Developing a Subset of Staggered Alpha Factor Parameter Estimates

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Abstract: One of the standard common cause failure models used in US NPPs is the alpha factor model. The alpha factor model uses the multi-parameter generalizations of event-based parameters directly to estimate the common cause basic event probabilities. NUREG/CR-5485 provides a discussion on the alpha factor model but explicitly distinguishes the CCF probability estimates based on a selected test scheme, namely, staggered or non-staggered testing. It is noted that an explicit form for the alpha factors for non-staggered testing is explicitly provided, whereas an equivalence for staggered testing is not detailed. Various white papers have been developed which discuss the importance of the test scheme on the alpha factors and the difficulty in developing detailed estimates given the currently available data. This paper discusses the development of staggered alpha factor parameter estimates for a subset of important plant equipment.

1. INTRODUCTION

NUREG/CR-5485 [1] discusses a set of popular parametric models used to estimate the failure probability of common cause failure (CCF) basic events. Amongst those models includes a thorough discussion on the alpha factor model. The discussion includes a derivation of equations that can be used to calculate the various CCF basic event probabilities when using the alpha factor model, including specific consideration for the test scheme of the common cause component group (CCCG). It has been suggested in various papers ([2], [3]) that the numerical values of the alpha factors are not equivalent under the different test schemes, leading to an erroneous calculation of CCF probabilities. This paper builds upon the previously mentioned white paper guidance and develops a set of alpha factor parameter estimates for emergency diesel generators assuming a staggered test scheme.

2. TEST SCHEMES

There are two main types of test schemes used for components in US nuclear power plants (NPPs): staggered, or non-staggered testing. The following sections describe some of the differences in the test schemes and the impact it has on the expected number of failure events. Foremost, it is important to note that within a single US NPP, a mixture of tests schemes may be used.

For example, some equipment (such as emergency diesel generators) is tested on a staggered basis to ensure that back-up power to a single safety bus still remains available when testing is performed. Furthermore, this equipment is governed by the Technical Specifications (herein referred to as Tech. Specs.) and has explicit requirements to perform follow-up activities to ensure other redundant equipment is still functional given a failure of the test component.

For equipment not governed by Tech. Specs., the selected strategy is determined by the NPP. The selected test schemes may include non-staggered test schemes, or even staggered testing without follow-up activities depending on the equipment and its importance to safety.

2.1. Non-staggered Testing

The NRC white paper [2] describes non-staggered testing as follows: *In a non-staggered test scheme, for a given test episode, the entire group of m components is tested. If any of the components are* *determined to be failed, they are repaired and returned to service. It should be noted that in practice, when components are tested using a non-staggered test scheme, the tests aren't perfectly simultaneous. However, it is assumed that this type of testing is a good surrogate for an unplanned demand in which all components would be demanded simultaneously.*

When a test scheme is selected, information is obtained about certain types of failure events. For example, if a given component is tested and is successful, it infers that a common cause event involving that component has not occurred. To help visualize which events are challenged in a non-staggered test scheme, an example group of three components and a count of the events that are challenged is shown in Table 1. A few key points regarding Table 1:

- In a non-staggered test scheme, the number of test episodes ($N_{E,NS}$) is equal to the number of demands ($N_{D,NS}$).
- Events denoted with an I represent independent component failures, whereas events denoted with a C represent common cause failures. The subscript denotes the component(s) of interest. For example, I_A represents an independent failure of Component A, and C_{AB} represents a common cause failure of Component A and Component B. This notation is slightly different than other references.

Table 1: Non-Staggered Test Scheme

Test Episode	Demand No.	Events Tested			Events Challenged						
No. 1	No. 1	A	B	C	I_A	I_B	I_C	C_{AB}	C_{AC}	C_{BC}	C_{ABC}
# of events challenged in a single test episode					$\binom{m}{k} = \binom{3}{1} = 3$			$\binom{m}{k} = \binom{3}{2} = 3$			$\binom{m}{k} = \binom{3}{3} = 1$

What is truly of interest is how the number of failure events in a non-staggered test scheme is distributed. In a non-staggered test scheme, each demand effectively represents a multinoulli process where there are k distinct outcomes. In our specific case for a CCCG of size 3, the distinct outcomes are (1) an independent component failure, (2) a common cause failure of two components, or (3) a common cause failure of all three components. It is noted for a non-staggered test scheme:

- The failure probability of a given k component group remains the same across trials. The failure probability of a k component group is equivalent to $\binom{m}{k} Q_k^{(m)}$. Where $Q_k^{(m)}$ represents the probability of failure of a given k component group in a CCCG of size m.

Thus, for multiple demands in a non-staggered test scheme, the total number of failures follows a multinomial distribution. Looking at any specific distinct outcome, it can be shown that the distribution of k specific failures (i.e., the marginal distribution) is binomial. Thus, failures associated with any k component group using a non-staggered test scheme are binomially distributed:

$$n_k^{NS} \sim binomial(N_{D,NS}, \binom{m}{k} Q_{k,NS}^{(m)}) \tag{1}$$

Where n_k^{NS} represents the number of failures of a k component group for a non-staggered test scheme.

The maximum likelihood estimate of the binomial likelihood can be obtained for each k component group. For convenience this value is found and then rearranged to provide a solution for the MLE of the $Q_k^{(m)}$ term.

$$\hat{Q}_{k,NS}^{(m)} = \frac{n_{k,NS}}{\binom{m}{k} N_{D,NS}} \tag{2}$$

2.2. Staggered Testing

In a staggered test scheme, a distinction needs to be made between a test scheme which includes or excludes follow-up activities. The NRC white paper [2] describes staggered testing as follows: *If follow-up activities are taken in a staggered test scheme, the components are tested one at a time so that the entire cycle of m components is tested periodically. If a component passes a scheduled test, nothing more is done until it is time for the next component to be tested. If instead, a component fails its scheduled test, then all the other components are tested, and any failed components are repaired and returned to service. Conversely, if no follow-up activities are taken, when a component fails its scheduled test, it alone is repaired, and the other components are not tested until their scheduled times.*

To help visualize which events are challenged in a staggered test scheme, an example group of three components and a count of the events that are challenged are shown in Table 2. A few key points regarding Table 2:

- In a staggered test scheme, the number of test episodes ($N_{E,S}$) is not equal to the number of demands ($N_{D,S}$). In a staggered test scheme, the number of demands is equal to $mN_{E,S}$ since in each test episode m demands occur.
- Table 2 does not explicitly show the count of all events challenged, but an approximation*. In a staggered test scheme that includes follow-up activities, if a component is found to be failed on a given demand, all remaining components would be tested.

Table 2: Staggered Test Scheme

Test Episode	Demand No.	Events Tested			Events Challenged						
No. 1	No. 1	A			I_A			C_{AB}	C_{AC}		C_{ABC}
	No. 2		B			I_B		C_{AB}		C_{BC}	C_{ABC}
	No. 3			C			I_C		C_{AC}	C_{BC}	C_{ABC}
# of events challenged in a single demand					$\binom{m-1}{k-1} = \binom{2}{0} = 1$			$\binom{m-1}{k-1} = \binom{2}{1} = 2$			$\binom{m-1}{k-1} = \binom{2}{2} = 1$
# of events challenged in a single test episode					$k\binom{m}{k} = 1\binom{3}{1} = 3$			$k\binom{m}{k} = 2\binom{3}{2} = 6$			$k\binom{m}{k} = 3\binom{3}{3} = 3$

Similarly to the discussion for a non-staggered test scheme, the analyst is interested in how the number of failures under s staggered test scheme is distributed. It can be similarly shown that the total number of failure events follows a multinomial distribution, and thus the failure events of any specific k component group follow a binomial distribution. For a staggered test scheme, we note that:

- The failure probability of a given k component group remains the same across trials. The failure probability of a k component group is equivalent to $k\binom{m}{k}Q_k^{(m)}$. Where $Q_k^{(m)}$ represents the probability of failure of a given k component group in a CCCG of size m.

Thus, failure associated with any k component group using a staggered test scheme are binomially distributed.

*In a staggered test scheme with follow-up activities, the number of components challenged in a given test episode can be expressed as:

$$N_{D,S} = mN_{E,S}\binom{m-1}{k-1} + N_F\binom{m}{k} - N_F\binom{m-1}{k-1}$$

Where, $N_{D,S}$ is the number of component demands under a staggered test scheme, and N_F is the number of demands where there was a failure of the first component. If a component fails, all remaining components in that group are tested. These tests are counted as sequential demands as compared to simultaneous demands. Practically speaking however, the number of demands where a failure occurs is typically much less than the number of demands where the first component tested is successful, resulting in the following approximation:

$$N_{D,S} \approx mN_{E,S}\binom{m-1}{k-1}$$

$$n_k^S \sim binomial(N_{D,S}, k\binom{m}{k} Q_{k,NS}^{(m)}) \tag{3}$$

Where n_k^Srepresents the number of failures of a k component group for a staggered test scheme.

The maximum likelihood estimate of the binomial likelihood can be obtained for each k component group. For convenience this value is found and then rearranged to provide a solution for the MLE of the $Q_k^{(m)}$ term.

$$\hat{Q}_{k,S}^{(m)} = \frac{n_{k,S}}{k\binom{m}{k} N_{D,S}} \tag{4}$$

3. ALPHA FACTOR PARAMETER ESTIMATORS

Throughout the various discussions on the alpha factor model, the discussion on parameter estimates for alpha factors is not always intuitive. It is important to recognize that there is an implicit dependence between the observed number of failures in the industry operating experience and the test scheme from which those failures arose. That is, if a certain component type only undergoes staggered testing, then the observed failure inherently reflects observations of a staggered test scheme. This level of detail is generally not detailed when the industry operating data is collected. Thus, the analyst must make a choice on how to treat the generic data set, which also then dictates the remainer of the necessary calculations. There are two obvious choices that can be made: (1) assuming the observed failure events represent observations from a non-staggered test scheme, or (2) assuming the observed failure events represent observations from a staggered test scheme. In practice, it is recognized that failure events could come from a mixture of test schemes. Regardless of the choice, the analyst can assess the impact of the alternate test scheme providing for a convenient comparison.

3.1. Case 1 – Observed Failures Based on a Non-staggered Test Scheme

If the observed failure events are assumed to be based on a non-staggered test scheme, the alpha factor is defined as shown in (5):

$$\alpha_k^{(m)} = \frac{\binom{m}{k} Q_k^{(m)}}{\sum_{k=1}^{m} \binom{m}{k} Q_k^{(m)}} \tag{5}$$

Following the derivations described in NUREG/CR-5485 [1], an equation for the $\boldsymbol{Q_k^{(m)}}$ in terms of the other parameters can be obtained. This results in the equation used to calculate the CCF basic event probabilities for a non-staggered test scheme (6).

$$Q_k^{(m)} = \frac{k}{\binom{m-1}{k-1}} \frac{\alpha_k^{(m)}}{\alpha_t} Q_t \tag{6}$$

The impact of different test scheme assumptions on the resultant alpha factors can be estimated by replacing the $\boldsymbol{Q_k^{(m)}}$ terms in (5) with the maximum likelihood estimates ((2) or (4)) for the respective test schemes. The resultant alpha factor MLEs for the different test schemes are shown in Table 3.

Table 3: Alpha Factor MLE Values Under Various Test Schemes (Based on a Non-Staggered Alpha Factor)

Test Scheme	$\alpha_k^{(m)}$ MLE
Non-Staggered	$\hat{\alpha}_{k,NS}^{(m)} = \frac{n_{k,NS}}{\sum_{k=1}^{m} n_{k,NS}}$
Staggered	$\hat{\alpha}_{k,S}^{(m)} = \frac{\frac{n_{k,S}}{k}}{\sum_{k=1}^{m} \frac{n_{k,S}}{k}}$

3.1. Case 2 – Observed Failures Based on a Staggered Test Scheme

If the observed failure events are assumed to be based on a staggered test scheme, the alpha factor can be defined as shown in (7).

$$\alpha_k^{(m)} = \frac{k \binom{m}{k} Q_k^{(m)}}{\sum_{k=1}^{m} k \binom{m}{k} Q_k^{(m)}} \quad (7)$$

Following the same procedure for the derivation of the non-staggered equation, an equation for the $Q_k^{(m)}$ in terms of the other parameters can be obtained. This results in the equation used to calculate the CCF basic event probabilities for a staggered test scheme (8).

$$Q_k^{(m)} = \frac{1}{\binom{m-1}{k-1}} \alpha_k^{(m)} Q_t \quad (8)$$

Once again replacing the $Q_k^{(m)}$ terms in (7) with the maximum likelihood estimates ((2) or (4)) for the respective test schemes results in MLEs for the alpha factors for the different test schemes which are shown in Table 4.

Table 4: Alpha Factor MLE Values Under Various Test Schemes (Based on a Staggered Alpha Factor)

Test Scheme	$\alpha_k^{(m)}$ MLE
Non-Staggered	$\hat{\alpha}_{k,NS}^{(m)} = \frac{k n_{k,NS}}{\sum_{k=1}^{m} k n_{k,NS}}$
Staggered	$\hat{\alpha}_{k,S}^{(m)} = \frac{n_{k,S}}{\sum_{k=1}^{m} n_{k,S}}$

3.3. CCF Event Characterization

A critical part of the development of CCF parameters is the characterization of industry CCF events. At this stage, component degradation, timing, and shared cause factors are generally assigned to CCF events. One key piece of information that isn't explicitly detailed is whether the components of interest are tested in a staggered or non-staggered manner.

This paper looks at delineating non-staggered and staggered alpha factor estimates for emergency diesel generators (EDGs). The EDGs are governed by Technical Specifications (e.g., [4]). Furthermore, given a single EDG is determined to be inoperable, the Technical Specifications require follow-up activities on the operable EDG within 24 hours (see LCO 3.8.1B.3.1 [4]). Thus, it can be assumed that for industry CCF events involving EDGs that they are tested on a staggered basis with follow-up activities.

The 2020 CCF data analysis [5] documents CCF events associated with EDGs failing to start, failing to load/run, and failing to run. The CCF events and their characterization are shown in Table 5, Table 6, and Table 7. It is noted that the unadjusted number of independent failures[†] are 145.4, 173.8, 177.6, for EDGs FTS, FTLR, and FTR, respectively.

Table 5: EDG-FTS 2020 CCF Event Characterization

CCF Name	System	k	m	p_1	p_2	c	q	CCF Degree	Cause
336-2009-0384	EPS	2	2	1	1	1	1	Complete	PA

Table 6: EDG-FTLR 2020 CCF Event Characterization

CCF Name	System	k	m	p_1	p_2	p_3	p_4	c	q	CCF Degree	Cause
333-2013-0454	EPS	2	4	1	1	0	0	1	1	Partial	IC
324-2015-0497	EPS	2	4	0	0.1	0	0	1	1	Partial	DE

Table 7: EDG-FTR 2020 CCF Event Characterization

CCF Name	System	k	m	p_1	p_2	p_3	p_4	p_5	c	q	CCF Degree	Cause
366-2008-0421	EPS	5	5	1	0.1	0.1	0.1	0.1	1	1	Partial	HM
282-2012-0451	EPS	2	2	1	1	-	-	-	1	1	Complete	IC
323-2014-0489	EPS	2	3	1	1	0	-	-	1	1	Almost	DM

3.4. Development of MLEs for Alpha Factors

The MLEs for the alpha factors are developed once the mapped impact vectors have been obtained. As discussed in Section 3, the numerical value of the MLE depends on the test scheme. The mapped impact vectors for a group size of 2 for the various failure modes are shown in Table 8, Table 9, and Table 10.

Finally, the resultant MLE values for the alpha factors under the various test schemes and cases are shown in Table 11. It is important to note that the estimators change depending on the equation used to estimate the CCF basic event probabilities.

[†] It is noted that the number of independent component failures may differ from those published in [5]. The count of independent failures is taken from the NROD database which is periodically updated.

Table 8: EDG-FTS Mapped Impact Vector (CCCG=2)

CCF Name	F_1	F_2
336-2009-0384	0	1

Table 9: EDG-FTLR Mapped Impact Vector (CCCG=2)

CCF Name	F_1	F_2
324-2015-0497	0.09667	0.00167
333-2013-0454	0.66667	0.16667

Table 10: EDG-FTR Mapped Impact Vector (CCCG=2)

CCF Name	F_1	F_2
282-2012-0451	0	1
323-2014-0489	0.66667	0.33333
366-2008-0421	0.46796	0.046

Table 11: Alpha Factor MLEs for Various Test Schemes

Parameter	Observed Failures Based on Non-Staggered Test Scheme		Observed Failures Based on Staggered Test Scheme	
	Non-Staggered Alpha Factor	Staggered Alpha Factor	Non-Staggered Alpha Factor	Staggered Alpha Factor
EDG-FTS (CCCG = 2)				
$\hat{\alpha}_1^{(2)}$	0.9932	0.9966	0.9864	0.9932
$\hat{\alpha}_2^{(2)}$	6.83E-03	3.43E-03	1.36E-02	6.83E-03
EDG-FTLR (CCCG = 2)				
$\hat{\alpha}_1^{(2)}$	0.9990	0.9995	0.9981	0.9990
$\hat{\alpha}_2^{(2)}$	9.63E-04	4.82E-04	1.92E-03	9.63E-04
EDG-FTR (CCCG = 2)				
$\hat{\alpha}_1^{(2)}$	0.9923	0.9962	0.9848	0.9923
$\hat{\alpha}_2^{(2)}$	7.66E-03	3.84E-03	1.52E-02	7.66E-03

3.5. Development of Mean Values for Alpha Factors

The mean values for alpha factors are developed using a Bayesian approach which combines a prior distribution and industry operating experience to obtain posterior distribution parameters. It is noted that the generic prior used in CCF parameter estimates includes CCF events for multiple component types, failure modes, and test schemes. It is possible that a test-scheme specific prior distribution could be generated but is beyond the scope of this paper.

From probability theory, we know that the binomial likelihood and beta distribution are conjugate distributions. Thus, the resultant posterior distribution is also a beta distribution with the following shape parameters as shown in (9) and (10). Table 12 summarizes the formulas that can be used to obtain the resultant beta distribution shape parameters in terms of the counts of specific k failure events.

$$a_{post,i} = a_{prior,i} + n_i \quad (9)$$

$$b_{post,i} = b_{prior,i} + N_D - n_i \quad (10)$$

Table 12: Beta Distribution Shape Parameter Estimates for Various Test Schemes

Parameter	Non-Staggered Equation		Staggered Equation	
	Non-Staggered Alpha Factor	**Staggered Alpha Factor**	**Non-Staggered Alpha Factor**	**Staggered Alpha Factor**
$a_{post,i}$	$a_{prior,i} + n_i$	$a_{prior,i} + \frac{n_i}{i}$	$a_{prior,i} + in_i$	$a_{prior,i} + n_i$
$b_{post,i}$	$b_{prior,i} + \sum_{k=1}^{m} n_k - n_i$	$b_{prior,i} + \sum_{k=1}^{m} \frac{n_k}{k} - \frac{n_i}{i}$	$b_{prior,i} + \sum_{k=1}^{m} kn_k - in_i$	$b_{prior,i} + \sum_{k=1}^{m} n_k - n_i$

The 2020 CCF data analysis [5] uses the prior distribution shown in Table 13 for a CCCG of size 2. The resultant mean values for the alpha factors are shown in Table 14. The final CCF probabilities to be used in the PRA model assuming a representative total failure probability for the various failure modes (i.e., 2.22E-03, 3.31E-03, and 1.18E-03, for FTS, FTLR, and FTR, respectively).

Table 13: CCF Prior Beta Distribution Shape Parameters (Table 13 of [6])

Parameter	Distribution	a	b	Date
$\alpha_1^{(2)}$	Beta	2.24E+01	4.69E-01	1997-2015
$\alpha_2^{(2)}$	Beta	4.69E-01	2.24E+01	1997-2015

Table 14: Alpha Factor Mean Values for Various Test Schemes

Parameter	Observed Failures Based on Non-Staggered Test Scheme		Observed Failures Based on Staggered Test Scheme	
	Non-Staggered Alpha Factor	**Staggered Alpha Factor**	**Non-Staggered Alpha Factor**	**Staggered Alpha Factor**
EDG-FTS (CCCG = 2)				
$\alpha_1^{(2)}$	0.9913	0.9943	0.9855	0.9913
$\alpha_2^{(2)}$	8.68E-03	5.74E-03	1.45E-02	8.68E-03
EDG-FTLR (CCCG = 2)				
$\alpha_1^{(2)}$	0.9968	0.9972	0.9959	0.9968
$\alpha_2^{(2)}$	3.23E-03	2.80E-03	4.07E-03	3.23E-03
EDG-FTR (CCCG = 2)				
$\alpha_1^{(2)}$	0.9909	0.9943	0.9842	0.9909
$\alpha_2^{(2)}$	9.11E-03	5.73E-03	1.58E-02	9.11E-03

Table 15: Example CCF Basic Event Probabilities for Various Test Schemes

Parameter	Observed Failures Based on Non-Staggered Test Scheme		Observed Failures Based on Staggered Test Scheme	
	Non-Staggered Alpha Factor	**Staggered Alpha Factor**	**Non-Staggered Alpha Factor**	**Staggered Alpha Factor**
EDG-FTS (CCCG = 2)				
$Q_1^{(2)}$	2.18E-03	2.19E-03	2.19E-03	2.20E-03
$Q_2^{(2)}$	1.91E-05	1.27E-05	3.22E-05	1.93E-05
EDG-FTLR (CCCG = 2)				
$Q_1^{(2)}$	3.29E-03	3.29E-03	3.30E-03	3.30E-03
$Q_2^{(2)}$	1.06E-05	9.24E-06	1.35E-05	1.07E-05
EDG-FTR (CCCG = 2)				
$Q_1^{(2)}$	1.16E-03	1.17E-03	1.16E-03	1.17E-03
$Q_2^{(2)}$	1.06E-05	6.72E-06	1.86E-05	1.07E-05

4. CONCLUSION

There is a well-known paradox in probability posed by Joseph Bertrand in which Bertrand discusses an inscribed equilateral triangle in a circle. He proposes a chord of the circle is chosen at random, and it is desired to calculate the probability that the randomly chosen chord is longer than a side of the inscribed equilateral triangle. Three arguments are provided as potential solutions, all which seem valid, but result in differing probabilities. It is not until the method of random selection is specified that the problem will have a well-defined solution. The discussion on alpha factors provided in various industry references seems to follow the same conundrum as Bertrand's paradox, that is, the testing method must first be specified to obtain appropriate estimates of the alpha factors.

The discussion in this paper shows that careful consideration is needed when selecting the appropriate alpha factor estimate to use when CCF basic event probabilities are desired. Some of the main considerations are:

- What test scheme generated the observed CCF events? While for some component types (e.g., EDGs) this may be more obvious, it is not necessarily trivial to determine for other component types.
- What rest scheme generated the observed CCF events used to generate the prior CCF distribution? It is recognized that the observed CCF events that are used to develop the prior represent various test schemes.
- While the resultant probability estimates are generally closed for the EDG example provided, the alpha factor estimates are more varied. Differing alpha factor estimates can have a significant impact on analyses such as event and condition assessment (ECA) which is used in the significant determination process (SDP).

The author recommends the following approach for dealing with test schemes in common cause modelling:

1. Only make use of the non-staggered equation to calculate CCF basic event probabilities.
2. By default, make use of the non-staggered alpha factor estimates. The generic CCF parameter estimates [5] should be treated as estimates of non-staggered alpha factors to be used in the non-staggered equation.
3. Use the staggered alpha factor estimates when it can be justified that the observed CCF events were generated using a staggered test scheme. It is noted that the generic CCF data may need to be reviewed and new calculations performed to generate these estimates. The author recommends, at a minimum, EDGs (in the context of a single unit) be treated in this manner.

References

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