	7.485E+00	1.049E+04	6.255E+00	1.049E+04	5.059E+00	1.049E+04	3.780E+00	1.049E+04	2.504E+00	1.049E+04	1.418E+00	1.050E+04	6.702E-01	1.050E+04
13	1.316E+04	3.289E+01	8.258E+00	1.319E+04	6.999E+00	1.319E+04	5.828E+00	1.319E+04	4.583E+00	1.319E+04	3.284E+00	1.319E+04	2.071E+00	1.319E+04	1.123E+00	1.319E+04
14	1.639E+04	3.908E+01	9.133E+00	1.642E+04	7.810E+00	1.642E+04	6.631E+00	1.642E+04	5.411E+00	1.642E+04	4.116E+00	1.643E+04	2.823E+00	1.643E+04	1.705E+00	1.643E+04
15	2.192E+04	4.998E+01	1.095E+01	2.196E+04	9.422E+00	2.196E+04	8.105E+00	2.197E+04	6.795E+00	2.197E+04	5.405E+00	2.197E+04	3.962E+00	2.197E+04	2.608E+00	2.197E+04
16	2.553E+04	5.578E+01	1.153E+01	2.558E+04	9.963E+00	2.558E+04	8.644E+00	2.558E+04	7.391E+00	2.558E+04	6.077E+00	2.558E+04	4.692E+00	2.559E+04	3.312E+00	2.559E+04

Group Size	α_9	b_9	α_{10}	b_{10}	α_{11}	b_{11}	α_{12}	b_{12}	α_{13}	b_{13}	α_{14}	b_{14}	α_{15}	b_{15}	α_{16}	b_{16}
9	5.119E-03	4.913E+03														
10	3.081E-02	6.418E+03	3.010E-03	6.418E+03												
11	1.032E-01	8.259E+03	1.965E-02	8.260E+03	1.761E-03	8.260E+03										
12	2.535E-01	1.050E+04	7.040E-02	1.050E+04	1.242E-02	1.050E+04	1.026E-03	1.050E+04								
13	5.097E-01	1.319E+04	1.831E-01	1.319E+04	4.756E-02	1.319E+04	7.782E-03	1.319E+04	5.954E-04	1.319E+04						
14	8.904E-01	1.643E+04	3.868E-01	1.643E+04	1.311E-01	1.643E+04	3.179E-02	1.643E+04	4.836E-03	1.643E+04	3.443E-04	1.643E+04				
15	1.520E+00	2.197E+04	7.638E-01	2.197E+04	3.157E-01	2.197E+04	1.006E-01	2.197E+04	2.277E-02	2.197E+04	3.231E-03	2.197E+04	7.043E-05	2.197E+04		
16	2.106E+00	2.559E+04	1.187E+00	2.559E+04	5.718E-01	2.559E+04	2.237E-01	2.559E+04	6.688E-02	2.559E+04	1.416E-02	2.559E+04	1.880E-03	2.559E+04	7.690E-05	2.559E+04

5. VARIOUS ITEMS ON PRIOR DISTRIBUTION DEVELOPMENT AND CCF ANALYSIS

While this report follows the existing process of updating (or developing) generic prior distributions for CCF alpha factors (or causal alpha factors), certain issues were noted and discussed during the study, including whether the impact vector and mapping method is appropriate for use in prior distribution development, and whether better methodologies are available. The following is a list of such items, along with preliminary thoughts on them.

1. ***Is the impact vector and mapping method really appropriate for CCF parameter estimations or prior determination? Are there any other alternative approaches for developing the prior distributions?***

   The impact vector and mapping method was introduced in NUREG/CR-4780, published in 1988. To obtain a high degree of consensus on the principles of treating CCF in risk analysis, the report was reviewed by many experts and organizations in the U.S. and Europe. Appendix D of NUREG/CR-4780 provides a detailed discussion on the background and justification for using the mapping method in parameter estimation. While mapping up and mapping down does introduce greater uncertainties in CCF parameter estimation, the method seems reasonable for use in treating scarce CCF data and estimating associated CCF parameters. Actually, the impact vector and mapping method was used consistently in the subsequent NRC CCF studies, becoming the state-of-the-art in CCF event characterization and CCF parameter estimation.

   On the other hand, one could always look for alternative approaches that may be better for CCF parameter estimation or prior distribution development. After nearly 30 years of using the approach, it may be worthwhile to survey what other methodologies may be available, enabling a determination as to whether any alternative approaches exist that are better suited for prior distribution development. It should be noted that regardless of the method selected, there will always be uncertainty related to it. At minimum, certain kinds of sensitivity studies could be conducted to compare the mapping method with other methods of obtaining prior distributions. These sensitivity studies could then be evaluated to determine the potential impact of different methodologies on the associated risk applications (e.g., the significance determination process).

2. ***What is the actual process for developing prior distributions for CCF parameters? Is this process defensible? Are there any issues involved?***

   While NUREG/CR-5485 provides a brief description of several practical approaches to developing prior distributions for CCF parameters, no published papers describe the actual process. One objective of this report is to document the existing process of developing prior distributions for CCF parameters. To engage outside experts for their insights, other efforts (e.g., publishing the process in national and international conferences/journals and on the NRC website) are considered.

   The impact vector and mapping method has been used consistently in the NRC CCF studies, becoming the state-of-the-art in CCF event characterization and CCF parameter estimation. However, additional uncertainties are associated with this approach. Sensitivity analysis should be performed to understand the impact associated with this model uncertainty.

   During the study, we also encountered several issues involving the details of the existing process (e.g., the binomial regression treatment for complete CCF events, estimation of the ρ parameter associated with the mapping up methodology, and the question of whether different prior distributions should be developed for different component types). These specific issues are discussed in more detail below.

3. ***Is using the binomial regression treatment for complete CCF events in the current prior development process appropriate? What should be the proper function for use in curve fitting*?**

The background on why a different treatment was used for complete CCF events in the prior distribution development process is unclear, but it appears to be a compromise addressing the concern that the mapping technique adds too many pseudo-CCF events into the data analysis. As to whether the treatment is appropriate, and which function should be used for curve fitting, these may be good topics for further discussion. For example:

a) When using MatLab and Eq. 5 to curve fit the CCF data for the GE cause group from 1997 through 2015, negative values would be obtained for the probability of complete CCF event in the larger group sizes.

b) For causal CCF data, many group sizes feature zero complete CCF events, or even zero total CCF events. This leads to less valid data points for a good curve fitting.

c) The variables used in curve fitting complete CCF events are group size and probability of complete CCF event. The estimated number of complete CCF events is obtained by multiplying the probability of complete CCF event by the total number of CCF events. With the larger values in the total number of CCF events for some group sizes (e.g., group sizes 12 and 16), the estimated number of complete CCF events is no longer a smooth curve for some group sizes but appears as spikes.

d) The current binomial regression treatment of complete CCF events does not distinguish lethal shock events from nonlethal shock but complete CCF events. For lethal shocks, the impact vector should be mapped directly (i.e., the probability that all x components in a system of x components have failed due to a lethal shock is mapped directly and equals the probability of failing all y components in a system of y components). The correct process should treat lethal shock events and non-lethal shock but complete CCF events differently: mapping the lethal shock events directly, while curve fitting the nonlethal shock but complete CCF events.

e) Fortunately, the lethal event issue should have little impact on the results, as a review of the CCF data used in this study (1997–2015) only found three CCF events coded as have been induced by lethal shock.

4. ***How is the mapping up factor ρ determined in the current process? Is there a better way to estimate ρ?***

The mapping up factor ρ is a very important parameter in the mapping methodology, as it is included in the mapping up formula and would greatly impact the mapping results, depending on its assumed value. The parameter ρ is defined in the Binomial Failure Rate (BFR) model as the conditional probability of failure of each component, given a nonlethal shock. For example, consider the following formula, used to map a system of group size 2 up to a system of group size 3 or 4:

$$P_3^{(3)} = \rho P_2^{(2)} \quad \text{(Eq. 6)}$$

$$P_4^{(4)} = \rho^2 P_2^{(2)} \quad \text{(Eq. 7)}$$

where $P_x^{(x)}$ is the probability of all x components failing in a system of x components. Depending on the assumed value of ρ, the mapped up results of $P_3^{(3)}$ and $P_4^{(4)}$ would change significantly for the same $P_2^{(2)}$ (1 or 0.5 in the example below):

Table 40. Impact of mapping up factor.

	$P_2^{(2)} = 1$				$P_2^{(2)} = 0.5$			
	ρ=1	ρ=0.8	ρ=0.5	ρ=0.2	ρ=1	ρ=0.8	ρ=0.5	ρ=0.2
$P_3^{(3)}$	1	0.8	0.5	0.2	0.5	0.4	0.25	0.1
$P_4^{(4)}$	1	0.64	0.25	0.04	0.5	0.32	0.125	0.02

NUREG/CR-6268 Rev.1 provides a method of estimating the mapping up factor ρ via the following equation:

$$\rho = \frac{\sum_{i=1}^{m} i(i-1) f_i}{(m-1)\sum_{i=1}^{m} i(f_i)} \qquad (7\text{-}16)$$

where

m = the number of elements in the group (CCCG)

f_i = the i^{th} element of the generic impact vector.

(Eq. 8)

where a maximum value of 0.85 is established based on observed trends and empirical studies. In the CCF Parameter Estimations 2003 Update, the previously recommended value of 0.85 was considered too conservative, so 0.50 was recommended and has been used ever since.

Appendix C develops a process for estimating the mapping up factor ρ. This process underwent preliminarily testing using the pump CCF data. Whether this new process to estimate ρ should be applied to prior development is subject to further review and decision.

5. ***Should different prior distributions be developed for different component groups?***

With some simple examinations of the CCF data, Atwood suggests that (a) different component types have quite different alpha factors and should thus be analyzed separately; and (b) if the different failure causes are to be considered, the analysis must distinguish among component types, as various components have different susceptibilities to the different failure causes.

6. ***Is there a general formula for mapping up CCF data?***

A table of formulas is presented in NUREG/CR4780 (Table D-5) and NUREG/CR-5485 (Table C-5) for mapping up events classified as nonlethal shocks. This table is expanded in NUREG/CR-6268, Rev. 1 (Table 7-4), with the maximum size of system mapping to being increased from 4 to 6.

Table 7-4. Formulas for upward mapping of events classified as non-lethal shocks.

Size of System Mapping From	Size of System Mapping To (Number of Identical Trains)				
	2	3	4	5	6
1	$f_1^{(2)}=2(1-\rho)f_1^{(1)}$ $f_2^{(2)}=\rho f_1^{(1)}$	$f_1^{(3)}=3(1-\rho)^2 f_1^{(1)}$ $f_2^{(3)}=3\rho(1-\rho)f_1^{(1)}$ $f_3^{(3)}=\rho^2 f_1^{(1)}$	$f_1^{(4)}=4(1-\rho)^3 f_1^{(1)}$ $f_2^{(4)}=6\rho(1-\rho)^2 f_1^{(1)}$ $f_3^{(4)}=4\rho^2(1-\rho)f_1^{(1)}$ $f_4^{(4)}=\rho^3 f_1^{(1)}$	$f_1^{(5)}=5(1-\rho)^4 f_1^{(1)}$ $f_2^{(5)}=10\rho(1-\rho)^3 f_1^{(1)}$ $f_3^{(5)}=10\rho^2(1-\rho)^2 f_1^{(1)}$ $f_4^{(5)}=5\rho^3(1-\rho)f_1^{(1)}$ $f_5^{(5)}=\rho^4 f_1^{(1)}$	$f_1^{(6)}=6(1-\rho)^5 f_1^{(1)}$ $f_2^{(6)}=15\rho(1-\rho)^4 f_1^{(1)}$ $f_3^{(6)}=20\rho^2(1-\rho)^3 f_1^{(1)}$ $f_4^{(6)}=15\rho^3(1-\rho)^2 f_1^{(1)}$ $f_5^{(6)}=6\rho^4(1-\rho)f_1^{(1)}$ $f_6^{(6)}=\rho^5 f_1^{(1)}$
2		$f_1^{(3)}=(3/2)(1-\rho)f_1^{(2)}$ $f_2^{(3)}=\rho f_1(2)+(1-\rho)f_2^{(2)}$ $f_3^{(3)}=\rho f_2^{(2)}$	$f_1^{(4)}=2(1-\rho)^2 f_1^{(2)}$ $f_2^{(4)}=(5/2)\rho(1-\rho)f_1^{(2)}+(1-\rho)^2 f_2^{(2)}$ $f_3^{(4)}=\rho^2 f_1^{(2)}+2\rho(1-\rho)f_2^{(2)}$ $f_4^{(4)}=\rho^2 f_2^{(2)}$	$f_1^{(5)}=(5/2)(1-\rho)^3 f_1^{(2)}$ $f_2^{(5)}=(9/2)\rho(1-\rho)^2 f_1^{(2)}+(1-\rho)^3 f_2^{(2)}$ $f_3^{(5)}=(7/2)\rho^2(1-\rho)f_1^{(2)}+3\rho(1-\rho)^2 f_2^{(2)}$ $f_4^{(5)}=\rho^3 f_1^{(2)}+3\rho^2(1-\rho)f_2^{(2)}$ $f_5^{(5)}=\rho^3 f_2^{(2)}$	$f_1^{(6)}=3(1-\rho)^4 f_1^{(2)}$ $f_2^{(6)}=7\rho(1-\rho)^3 f_1^{(2)}+(1-\rho)^4 f_2^{(2)}$ $f_3^{(6)}=8\rho^2(1-\rho)^2 f_1^{(2)}+4\rho(1-\rho)^3 f_2^{(2)}$ $f_4^{(6)}=(9/2)\rho^3(1-\rho)f_1^{(2)}+6\rho^2(1-\rho)^2 f_2^{(2)}$ $f_5^{(6)}=\rho^4 f_1^{(2)}+4\rho^3(1-\rho)f_2^{(2)}$ $f_6^{(6)}=\rho^4 f_2^{(2)}$
3			$f_1^{(4)}=(4/3)(1-\rho)f_1^{(3)}$ $f_2^{(4)}=\rho f_1^{(3)}+(1-\rho)f_2^{(3)}$ $f_3^{(4)}=\rho f_2^{(3)}+(1-\rho)f_3^{(3)}$ $f_4^{(4)}=\rho f_3^{(3)}$	$f_1^{(5)}=(5/3)(1-\rho)^2 f_1^{(3)}$ $f_2^{(5)}=(7/3)\rho(1-\rho)f_1^{(3)}+(1-\rho)^2 f_2^{(3)}$ $f_3^{(5)}=\rho^2 f_1^{(3)}+2\rho(1-\rho)f_2^{(3)}+(1-\rho)^2 f_3^{(3)}$ $f_4^{(5)}=\rho^2 f_2^{(3)}+2\rho(1-\rho)f_3^{(3)}$ $f_5^{(5)}=\rho^2 f_3^{(3)}$	$f_1^{(6)}=2(1-\rho)^3 f_1^{(3)}$ $f_2^{(6)}=4\rho(1-\rho)^2 f_1^{(3)}+(1-\rho)^3 f_2^{(3)}$ $f_3^{(6)}=(10/3)\rho^2(1-\rho)f_1^{(3)}+3\rho(1-\rho)^2 f_2^{(3)}$ $+(1-\rho)^3 f_3^{(3)}$ $f_4^{(6)}=\rho^3 f_1^{(3)}+3\rho^2(1-\rho)f_2^{(3)}+3\rho(1-\rho)^2 f_3^{(3)}$ $f_5^{(6)}=\rho^3 f_2^{(3)}+3\rho^2(1-\rho)f_3^{(3)}$ $f_6^{(6)}=\rho^3 f_3^{(3)}$
4				$f_1^{(5)}=(5/4)(1-\rho)f_1^{(4)}$ $f_2^{(5)}=\rho f_1^{(4)}+(1-\rho)f_2^{(4)}$ $f_3^{(5)}=\rho f_2^{(4)}+(1-\rho)f_3^{(4)}$ $f_4^{(5)}=\rho f_3^{(4)}+(1-\rho)f_4^{(4)}$ $f_5^{(5)}=\rho f_4^{(4)}$	$f_1^{(6)}=(3/2)(1-\rho)^2 f_1^{(4)}$ $f_2^{(6)}=(9/4)\rho(1-\rho)f_1^{(4)}+(1-\rho)^2 f_2^{(4)}$ $f_3^{(6)}=\rho^2 f_1^{(4)}+2\rho(1-\rho)f_2^{(4)}+(1-\rho)^2 f_3^{(4)}$ $f_4^{(6)}=\rho^2 f_2^{(4)}+2\rho(1-\rho)f_3^{(4)}+(1-\rho)^2 f_4^{(4)}$ $f_5^{(6)}=\rho^2 f_3^{(4)}+2\rho(1-\rho)f_4^{(4)}$ $f_6^{(6)}=\rho^2 f_4^{(4)}$
5					$f_1^{(6)}=(6/5)(1-\rho)f_1^{(5)}$ $f_2^{(6)}=\rho f_1^{(5)}+(1-\rho)f_2^{(5)}$ $f_3^{(6)}=\rho f_2^{(5)}+(1-\rho)f_3^{(5)}$ $f_4^{(6)}=\rho f_3^{(5)}+(1-\rho)f_4^{(5)}$ $f_5^{(6)}=\rho f_4^{(5)}+(1-\rho)f_5^{(5)}$ $f_6^{(6)}=\rho f_5^{(5)}$

Appendix D provides explicit justification—as well as an explicit general formula—for the mapping up method. The following proposed general equation for calculating the mapping up formulas is compared with the above NUREG/CR6268 table:

$$n_K^{(M)} = \frac{\binom{M}{K}}{\binom{M}{K}-\binom{M-m}{K}}\left[\sum_k \binom{M-m}{K-k}\rho^{K-k}(1-\rho)^{(M-m)-(K-k)} n_k^{(m)}\right] \qquad \text{(Eq. 9)}$$

Several differences are found, as seen in the following table. For example, the NUREG table includes the following formula for mapping a system of size 2 to a system of size 4:

$$f(2,4) = (5/2)\rho(1-\rho)\ f(1,2)+(1-\rho)\text{^}2\ f(2,2) \qquad \text{(Eq. 10)}$$

whereas the general formula includes the following:

$$f(2,4)=(12/5)\rho(1-\rho)\ f(1,2)+(6/5)(1-\rho)\text{^}2\ f(2,2) \qquad \text{(Eq. 11)}$$

Using the same deduction as found in Appendix C.4.3 of NUREG/CR-5485, we see that the f(2,4) equation derived from the general formula (Eq. 9) is actually correct.

Mapping Up Formulas		Size of System Mapping To (Number of Identical Trains)				
		2	3	4	5	6
Size of System Mapping From	1	f(1,2)=2(1−ρ) f(1,1) f(2,2)=ρ f(1,1)	f(1,3)=3(1−ρ)^2 f(1,1) f(2,3)=3ρ(1−ρ) f(1,1) f(3,3)=ρ^2 f(1,1)	f(1,4)=4(1−ρ)^3 f(1,1) f(2,4)=6ρ(1−ρ)^2 f(1,1) f(3,4)=4ρ^2 (1−ρ) f(1,1) f(4,4)=ρ^3 f(1,1)	f(1,5)=5(1−ρ)^4 f(1,1) f(2,5)=10ρ(1−ρ)^3 f(1,1) f(3,5)=10ρ^2 (1−ρ)^2 f(1,1) f(4,5)=5ρ^3 (1−ρ) f(1,1) f(5,5)=ρ^4 f(1,1)	f(1,6)=6(1−ρ)^5 f(1,1) f(2,6)=15ρ(1−ρ)^4 f(1,1) f(3,6)=20ρ^2 (1−ρ)^3 f(1,1) f(4,6)=15ρ^3 (1−ρ)^2 f(1,1) f(5,6)=6ρ^4 (1−ρ) f(1,1) f(6,6)=ρ^5 f(1,1)
	2		f(1,3)=(3/2)(1−ρ) f(1,2) f(2,3)=ρ f(1,2)+(1−ρ) f(2,2) f(3,3)=ρ f(2,2)	f(1,4)=2(1−ρ)^2 f(1,2) ~~f(2,4)=(**5/2**)ρ(1−ρ) f(1,2)+(1−ρ)^2 f(2,2)~~ f(2,4)=(**12/5**)ρ(1−ρ) f(1,2)+(**6/5**)(1−ρ)^2 f(2,2) f(3,4)=ρ^2 f(1,2)+2ρ(1−ρ)f(2,2) f(4,4)=ρ^2 f(2,2)	f(1,5)=(5/2)(1−ρ)^3 f(1,2) ~~f(2,5)=(**9/2**)ρ(1−ρ)^2 f(1,2)+(1−ρ)^3 f(2,2)~~ f(2,5)=(**30/7**)ρ(1−ρ)^2 f(1,2)+(**10/7**)(1−ρ)^3 f(2,2) ~~f(3,5)=(**7/2**)ρ^2 (1−ρ) f(1,2)+**3**ρ(1−ρ)^2 f(2,2)~~ f(3,5)=(**10/3**)ρ^2 (1−ρ) f(1,2)+(**10/3**)ρ(1−ρ)^2 f(2,2) f(4,5)=ρ^3 f(1,2)+3ρ^2 (1−ρ) f(2,2) f(5,5)=ρ^3 f(2,2)	f(1,6)=3(1−ρ)^4 f(1,2) ~~f(2,6)=**7**ρ(1−ρ)^3 f(1,2)+(1−ρ)^4 f(2,2)~~ f(2,6)=(**20/3**)ρ(1−ρ)^3 f(1,2)+(**5/3**)(1−ρ)^4 f(2,2) ~~f(3,6)=**8**ρ^2 (1−ρ)^ 2 f(1,2)+**4**ρ(1−ρ)^3 f(2,2)~~ f(3,6)=(**15/2**)ρ^2 (1−ρ)^ 2 f(1,2)+**5**ρ(1−ρ)^3 f(2,2) ~~f(4,6)=(**9/2**)ρ^3 (1−ρ) f(1,2)+**6**ρ^2 (1−ρ)^2 f(2,2)~~ f(4,6)=(**30/7**)ρ^3 (1−ρ) f(1,2)+(**45/7**)ρ^2 (1−ρ)^2 f(2,2) f(5,6)=ρ^4 f(1,2)+4ρ^3 (1−ρ) f(2,2) f(6,6)=ρ^4 f(2,2)
	3			f(1,4)=(4/3)(1−ρ) f(1,3) f(2,4)=ρ f(1,3)+(1−ρ) f(2,3) f(3,4)=ρ f(2,3)+(1−ρ) f(3,3) f(4,4)=ρ f(3,3)	f(1,5)=(5/3)(1−ρ)^2 f(1,3) ~~f(2,5)=(**7/3**)ρ(1−ρ) f(1,3)+(1−ρ)^2 f(2,3)~~ f(2,5)=(**20/9**)ρ(1−ρ) f(1,3)+(**10/9**)(1−ρ)^2 f(2,3) f(3,5)=ρ^2 f(1,3)+2ρ(1−ρ) f(2,3)+(1−ρ)^2 f(3,3) f(4,5)=ρ^2 f(2,3)+2ρ(1−ρ) f(3,3) f(5,5)=ρ^2 f(3,3)	f(1,6)=2(1−ρ)^3 f(1,3) ~~f(2,6)=**4**ρ(1−ρ)^2 f(1,3)+(1−ρ)^3 f(2,3)~~ f(2,6)=(**15/4**)ρ(1−ρ)^2 f(1,3)+(**5/4**)(1−ρ)^3 f(2,3) ~~f(3,6)=(**10/3**)ρ^2 (1−ρ) f(1,3)+**3**ρ(1−ρ)^2 f(2,3)+(1−ρ)^3 f(3,3)~~ f(3,6)=(**60/19**)ρ^2 (1−ρ) f(1,3)+(**60/19**)ρ(1−ρ)^2 f(2,3)+(**20/19**)(1−ρ)^3 f(3,3) f(4,6)=ρ^3 f(1,3)+3ρ^2 (1−ρ) f(2,3)+3ρ(1−ρ)^2 f(3,3) f(5,6)=ρ^3 f(2,3)+3ρ^2 (1−ρ) f(3,3) f(6,6)=ρ^3 f(3,3)

Mapping Up Formulas	Size of System Mapping To (Number of Identical Trains)				
	2	3	4	5	6
4				f(1,5)=(5/4)(1−ρ) f(1,4) f(2,5)=ρ f(1,4)+(1−ρ) f(2,4) f(3,5)=ρ f(2,4)+(1−ρ) f(3,4) f(4,5)=ρ f(3,4)+(1−ρ) f(4,4) f(5,5)=ρ f(4,4)	f(1,6)=(3/2)(1−ρ)^2 f(1,4) ~~f(2,6)=(9/4)ρ(1−ρ) f(1,4)+(1−ρ)^2 f(2,4)~~ f(2,6)=(**15/7**)ρ(1−ρ) f(1,4)+(**15/14**)(1−ρ)^2 f(2,4) f(3,6)=ρ^2 f(1,4)+2ρ(1−ρ) f(2,4)+(1−ρ)^2 f(3,4) f(4,6)=ρ^2 f(2,4)+2ρ(1−ρ) f(3,4)+(1−ρ)^2 f(4,4) f(5,6)=ρ^2 f(3,4)+2ρ(1−ρ) f(4,4) f(6,6)=ρ^2 f(4,4)
5					f(1,6)=(6/5)(1−ρ) f(1,5) f(2,6)=ρ f(1,5)+(1−ρ) f(2,5) f(3,6)=ρ f(2,5)+(1−ρ) f(3,5) f(4,6)=ρ f(3,5)+(1−ρ) f(4,5) f(5,6)=ρ f(4,5)+(1−ρ) f(5,5) f(6,6)=ρf5

7. ***Can a single prior work for all causes?***

It would be convenient if one prior could be used for every cause type. The causal CCF data presented in this report could be reviewed to determine whether the differences in the various cause groups significantly prohibit the use of a single prior for all causes.

8. ***How is the average group size calculated? What is its impact on CCF parameter estimations?***

When using the impact vector and mapping method to estimate CCF parameters, independent events can be mapped from group size *k* to group size *l* via the following equation:

$$n_I^{(l)} = \frac{l}{k} n_I^{(k)} \quad \text{(Eq. 12)}$$

However, for the above explicit mapping method, the group size for independent failure events is unavailable in the NRC Reliability and Availability Data System. So, the concept of average group size is introduced and used to map independent events. Assuming N_g is the number of groups of size g, the average group size can be defined as:

$$Avg = \sum gN_g \,/\sum N_g \quad \text{(Eq. 13)}$$

where ΣN_g is the total number of groups and ΣgN_g is the total number of components. The equivalent number of independent events for group size l can be estimated as:

$$n_I^{(l)} = \frac{l}{\sum gN_g \,/\sum N_g} n_I = \frac{l}{Avg} n_I \quad \text{(Eq. 14)}$$

where n_I is the total number of independent component failures.

Without knowing group size information for the associated independent failure events, the current approach as employed in the CCF database software system uses the average group size of the relevant CCF events to map the independent events. Apparently, the average group size for CCF events is usually different than the average group size that should be used to map independent events.

9. ***Will the testing scheme for various components impact priors?***

It is unclear whether different component testing schemes (staggered testing vs. non-staggered or "simultaneous" testing) would impact the prior estimation, or whether separate data analyses are needed for them. One quick thought is that, if (for example) some valves undergo staggered testing and some undergo nearly simultaneous testing, the data for those two kinds of valves must be analyzed separately, since the two kinds of testing will include numerically different alphas. Mixing the two kinds of data would not give a correct result for either valve type.

6. FUTURE WORK

This report documents the current process of developing CCF prior distributions, updating alpha factor priors using data from 1997 through 2015, and developing causal alpha factor priors for five CCF cause groups: Component, Design, Environment, Human, and Other. While these new priors were developed to serve as replacements for the existing ones, the following work were provided in the original study of INL/LTD-17-43723 to address the issues listed in Section 5:

1. Perform sensitivity analysis to understand the impact of different prior distributions on event and condition assessment. NRC has proposed one to identify three or so component groups (one with very sparse data, one with a lot of data, and one somewhere in between), identify three prior distributions (an existing one, a non-informative one, and something in between), calculate alpha parameters for each of the three component groups using three different priors, and plug the resultant alpha factors into one or two SPAR models. This original proposal could be expanded to include the new priors and causal priors developed in the report.
2. Publish the prior development process in national and international conferences/journals and on the NRC website so as to engage outside experts for extensive discussion and improvements.
3. Evaluate the general formula for mapping up CCF data, as described in Item 6 in Section 5. Revise the potential errors in the current mapping up formulas used in the CCF Data Software.
4. Evaluate whether the new approach for estimating the mapping up factor ρ (refer to Item #4 and #6 in Section 5) should (and could) be incorporated into the CCF Data Software.
5. Evaluate the calculation of the average group size in the CCF Data Software and its impact on the results (refer to Item #8 in Section 5). If an alternative determination of the average group size proves more proper, revise the CCF Data Software with the new average group size formula.
6. Evaluate whether the binomial regression treatment of complete CCF events in the prior development process is appropriate.
7. Evaluate whether a single prior could work for all causes.
8. Determine whether different priors should be developed for different component groups for alpha factors and for causal alpha factors. If yes, revise the CCF Data Software accordingly.
9. Evaluate whether there are any other alternative approaches for developing prior distributions, apart from the current impact vector and mapping approach.

Since the original study in 2017 and INL/LTD-17-43723, some of the above suggested works were conducted (e.g., Item #1 for the impact of prior distributions on CCF parameter estimation), some were planned to be conducted (e.g., #8 for component-specific priors), while others may be planned in the future based on the inputs from the NRC and other stakeholders. A conference paper [23] was published in August 2018 that describes the CCF prior distribution development process. Another conference paper [24] will be published in November 2021 that presents the more recent CCF research activities that includes the sensitivity analyses to evaluate the impact of various prior distributions might have on CCF parameter estimations.

7. REFERENCES

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APPENDIX A

PRIOR DISTRIBUTIONS IN PREVIOUS CCF PARAMETER ESTIMATION REPORTS

This Appendix provides a summary of the prior distributions included in NUREG/CR-5485 and the CCF Parameter Estimations Update Reports (2003, 2005, 2007, 2009, 2010, 2012, and 2015)[c]. For simplicity, only alpha factor distributions up to a common cause component group (CCCG) size of 4 are presented for the update reports here. The complete prior distributions for each update report can be located in the corresponding reports via the NRC CCF Results and Databases website: http://nrcoe.inl.gov/resultsdb/ParamEstSpar/.

The CCF prior distributions—called "No Data (Prior Only)" distributions in the update reports—are published in the 2003 report, and updated in the 2005 report with a data version of 2005/12/31 and in the 2007 report with a data version of 2007/12/31. The CCF prior distributions stopped being updated after 2007. The same CCF prior distributions with the data version of 2007/12/31 are provided in the subsequent update reports (i.e., 2009, 2010, 2012, and 2015).

Since 2007, the update reports provide not only the CCF Prior Distributions, but also "Generic Demand" and "Generic Rate" distributions. While the update reports after 2007 do not update the CCF "No Data (Prior Only)" prior distributions, they do update the "Generic Demand" and "Generic Rate" distributions. (Note that the CCF data used in the 2007 update for the "Generic Demand" and "Generic Rate" distributions starts from 1991, while those used in all of the subsequent update reports start from 1997.)

[c] NUREG/CR-5497, Common-Cause Failure Parameter Estimations, published in October 1998, does not include CCF prior distributions. It may have used the prior distributions presented in NUREG/CR-5485, Table 5-11 for parameter estimations.

NUREG/CR-5485, Table 5-11. Generic prior distributions for various system sizes.

CCCG Size m	α-Factor	Distributions Parameters		Percentiles			Mean
		a	b	P_{05}	P_{50}	P_{95}	
2	α_1	9.5300	0.470	8.20E-01	9.78E-01	1.00E-00	0.95300
	α_2	0.4700	9.530	1.42E-04	2.16E-02	1.81E-01	0.04700
3	α_1	15.2000	0.800	8.42E-01	9.67E-01	9.99E-01	0.95000
	α_2	0.3872	15.613	2.10E-05	8.79E-03	1.01E-01	0.02420
	α_3	0.4128	15.587	3.45E-05	1.01E-02	1.05E-01	0.02580
4	α_1	24.7000	1.300	8.67E-01	9.61E-01	9.95E-01	0.95000
	α_2	0.5538	25.446	1.44E-04	1.08E-02	7.81E-02	0.02130
	α_3	0.2626	25.737	2.98E-07	1.99E-03	4.82E-02	0.01010
	α_4	0.4836	25.516	6.29E-05	8.42E-03	7.17E-02	0.01860
5	α_1	38.042	1.958	8.86E-01	9.58E-01	9.91E-01	0.95106
	α_2	0.7280	39.272	3.72E-04	1.10E-02	6.05E-02	0.01820
	α_3	0.4120	39.588	1.32E-05	3.93E-03	4.22E-02	0.01030
	α_4	0.2336	39.766	4.57E-08	8.97E-04	2.89E-02	0.00584
	α_5	0.5840	39.416	1.24E-04	7.66E-03	5.27E-02	0.01460
6	α_1	50.4724	2.528	8.97E-01	9.58E-01	9.89E-01	0.95231
	α_2	0.7791	52.221	3.76E-04	9.20E-03	4.78E-02	0.01470
	α_3	0.5406	52.459	6.04E-05	5.02E-03	3.79E-02	0.01020
	α_4	0.3127	52.687	9.28E-07	1.56E-03	2.66E-02	0.00590
	α_5	0.2433	52.757	5.77E-08	7.67E-04	2.24E-02	0.00459
	α_6	0.6519	52.348	1.66E-04	6.93E-03	4.27E-02	0.01230
7	α_1	74.5360	3.464	9.12E-01	9.59E-01	9.86E-01	0.95559
	α_2	0.9906	77.009	6.44E-04	8.84E-03	3.79E-02	0.01270
	α_3	0.6817	77.318	1.39E-04	5.05E-03	2.99E-02	0.00874
	α_4	0.4891	77.511	2.21E-05	2.82E-03	2.42E-02	0.00627
	α_5	0.2941	77.706	3.39E-07	8.97E-04	1.74E-02	0.00377
	α_6	0.2051	77.795	3.84E-09	2.94E-04	1.35E-02	0.00263
	α_7	0.8034	77.197	2.89E-04	6.52E-03	3.32E-02	0.01030
8	α_1	97.6507	4.349	9.20E-01	9.60E-01	9.84E-01	0.95736
	α_2	1.1118	100.888	7.25E-04	7.91E-03	3.13E-02	0.01090
	α_3	0.7915	101.209	2.07E-04	4.87E-03	2.52E-02	0.00776
	α_4	0.6253	101.375	6.92E-05	3.34E-03	2.17E-02	0.00613
	α_5	0.4417	101.558	8.51E-06	1.76E-03	1.74E-02	0.00433
	α_6	0.2581	101.742	6.09E-08	4.74E-04	1.21E-02	0.00253
	α_7	0.1969	101.803	1.59E-09	1.93E-04	1.00E-02	0.00193
	α_8	0.9241	101.076	3.82E-04	6.12E-03	2.78E-02	0.00906

CCF Parameter Estimations 2003, Section 2, No Data (Prior Only)

Section 2.1.1.1, All Failure Modes. No data version is provided.

ALPHA FACTOR DISTRIBUTIONS

CCCG = 2 Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.8783440	0.9690420	0.9866290	0.9999290	----	1.4131E+01	4.5144E-01
2	7.24E-05	3.09E-02	1.33E-02	1.21E-01	----	4.5144E-01	1.4131E+01

CCCG = 3 Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9148940	0.9700020	0.9779420	0.9979420	----	3.6141E+01	1.1176E+00
2	7.72E-04	2.28E-02	1.50E-02	7.15E-02	----	8.5035E-01	3.6408E+01
3	2.53E-07	7.17E-03	1.45E-03	3.40E-02	----	2.6733E-01	3.6991E+01

CCCG = 4 Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9243310	0.9682640	0.9733830	0.9946800	----	5.7379E+01	1.8806E+00
2	1.80E-03	2.10E-02	1.59E-02	5.78E-02	----	1.2495E+00	5.8010E+01
3	8.65E-06	6.92E-03	2.61E-03	2.84E-02	----	4.1063E-01	5.8849E+01
4	1.42E-08	3.72E-03	4.98E-04	1.86E-02	----	2.2054E-01	5.9039E+01

CCCG = 5 Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9416970	0.9705760	0.9731470	0.9906680	----	1.1687E+02	3.5429E+00
2	3.47E-03	1.77E-02	1.51E-02	4.09E-02	----	2.1414E+00	1.1827E+02
3	3.67E-04	7.95E-03	5.44E-03	2.40E-02	----	9.5737E-01	1.1945E+02
4	1.80E-06	3.06E-03	1.01E-03	1.30E-02	----	3.6878E-01	1.2004E+02
5	2.81E-20	6.26E-04	5.08E-07	3.64E-03	----	7.5435E-02	1.2033E+02

CCCG = 6 Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9444530	0.9705190	0.9726530	0.9893010	----	1.4121E+02	4.2894E+00
2	3.35E-03	1.58E-02	1.36E-02	3.57E-02	----	2.3037E+00	1.4319E+02
3	4.86E-04	7.54E-03	5.44E-03	2.17E-02	----	1.0979E+00	1.4440E+02
4	3.30E-05	3.99E-03	2.06E-03	1.45E-02	----	5.8178E-01	1.4491E+02
5	4.45E-09	1.48E-03	1.89E-04	7.50E-03	----	2.1648E-01	1.4528E+02
6	1.23E-17	6.15E-04	1.80E-06	3.59E-03	----	8.9555E-02	1.4541E+02

CCCG = 7 Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9516920	0.9716290	0.9729760	0.9869580	----	2.2464E+02	6.5594E+00
2	4.13E-03	1.40E-02	1.26E-02	2.87E-02	----	3.2518E+00	2.2794E+02
3	9.24E-04	6.97E-03	5.61E-03	1.76E-02	----	1.6135E+00	2.2958E+02
4	1.95E-04	4.16E-03	2.85E-03	1.26E-02	----	9.6383E-01	2.3023E+02
5	1.06E-05	2.24E-03	1.05E-03	8.49E-03	----	5.1822E-01	2.3068E+02
6	2.00E-10	7.87E-04	6.28E-05	4.15E-03	----	1.8209E-01	2.3101E+02
7	1.08E-46	1.29E-04	2.31E-13	5.03E-04	----	3.0005E-02	2.3116E+02

CCCG = 8 Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9540630	0.9722080	0.9733600	0.9864020	----	2.6325E+02	7.5254E+00
2	4.02E-03	1.29E-02	1.17E-02	2.58E-02	----	3.4977E+00	2.6727E+02
3	9.44E-04	6.40E-03	5.23E-03	1.58E-02	----	1.7348E+00	2.6904E+02
4	2.55E-04	4.02E-03	2.89E-03	1.16E-02	----	1.0910E+00	2.6968E+02
5	4.14E-05	2.53E-03	1.46E-03	8.68E-03	----	6.8763E-01	2.7008E+02
6	6.49E-07	1.32E-03	4.24E-04	5.72E-03	----	3.5982E-01	2.7041E+02
7	1.78E-14	4.32E-04	6.14E-06	2.47E-03	----	1.1715E-01	2.7065E+02
8	3.39E-38	1.38E-04	1.90E-11	6.36E-04	----	3.7386E-02	2.7073E+02

CCF Parameter Estimations 2005, Section 3, No Data (Prior Only)

Section 3, No Data (Prior Only). Data Version 2005/12/31

ALPHA FACTOR DISTRIBUTIONS

Data Version :	2005/12/31

CCCG = 2 Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.8386830	0.9593170	0.9828300	0.9999250	----	1.0246E+01	4.3452E-01
2	7.69E-05	4.06E-02	1.71E-02	1.61E-01	----	4.3452E-01	1.0246E+01

CCCG = 3 Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.8979020	0.9640890	0.9736330	0.9976040	----	2.9555E+01	1.1008E+00
2	8.71E-04	2.71E-02	1.77E-02	8.57E-02	----	8.3366E-01	2.9822E+01
3	3.07E-07	8.71E-03	1.77E-03	4.13E-02	----	2.6722E-01	3.0388E+01

CCCG = 4 Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9077330	0.9613450	0.9675780	0.9936050	----	4.6136E+01	1.8550E+00
2	2.13E-03	2.55E-02	1.93E-02	7.04E-02	----	1.2281E+00	4.6763E+01
3	9.52E-06	8.42E-03	3.13E-03	3.47E-02	----	4.0431E-01	4.7586E+01
4	2.00E-08	4.64E-03	6.37E-04	2.32E-02	----	2.2267E-01	4.7768E+01

CCCG = 5 Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9298110	0.9645110	0.9675740	0.9887220	----	9.6161E+01	3.5382E+00
2	4.08E-03	2.12E-02	1.80E-02	4.89E-02	----	2.1142E+00	9.7585E+01
3	4.79E-04	9.80E-03	6.77E-03	2.94E-02	----	9.7738E-01	9.8721E+01
4	2.47E-06	3.75E-03	1.26E-03	1.59E-02	----	3.7439E-01	9.9324E+01
5	5.98E-21	7.25E-04	4.10E-07	4.19E-03	----	7.2277E-02	9.9627E+01

CCCG = 6 Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9335790	0.9647030	0.9672350	0.9871780	----	1.1694E+02	4.2786E+00
2	3.80E-03	1.84E-02	1.58E-02	4.19E-02	----	2.2392E+00	1.1897E+02
3	6.63E-04	9.41E-03	6.89E-03	2.68E-02	----	1.1418E+00	1.2007E+02
4	4.37E-05	4.88E-03	2.56E-03	1.76E-02	----	5.9222E-01	1.2062E+02
5	7.66E-09	1.83E-03	2.48E-04	9.18E-03	----	2.2220E-01	1.2099E+02
6	1.16E-18	6.86E-04	1.20E-06	4.00E-03	----	8.3237E-02	1.2113E+02

CCCG = 7 Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9422570	0.9661670	0.9677850	0.9845420	----	1.8405E+02	6.4449E+00
2	4.56E-03	1.62E-02	1.45E-02	3.35E-02	----	3.0878E+00	1.8740E+02
3	1.15E-03	8.56E-03	6.91E-03	2.16E-02	----	1.6312E+00	1.8886E+02
4	2.60E-04	5.19E-03	3.59E-03	1.55E-02	----	9.8887E-01	1.8950E+02
5	1.34E-05	2.73E-03	1.29E-03	1.03E-02	----	5.2177E-01	1.8997E+02
6	3.52E-10	9.77E-04	8.35E-05	5.13E-03	----	1.8628E-01	1.9030E+02
7	5.33E-48	1.52E-04	1.33E-13	5.74E-04	----	2.9071E-02	1.9046E+02

CCCG = 8 Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9454620	0.9670150	0.9683850	0.9838980	----	2.1873E+02	7.4609E+00
2	4.45E-03	1.47E-02	1.33E-02	2.99E-02	----	3.3447E+00	2.2284E+02
3	1.13E-03	7.68E-03	6.29E-03	1.90E-02	----	1.7384E+00	2.2445E+02
4	3.58E-04	5.06E-03	3.70E-03	1.44E-02	----	1.1465E+00	2.2504E+02
5	5.70E-05	3.13E-03	1.84E-03	1.06E-02	----	7.0833E-01	2.2548E+02
6	9.18E-07	1.62E-03	5.31E-04	6.94E-03	----	3.6696E-01	2.2582E+02
7	7.20E-14	5.43E-04	9.77E-06	3.09E-03	----	1.2297E-01	2.2606E+02
8	1.34E-42	1.46E-04	2.08E-12	6.19E-04	----	3.3124E-02	2.2615E+02

CCF Parameter Estimations 2007, Section 3, No Data (Prior Only)

Section 3.1.3, CCF Prior Distribution, Data Version 2007/12/31

Data Version :	2007/12/31

Total Number of Independent Failure Events: 0
Total Number of Common-Cause Failure Events: 0

ALPHA FACTOR DISTRIBUTIONS

CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.8993200	0.9742690	0.9887700	0.9999290	----	1.7418E+01	4.6002E-01
2	6.65E-05	2.57E-02	1.12E-02	1.00E-01	----	4.6002E-01	1.7418E+01

CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9306240	0.9755060	0.9819700	0.9982830	----	4.5105E+01	1.1325E+00
2	6.61E-04	1.87E-02	1.23E-02	5.84E-02	----	8.6476E-01	4.5372E+01
3	2.07E-07	5.79E-03	1.17E-03	2.74E-02	----	2.6776E-01	4.5969E+01

CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9380870	0.9740820	0.9782970	0.9956540	----	7.0868E+01	1.8856E+00
2	1.43E-03	1.70E-02	1.28E-02	4.69E-02	----	1.2400E+00	7.1513E+01
3	9.66E-06	5.89E-03	2.32E-03	2.38E-02	----	4.2870E-01	7.2324E+01
4	9.21E-09	2.98E-03	3.83E-04	1.50E-02	----	2.1695E-01	7.2536E+01

CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9521790	0.9760740	0.9782400	0.9925770	----	1.4106E+02	3.4576E+00
2	2.59E-03	1.41E-02	1.19E-02	3.30E-02	----	2.0400E+00	1.4247E+02
3	3.01E-04	6.59E-03	4.50E-03	2.00E-02	----	9.5369E-01	1.4356E+02
4	2.21E-06	2.67E-03	9.37E-04	1.12E-02	----	3.8684E-01	1.4413E+02
5	5.61E-20	5.33E-04	5.18E-07	3.10E-03	----	7.7129E-02	1.4444E+02

CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9553700	0.9762820	0.9779970	0.9913440	----	1.7893E+02	4.3470E+00
2	2.60E-03	1.24E-02	1.07E-02	2.81E-02	----	2.2804E+00	1.8099E+02
3	4.16E-04	6.13E-03	4.45E-03	1.75E-02	----	1.1245E+00	1.8215E+02
4	3.82E-05	3.40E-03	1.85E-03	1.20E-02	----	6.2471E-01	1.8265E+02
5	1.60E-08	1.32E-03	2.18E-04	6.46E-03	----	2.4272E-01	1.8303E+02
6	1.26E-20	4.07E-04	3.05E-07	2.36E-03	----	7.4722E-02	1.8320E+02

CCCG = 7

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9603690	0.9769760	0.9781320	0.9896440	----	2.6720E+02	6.2971E+00
2	3.14E-03	1.12E-02	1.00E-02	2.33E-02	----	3.0721E+00	2.7042E+02
3	6.66E-04	5.55E-03	4.40E-03	1.43E-02	----	1.5182E+00	2.7197E+02
4	1.58E-04	3.48E-03	2.37E-03	1.06E-02	----	9.5310E-01	2.7254E+02
5	1.00E-05	1.93E-03	9.22E-04	7.26E-03	----	5.2795E-01	2.7296E+02
6	4.58E-10	7.08E-04	6.75E-05	3.68E-03	----	1.9373E-01	2.7330E+02
7	5.03E-44	1.17E-04	8.41E-13	4.81E-04	----	3.2027E-02	2.7346E+02

CCCG = 8

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9622170	0.9773660	0.9783580	0.9891370	----	3.1221E+02	7.2302E+00
2	3.13E-03	1.04E-02	9.45E-03	2.12E-02	----	3.3414E+00	3.1609E+02
3	6.67E-04	5.04E-03	4.06E-03	1.28E-02	----	1.6130E+00	3.1782E+02
4	1.86E-04	3.26E-03	2.30E-03	9.62E-03	----	1.0438E+00	3.1839E+02
5	3.88E-05	2.20E-03	1.28E-03	7.47E-03	----	7.0280E-01	3.1873E+02
6	5.77E-07	1.13E-03	3.63E-04	4.86E-03	----	3.6184E-01	3.1907E+02
7	1.19E-13	3.98E-04	8.44E-06	2.25E-03	----	1.2739E-01	3.1931E+02
8	5.47E-36	1.25E-04	5.43E-11	6.01E-04	----	4.0005E-02	3.1940E+02

CCF Parameter Estimations 2007, Section 3

Section 3.1.1, Generic Demand CCF Prior Distribution: CCF-DEM

Failure Mode :	FAIL TO CLOSE (NORMALLY OPEN) FAIL TO OPEN (NORMALLY CLOSED) FAIL TO START FAIL TO STOP
Start Date :	1991/01/01
Data Version :	2007/12/31

Total Number of Independent Failure Events: 5722
Total Number of Common-Cause Failure Events: 375

ALPHA FACTOR DISTRIBUTIONS

CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9575610	0.9648240	0.9649860	0.9715280	0.9647330	1.8100E+03	6.5990E+01
2	2.85E-02	3.52E-02	3.50E-02	4.24E-02	3.53E-02	6.5990E+01	1.8100E+03

CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9579120	0.9639110	0.9640230	0.9695270	0.9637140	2.6833E+03	1.0046E+02
2	1.94E-02	2.39E-02	2.38E-02	2.89E-02	2.40E-02	6.6566E+01	2.7172E+03
3	8.97E-03	1.22E-02	1.21E-02	1.58E-02	1.23E-02	3.3898E+01	2.7499E+03

CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9596480	0.9647820	0.9648640	0.9696300	0.9645940	3.5506E+03	1.2961E+02
2	1.59E-02	1.95E-02	1.94E-02	2.34E-02	1.96E-02	7.1769E+01	3.6084E+03
3	7.69E-03	1.03E-02	1.02E-02	1.31E-02	1.04E-02	3.7766E+01	3.6424E+03
4	3.62E-03	5.45E-03	5.37E-03	7.59E-03	5.50E-03	2.0074E+01	3.6601E+03

CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9634500	0.9678320	0.9679010	0.9719870	0.9675650	4.4690E+03	1.4854E+02
2	1.20E-02	1.48E-02	1.47E-02	1.78E-02	1.48E-02	6.8136E+01	4.5494E+03
3	6.70E-03	8.84E-03	8.77E-03	1.12E-02	8.91E-03	4.0807E+01	4.5767E+03
4	4.33E-03	6.08E-03	6.01E-03	8.08E-03	6.19E-03	2.8077E+01	4.5895E+03
5	1.42E-03	2.49E-03	2.42E-03	3.81E-03	2.56E-03	1.1519E+01	4.6060E+03

CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9658770	0.9697650	0.9698190	0.9734600	0.9695410	5.3515E+03	1.6685E+02
2	1.02E-02	1.26E-02	1.25E-02	1.52E-02	1.26E-02	6.9522E+01	5.4488E+03
3	5.42E-03	7.19E-03	7.13E-03	9.15E-03	7.22E-03	3.9655E+01	5.4787E+03
4	4.09E-03	5.64E-03	5.59E-03	7.40E-03	5.72E-03	3.1149E+01	5.4872E+03
5	2.30E-03	3.50E-03	3.44E-03	4.90E-03	3.57E-03	1.9307E+01	5.4990E+03
6	6.22E-04	1.31E-03	1.25E-03	2.20E-03	1.34E-03	7.2149E+00	5.5111E+03

Section 3.1.2, Generic Rate CCF Prior Distribution: CCF-RATE

Failure Mode :	SPURIOUS ACTUATION FAIL TO RUN FAIL TO REMAIN CLOSED (DETECTABLE LEAKAGE) NO VOLTAGE/AMPERAGE OUTPUT HIGH VOLTAGE/AMPERAGE OUTPUT NO FLOW/PLUGGED
Start Date :	1991/01/01
Data Version :	2007/12/31

Total Number of Independent Failure Events: 4161

Total Number of Common-Cause Failure Events: 270

ALPHA FACTOR DISTRIBUTIONS

CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9654480	0.9721610	0.9723360	0.9782680	0.9721390	1.7231E+03	4.9343E+01
2	2.17E-02	2.78E-02	2.77E-02	3.46E-02	2.79E-02	4.9343E+01	1.7231E+03

CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9667950	0.9722490	0.9723650	0.9772920	0.9721910	2.5686E+03	7.3317E+01
2	1.34E-02	1.73E-02	1.72E-02	2.17E-02	1.73E-02	4.5816E+01	2.5961E+03
3	7.39E-03	1.04E-02	1.03E-02	1.39E-02	1.05E-02	2.7501E+01	2.6144E+03

CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9686110	0.9732420	0.9733290	0.9775700	0.9732230	3.4094E+03	9.3738E+01
2	1.07E-02	1.37E-02	1.36E-02	1.71E-02	1.36E-02	4.8060E+01	3.4551E+03
3	5.97E-03	8.33E-03	8.23E-03	1.10E-02	8.38E-03	2.9168E+01	3.4740E+03
4	2.98E-03	4.71E-03	4.62E-03	6.76E-03	4.75E-03	1.6510E+01	3.4866E+03

CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9707490	0.9747580	0.9748320	0.9785210	0.9747130	4.2943E+03	1.1120E+02
2	8.72E-03	1.12E-02	1.11E-02	1.39E-02	1.11E-02	4.9342E+01	4.3562E+03
3	5.10E-03	7.04E-03	6.96E-03	9.23E-03	7.05E-03	3.1009E+01	4.3745E+03
4	3.30E-03	4.89E-03	4.82E-03	6.74E-03	4.97E-03	2.1551E+01	4.3840E+03
5	1.12E-03	2.11E-03	2.04E-03	3.36E-03	2.16E-03	9.3017E+00	4.3962E+03

CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
1	0.9724430	0.9760120	0.9760750	0.9793740	0.9760020	5.1456E+03	1.2647E+02
2	7.54E-03	9.65E-03	9.59E-03	1.20E-02	9.55E-03	5.0864E+01	5.2212E+03
3	4.25E-03	5.87E-03	5.81E-03	7.70E-03	5.86E-03	3.0945E+01	5.2411E+03
4	3.19E-03	4.61E-03	4.55E-03	6.24E-03	4.65E-03	2.4301E+01	5.2478E+03
5	1.69E-03	2.77E-03	2.71E-03	4.06E-03	2.82E-03	1.4595E+01	5.2575E+03
6	4.66E-04	1.09E-03	1.03E-03	1.93E-03	1.12E-03	5.7620E+00	5.2663E+03

CCF Parameter Estimations 2009, Section 2, No Data (Prior Only)

Section 2.1.3, CCF Prior Distribution, Data Version 2007/12/31

Data Version : 2007/12/31

Total Number of Independent Failure Events: 0
Total Number of Common-Cause Failure Events: 0

ALPHA FACTOR DISTRIBUTIONS

CCCG = **2**

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8993200	0.9742690	0.9887700	0.9999290	----	1.7418E+01	4.6002E-01
α_2	6.65E-05	2.57E-02	1.12E-02	1.00E-01	----	4.6002E-01	1.7418E+01

CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9306240	0.9755060	0.9819700	0.9982830	----	4.5105E+01	1.1325E+00
α_2	6.61E-04	1.87E-02	1.23E-02	5.84E-02	----	8.6476E-01	4.5372E+01
α_3	2.07E-07	5.79E-03	1.17E-03	2.74E-02	----	2.6776E-01	4.5969E+01

CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9380870	0.9740820	0.9782970	0.9956540	----	7.0868E+01	1.8856E+00
α_2	1.43E-03	1.70E-02	1.28E-02	4.69E-02	----	1.2400E+00	7.1513E+01
α_3	9.66E-06	5.89E-03	2.32E-03	2.38E-02	----	4.2870E-01	7.2324E+01
α_4	9.21E-09	2.98E-03	3.83E-04	1.50E-02	----	2.1695E-01	7.2536E+01

CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9521790	0.9760740	0.9782400	0.9925770	----	1.4106E+02	3.4576E+00
α_2	2.59E-03	1.41E-02	1.19E-02	3.30E-02	----	2.0400E+00	1.4247E+02
α_3	3.01E-04	6.59E-03	4.50E-03	2.00E-02	----	9.5369E-01	1.4356E+02
α_4	2.21E-06	2.67E-03	9.37E-04	1.12E-02	----	3.8684E-01	1.4413E+02
α_5	5.61E-20	5.33E-04	5.18E-07	3.10E-03	----	7.7129E-02	1.4444E+02

CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9553700	0.9762820	0.9779970	0.9913440	----	1.7893E+02	4.3470E+00
α_2	2.60E-03	1.24E-02	1.07E-02	2.81E-02	----	2.2804E+00	1.8099E+02
α_3	4.16E-04	6.13E-03	4.45E-03	1.75E-02	----	1.1245E+00	1.8215E+02
α_4	3.82E-05	3.40E-03	1.85E-03	1.20E-02	----	6.2471E-01	1.8265E+02
α_5	1.60E-08	1.32E-03	2.18E-04	6.46E-03	----	2.4272E-01	1.8303E+02
α_6	1.26E-20	4.07E-04	3.05E-07	2.36E-03	----	7.4722E-02	1.8320E+02

CCCG = 7

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9603690	0.9769760	0.9781320	0.9896440	----	2.6720E+02	6.2971E+00
α_2	3.14E-03	1.12E-02	1.00E-02	2.33E-02	----	3.0721E+00	2.7042E+02
α_3	6.66E-04	5.55E-03	4.40E-03	1.43E-02	----	1.5182E+00	2.7197E+02
α_4	1.58E-04	3.48E-03	2.37E-03	1.06E-02	----	9.5310E-01	2.7254E+02
α_5	1.00E-05	1.93E-03	9.22E-04	7.26E-03	----	5.2795E-01	2.7296E+02
α_6	4.58E-10	7.08E-04	6.75E-05	3.68E-03	----	1.9373E-01	2.7330E+02
α_7	5.03E-44	1.17E-04	8.41E-13	4.81E-04	----	3.2027E-02	2.7346E+02

CCCG = 8

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9622170	0.9773660	0.9783580	0.9891370	----	3.1221E+02	7.2302E+00
α_2	3.13E-03	1.04E-02	9.45E-03	2.12E-02	----	3.3414E+00	3.1609E+02
α_3	6.67E-04	5.04E-03	4.06E-03	1.28E-02	----	1.6130E+00	3.1782E+02
α_4	1.86E-04	3.26E-03	2.30E-03	9.62E-03	----	1.0438E+00	3.1839E+02
α_5	3.88E-05	2.20E-03	1.28E-03	7.47E-03	----	7.0280E-01	3.1873E+02
α_6	5.77E-07	1.13E-03	3.63E-04	4.86E-03	----	3.6184E-01	3.1907E+02
α_7	1.19E-13	3.98E-04	8.44E-06	2.25E-03	----	1.2739E-01	3.1931E+02
α_8	5.47E-36	1.25E-04	5.43E-11	6.01E-04	----	4.0005E-02	3.1940E+02

CCF Parameter Estimations 2009, Section 2

Section 2.1.1, Generic Demand CCF Prior Distribution: CCF-DEM

Failure Mode :	Fail to close (reseat) on demand Fail to open on demand Fail to start Fail to Operate (Open/Close) Fail to stop
Start Date :	1997/01/01
Data Version :	2009/12/31

Total Number of Independent Failure Events: 2446.50
Total Number of Common-Cause Failure Events: 97

ALPHA FACTOR DISTRIBUTIONS

CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9634050	0.9726920	0.9730300	0.9808300	0.9728470	9.1215E+02	2.5608E+01
α_2	1.92E-02	2.73E-02	2.70E-02	3.66E-02	2.72E-02	2.5608E+01	9.1215E+02

CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9656500	0.9731230	0.9733470	0.9798310	0.9733270	1.3609E+03	3.7587E+01
α_2	1.12E-02	1.63E-02	1.61E-02	2.22E-02	1.61E-02	2.2803E+01	1.3757E+03
α_3	6.51E-03	1.06E-02	1.03E-02	1.54E-02	1.06E-02	1.4784E+01	1.3837E+03

CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9663450	0.9728260	0.9729930	0.9787330	0.9731310	1.8052E+03	5.0425E+01
α_2	1.12E-02	1.56E-02	1.54E-02	2.06E-02	1.53E-02	2.8905E+01	1.8267E+03
α_3	3.63E-03	6.33E-03	6.15E-03	9.62E-03	6.27E-03	1.1737E+01	1.8439E+03
α_4	2.84E-03	5.27E-03	5.10E-03	8.31E-03	5.29E-03	9.7833E+00	1.8458E+03

CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9696730	0.9751830	0.9753210	0.9802270	0.9756580	2.2837E+03	5.8116E+01
α_2	8.25E-03	1.16E-02	1.15E-02	1.55E-02	1.12E-02	2.7259E+01	2.3146E+03
α_3	4.07E-03	6.55E-03	6.41E-03	9.51E-03	6.40E-03	1.5335E+01	2.3265E+03
α_4	1.75E-03	3.49E-03	3.35E-03	5.70E-03	3.47E-03	8.1629E+00	2.3337E+03
α_5	1.51E-03	3.14E-03	3.00E-03	5.25E-03	3.25E-03	7.3588E+00	2.3345E+03

CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9724050	0.9772250	0.9773410	0.9816580	0.9777920	2.7361E+03	6.3768E+01
α_2	6.22E-03	8.93E-03	8.81E-03	1.20E-02	8.50E-03	2.5000E+01	2.7749E+03
α_3	3.92E-03	6.13E-03	6.01E-03	8.74E-03	5.98E-03	1.7153E+01	2.7827E+03
α_4	1.94E-03	3.57E-03	3.45E-03	5.60E-03	3.51E-03	9.9848E+00	2.7899E+03
α_5	7.95E-04	1.93E-03	1.81E-03	3.46E-03	1.93E-03	5.4037E+00	2.7945E+03
α_6	9.88E-04	2.22E-03	2.11E-03	3.86E-03	2.29E-03	6.2261E+00	2.7936E+03

CCF Parameter Estimations 2009, Section 2

Section 2.1.2, Generic Rate CCF Prior Distribution: CCF-RATE

Failure Mode :	Spurious operation open or close Fail to run Filter media allows the pass through of debris High dP across filter Fail to control flow High voltage/ amperage output Loss of heat transfer capabilities in heat exchangers No voltage/amperage output No flow/plugged
Start Date :	1997/01/01
Data Version :	2009/12/31

Total Number of Independent Failure Events: 1857.60
Total Number of Common-Cause Failure Events: 67

ALPHA FACTOR DISTRIBUTIONS

CCCG = **2**

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9641020	0.9733720	0.9737170	0.9814740	0.9735380	8.9523E+02	2.4490E+01
α_2	1.85E-02	2.66E-02	2.63E-02	3.59E-02	2.65E-02	2.4490E+01	8.9523E+02

CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9668950	0.9742880	0.9745210	0.9808970	0.9745220	1.3372E+03	3.5289E+01
α_2	1.00E-02	1.50E-02	1.47E-02	2.07E-02	1.47E-02	2.0532E+01	1.3520E+03
α_3	6.61E-03	1.08E-02	1.05E-02	1.57E-02	1.08E-02	1.4757E+01	1.3577E+03

CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9702030	0.9763400	0.9765110	0.9818840	0.9767450	1.7802E+03	4.3139E+01
α_2	7.13E-03	1.08E-02	1.06E-02	1.50E-02	1.04E-02	1.9652E+01	1.8037E+03
α_3	5.26E-03	8.45E-03	8.27E-03	1.23E-02	8.45E-03	1.5406E+01	1.8079E+03
α_4	2.22E-03	4.43E-03	4.25E-03	7.26E-03	4.43E-03	8.0813E+00	1.8153E+03

CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9736030	0.9787670	0.9789070	0.9834530	0.9794110	2.2573E+03	4.8969E+01
α_2	4.92E-03	7.64E-03	7.50E-03	1.08E-02	7.02E-03	1.7615E+01	2.2887E+03
α_3	4.25E-03	6.81E-03	6.66E-03	9.84E-03	6.67E-03	1.5698E+01	2.2906E+03
α_4	2.74E-03	4.85E-03	4.71E-03	7.45E-03	4.90E-03	1.1185E+01	2.2951E+03
α_5	7.14E-04	1.94E-03	1.80E-03	3.65E-03	1.99E-03	4.4708E+00	2.3018E+03

CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9762820	0.9807670	0.9808860	0.9848620	0.9815060	2.7062E+03	5.3068E+01
α_2	3.50E-03	5.62E-03	5.50E-03	8.15E-03	5.03E-03	1.5513E+01	2.7438E+03
α_3	3.30E-03	5.37E-03	5.25E-03	7.84E-03	5.18E-03	1.4806E+01	2.7445E+03
α_4	2.71E-03	4.61E-03	4.49E-03	6.92E-03	4.60E-03	1.2730E+01	2.7465E+03
α_5	1.24E-03	2.61E-03	2.49E-03	4.39E-03	2.65E-03	7.2117E+00	2.7521E+03
α_6	2.61E-04	1.02E-03	9.00E-04	2.18E-03	1.03E-03	2.8070E+00	2.7565E+03

CCF Parameter Estimations 2010, Section 2, No Data (Prior Only)

Section 2.2.3, CCF Prior Distribution, Data Version 2007/12/31

Data Version : 2007/12/31

Total Number of Independent Failure Events: 0
Total Number of Common-Cause Failure Events: 0

ALPHA FACTOR DISTRIBUTIONS

CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8993200	0.9742690	0.9887700	0.9999290	----	1.7418E+01	4.6002E-01
α_2	6.65E-05	2.57E-02	1.12E-02	1.00E-01	----	4.6002E-01	1.7418E+01

CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9306240	0.9755060	0.9819700	0.9982830	----	4.5105E+01	1.1325E+00
α_2	6.61E-04	1.87E-02	1.23E-02	5.84E-02	----	8.6476E-01	4.5372E+01
α_3	2.07E-07	5.79E-03	1.17E-03	2.74E-02	----	2.6776E-01	4.5969E+01

CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9380870	0.9740820	0.9782970	0.9956540	----	7.0868E+01	1.8856E+00
α_2	1.43E-03	1.70E-02	1.28E-02	4.69E-02	----	1.2400E+00	7.1513E+01
α_3	9.66E-06	5.89E-03	2.32E-03	2.38E-02	----	4.2870E-01	7.2324E+01
α_4	9.21E-09	2.98E-03	3.83E-04	1.50E-02	----	2.1695E-01	7.2536E+01

CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9521790	0.9760740	0.9782400	0.9925770	----	1.4106E+02	3.4576E+00
α_2	2.59E-03	1.41E-02	1.19E-02	3.30E-02	----	2.0400E+00	1.4247E+02
α_3	3.01E-04	6.59E-03	4.50E-03	2.00E-02	----	9.5369E-01	1.4356E+02
α_4	2.21E-06	2.67E-03	9.37E-04	1.12E-02	----	3.8684E-01	1.4413E+02
α_5	5.61E-20	5.33E-04	5.18E-07	3.10E-03	----	7.7129E-02	1.4444E+02

CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9553700	0.9762820	0.9779970	0.9913440	----	1.7893E+02	4.3470E+00
α_2	2.60E-03	1.24E-02	1.07E-02	2.81E-02	----	2.2804E+00	1.8099E+02
α_3	4.16E-04	6.13E-03	4.45E-03	1.75E-02	----	1.1245E+00	1.8215E+02
α_4	3.82E-05	3.40E-03	1.85E-03	1.20E-02	----	6.2471E-01	1.8265E+02
α_5	1.60E-08	1.32E-03	2.18E-04	6.46E-03	----	2.4272E-01	1.8303E+02
α_6	1.26E-20	4.07E-04	3.05E-07	2.36E-03	----	7.4722E-02	1.8320E+02

CCCG = 7

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9603690	0.9769760	0.9781320	0.9896440	----	2.6720E+02	6.2971E+00
α_2	3.14E-03	1.12E-02	1.00E-02	2.33E-02	----	3.0721E+00	2.7042E+02
α_3	6.66E-04	5.55E-03	4.40E-03	1.43E-02	----	1.5182E+00	2.7197E+02
α_4	1.58E-04	3.48E-03	2.37E-03	1.06E-02	----	9.5310E-01	2.7254E+02
α_5	1.00E-05	1.93E-03	9.22E-04	7.26E-03	----	5.2795E-01	2.7296E+02
α_6	4.58E-10	7.08E-04	6.75E-05	3.68E-03	----	1.9373E-01	2.7330E+02
α_7	5.03E-44	1.17E-04	8.41E-13	4.81E-04	----	3.2027E-02	2.7346E+02

CCCG = 8

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9622170	0.9773660	0.9783580	0.9891370	----	3.1221E+02	7.2302E+00
α_2	3.13E-03	1.04E-02	9.45E-03	2.12E-02	----	3.3414E+00	3.1609E+02
α_3	6.67E-04	5.04E-03	4.06E-03	1.28E-02	----	1.6130E+00	3.1782E+02
α_4	1.86E-04	3.26E-03	2.30E-03	9.62E-03	----	1.0438E+00	3.1839E+02
α_5	3.88E-05	2.20E-03	1.28E-03	7.47E-03	----	7.0280E-01	3.1873E+02
α_6	5.77E-07	1.13E-03	3.63E-04	4.86E-03	----	3.6184E-01	3.1907E+02
α_7	1.19E-13	3.98E-04	8.44E-06	2.25E-03	----	1.2739E-01	3.1931E+02
α_8	5.47E-36	1.25E-04	5.43E-11	6.01E-04	----	4.0005E-02	3.1940E+02

CCF Parameter Estimations 2010, Section 2

Section 2.2.1, Generic Demand CCF Prior Distribution: CCF-DEM

Failure Mode :	Fail to close (reseat) on demand Fail to Open/Close Mode Unspecified (demand based) Fail to open on demand Fail to start Fail to Load/Run Fail to stop
Start Date :	1997/01/01
Data Version :	2010/12/31

Total Number of Independent Failure Events: 2821.80
Total Number of Common-Cause Failure Events: 95

ALPHA FACTOR DISTRIBUTIONS

CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9679280	0.9760020	0.9762900	0.9830830	0.9761660	1.0674E+03	2.6245E+01
α_2	1.69E-02	2.40E-02	2.37E-02	3.21E-02	2.38E-02	2.6245E+01	1.0674E+03

CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9689110	0.9755070	0.9756980	0.9814460	0.9757250	1.5955E+03	4.0060E+01
α_2	1.15E-02	1.62E-02	1.60E-02	2.17E-02	1.60E-02	2.6557E+01	1.6090E+03
α_3	4.95E-03	8.26E-03	8.06E-03	1.22E-02	8.25E-03	1.3503E+01	1.6221E+03

CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9689330	0.9747150	0.9748630	0.9799950	0.9750170	2.1153E+03	5.4874E+01
α_2	1.13E-02	1.54E-02	1.53E-02	2.00E-02	1.52E-02	3.3455E+01	2.1367E+03
α_3	3.95E-03	6.50E-03	6.35E-03	9.57E-03	6.46E-03	1.4109E+01	2.1561E+03
α_4	1.61E-03	3.37E-03	3.22E-03	5.64E-03	3.34E-03	7.3097E+00	2.1629E+03

CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9721560	0.9770540	0.9771730	0.9815520	0.9775280	2.6748E+03	6.2818E+01
α_2	8.03E-03	1.11E-02	1.10E-02	1.46E-02	1.07E-02	3.0426E+01	2.7072E+03
α_3	4.24E-03	6.55E-03	6.43E-03	9.28E-03	6.43E-03	1.7939E+01	2.7197E+03
α_4	2.18E-03	3.91E-03	3.79E-03	6.06E-03	3.92E-03	1.0711E+01	2.7269E+03
α_5	4.45E-04	1.37E-03	1.25E-03	2.70E-03	1.39E-03	3.7417E+00	2.7339E+03

CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9745600	0.9788530	0.9789530	0.9828180	0.9793970	3.2045E+03	6.9231E+01
α_2	6.15E-03	8.63E-03	8.53E-03	1.14E-02	8.25E-03	2.8242E+01	3.2455E+03
α_3	3.83E-03	5.84E-03	5.74E-03	8.19E-03	5.70E-03	1.9120E+01	3.2546E+03
α_4	2.22E-03	3.80E-03	3.70E-03	5.72E-03	3.76E-03	1.2439E+01	3.2613E+03
α_5	1.09E-03	2.27E-03	2.16E-03	3.78E-03	2.28E-03	7.4165E+00	3.2663E+03
α_6	1.10E-04	6.15E-04	5.17E-04	1.46E-03	6.12E-04	2.0134E+00	3.2717E+03

CCF Parameter Estimations 2010, Section 2

Section 2.2.2, Generic Rate CCF Prior Distribution: CCF-RATE

Failure Mode : Spurious operation open or close
Fail to Run (Normally running equipment)
Filter media allows the pass through of debris
Failure of Control Function Only
High dP across filter
Fail to Run >1 Hour (Standby equipment)
Fail to control flow
Fail to Run less than 1 Hour
Fail to Operate (General operation failure, rate based)

Loss of heat transfer capabilities in heat exchangers

No flow/plugged

Start Date : 1997/01/01
Data Version : 2010/12/31

Total Number of Independent Failure Events: 2433.50
Total Number of Common-Cause Failure Events: 99

ALPHA FACTOR DISTRIBUTIONS

CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9546190	0.9640470	0.9643150	0.9725600	0.9640900	1.1169E+03	4.1654E+01
α_2	2.74E-02	3.60E-02	3.57E-02	4.54E-02	3.59E-02	4.1654E+01	1.1169E+03

CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9582460	0.9657470	0.9659280	0.9726330	0.9657760	1.6645E+03	5.9037E+01
α_2	1.45E-02	1.97E-02	1.95E-02	2.55E-02	1.95E-02	3.3908E+01	1.6896E+03
α_3	1.02E-02	1.46E-02	1.44E-02	1.96E-02	1.47E-02	2.5129E+01	1.6984E+03

CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9618670	0.9681350	0.9682740	0.9739420	0.9682810	2.2088E+03	7.2699E+01
α_2	1.10E-02	1.50E-02	1.48E-02	1.94E-02	1.47E-02	3.4148E+01	2.2474E+03
α_3	6.89E-03	1.01E-02	9.92E-03	1.37E-02	1.01E-02	2.2953E+01	2.2585E+03
α_4	4.27E-03	6.84E-03	6.69E-03	9.90E-03	6.88E-03	1.5598E+01	2.2659E+03

CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9665110	0.9717760	0.9718820	0.9766630	0.9720370	2.7911E+03	8.1064E+01
α_2	7.42E-03	1.03E-02	1.02E-02	1.36E-02	9.92E-03	2.9626E+01	2.8425E+03
α_3	5.93E-03	8.55E-03	8.44E-03	1.16E-02	8.51E-03	2.4566E+01	2.8476E+03
α_4	3.54E-03	5.62E-03	5.50E-03	8.09E-03	5.69E-03	1.6139E+01	2.8560E+03
α_5	2.08E-03	3.74E-03	3.62E-03	5.78E-03	3.85E-03	1.0733E+01	2.8614E+03

CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9701220	0.9746820	0.9747770	0.9789330	0.9750480	3.3448E+03	8.6882E+01
α_2	5.07E-03	7.29E-03	7.19E-03	9.83E-03	6.88E-03	2.5014E+01	3.4067E+03
α_3	4.91E-03	7.10E-03	7.00E-03	9.60E-03	7.01E-03	2.4348E+01	3.4073E+03
α_4	3.55E-03	5.44E-03	5.34E-03	7.65E-03	5.46E-03	1.8666E+01	3.4130E+03
α_5	1.67E-03	3.03E-03	2.94E-03	4.72E-03	3.08E-03	1.0408E+01	3.4213E+03
α_6	1.25E-03	2.46E-03	2.37E-03	4.00E-03	2.53E-03	8.4458E+00	3.4232E+03

CCF Parameter Estimations 2012, Section 2, No Data (Prior Only)

Section 2.2.3, CCF Prior Distribution, Data Version 2007/12/31

Data Version : 2007/12/31

Total Number of Independent Failure Events: 0
Total Number of Common-Cause Failure Events: 0

ALPHA FACTOR DISTRIBUTIONS

CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8993200	0.9742690	0.9887700	0.9999290	----	1.7418E+01	4.6002E-01
α_2	6.65E-05	2.57E-02	1.12E-02	1.00E-01	----	4.6002E-01	1.7418E+01

CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9306240	0.9755060	0.9819700	0.9982830	----	4.5105E+01	1.1325E+00
α_2	6.61E-04	1.87E-02	1.23E-02	5.84E-02	----	8.6476E-01	4.5372E+01
α_3	2.07E-07	5.79E-03	1.17E-03	2.74E-02	----	2.6776E-01	4.5969E+01

CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9380870	0.9740820	0.9782970	0.9956540	----	7.0868E+01	1.8856E+00
α_2	1.43E-03	1.70E-02	1.28E-02	4.69E-02	----	1.2400E+00	7.1513E+01
α_3	9.66E-06	5.89E-03	2.32E-03	2.38E-02	----	4.2870E-01	7.2324E+01
α_4	9.21E-09	2.98E-03	3.83E-04	1.50E-02	----	2.1695E-01	7.2536E+01

CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9521790	0.9760740	0.9782400	0.9925770	----	1.4106E+02	3.4576E+00
α_2	2.59E-03	1.41E-02	1.19E-02	3.30E-02	----	2.0400E+00	1.4247E+02
α_3	3.01E-04	6.59E-03	4.50E-03	2.00E-02	----	9.5369E-01	1.4356E+02
α_4	2.21E-06	2.67E-03	9.37E-04	1.12E-02	----	3.8684E-01	1.4413E+02
α_5	5.61E-20	5.33E-04	5.18E-07	3.10E-03	----	7.7129E-02	1.4444E+02

CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9553700	0.9762820	0.9779970	0.9913440	----	1.7893E+02	4.3470E+00
α_2	2.60E-03	1.24E-02	1.07E-02	2.81E-02	----	2.2804E+00	1.8099E+02
α_3	4.16E-04	6.13E-03	4.45E-03	1.75E-02	----	1.1245E+00	1.8215E+02
α_4	3.82E-05	3.40E-03	1.85E-03	1.20E-02	----	6.2471E-01	1.8265E+02
α_5	1.60E-08	1.32E-03	2.18E-04	6.46E-03	----	2.4272E-01	1.8303E+02
α_6	1.26E-20	4.07E-04	3.05E-07	2.36E-03	----	7.4722E-02	1.8320E+02

CCCG = 7

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9603690	0.9769760	0.9781320	0.9896440	----	2.6720E+02	6.2971E+00
α_2	3.14E-03	1.12E-02	1.00E-02	2.33E-02	----	3.0721E+00	2.7042E+02
α_3	6.66E-04	5.55E-03	4.40E-03	1.43E-02	----	1.5182E+00	2.7197E+02
α_4	1.58E-04	3.48E-03	2.37E-03	1.06E-02	----	9.5310E-01	2.7254E+02
α_5	1.00E-05	1.93E-03	9.22E-04	7.26E-03	----	5.2795E-01	2.7296E+02
α_6	4.58E-10	7.08E-04	6.75E-05	3.68E-03	----	1.9373E-01	2.7330E+02
α_7	5.03E-44	1.17E-04	8.41E-13	4.81E-04	----	3.2027E-02	2.7346E+02

CCCG = 8

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9622170	0.9773660	0.9783580	0.9891370	----	3.1221E+02	7.2302E+00
α_2	3.13E-03	1.04E-02	9.45E-03	2.12E-02	----	3.3414E+00	3.1609E+02
α_3	6.67E-04	5.04E-03	4.06E-03	1.28E-02	----	1.6130E+00	3.1782E+02
α_4	1.86E-04	3.26E-03	2.30E-03	9.62E-03	----	1.0438E+00	3.1839E+02
α_5	3.88E-05	2.20E-03	1.28E-03	7.47E-03	----	7.0280E-01	3.1873E+02
α_6	5.77E-07	1.13E-03	3.63E-04	4.86E-03	----	3.6184E-01	3.1907E+02
α_7	1.19E-13	3.98E-04	8.44E-06	2.25E-03	----	1.2739E-01	3.1931E+02
α_8	5.47E-36	1.25E-04	5.43E-11	6.01E-04	----	4.0005E-02	3.1940E+02

CCF Parameter Estimations 2012, Section 2

Section 2.2.1, Generic Demand CCF Prior Distribution: CCF-DEM

Failure Mode :	Fail to close (reseat) on demand Fail to Open/Close Mode Unspecified (demand based) Fail to open on demand Fail to start Fail to Load/Run Fail to stop
Start Date :	1997/01/01
Data Version :	2012/12/31

Total Number of Independent Failure Events: 3104.30
Total Number of Common-Cause Failure Events: 102

ALPHA FACTOR DISTRIBUTIONS

CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9707550	0.9781220	0.9783890	0.9845880	0.9782910	1.1730E+03	2.6237E+01
α_2	1.54E-02	2.19E-02	2.16E-02	2.92E-02	2.17E-02	2.6237E+01	1.1730E+03

CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9704140	0.9765760	0.9767500	0.9821350	0.9767940	1.7510E+03	4.1999E+01
α_2	1.16E-02	1.62E-02	1.60E-02	2.13E-02	1.60E-02	2.8978E+01	1.7640E+03
α_3	4.31E-03	7.26E-03	7.08E-03	1.08E-02	7.24E-03	1.3021E+01	1.7800E+03

CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9698830	0.9753330	0.9754690	0.9803240	0.9756210	2.3202E+03	5.8679E+01
α_2	1.18E-02	1.57E-02	1.56E-02	2.02E-02	1.55E-02	3.7438E+01	2.3414E+03
α_3	3.62E-03	5.96E-03	5.82E-03	8.77E-03	5.91E-03	1.4181E+01	2.3647E+03
α_4	1.40E-03	2.97E-03	2.83E-03	5.01E-03	2.93E-03	7.0597E+00	2.3718E+03

CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9730170	0.9776340	0.9777440	0.9818860	0.9780860	2.9304E+03	6.7040E+01
α_2	8.24E-03	1.12E-02	1.11E-02	1.45E-02	1.09E-02	3.3592E+01	2.9638E+03
α_3	4.22E-03	6.42E-03	6.31E-03	8.99E-03	6.30E-03	1.9244E+01	2.9782E+03
α_4	1.96E-03	3.53E-03	3.42E-03	5.48E-03	3.52E-03	1.0587E+01	2.9869E+03
α_5	3.83E-04	1.21E-03	1.10E-03	2.40E-03	1.22E-03	3.6167E+00	2.9938E+03

CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9753380	0.9793890	0.9794810	0.9831360	0.9799030	3.5107E+03	7.3882E+01
α_2	6.25E-03	8.63E-03	8.54E-03	1.13E-02	8.28E-03	3.0929E+01	3.5537E+03
α_3	3.92E-03	5.84E-03	5.75E-03	8.08E-03	5.72E-03	2.0938E+01	3.5636E+03
α_4	2.10E-03	3.56E-03	3.47E-03	5.34E-03	3.52E-03	1.2773E+01	3.5718E+03
α_5	9.73E-04	2.03E-03	1.94E-03	3.41E-03	2.04E-03	7.2915E+00	3.5773E+03
α_6	9.37E-05	5.44E-04	4.55E-04	1.30E-03	5.39E-04	1.9509E+00	3.5826E+03

CCCG = 7

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9771660	0.9807650	0.9808440	0.9841110	0.9814550	4.1375E+03	8.1145E+01
α_2	5.19E-03	7.19E-03	7.11E-03	9.45E-03	6.76E-03	3.0330E+01	4.1883E+03
α_3	3.24E-03	4.85E-03	4.77E-03	6.73E-03	4.68E-03	2.0467E+01	4.1982E+03
α_4	2.15E-03	3.49E-03	3.42E-03	5.11E-03	3.41E-03	1.4740E+01	4.2039E+03
α_5	1.25E-03	2.31E-03	2.24E-03	3.65E-03	2.29E-03	9.7630E+00	4.2089E+03
α_6	4.39E-04	1.14E-03	1.06E-03	2.11E-03	1.15E-03	4.8083E+00	4.2138E+03
α_7	1.37E-05	2.46E-04	1.73E-04	7.27E-04	2.50E-04	1.0362E+00	4.2176E+03

CCCG = 8

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9786350	0.9819010	0.9819650	0.9849440	0.9826340	4.7312E+03	8.7210E+01
α_2	4.54E-03	6.29E-03	6.23E-03	8.28E-03	5.88E-03	3.0325E+01	4.7881E+03
α_3	2.69E-03	4.07E-03	4.00E-03	5.68E-03	3.89E-03	1.9601E+01	4.7988E+03
α_4	1.93E-03	3.12E-03	3.06E-03	4.55E-03	3.03E-03	1.5052E+01	4.8034E+03
α_5	1.34E-03	2.36E-03	2.29E-03	3.61E-03	2.32E-03	1.1349E+01	4.8071E+03
α_6	7.16E-04	1.50E-03	1.43E-03	2.52E-03	1.50E-03	7.2366E+00	4.8112E+03
α_7	1.75E-04	6.33E-04	5.66E-04	1.32E-03	6.38E-04	3.0513E+00	4.8154E+03
α_8	1.12E-06	1.23E-04	6.45E-05	4.45E-04	1.22E-04	5.9462E-01	4.8178E+03

CCF Parameter Estimations 2012, Section 2

Section 2.2.2, Generic Rate CCF Prior Distribution: CCF-RATE

Failure Mode : Spurious operation open or close
Fail to Run (Normally running equipment)
Filter media allows the pass through of debris
Failure of Control Function Only
High dP across filter
Fail to Run >1 Hour (Standby equipment)
Fail to control flow
Fail to Run less than 1 Hour
Fail to Operate (General operation failure, rate based)

Loss of heat transfer capabilities in heat exchangers

No flow/plugged

Start Date : 1997/01/01
Data Version : 2012/12/31

Total Number of Independent Failure Events: 2658.10
Total Number of Common-Cause Failure Events: 108

ALPHA FACTOR DISTRIBUTIONS

CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9555480	0.9644040	0.9646440	0.9724410	0.9644470	1.2489E+03	4.6097E+01
α_2	2.76E-02	3.56E-02	3.54E-02	4.45E-02	3.56E-02	4.6097E+01	1.2489E+03

CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9596820	0.9666770	0.9668420	0.9731210	0.9667200	1.8600E+03	6.4117E+01
α_2	1.41E-02	1.89E-02	1.87E-02	2.43E-02	1.88E-02	3.6365E+01	1.8878E+03
α_3	1.03E-02	1.44E-02	1.43E-02	1.92E-02	1.45E-02	2.7752E+01	1.8964E+03

CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9633270	0.9691590	0.9692800	0.9745740	0.9693100	2.4685E+03	7.8553E+01
α_2	1.07E-02	1.43E-02	1.42E-02	1.84E-02	1.41E-02	3.6446E+01	2.5106E+03
α_3	6.90E-03	9.89E-03	9.76E-03	1.33E-02	9.92E-03	2.5196E+01	2.5219E+03
α_4	4.23E-03	6.64E-03	6.51E-03	9.49E-03	6.68E-03	1.6911E+01	2.5301E+03

CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9679240	0.9728100	0.9729050	0.9773640	0.9730770	3.1156E+03	8.7082E+01
α_2	7.06E-03	9.73E-03	9.63E-03	1.27E-02	9.36E-03	3.1158E+01	3.1715E+03
α_3	5.86E-03	8.31E-03	8.21E-03	1.11E-02	8.26E-03	2.6614E+01	3.1761E+03
α_4	3.62E-03	5.60E-03	5.49E-03	7.92E-03	5.65E-03	1.7920E+01	3.1848E+03
α_5	2.02E-03	3.56E-03	3.45E-03	5.44E-03	3.65E-03	1.1390E+01	3.1913E+03

CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9714630	0.9756960	0.9757760	0.9796470	0.9760550	3.7341E+03	9.3015E+01
α_2	4.78E-03	6.81E-03	6.72E-03	9.13E-03	6.43E-03	2.6061E+01	3.8011E+03
α_3	4.77E-03	6.80E-03	6.72E-03	9.12E-03	6.72E-03	2.6036E+01	3.8011E+03
α_4	3.58E-03	5.36E-03	5.28E-03	7.44E-03	5.38E-03	2.0517E+01	3.8066E+03
α_5	1.74E-03	3.04E-03	2.95E-03	4.63E-03	3.08E-03	1.1627E+01	3.8155E+03
α_6	1.19E-03	2.29E-03	2.21E-03	3.69E-03	2.35E-03	8.7739E+00	3.8183E+03

CCCG = 7

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9743460	0.9780530	0.9781220	0.9815230	0.9785790	4.3999E+03	9.8731E+01
α_2	3.64E-03	5.29E-03	5.21E-03	7.18E-03	4.80E-03	2.3781E+01	4.4748E+03
α_3	3.52E-03	5.14E-03	5.06E-03	7.01E-03	4.99E-03	2.3108E+01	4.4755E+03
α_4	3.13E-03	4.66E-03	4.59E-03	6.45E-03	4.64E-03	2.0984E+01	4.4776E+03
α_5	2.23E-03	3.55E-03	3.48E-03	5.12E-03	3.59E-03	1.5969E+01	4.4827E+03
α_6	1.21E-03	2.22E-03	2.15E-03	3.49E-03	2.28E-03	9.9932E+00	4.4886E+03
α_7	4.24E-04	1.09E-03	1.02E-03	2.00E-03	1.13E-03	4.8954E+00	4.4937E+03

CCCG = 8

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9766000	0.9799240	0.9799840	0.9830350	0.9805190	5.0330E+03	1.0311E+02
α_2	3.02E-03	4.43E-03	4.36E-03	6.05E-03	3.95E-03	2.2735E+01	5.1134E+03
α_3	2.51E-03	3.80E-03	3.74E-03	5.32E-03	3.62E-03	1.9535E+01	5.1166E+03
α_4	2.64E-03	3.97E-03	3.91E-03	5.51E-03	3.92E-03	2.0387E+01	5.1157E+03
α_5	2.14E-03	3.35E-03	3.29E-03	4.78E-03	3.36E-03	1.7216E+01	5.1189E+03
α_6	1.52E-03	2.55E-03	2.49E-03	3.81E-03	2.60E-03	1.3117E+01	5.1230E+03
α_7	6.59E-04	1.39E-03	1.33E-03	2.34E-03	1.43E-03	7.1431E+00	5.1290E+03
α_8	1.57E-04	5.80E-04	5.17E-04	1.22E-03	6.00E-04	2.9799E+00	5.1331E+03

CCF Parameter Estimations 2015, Section 3, No Data (Prior Only)

Section 3.1.3, CCF Prior Distribution, Data Version 2007/12/31

Data Version : 2007/12/31

Total Number of Independent Failure Events: 0
Total Number of Common-Cause Failure Events: 0

ALPHA FACTOR DISTRIBUTIONS

CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.8993200	0.9742690	0.9887700	0.9999290	----	1.7418E+01	4.6002E-01
α_2	6.65E-05	2.57E-02	1.12E-02	1.00E-01	----	4.6002E-01	1.7418E+01

CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9306240	0.9755060	0.9819700	0.9982830	----	4.5105E+01	1.1325E+00
α_2	6.61E-04	1.87E-02	1.23E-02	5.84E-02	----	8.6476E-01	4.5372E+01
α_3	2.07E-07	5.79E-03	1.17E-03	2.74E-02	----	2.6776E-01	4.5969E+01

CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9380870	0.9740820	0.9782970	0.9956540	----	7.0868E+01	1.8856E+00
α_2	1.43E-03	1.70E-02	1.28E-02	4.69E-02	----	1.2400E+00	7.1513E+01
α_3	9.66E-06	5.89E-03	2.32E-03	2.38E-02	----	4.2870E-01	7.2324E+01
α_4	9.21E-09	2.98E-03	3.83E-04	1.50E-02	----	2.1695E-01	7.2536E+01

CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9521790	0.9760740	0.9782400	0.9925770	----	1.4106E+02	3.4576E+00
α_2	2.59E-03	1.41E-02	1.19E-02	3.30E-02	----	2.0400E+00	1.4247E+02
α_3	3.01E-04	6.59E-03	4.50E-03	2.00E-02	----	9.5369E-01	1.4356E+02
α_4	2.21E-06	2.67E-03	9.37E-04	1.12E-02	----	3.8684E-01	1.4413E+02
α_5	5.61E-20	5.33E-04	5.18E-07	3.10E-03	----	7.7129E-02	1.4444E+02

CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9553700	0.9762820	0.9779970	0.9913440	----	1.7893E+02	4.3470E+00
α_2	2.60E-03	1.24E-02	1.07E-02	2.81E-02	----	2.2804E+00	1.8099E+02
α_3	4.16E-04	6.13E-03	4.45E-03	1.75E-02	----	1.1245E+00	1.8215E+02
α_4	3.82E-05	3.40E-03	1.85E-03	1.20E-02	----	6.2471E-01	1.8265E+02
α_5	1.60E-08	1.32E-03	2.18E-04	6.46E-03	----	2.4272E-01	1.8303E+02
α_6	1.26E-20	4.07E-04	3.05E-07	2.36E-03	----	7.4722E-02	1.8320E+02

CCCG = 7

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9603690	0.9769760	0.9781320	0.9896440	----	2.6720E+02	6.2971E+00
α_2	3.14E-03	1.12E-02	1.00E-02	2.33E-02	----	3.0721E+00	2.7042E+02
α_3	6.66E-04	5.55E-03	4.40E-03	1.43E-02	----	1.5182E+00	2.7197E+02
α_4	1.58E-04	3.48E-03	2.37E-03	1.06E-02	----	9.5310E-01	2.7254E+02
α_5	1.00E-05	1.93E-03	9.22E-04	7.26E-03	----	5.2795E-01	2.7296E+02
α_6	4.58E-10	7.08E-04	6.75E-05	3.68E-03	----	1.9373E-01	2.7330E+02
α_7	5.03E-44	1.17E-04	8.41E-13	4.81E-04	----	3.2027E-02	2.7346E+02

CCCG = 8

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9622170	0.9773660	0.9783580	0.9891370	----	3.1221E+02	7.2302E+00
α_2	3.13E-03	1.04E-02	9.45E-03	2.12E-02	----	3.3414E+00	3.1609E+02
α_3	6.67E-04	5.04E-03	4.06E-03	1.28E-02	----	1.6130E+00	3.1782E+02
α_4	1.86E-04	3.26E-03	2.30E-03	9.62E-03	----	1.0438E+00	3.1839E+02
α_5	3.88E-05	2.20E-03	1.28E-03	7.47E-03	----	7.0280E-01	3.1873E+02
α_6	5.77E-07	1.13E-03	3.63E-04	4.86E-03	----	3.6184E-01	3.1907E+02
α_7	1.19E-13	3.98E-04	8.44E-06	2.25E-03	----	1.2739E-01	3.1931E+02
α_8	5.47E-36	1.25E-04	5.43E-11	6.01E-04	----	4.0005E-02	3.1940E+02

CCF Parameter Estimations 2015, Section 3

Section 3.1.1, Generic Demand CCF Prior Distribution: CCF-DEM

Failure Modes/Fail to Close
Failure Modes/Fail to Load and-or Run
Failure Modes/Fail to Open
Failure Modes/Fail to Open and-or Close
Failure Modes/Fail to Start
Failure Modes/Fail to Stop
Date Range: 1997 through 2015

Total Number of Independent Failure Events: 3598.9
Total Number of Common-Cause Failure Events: 107

ALPHA FACTOR DISTRIBUTIONS

CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9739095	0.9802993	0.9805202	0.9859305	0.9804566	1.407E+03	2.827E+01
α_2	1.41E-02	1.97E-02	1.95E-02	2.61E-02	1.95E-02	2.827E+01	1.407E+03

CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9736531	0.9789883	0.9791353	0.9838123	0.9792043	2.100E+03	4.508E+01
α_2	1.07E-02	1.47E-02	1.46E-02	1.92E-02	1.45E-02	3.154E+01	2.114E+03
α_3	3.78E-03	6.31E-03	6.16E-03	9.36E-03	6.28E-03	1.354E+01	2.132E+03

CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9736328	0.9783076	0.9784225	0.9826016	0.9785984	2.786E+03	6.177E+01
α_2	1.02E-02	1.35E-02	1.34E-02	1.72E-02	1.33E-02	3.847E+01	2.809E+03
α_3	3.50E-03	5.59E-03	5.47E-03	8.07E-03	5.54E-03	1.591E+01	2.832E+03
α_4	1.25E-03	2.60E-03	2.48E-03	4.34E-03	2.56E-03	7.393E+00	2.840E+03

CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9763661	0.9803297	0.9804199	0.9839886	0.9807825	3.512E+03	7.047E+01
α_2	7.06E-03	9.57E-03	9.48E-03	1.24E-02	9.24E-03	3.430E+01	3.548E+03
α_3	3.87E-03	5.78E-03	5.69E-03	8.01E-03	5.67E-03	2.072E+01	3.562E+03
α_4	1.85E-03	3.24E-03	3.15E-03	4.94E-03	3.22E-03	1.161E+01	3.571E+03
α_5	3.57E-04	1.07E-03	9.82E-04	2.10E-03	1.08E-03	3.847E+00	3.579E+03

CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9784444	0.9819123	0.9819850	0.9851296	0.9824132	4.209E+03	7.753E+01
α_2	5.32E-03	7.32E-03	7.25E-03	9.59E-03	7.00E-03	3.140E+01	4.255E+03
α_3	3.50E-03	5.15E-03	5.08E-03	7.08E-03	5.03E-03	2.209E+01	4.264E+03
α_4	1.97E-03	3.26E-03	3.19E-03	4.81E-03	3.22E-03	1.398E+01	4.272E+03
α_5	9.19E-04	1.85E-03	1.77E-03	3.05E-03	1.85E-03	7.937E+00	4.278E+03
α_6	9.39E-05	4.94E-04	4.18E-04	1.15E-03	4.88E-04	2.115E+00	4.284E+03

CCCG = 7

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9800577	0.9831435	0.9832097	0.9860157	0.9838109	4.952E+03	8.490E+01
α_2	4.39E-03	6.07E-03	6.00E-03	7.97E-03	5.67E-03	3.056E+01	5.006E+03
α_3	2.86E-03	4.24E-03	4.18E-03	5.85E-03	4.07E-03	2.138E+01	5.015E+03
α_4	1.98E-03	3.16E-03	3.09E-03	4.56E-03	3.08E-03	1.590E+01	5.021E+03
α_5	1.17E-03	2.11E-03	2.05E-03	3.28E-03	2.09E-03	1.065E+01	5.026E+03
α_6	4.23E-04	1.04E-03	9.78E-04	1.89E-03	1.05E-03	5.253E+00	5.031E+03
α_7	1.64E-05	2.29E-04	1.68E-04	6.53E-04	2.32E-04	1.155E+00	5.035E+03

CCCG = 8

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9813790	0.9841756	0.9842349	0.9867847	0.9848780	5.661E+03	9.103E+01
α_2	3.81E-03	5.28E-03	5.22E-03	6.94E-03	4.89E-03	3.038E+01	5.722E+03
α_3	2.35E-03	3.53E-03	3.47E-03	4.91E-03	3.36E-03	2.031E+01	5.732E+03
α_4	1.76E-03	2.79E-03	2.74E-03	4.03E-03	2.70E-03	1.607E+01	5.736E+03
α_5	1.25E-03	2.14E-03	2.09E-03	3.24E-03	2.10E-03	1.234E+01	5.740E+03
α_6	6.76E-04	1.37E-03	1.31E-03	2.26E-03	1.36E-03	7.870E+00	5.745E+03
α_7	1.77E-04	5.88E-04	5.32E-04	1.19E-03	5.90E-04	3.384E+00	5.749E+03
α_8	1.84E-06	1.18E-04	6.75E-05	4.06E-04	1.17E-04	6.793E-01	5.752E+03

CCF Parameter Estimations 2015, Section 3

Section 3.1.2, Generic Rate CCF Prior Distribution: CCF-RATE

Failure Modes/Bypass
Failure Modes/Control Function
Failure Modes/Fail to Control
Failure Modes/Fail to Operate
Failure Modes/Fail to Run <1H
Failure Modes/Fail to Run > 1H (Standby equipment)
Failure Modes/High dP
Failure Modes/Loss of Heat Transfer
Failure Modes/Plug
Failure Modes/Spurious Operation
Date Range: 1997 through 2015

Total Number of Independent Failure Events: 3224.0
Total Number of Common-Cause Failure Events: 116

ALPHA FACTOR DISTRIBUTIONS

CCCG = 2

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9619669	0.9694654	0.9696695	0.9762778	0.9695356	1.508E+03	4.748E+01
α_2	2.37E-02	3.05E-02	3.03E-02	3.80E-02	3.05E-02	4.748E+01	1.508E+03

CCCG = 3

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9646529	0.9706436	0.9707767	0.9761762	0.9707316	2.246E+03	6.792E+01
α_2	1.33E-02	1.75E-02	1.74E-02	2.22E-02	1.74E-02	4.050E+01	2.273E+03
α_3	8.41E-03	1.19E-02	1.17E-02	1.58E-02	1.19E-02	2.743E+01	2.286E+03

CCCG = 4

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9678618	0.9728563	0.9729563	0.9775041	0.9730394	2.982E+03	8.320E+01
α_2	9.75E-03	1.29E-02	1.28E-02	1.64E-02	1.27E-02	3.960E+01	3.025E+03
α_3	6.19E-03	8.77E-03	8.66E-03	1.17E-02	8.77E-03	2.688E+01	3.038E+03
α_4	3.47E-03	5.46E-03	5.35E-03	7.81E-03	5.47E-03	1.672E+01	3.048E+03

CCCG = 5

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9716549	0.9758620	0.9759421	0.9797885	0.9761639	3.756E+03	9.290E+01
α_2	6.59E-03	8.93E-03	8.85E-03	1.16E-02	8.61E-03	3.438E+01	3.814E+03
α_3	5.33E-03	7.46E-03	7.37E-03	9.88E-03	7.40E-03	2.870E+01	3.820E+03
α_4	3.14E-03	4.81E-03	4.73E-03	6.78E-03	4.84E-03	1.852E+01	3.830E+03
α_5	1.66E-03	2.94E-03	2.85E-03	4.50E-03	2.99E-03	1.130E+01	3.837E+03

CCCG = 6

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9746515	0.9783006	0.9783677	0.9817130	0.9786685	4.501E+03	9.984E+01
α_2	4.55E-03	6.34E-03	6.27E-03	8.38E-03	6.02E-03	2.919E+01	4.572E+03
α_3	4.42E-03	6.19E-03	6.12E-03	8.20E-03	6.10E-03	2.847E+01	4.572E+03
α_4	3.16E-03	4.69E-03	4.62E-03	6.46E-03	4.68E-03	2.158E+01	4.579E+03
α_5	1.48E-03	2.58E-03	2.51E-03	3.92E-03	2.60E-03	1.187E+01	4.589E+03
α_6	9.78E-04	1.90E-03	1.83E-03	3.06E-03	1.93E-03	8.727E+00	4.592E+03

CCCG = 7

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9771278	0.9803354	0.9803974	0.9833355	0.9808535	5.294E+03	1.062E+02
α_2	3.51E-03	4.98E-03	4.91E-03	6.65E-03	4.56E-03	2.687E+01	5.373E+03
α_3	3.25E-03	4.67E-03	4.60E-03	6.29E-03	4.52E-03	2.519E+01	5.375E+03
α_4	2.85E-03	4.18E-03	4.12E-03	5.72E-03	4.14E-03	2.257E+01	5.378E+03
α_5	1.95E-03	3.07E-03	3.01E-03	4.41E-03	3.09E-03	1.660E+01	5.384E+03
α_6	1.02E-03	1.87E-03	1.81E-03	2.93E-03	1.90E-03	1.009E+01	5.390E+03
α_7	3.50E-04	9.02E-04	8.41E-04	1.66E-03	9.30E-04	4.872E+00	5.395E+03

CCCG = 8

Alpha Factor	5th%	Mean	Median	95th%	MLE	a	b
α_1	0.9790895	0.9819652	0.9820155	0.9846638	0.9825346	6.054E+03	1.112E+02
α_2	2.94E-03	4.20E-03	4.14E-03	5.63E-03	3.79E-03	2.587E+01	6.139E+03
α_3	2.34E-03	3.47E-03	3.42E-03	4.79E-03	3.31E-03	2.140E+01	6.144E+03
α_4	2.42E-03	3.57E-03	3.52E-03	4.91E-03	3.52E-03	2.204E+01	6.143E+03
α_5	1.92E-03	2.96E-03	2.91E-03	4.18E-03	2.96E-03	1.826E+01	6.147E+03
α_6	1.31E-03	2.19E-03	2.13E-03	3.25E-03	2.21E-03	1.348E+01	6.152E+03
α_7	5.53E-04	1.16E-03	1.11E-03	1.96E-03	1.19E-03	7.177E+00	6.158E+03
α_8	1.30E-04	4.81E-04	4.29E-04	1.01E-03	4.94E-04	2.968E+00	6.162E+03

APPENDIX B

EXAMPLE OF HOW TO PERFORM A BAYESIAN UPDATE ON CCF PARAMETERS USING PRIOR DISTRIBUTIONS

This appendix presents an example of how to perform a Bayesian update on CCF parameters (specifically, the alpha factors, as in the Alpha Factor Model) using the prior distributions.

CCF SPAR Rules 2015 → 2.1.1.1 ALL-MDP-FS is used as the example (see Figure B-1): Go to the RADS/CCF website https://rads.inl.gov/Pages/CCF.aspx; click the CCF Rules tab on the left side; select SPAR Rules 2015 → 2.1.1.1 ALL-MDP-FS; and run the rule by clicking the *Run Rule* tab on the bottom.

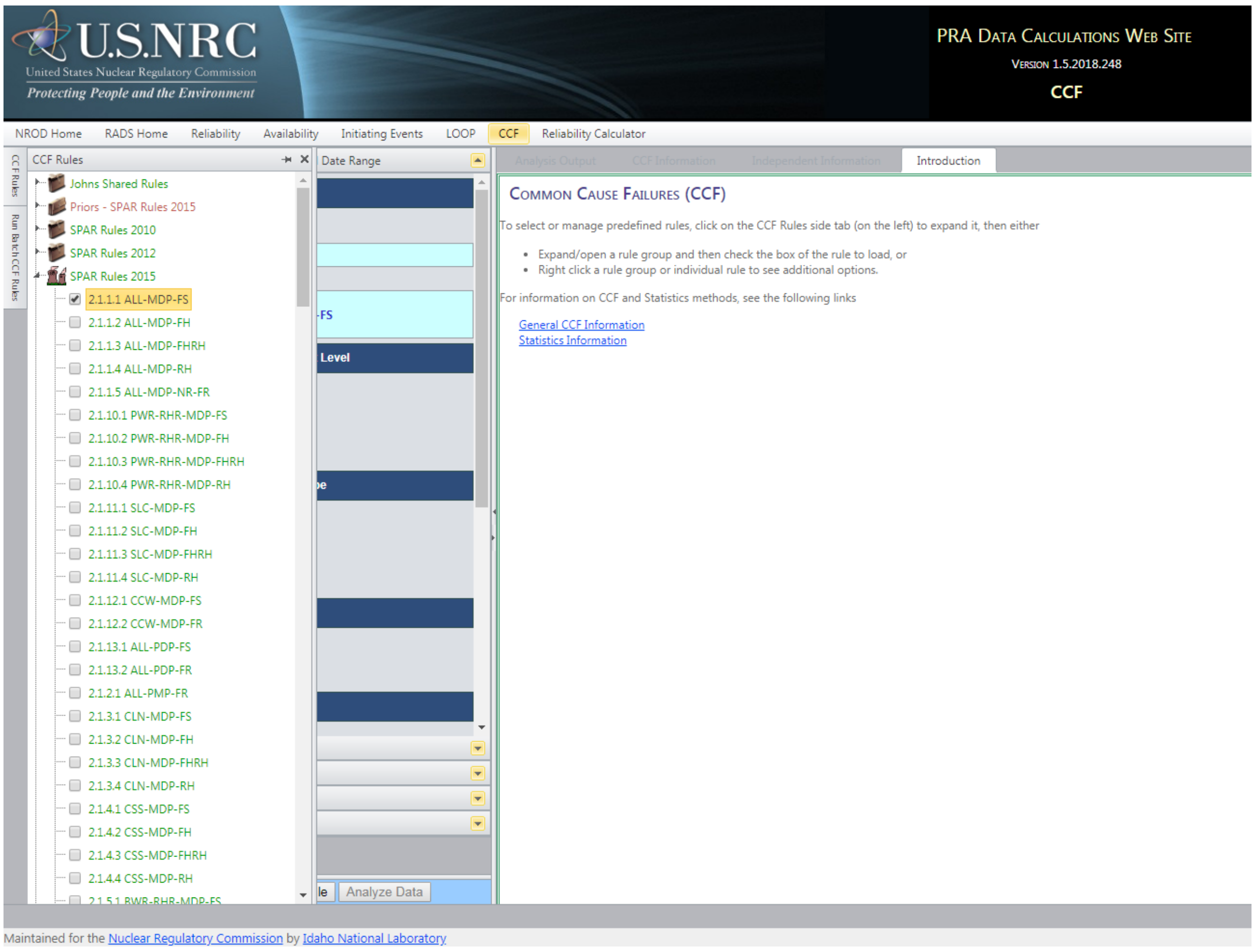

Figure B-1. Run CCF Rule ALL-MDP-FS.

The alpha factor results will be displayed as in Figure B-2.

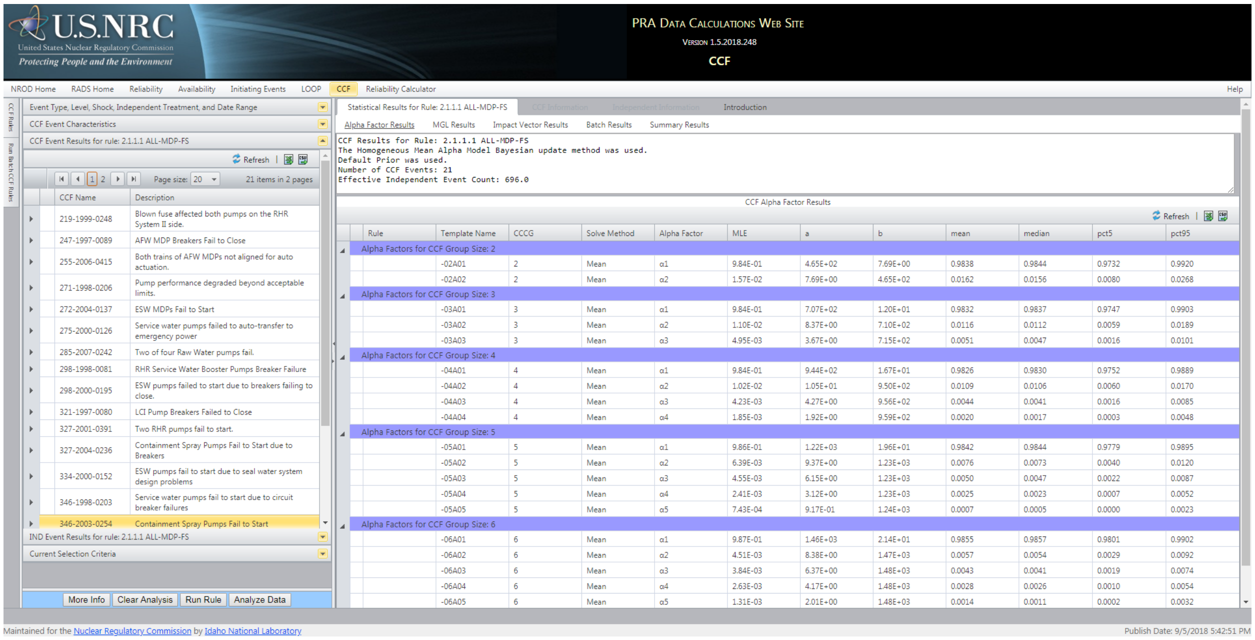

Figure B-2. CCF Alpha Factor Results for ALL-MDP-FS.

Now go to the Impact Vector Results tab.

For CCCG=2, it shows:

Adjusted Independent Count n(I) = 442.91

n1 = 12.262

n2 = 7.2523

So $\sum n$ = n(I) + n1 + n2 = 462.4243

One can then obtain the MLE of the alpha factors:

$$\alpha_1 = [n(I) + n1] / \sum_i n = \frac{442.91+12.262}{462.4243} = 0.9843$$

$$\alpha_2 = n2 / \sum_i n = 7.2523/462.4243 = 0.0157$$

The current default prior in the database is the 2005 Prior (see Appendix A)[d], which has the following distribution parameters for CCCG=2:

α1: a1 = 10.246

b_1 = 0.43452

α_2: a_2 = 0.43452

b_2 = 10.246

The posterior distribution parameters can be calculated as:

α1: a1' = a1 + n(I) + n1 = 465.418

---

[d] Note the CCF database now includes a selection of prior distributions to be used, under the tab Event Type, Level, Shock, Independent Treatment, and Date Range -> Prior Distribution. The 2005 Priors are called "Default," the new priors developed in Section 3 are "Default 2015," and the causal priors developed in Section 4 are "Component," "Design," "Environment," "Human," and "Other."

$b1' = b1 + n2 = 7.68682$

The mean of $\alpha 1 = a1' / (a1' + b1') = 0.9838$

$\alpha 2$: $a2' = a2 + n2 = 7.6868$

$b_2' = b_2 + n(I) + n1 = 465.418$

The mean of $\alpha_2 = a_2' / (a_2' + b_2') = 0.0162$

For CCCG=3, the Impact Vector Results tab shows:

Adjusted Independent Count n(I) = 664.36

n1 = 12.856

n2 = 7.5369

n3 = 3.4067

So $\sum n = n(I) + n1 + n2 + n3 = 688.1596$

One can then obtain the MLE of the alpha factors:

$$\alpha_1 = [n(I) + n1]/\sum_i n = \frac{664.36+12.856}{688.1596} = 0.98410$$

$$\alpha_2 = n2/\sum_i n = 7.5369/688.1596 = 0.01095$$

$$\alpha_3 = n3/\sum_i n = 3.4067/688.1596 = 0.00495$$

The 2005 Prior has the following distribution parameters for CCCG=3:

α_1: $a_1 = 29.555$

$b_1 = 1.1008$

α_2: $a_2 = 0.83366$

$b_2 = 29.822$

α_3: $a_3 = 0.26722$

$b_3 = 30.388$

The posterior distribution parameters can be calculated as:

α_1: $a_1' = a_1 + n(I) + n1 = 706.771$

$b_1' = b_1 + n2 + n3 = 12.0444$

The mean of $\alpha_1 = a_1' / (a_1' + b_1') = 0.98324$

α_2: $a_2' = a_2 + n2 = 8.37056$

$b_2' = b_2 + n(I) + n1 + n3 = 710.4447$

The mean of $\alpha_2 = a_2' / (a_2' + b_2') = 0.01165$

α_3: $a_3' = a_3 + n3 = 3.67392$

$b_3' = b_3 + n(I) + n1 + n2 = 715.1409$

The mean of $\alpha_3 = a_3' / (a_3' + b_3') = 0.00511$

The above hand calculation results (MLE and mean of alpha factors α_k, and posterior distribution parameters a_k' and b_k') were checked against and found identical to those in the *Alpha Factor Results* tab.

Template Name	CCCG	Solve Method	Alpha Factor	MLE	a	b	mean
CF Group Size: 2							
-02A01	2	Mean	α1	9.84E-01	4.65E+02	7.69E+00	0.9838
-02A02	2	Mean	α2	1.57E-02	7.69E+00	4.65E+02	0.0162
CF Group Size: 3							
-03A01	3	Mean	α1	9.84E-01	7.07E+02	1.20E+01	0.9832
-03A02	3	Mean	α2	1.10E-02	8.37E+00	7.10E+02	0.0116
-03A03	3	Mean	α3	4.95E-03	3.67E+00	7.15E+02	0.0051

Figure B-3. ALL-MDP-FS CCF Alpha Factor Results for CCCG of 2 and 3.

APPENDIX C

NEW PROCESS TO ESTIMATE MAPPING UP FACTOR ρ

Background

Proposed work for a generic prior for the alpha factors requires mapping up among various common-cause group sizes. For this, the Binomial Failure Rate (BFR) parameter (or mapping up factor) ρ must be estimated. No estimate is given in Ref. [C-1], only some advice as to when ρ should be "small" or "large." The maximum likelihood estimate (MLE) of ρ can be found numerically using the work given in this appendix. Alternatively, the Method of Moments (MM) can be used to estimate ρ.

Consider the data from system sizes m_i (Impact vectors, as distinguished from raw data, are discussed at the very end of this appendix.) Ref. [C-1] suggests using a different ρ for each event. However, for a generic prior, we will use the data from many group sizes together. The MLE will be found using all the data together. The Method of Moments will obtain a separate ρ for each group size m, combining all the data with that m to obtain ρ. Further work will be needed to help decide which method is preferable.

The following restrictions limit the data that should be used.

- Lethal events are not relevant. In such events, occurrence of the cause guarantees that all components fail, so ρ must equal to 1. However, *non*lethal events can be used even if all m components happen to fail, and the formula derived below can be used for nonlethal events.
- Of course, events with no failed components cannot be used. Also, events with exactly one failed component are for the most part classified as independent failures, even if they may have potential CCF linkages to other components. Therefore, only events with 2 or more failed components give trustworthy information about ρ. In summary, the values of counts $n_2^{(m)}$ through $n_m^{(m)}$ should be used, excluding the single failures and the lethal events. In the notation here, m in parentheses is an index, showing dependence on m; it does not mean "to the mth power".
- Data from a group of size 2 give no information about ρ, because the rules of the above bullet would force every included event to have 2 failed components, regardless of ρ.
- If the data have no triple failures or higher, that is $n_k^{(m)}=0$ for $k > 2$, it will be seen below that ρ is estimated as 0, whether the MLE or the MM is used.

The derivations below treat the numbers of failed components as known. A discussion at the end of this appendix shows how to use these formulas even when the numbers are estimated by impact vectors.

Maximum Likelihood Estimation of ρ

For each $m > 2$, let $n_k^{(m)}$ be the number of events with k failed components, $2 \le k \le m$. The work below uses all the data, from varying group sizes m. If it is desired to use only one m, simply ignore the data from other groups.

To estimate ρ, treat the data as if generated from the BFR model, with the same ρ for every event. That is, let X have a binomial(m, ρ) distribution, and exclude the possibilities that $X = 0$ or 1. The probability that one of these common cause (CC) events has k failed components is, by the binomial formula,

$$\Pr(X=k \mid X\ge 2) = \Pr(X=k)/\Pr(X\ge 2)$$

$$= \binom{m}{k}\rho^k(1-\rho)^{m-k} \Big/ \left[1-(1-\rho)^m - m\rho(1-\rho)^{m-1}\right]. \quad \text{(Eq. C-1)}$$

To eliminate some clutter below, define

$$P2^{(m)} = \left[1-(1-\rho)^m - m\rho(1-\rho)^{m-1}\right]. \quad \text{(Eq. C-2)}$$

The interpretation of $P2^{(m)}$ is the probability that a CC shock causes at least 2 failed components. It is worth noting that

$$\frac{\partial}{\partial\rho}P2^{(m)} = m(1-\rho)^{m-1} - m(1-\rho)^{m-1} + m\rho(m-1)(1-\rho)^{m-2} = m(m-1)\rho(1-\rho)^{m-2}. \quad \text{(Eq. C-3)}$$

Let $n_k^{(m)}$ be the number of events with k failed components in a group of size m. Then the probability that $n_k^{(m)}$ particular events had k failed components is given by Eq. C-1 raised to the $n_k^{(m)}$ power. Therefore, the likelihood is

$$L = \prod_{m>2}\prod_{k=2}^{m}\left[Pr(X=k|X\ge 2)\right]^{n_k^{(m)}} \quad .$$

The logarithm of this, after collecting similar terms, is

$$\ln(L) = C + \left[\sum_m\left(\sum_{k=2}^{m} k n_k^{(m)}\right)\right]\ln(\rho/(1-\rho)) + \left[\sum_m m\left(\sum_{k=2}^{m} n_k^{(m)}\right)\right]\ln(1-\rho) - \sum_m\left[\ln\left(P2^{(m)}\right)\sum_{k=2}^{m} n_k^{(m)}\right],$$

where C includes the binomial coefficients, which do not depend on ρ.

This can be rewritten more compactly as

$$\ln(L) = C + CF\ln(\rho/(1-\rho)) + CAR\ln(1-\rho) - \sum_{m>2}\left[\ln\left(P2^{(m)}\right)n_T^{(m)}\right] \quad ,$$

where

CF = number of component failures,

CAR = number of components at risk, i.e. components in groups where failure events occurred,

$n_T^{(m)}$ = total number of failure events in groups of size m.

It follows, making use of Eq. C-3 that

$$\frac{\partial}{\partial\rho}\ln(L) = \frac{CF}{\rho} + \frac{CF}{1-\rho} - \frac{CAR}{1-\rho} - \sum_m\left[n_T^{(m)}\frac{m(m-1)\rho(1-\rho)^{m-2}}{P2^{(m)}}\right]$$

$$= \frac{CF-\rho CAR}{\rho(1-\rho)} - \rho\sum_m\left[n_T^{(m)}\frac{m(m-1)(1-\rho)^{m-2}}{P2^{(m)}}\right] \quad \text{(Eq. C-4)}$$

Note first that if ρ is as large as CF/CAR or more, then the derivative (4) is negative. Therefore, ln(L) can only be maximized by a value of ρ between CF/CAR and 0. To examine the behavior for ρ near 0, recall that $P2^{(m)} = \Pr(X\ge 2)$, Based on the elements of a binomial distribution, observe that as $\rho \to 0$, $\Pr(X\ge 2)/\Pr(X=2) \to 1$. $\Pr(X=2)$ is equal to,

$$\frac{m(m-1)}{2}\rho^2(1-\rho)^{m-2} .$$

Substitute this into Eq. C-4 to see that, as $\rho \to 0$

$$\frac{\partial}{\partial\rho}ln(L) \approx \frac{CF-\rho CAR}{\rho(1-\rho)} - \rho\sum_m\left[{n_T}^{(m)}\frac{2}{\rho^2}\right]$$
$$= \frac{CF-\rho CAR}{\rho(1-\rho)} - \frac{2n_{TOT}}{\rho}$$
$$= \frac{CF-2n_{TOT}-\rho CAR+\rho 2n_{TOT}}{\rho(1-\rho)} . \qquad \text{(Eq. C-5)}$$

In the special case with only double failures, the number of failed components equals twice the number of failure events, that is, $CF = 2n_{TOT}$. Therefore,

$$\frac{\partial}{\partial\rho}ln(L) \approx \frac{-CAR+2n_{TOT}}{1-\rho} < 0 .$$

Because the derivative is negative in this special case, the MLE of ρ is 0.

In the more general case with $CF > 2n_{TOT}$, Eq. C-5 yields

$$\frac{\partial}{\partial\rho}ln(L) \approx \frac{CF-2n_{TOT}}{\rho} > 0 .$$

Note, the sign is now positive. In conclusion, if the data contain at least one event with more than two failed components, the derivative of Eq. C-4 is positive for ρ near 0 and negative for ρ=CF/CAR. The exact value of ρ that makes the derivative equal to 0 is the MLE. It must be found numerically. (This discussion has avoided the question of whether there are multiple solutions; that should be checked during the process of finding a numerical solution.)

An issue that has not yet been considered is the uncertainty in ρ. If we used observed raw data, the second derivative of ln(L) could, in principle, be used to find the asymptotic variance of ρ. However, the use of impact vectors instead of pure data will greatly complicate this approach.

Method of Moments for Estimating ρ

Kvam [C-2] presents a method of moments (MM) estimator for ρ. However, his method assumes that single failures can be accurately classified as either independent or common cause, unlike the present situation. Therefore, Kvam's method will need modification.

His approach is as follows. Let U be the number of failed components during a nonlethal common cause event, except $U = 0$ can never be observed. Therefore, U is a binomial(m, ρ) random variable truncated to always have values ≥ 1. It is a moderately straightforward calculation to show that

$$\frac{E[U(U-1)]}{(m-1)E(U)} = \rho \ . \qquad \text{(Eq. C-6)}$$

The expectations (or moments) on the left can be estimated from the data. Using the notation for ${n_k}^{(m)}$ defined just below Eq. C-3, estimate Pr($U = k$) by ${n_k}^{(m)}/{n_T}^{(m)}$. Here, n_T is the sum of the n_ks. Then the ratio on the left side of Eq. C-6 is estimated by

$$\frac{\sum_{k=1}^m k(k-1){n_k}^{(m)}}{(m-1)\sum_{k=1}^m k{n_k}^{(m)}} .$$

This is Kvam's estimate of ρ, for any one value of m.

This method can be adapted as follows to the INL situation, in which single failures are generally not identified as common cause. For the INL applications, let U be the number of failed components during a nonlethal common cause event, except $U \le 1$ is not observed. Therefore, U is a binomial(m, ρ) random variable truncated to always have values ≥ 2. This is consistent with bullet 2 at the start of this note.

Now the moments must be calculated. Let V be a binomial(m, ρ), which can be thought of as U if the values 0 and 1 could be observed. The distribution of U is given by

$$
\begin{aligned}
\Pr(U = k) &= \Pr(V = k \mid V \ge 2) \\
&= \Pr(V = k) / \Pr(V \ge 2) \\
&= \Pr(V = k) / \mathrm{P2}^{(m)} ,
\end{aligned}
$$

where $\mathrm{P2}^{(m)}$ is defined by Eq. C-2.

Therefore

$$
\begin{aligned}
E(U) &= \sum_{k=2}^{m} k\Pr(U = k) \\
&= \frac{\sum_{k=2}^{m} k\Pr(V = k)}{\mathrm{P2}^{(m)}} \\
&= \frac{\sum_{k=0}^{m} k\Pr(V = k) - \sum_{k=0}^{1} k\Pr(V = k)}{\mathrm{P2}^{(m)}} \\
&= \frac{E(V) - \Pr(V = 1)}{\mathrm{P2}^{(m)}} \\
&= \frac{m\rho - m\rho(1-\rho)^{m-1}}{\mathrm{P2}^{(m)}} \quad .
\end{aligned}
$$

In similar manner, it can be shown that

$$
\begin{aligned}
E[U(U-1)] &= E(U^2) - E(U) \\
&= \frac{E(V^2) - \Pr(V=1)}{\mathrm{P2}^{(m)}} - \frac{E(V) - \Pr(V=1)}{\mathrm{P2}^{(m)}} \\
&= \frac{E(V^2) - E(V)}{\mathrm{P2}^{(m)}} \\
&= \frac{\mathrm{var}(V) + E^2(V) - E(V)}{\mathrm{P2}^{(m)}} \\
&= \frac{m\rho(1-\rho) + (m\rho)^2 - m\rho}{\mathrm{P2}^{(m)}} \\
&= \frac{m(m-1)\rho^2}{\mathrm{P2}^{(m)}}
\end{aligned}
$$

Therefore, the analogue of Kvam's Eq. C-6 is

$$
\frac{E[U(U-1)]}{(m-1)E(U)} = \frac{\rho}{1-(1-\rho)^{m-1}} \quad .
$$

Estimate the expectations from the data, giving the equation

$$\frac{\sum_{k=2}^{m} k(k-1)n_k{}^{(m)}}{(m-1)\sum_{k=2}^{m} kn_k{}^{(m)}} = \frac{\rho}{1-(1-\rho)^{m-1}} \qquad \text{(Eq. C-7)}$$

This must be solved numerically for the MM estimate of ρ.

Just as for the MLE, there are two special cases. First, if $m = 2$, Eq. C-7 reduces to $1 = \rho/\rho$, which does not determine a unique value of ρ. This is what must follow from the third bullet in the above background section. The second special case occurs when the data for some $m > 2$ contain no multiple failures of more than two components, that is, $n_k{}^{(m)} = 0$ for $k > 2$. Then the left-hand side of the Eq. C-7 reduces to $1/(m-1)$. The right-hand side equals this value only when $\rho = 0$. This is mentioned in the fourth bullet in the background section.

This method gives a separate estimate of ρ for each m. In Ref. [C-2], Kvam combines results from various m without specifying the details. At present we do not see a "best" way to obtain one estimate from the combined data using all the different group sizes m.

Impact Vectors or Data?

The methods above all assume that the numbers of failed components are known. This is also assumed in Refs. [C-1] and [C-2]. However, the events occurring in failure reports are often not so clear. For example, it might happen that two pumps were clearly in a failed state but a third was degraded and might have failed if demanded. For this reason, *impact vectors* are defined, which are the *expected* numbers of events, in the probability sense of expected values. For details, see Ref. [C-3]. In the first example considered here, suppose that the analyst decides, with probability 0.9, that the third pump was not failed, and with probability 0.1 the third pump was failed. Then the vector $(n_1{}^{(3)}, n_2{}^{(3)}, n_3{}^{(3)}) = (0, 1, 0)$ under the first hypothesis and $= (0, 0, 1)$ under the second hypothesis. The impact vector is the expected value, or weighted average, of the two. This is denoted $(f_1{}^{(3)}, f_2{}^{(3)}, f_3{}^{(3)}) = (0, 0.9, 0.1)$.

In practice, since the true numbers are not easily known, the probability-weighted averages, that is, the impact vectors, must be used. However, replacing the theoretically true numbers with the expected numbers does not interfere with finding ρ to make the derivative in Eq. C-4 equal to zero or to solve Eq. C-7. This is how the MLE or MM estimate of ρ can be found in practice.

References

[C-1] Mosleh A, Rasmuson DM, Marshall F. *Guidelines on modeling common-cause failures in probabilistic risk assessment*. NUREG/CR-5485, U.S. Nuclear Regulatory Commission, 1998.

[C-2] Kvam, P. Estimation Techniques for Common Cause Failure Data with Different System Sizes. *Technometrics*, vol. 38, no. 4, pp. 382-388, 1996.

[C-3] Wierman TE, Rasmuson DM, Mosleh A. *Common-cause failure database and analysis system: event data collection, classification, and coding*. NUREG/CR-6268, Rev. 1, U.S. Nuclear Regulatory Commission, 2007.

APPENDIX D

GENERAL MAPPING UP FORMULA

Summary

Ref. [D-1] and its predecessor [D-2] propose a method for mapping data up, that is, for inferring a number of CCFs in a group of size M, based on an actual observed number in a smaller group of size m, with $m < M$. The proposed method is to imagine that the smaller group is embedded as a subgroup of the larger group. Then estimate the number of additional component failures that would be seen, assuming that the additional failures occur according to the BFR model.

Using the above approach, this appendix gives explicit reasons and an explicit general formula for the method of Ref. [D-1]. Though derived differently, the formula here agrees with method of Ref. [D-1], and with all the values tabulated there except for one apparent error.

Notation and Background

The BFR model asserts that common causes, “shocks,” occur externally to the components and affect the entire common-cause group of components. When such an event occurs the components have independent outcomes, each failing with probability ρ or succeeding with probability $1 - \rho$. Therefore, when a shock occurs in a group of size m, the probability of k failures is

$$\Pr(k \text{ out of } m \text{ components fail}) = \binom{m}{k} \rho^k (1-\rho)^{m-k} .$$

Let $n_k^{(m)}$ denote the number of events with k failed components. If N common-cause shocks occur, the value of $n_k^{(m)}$ is random,

$n_k^{(m)} \sim \text{binomial}(N, \Pr(k \text{ out of } m \text{ components fail}))$,

and the *expected* number is

$E(n_k^{(m)}) = N * \Pr(k \text{ out of } m \text{ components fail})$.

For the rest of this note, assume that the data consist of $n_1^{(m)}, \ldots, n_m^{(m)}$, the numbers of events observed in a group of size m. Assume that these counts are used to infer the corresponding counts in a larger group, of size M. The value of ρ must be estimated somehow; this will not be dealt with here.

The method regards the smaller group of size m as a subgroup of the larger group. More precisely, it behaves the same as a subgroup of the larger group. Then the BFR formulas are used to estimate the performance of the entire group, given the observed performance of the subgroup.

Formulas for mapping up

Ref. [D-1] presents its method by example, and this note does the same, with $m = 2$, $M = 4$. Table 1 shows the 16 possible sets of failed components. The components A and B are observed failed components in the group of 2 components. Because they are observable, they are shown in bold face. The components C and D are those that might fail if the 2-component system is embedded in a 4-component system.

Table D-1. Example of mapping up from 2-component system to 4 component system.

	Failed comps.				Failures in 1st	Total failures	Pr(2nd)
1	−	−	−	−	0	0	$(1-\rho)^2$
2	**A**	−	−	−	1	1	$(1-\rho)^2$
3	−	**B**	−	−	1	1	$(1-\rho)^2$
4	−	−	C	−	0	1	$\rho(1-\rho)$
5	−	−	−	D	0	1	$\rho(1-\rho)$
6	**A**	**B**	−	−	2	2	$(1-\rho)^2$
7	**A**	−	C	−	1	2	$\rho(1-\rho)$
8	**A**	−	−	D	1	2	$\rho(1-\rho)$
9	−	**B**	C	−	1	2	$\rho(1-\rho)$
10	−	**B**	−	D	1	2	$\rho(1-\rho)$
11	−	−	C	D	0	2	ρ^2
12	−	**B**	C	D	1	3	ρ^2
13	**A**	−	C	D	1	3	ρ^2
14	**A**	**B**	−	D	2	3	$\rho(1-\rho)$
15	**A**	**B**	C	−	2	3	$\rho(1-\rho)$
16	**A**	**B**	C	D	2	4	ρ^2

For example, row 2 has a failure of A, but of no other components. Row 12 shows a failure of B, C, and D.

To demonstrate the formulas for mapping up, suppose first that $n_1^{(2)}$ events have been observed in which A or B fails, but not both. Let us find the expected number of events with exactly 1 component failing out of the 4 in the larger group. This happens if neither C nor D fails in addition to A or B. From rows 2 and 3 of the table, we see that the expected number of events with A or B and nothing else failing is

$(1-\rho)^2\, n_1^{(2)}$.

However, these are not the only cases with exactly 1 failed component out of 4. Rows 4 and 5 also have this total number of failures, and by symmetry, all four of rows 2 through 5 have the same probability in the 4-component group. Therefore, the expected number of events with 1 failure out of 4 is

$n_1^{(4)} = 2(1-\rho)^2\, n_1^{(2)}$.

This agrees with Table C-5 of Ref. [D-1], although that table uses the notation *P* instead of *n*.

It is easy to overlook rows 4 and 5, because they were not observable in the data for the 2-component group. However, they must be counted. Anyone who objects to counting them should recall that similar reasoning is used when mapping independent failures up; in that situation, the additional independent failures inferred for the larger group are all in events for which the smaller group of components were successful.

Let us now go on to consider $n_2^{(4)}$. A total of two failed components can result when 0, 1, or 2 of A and B fail. Row 6 contributes to the total by an expected count of

$(1-\rho)^2\, n_2^{(2)}$.

Also, rows 7 through 10 contribute

$2\rho(1-\rho)^2\, n_1^{(2)}$.

In this last expression, the multiplier of 2 results from considering either C or D as a failed component; $n_1^{(2)}$ counts of all the events in which A or B fails, but not both.

Finally, we must deal with row 11, in which neither A nor B is observed to fail. There are 6 cases having a total of exactly 2 failed components, rows 6 through 11. By symmetry, they all have the same probability. Therefore, the total for $n_2^{(4)}$ must be 6/5 of the total from the 5 rows considered above:

$n_2^{(4)} = (6/5)[\, (1-\rho)^2\, n_2^{(2)} + 2\rho(1-\rho)^2\, n_1^{(2)}\,]$.

This does not agree with Table C-5 of Ref. [D-1]. It is believed that the tabulated value is erroneous, as discussed at the end of this note.

The remaining cases are straightforward. For $n_3^{(4)}$, rows 12 and 13 contribute

$\rho^2 n_1^{(2)}$,

and rows 14 and 15 contribute

$2\rho(1-\rho)^2\, n_2^{(2)}$.

This results in

$n_3^{(4)} = \rho^2 n_1^{(2)} + 2\rho(1-\rho)^2\, n_2^{(2)}$.

This agrees with Table C-5 of Ref. [D-1].

Finally, row 16 gives

$N_4^{(4)} = \rho^2 n_2^{(2)}$,

agreeing with Table C-5 of Ref. [D-1],

Using reasoning as in the example, it can be shown that the general formula for mapping up from size m to size M is

$$n_K^{(M)} = \frac{\binom{M}{K}}{\binom{M}{K} - \binom{M-m}{K}} \left[\sum_k \binom{M-m}{K-k} \rho^{K-k} (1-\rho)^{(M-m)-(K-k)} n_k^{(m)} \right] \quad . \qquad \text{(Eq. D-1)}$$

In the summation here, the limits on k are such that all the terms are defined and $k > 0$, that is,

$\max[1,\, m - (M-K)] \le k \le \min(K, m)$.

The multiplying fraction outside the square brackets accounts for the cases with no failures observed in the m-component group.

$\binom{M}{K}$ is the number of ways to choose K failed components out of M, and

$\binom{M-m}{K}$ is the number of ways to choose K of $M-m$, so that none of the first m components fail.

Therefore, the numerator of the fraction is the number of equally probable ways for K of M components to fail, and the denominator is the number of those ways that can be assessed based on observed failures in the m-component group. The fraction is defined to be 1 if $K > M - m$.

Using direct but tedious algebra, one can show that Eq. D-1 is identical to that applied in the examples on p. C-12 of Ref. [D-1] and to generalization of those examples. It also agrees with the formulas in Table C-5 of Ref. [D-1], except for the apparently erroneous tabulated value for $n_3^{(4)}$.

References

[D-1] Mosleh A, Rasmuson DM, Marshall F. *Guidelines on modeling common-cause failures in probabilistic risk assessment*. NUREG/CR-5485, U.S. Nuclear Regulatory Commission, 1998.

[D-2] Mosleh A, Fleming KN, Parry GW, Paula HM, Worledge DH, Rasmuson DM. 1989. *Procedures for Treating Common Cause Failures in Safety and Reliability Studies: Analytical Background and Techniques*. NUREG/CR-4720 Vol. 2, U.S. Nuclear Regulatory Commission; 1989.