Review of the Causal Alpha Factor Method

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Abstract: This paper provides a review of the Causal Alpha Factor Method (CAFM), an approach for quantifying common-cause failure (CCF) parameters in probabilistic risk assessments (PRAs) and probabilistic safety assessments (PSAs). CAFM aims to enhance the accuracy of risk modeling by explicitly incorporating failure causes into CCF analysis, thereby enabling more informed interpretations of operational events and supporting risk-informed decision-making. Building upon the traditional alpha factor framework, CAFM introduces cause-specific grouping, gamma weighting, and normalization techniques to reconcile cause-based estimates with generic CCF parameters. The paper reviews the methods development, and key challenges, including assigning single causes to complex events, extrapolating across varying component group sizes, and managing broad uncertainty distributions. This paper concludes with recommendations aimed at improving the CAFM approach to CCF modeling and improving CCF modeling more generally.

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1. INTRODUCTION

The causal alpha factors method (CAFM) is one methodology for calculating common-cause failure (CCF) alpha factor distributions that account for the causes of failure events [1]. The alpha factor method is one of the standard processes for developing CCF parameters from component failure evidence for use in probabilistic risk assessments (PRAs) and probabilistic safety assessments (PSAs) [2]. For CAFM, the coupling factors of interest are the causes of each specific independent and common-cause failure event. These causes – known as “causal factors” or “proximate causes” – are grouped into the following five categories: Component (GC), Design (GD), Environmental (GE), Human (GH), and Other (GO).

Development of CAFM was initially intended to support event and condition assessments (ECAs) [1], a process by which the United States Nuclear Regulatory Commission (NRC) grades the risk significance of a licensee's performance deficiency. In general, it is possible to determine the cause(s) of an actual failure event related to performance deficiency. If credible CCF parameters were available at the cause level (in addition to the component-type and failure-mode levels), they would support a more appropriate assessment of the event's risk significance. However, CAFM does not have direct application in a baseline PRA model since component failures are not modeled at the cause-level, apart from failures caused by internal or external hazard events – for example, failures directly caused by internal fires, or external flooding.

Additional information related to the development of CAFM, as well as an overview of the methodology and dataset, is presented in EPRI's report titled "Review of Methods to Quantify Common Cause Failure Parameters for use in Probabilistic Risk Assessments: Review of the Causal Alpha Factor Method (CAFM)" [3].

2. DEVELOPMENT OF FAILURE EVENT CAUSE CODES

Table 1 presents the cause coding used for CAFM and shows the five cause groups, their relation to the existing 16 CCF cause codes in NROD [4], and the definitions of each cause code. The following table is based on Table 4-5 [1].

Table 1: Cause group codes used in the causal alpha factor method

CCF Event	CCF Cause Code	Failure Cause Description
Component (GC)	IC	Internal to the component, piece-part
	IQ	Setpoint drift
	IW	Age/wear
Design (GD)	DC	Construction installation error or inadequacy
	DE	Design error or inadequacy
	DM	Manufacturing error or inadequacy
Environment (GE)	EA	Ambient environmental stress
	EE	Extreme environmental stress
	IE	Internal environment
Human (GH)	HA	Accidental Human Action
	HM	Inadequate Maintenance
	HP	Human action procedure
	PA	Inadequate procedure
Other (GO)	EC	State of the other component
	OT	Other
	OK	Unknown

NUREG/CR-6268 [5] provides the basis for the classification and coding of CCF events used in NROD to support the alpha factor calculations in RADS [6]. Section 3.1 [5] defines the coding for "failure causes." The following descriptions of CCF cause groups are taken from Figure 3-1 [5] and can also be found in RADS under "General CCF Information."

- **Design/Construction/Manufacture Inadequacy** encompasses actions and decisions taken during the design, manufacturing, or installation of components, both before and after the plant is operational.

- **Operations/Human Error (Plant Staff Error)** represents causes related to errors of omission and commission on the part of plant staff. An example is failing to follow the correct procedures. This category includes accidental actions and failure to follow procedures for construction, modification, operation, maintenance, calibration, and testing. It also includes ambiguity, incompleteness, or procedural errors in the operation and maintenance of equipment. This includes inadequacy in construction, modification, administrative, operational, maintenance, test, and calibration procedures.

- **External Environment** represents causes related to a harsh external environment that is not within component design specifications. Specific mechanisms include electromagnetic interference, fire/smoke, impact loads, moisture (for example, sprays, floods), radiation, abnormally high or low temperatures, and acts of nature.

- **Internal to Component** is associated with the malfunctioning of something internal to the component. Internal causes result from phenomena such as normal wear or other intrinsic failure mechanisms. It includes the influence of a component's internal environment. Specific mechanisms include erosion/corrosion, vibration, internal contamination, fatigue, and wear-out/end-of-life.

- **State of Other Component** is when the component is functionally unavailable because a supporting component or system has failed. For example, an air supply line connected to a valve breaks, or an electrical fuse in a control circuit opens. Excluded from CCF events are those events that have dependencies that would reasonably be expected to be modeled in an individual plant examination or PRA.

- **Unknown** is used when the cause of the component state cannot be identified.

- **Other** is used when the cause cannot be attributed to any of the previous cause categories. This category is most frequently used for cases of setpoint drift.

These groups correspond closely to the cause groups used in CAFM, with the following exceptions. The Environment (GE) cause group includes internal, ambient, and external environments. The Other (GO) cause group combines the last three groups listed above.

3. CHALLENGES WHEN ASSIGNING CAUSE

The CAFM approach has specific challenges when used to develop CCF parameters. For example, it can be difficult to assess a single cause for each failure event. Note that the current methodology for characterizing CCF events in NROD allows for only one of the five cause categories to be assigned to a failure event. It is also important to recognize that CAFM shares several broader technical challenges inherent to CCF modeling. EPRI report 3002020764, "Consideration of Common Cause Failures in Risk-Informed Decision-Making," [2] provides additional information regarding specific challenges when modeling common-cause failure.

3.1 Determining the Causal Chain

NUREG/CR-6268 provides a discussion of the challenges faced when determining an event's causal chain. Section 3.1 [5] states that the cause of a failure event is a condition or combination of conditions to which a change in the state of a component can be attributed. It is recognized that describing failures as due to a single cause is often too simplistic. The failure cause entered in the CCF database is usually the proximate cause. A proximate cause of a component failure event is a condition readily identifiable as having led to the failure. However, the proximate cause can be regarded as a symptom of the failure's cause and does not necessarily provide a complete understanding of what led to the failure. As such, the proximate cause may not be the best characterization of failure events for identifying appropriate corrective actions.

To expand the description of the causal chain of conditions resulting in a failure, the concepts of conditioning events and trigger events, defined as follows, are introduced [5]:

- **Conditioning events** are events that predispose a component to fail or increase a component's susceptibility to failure. The effect of the conditioning event is latent but nevertheless contributes to the failure mechanism.

- **Trigger events** activate failures or initiate the transition to a failed state.

NUREG/CR-6268 also provides an example to illustrate these concepts. A pump fails because of high humidity (the proximate cause). The conditioning event is the failure of maintenance personnel to seal the pump control cabinet properly after maintenance. A steam leak that led to high humidity in a room (and subsequent pump failure) is the trigger event. The example doesn't continue with the cause-tree, but one could speculate that the steam leak might have been caused by a manufacturing flaw in the pipe, a wear mechanism, or a maintenance error in failing to adequately tighten a flange. NUREG/CR-6268 goes on to describe that the root cause is the basic reason(s) why components fail. However, utility failure reports, license event reports (LERs), and/or Institute of Nuclear Power Operations (INPO) reports often do not identify the root cause. This may be because the root cause could not be determined or because the root cause analysis exceeded the required time for the failure report. As a result, failure cause coded into the CCF database is usually the proximate cause.

3.2 Assigning a Single Cause

An additional challenge is the NROD coding constraint that allows only one failure cause to be identified. Failure events are often due to multiple causes, each contributing to the causal failure chain. This specific challenge is illustrated by inconsistencies between cause coding and coupling factor coding for CCF events. Table 4-1 [1] shows the correlation between the 16 failure causes and the 11 coupling factors for the 434 CCF events that occurred from 1997 through 2020. Table 4-2 [1] shows a similar table but focused on emergency diesel generator CCF events. Both tables show that there is no one-to-one relationship between failure causes and coupling factors. For each failure cause, there are usually several coupling factors through which the cause can propagate. Conversely, for each coupling factor, there are several causes. In a recommendation to the NRC (see Section 5 [1]), INL suggested that the current database classification system be revised to meet the requirement for correlating failure causes and coupling factors. Note that the change would not address the fundamental issue of multiple causes for failure events.

3.3 Specific Cause Group Considerations

Cause group GC (component) contains three cause codes, each presenting a specific set of challenges. These codes may be appropriate proximate causes, but they are unlikely to be the root cause of a failure event. For example:

- Cause IW (age/wear) is used when the cause of a failure is a non-specific aging or wear. The equipment in a nuclear power plant is typically not operated until a failure occurs. Components are inspected, tested, repaired, and maintained via maintenance programs. As a result, failures due to equipment aging or wear-out are likely a symptom of a design or installation error and/or inadequate testing and maintenance. That is, the likely cause is a failure to identify and repair or replace components before they fail.

- Cause IC (internal to the component, piece-part) is used when the cause of a failure is a non-specific result of a failure internal to the component that results in failure other than aging or wear (code IW). This cause code seems similar to the unknown cause (code OK), except for information indicating the failure is internal to the component.

- Cause IQ (setpoint drift) is used when the cause of the failure is the result of setpoint drift or adjustment. This is linked to several failure modes, most commonly "setpoint." Note that the CCF event count for code IQ is zero, with 44.2 independent failures [4].

Cause group GE (environment) includes code EE (extreme environmental stress). This code is used when the failure is due to a transitory environmental condition that places a higher-than-expected load on the equipment. This is used for failures caused by external conditions that also challenge plant operations, leading to a plant trip. A total of 21 extreme environmental stress CCF events occurred from 2006 through 2020. This compares to 63.6 independent failure events with the same cause, resulting in a two-out-of-two alpha parameter (α_2^2) equal to 0.219.

This is a factor 10 times larger than the average two-of-two alpha parameter. For example, the all-cause prior alpha factor is 0.0205, provided in Section 3.1.3.1 [7]. As a result, failures due to extreme environmental stress are much more likely to be CCFs than failures caused by random hardware issues. The issue with the treatment of these CCF events is that, while they are modeled as random failures following any initiating event, they are not random events. Rather, they are directly linked to acute environmental stress events and are best modeled as the consequential failures (or increased failure likelihood) of initiating events caused by environmental stresses (for example, loss of circulating water due to debris intrusion into the intake structure). While the impacts of extreme environmental stress events should be accounted for in a PRA or PSA, they should be modeled as consequential failures rather than as parametric common-cause failures. Although such impacts are due to a common cause, they differ from traditional CCF events and should be modeled similarly to impacts from internal or external hazards (for example, fire, flooding, seismic events, high winds).

Cause group GO (other) contains three cause codes, each presenting a specific set of challenges. For example:

- Cause EC is used when the cause of a failure is the result of a component state that is not associated with the component that failed. For example, a diesel generator fails because there is no fuel in the fuel storage tanks. This effectively assigns failure to a component when the cause lies outside the component's analysis boundary. In this example, either the diesel’s analysis boundary should be expanded to include the fuel storage tanks, or the failure should be assigned to the fuel storage tanks and modeled as such.

- Cause OT is used when the cause of a failure is provided, but it does not meet any one of the other codes. Although these failure events could be used to expand the explicit list of causes, they appear to be utilized as an unknown cause group.

- Cause OK is used when the cause of the failure is not known. This coding is especially challenging when the cause codes are used to develop CAFM. Code OK includes two CCF events and 437.6 independent failure events [6]. The few CCF events coded as OK, compared to independent failure events, could be due to CCF event descriptions providing more causal information or to coding analysts spending more time evaluating the cause of a CCF. Regardless, events with unknown causes have lower CAFs than those with other known cause codes. This is likely due to the event coding rather than any real difference.

3.4 Inconsistent Cause Coding

Each CCF event record in NROD also has associated individual failure event records. Both the CCF event record and the individual failure event records are coded with a failure cause. A review of the NROD dataset shows that cause codes are not consistently applied across the same failure events in the CCF event record and individual failure event records. Table 2 provides examples of this inconsistency.

Table 2. Comparison between common-cause failure event coding and failure event coding

CCF Event	CCF Cause Code	Failure Event	Failure Event Cause Code
0555	DM	15230, 15231, 15232	IW, DM, DM
0543	DC	14756, 14757	PA, PA
0551	HP	15128, 15129	PA, PA
0516	IC	12515	IW
0255	EC	6566, 6567	HM, EC

3.5 Utilizing Limited Operational Data

Several entries in the CAFM dataset [8] and the CCF dataset [9] are parsed at the system level. The result is that the limited failure data (at the component-type and failure-mode level) are divided into even smaller groups. For the CAFM dataset, this is further compounded by the cause group subdivision. For subdivisions with limited failure data, the prior will dominate the resulting posterior distributions for the CCF parameters.

3.6 Utilizing the Setpoint Failure Mode

One of the failure modes in NROD is called “setpoint” (setpoint out of tolerance). Setpoint failures account for 53 out of the 164 CCF events (32%) from 2006 through 2020 [4]. However, there is no entry for component-types with setpoint as a failure mode in the CCF datasets [7]. This failure mode is also not included in the NRC component failure rate table [10, 11]. The implication of this exclusion is that setpoint out-of-tolerance events are deviations from technical specification limits rather than functional failures. If this is true, such events would not belong in the failure database.

Setpoint failure modes do appear in both the CAFM and CCF datasets. This failure mode is included in the “3.1.3.2 CCF ALL” CCF rules [6], which includes all component types and all failure modes. Setpoint failures are also included in the discussion of CCF experience, Section 1.4.6 [11]. The setpoint failure mode is excluded from the pooled entries in Sections 3.1.1.1 and 3.1.2.1 [11]. It is also excluded from the development of prior distributions [12]. While the setpoint failure mode has a limited direct impact, it is used as evidence of general CCF experience without being classified as a failure event.

4. CONCLUSION

A general conclusion from the development of PRAs for nuclear power plants is that common-cause failures are significant contributors to the loss of safety system functions. The intent of this report is to support the development of CCF parameters that reflect the current evidence of component performance in nuclear power plants.

4.1 Extreme Environmental Stress

Research by EPRI [3] provides a basis for considering eliminating CCF events caused by extreme environmental stress. As discussed above, the issue is that these events are not random but are directly linked to acute environmental stressors. As such, these CCF events could be better modeled as consequential failures (or increased failure likelihood) of the initiating events caused by an environmental stressor. While the impacts of extreme environmental stress events need to be accounted for in a PRA or PSA, they should not be modeled as parametric common-cause failures. This adjustment may require further research and development to generate suitable generic models that can account for plant-specific conditions and operating history.

4.2 Passive Failure Modes

The current CAF dataset includes several failure modes that are not well defined or not applicable to parametric common-cause failure modeling. These include:

- **Plugging:** Such failures apply primarily to CCF events caused by extreme environmental stress.

- **Setpoint:** This failure mode (setpoint out of tolerance) has a limited direct impact and is included in only a few places in CCF documentation. However, it does add complexity to the component failure and CCF datasets in NROD and RADS and is used as evidence regarding the general CCF operational history.

Consider eliminating these failures from the NROD characterization of failure events and CCF events. With that, the failure events associated with these failure modes should also be removed from the failure event and CCF event datasets. Although these events may have a role to play in other applications, they do not seem to meet the definition of a failure event.

4.3 System-Level Subdivisions

Several of the entries in the CAFM and the CCF datasets are parsed at the system level. This results in the already limited component type and failure mode data being divided into even smaller groups. For the CAFM dataset, this challenge is compounded by the additional subdivision by cause groups. The limited failure data in these subdivisions means that the prior may well dominate the resulting posterior distributions of CCF parameters. The consequence of this subdivision is to amplify the importance of the following three issues: 1) the subjective choices of key factors when characterizing CCF events, 2) the impact of the mapping-up process on CCF event vectors, and 3) the selection of prior distributions.

One option is to eliminate the system-level entries in future CCF datasets. The question of other parsing of data (for example, between MOV fail-to-open and fail-to-close failure modes) should be carefully evaluated using insights from operating experience (failure event data) and engineering experience (function and failure modes).

4.4 Wide Uncertainty Distributions

About one quarter of the entries in CAFM dataset [6] have an error factor greater than 20. Approximately 13% of the entries have an error factor greater than 100, 10% of the entries have an error factor greater than 1,000, and 5% of the entries have an error factor greater than 10,000. An alpha parameter with a wide uncertainty distribution (for example, error factors greater than 20) could generally be considered undetermined. Mean value estimates with such uncertain distributions do not provide insightful representation of the modeled parameters. As such, CCF entries with an error factor greater than 20 should be excluded from future CCF datasets. If there are modeling needs for such CCF parameters, the estimates need to be generated using a different approach, such as expert elicitation.

4.5 Cause Determination

One fundamental challenge for CAFM is the assignment of a single cause to each CCF event and independent failure event. This is due to the difficulties in identifying the complete causal chain of conditions resulting in failure, and the challenges to coding failure causes for each failure event. One suggestion is to revise the cause groups. A suggested set of cause groups is as follows:

- **Design (DES):** This includes causes of hardware failures that are linked to design error or inadequacy, manufacturing error or inadequacy, or construction installation error or inadequacy.

- **Component (COM):** This includes causes of hardware failures that are not linked to design, manufacturing, or installation errors. This includes failures that are non-specific results of internal component failures, such as aging or wear. This also includes failures due to ambient environmental stress or internal environmental stress.

- **Maintenance (MNT):** This includes causes of hardware failures due to human actions (or inactions) where inadequate maintenance is a contributing factor. This assumes a broad definition of maintenance that includes errors during maintenance, problems with maintenance procedures, and inadequate maintenance processes (that is, failure to identify the need for specific preventive maintenance when relevant information was available).

- **Operations (OPS):** This includes causes of failures due to human actions (or inactions), where the action was not attributed to maintenance. This includes accidental human action, failure to follow procedures, or inadequate procedures.

A second suggestion is to revise the coding of failure and CCF events in the NROD database to account for multiple causes and to include weighting factors for each cause. This could help reduce the constraint in coding failure events with only one failure cause. For example, the cause coding for a failure event caused by component wear out (COM) that could have been identified prior to failure (MNT) would be as follows: DES value of 0, COM value of 0.5, MNT value of 0.5, and OPS value of 0.

A third suggestion is to constrain the cause coding between failure events and associated CCF events in NROD so that the cause coding is the same.

It is recognized that these suggestions would require substantial rework of the coding in NROD since all failure events (both CCF and independent) would need to be reassessed. To determine failure causes with any precision would require careful review of all supporting failure information provided by industry members.

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