COMMON CAUSE FAILURES EXCEEDING CCF GROUPS

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In a probabilistic safety assessment (PSA), common cause failures (CCFs) are usually postulated for so-called CCF component groups which normally comprise the redundant components of the same type of one system. An analysis of the German operating experience of pressurized water reactors (PWR) up to the year 2002 has shown that approximately 15% of all CCF events affected components which according to current German PSA guidelines are modeled in different component groups. Such CCFs were observed for many different component types including pilot valves and other valves, batteries, relays, breakers, transducers, diesel generators and ventilators. The importance of CCFs exceeding present CCF component groups (X-CCFs) was further analyzed using the example of emergency diesel generators. A PSA model of a German PWR was modified such that X-CCFs of diesels are included. The basic events modeling X-CCFs were quantized from German operating experience using a newly developed procedure. A quantitative analysis of the initiating event "loss of offsite power" has shown that including X-CCFs of diesel generators significantly increases the estimated frequency of plant hazard states. Therefore, additional research efforts are planned to further investigate CCFs exceeding present CCF component groups, including X-CCFs that may affect very large numbers of components.

I. INTRODUCTION

The safety of nuclear power plants can be significantly affected by failures of multiple components due to a common cause. Despite the fact that such common cause failures (CCFs) are rare events, probabilistic safety assessments (PSA) of modern nuclear power plants have shown that unavailabilities due to CCFs often dominate PSA results. Therefore, the appropriate modelling of CCF is of great importance.

In PSA, CCF events are normally postulated for CCF component groups usually comprising redundant components of the same type of one system. Operating experience, however, has shown that common cause failures occur which affect components that are not assigned to one component group, including components belonging to different systems and even different component types. [1-3]

This paper describes recent research efforts by GRS to develop approaches for modelling and quantification of such CCFs exceeding present CCF component groups (X-CCFs) – which are also denoted cross component group CCFs – in order to assess their significance.

II. MODELLING OF COMMON CAUSE FAILURES IN A PSA

In a PSA, the unavailability of equipment is usually modelled on the component level of detail.[4] In Germany, the component boundaries include actuator (motor), electrical and I&C equipment (circuit breaker, power leads, local protective equipment, open/close limit switches, torque switches) and other support systems that can be assigned unambiguously to a specific component. This approach is widely used in other countries and international projects,[5,6] too. Operating experience is quantitatively assessed on that level of detail to estimate reliability parameters for these components including CCF probabilities.

The modelling of CCFs in a PSA is generally based on so-called CCF component groups. These groups constitute the sets of components for which a simultaneous unavailability due to a common cause is considered. CCF component groups are disjoint, i.e. each component is an element of at most one CCF component group. For each failure mode, the different possible combinations of failures of the components of a CCF component group are included as basic events in fault tree models, either explicitly or implicitly by the PSA software tools. These basic events are in most cases quantified from operating experience using CCF models, which usually are based on the assumption that all components of the group are statistically equivalent.

III. ANALYSIS OF GERMAN OPERATING EXPERIENCE

To find out whether this modeling is adequate and to develop possible approaches to improve modeling, German operating experience was analyzed based on the information in the CCF data base which GRS has developed during the last two decades.[7-10] All relevant information about CCFs and potential CCFs (i.e. events with multiple impairments of components due to a common cause but less than two actual failures) is accessible from that data base, including event reports by the utilities, characteristics of the components affected, qualitative and quantitative expert assessments of the events as well as additional information, like reports by expert organizations.[7-10]

All actual and potential CCF events in German PWRs up to the year 2002 were analyzed (847 events). In 123 of these events (14.5%), components were affected that exceed current CCF component groups as characterized above.

These X-CCFs affected most of the component types that are modeled in a PSA: pilot valves, check valves, motor operated valves, batteries, relays, breakers, pumps, transducers, emergency diesel generators, rectifiers and ventilators. Root causes include identical or similar piece parts (e.g. breakers), similar or identical materials and media, and maintenance[1, 2]

As an example, phenomena observed for emergency diesel generators (EDG), which serve as an example for a case study on the importance of modeling X-CCFs for quantitative PSA results described below, are discussed in the following. The emergency power supply system of modern German PWR units comprises eight emergency diesel generators. Four emergency diesel generators (D1) feed the 10kV emergency bus bars and four additional backup diesel generators of the backup emergency power supply system (D2) feed 380V bus bars. The D2 diesel generators have a lower nominal output, are bunkered, and can provide torque directly to the emergency feedwater pumps. They are designed to power the components of the emergency backup decay heat removal chains. In a PSA, the D1 and D2 emergency diesel generators are usually modeled as two separate component groups.

The following characteristics were found to contribute to the formation of X-CCF: While different types of engines are used within each plant, the manufacturer is often the same for both diesel groups. Due to this fact, both diesel component groups share the susceptibility to common cause failures due to similar subcomponents. Operating conditions (e.g. water chemistry) and operating and maintenance procedures are also factors that may cause X-CCFs.

The following events were observed where impairments of both D1 and D2 diesels occurred or where modifications were applied to both D1 and D2 diesels as a consequence of the event. These events also serve as basis for X-CCF quantification (see chapters VI and VII).

1. Supporting rings in the compensator used in the charging air intake of the turbochargers in one event lost some sleeves, which were sucked in and damaged the charger rotors. Both diesel groups had the same type of compensator in their turbocharger air intakes.
2. In one event corrosion in the internal cooling water system led to leakages that impaired the maximal achievable runtime. Changes in the water chemistry were required to prevent chemical environments that permit this type of corrosion. All diesel generators used the same water chemistry make-up procedures and the same material combinations in the internal water cooling water system.
3. Within two years there were several events at a plant where due to various different reasons during transients in the electrical system of the plant, signals were coupling into circuits of the protection system, leading to an inadvertent actuation of protection criteria. The diesels protection system is insofar unique among component protection systems in German nuclear plants as this protection system can shut the diesels down even while an active reactor protection system signal is demanding them to run. As corrective measure, modifications in the shielding of the affected cables were introduced.
4. During startup of the diesel, the fuel injection volume is limited. In one case the limitation was lifted based on the oil pressure instead of the revolution speed of the diesel. This led to a premature injection of the full fuel volume, which in turn led to the diesel not achieving its projected revolution speed. The diesel protection system then shut the diesel down. Both diesel groups had their startup fuel injection limitation modified.

5. In another event, the automatic diesel start-up by the reactor protection system in case of a loss of power on the safety bus bars was deactivated for all diesels for several hours due to a misinterpretation of a test instruction. However, the corresponding tests are only conducted during unit outages and not during power operation. The failure was detected before power operation commenced.

IV. POSSIBLE IMPORTANCE FOR PSA RESULTS

To assess whether a significant influence of such CCFs on quantitative PSA results is to be expected, a simple comparative study was carried out. An existing PSA was modified with respect to the modeling of emergency diesel generators.

To assess the possible importance of X-CCFs, a CCF component group comprising all eight (D1 and D2) diesels was considered. Basic events for CCFs of diesels of both groups were added to the relevant fault trees. For the initiating event "loss of offsite power", results of the previous model with two distinct CCF component groups for each group of diesels were compared with a model with only one group comprising all 8 diesels. The comparison of the quantification results showed that modeling X-CCFs may possibly have a large impact on PSA results.[1,2] Hence the necessity to further research CCFs exceeding present CCF component groups became obvious.

The approach described above is not suitable for the realistic consideration of X-CCFs in a PSA since it is overly simplistic and conservative. All CCFs are assumed to be exceeding the present CCF component groups, while in reality only a small albeit significant fraction is, as described in chapter III. Therefore, a research project has been initiated to develop methods for a more sophisticated modelling of CCFs exceeding present CCF component groups and gain deeper insight on their quantitative impact.

V. CHALLENGES TO PSA MODELING

The adequate and comprehensive consideration of common cause failures exceeding present CCF component groups poses two main challenges to PSA modeling.

Firstly, the set of components for which such CCFs need to be considered is usually partially diverse. Hence, for most component groups it is not appropriate to simply replace the current CCF component groups with a new larger group defined as a union of the current groups. This is underscored by the finding discussed above that a majority of CCF events does not exceed present CCF component groups.

Secondly, X-CCFs may potentially affect a very large number of components. For example, identical or similar breakers are part of a large number of components. In this respect, preliminary analyses showed that at least 28 similar 10 kV breakers are modeled as individual components or are part of other components in a PSA of a German PWR.

Currently, CCFs are usually included in PSA calculations by creating respective basic events, either explicitly in the fault tree model or implicitly by the PSA software. But the number of basic events n_{BE} grows with the size s of the CCF component group exponentially as

$$n_{BE} = 2^s - s - 1. \qquad (1)$$

For small groups of e.g. size $s = 4$ the $n_{BE} = 11$ basic elements can be easily handled manually and for medium sizes of e.g. $s = 10$ the resulting $n_{BE} = 1013$ basic elements can be managed using automated tools. Due to the large number of events, however, even automated analyses of PSA results, like lists of minimal cut sets or importance and sensitivity analyses, become increasingly difficult. For group sizes like $s = 28$, which corresponds to $n_{BE} > 10^8$, this approach is not feasible. PSA tools are not able to handle and analyze the corresponding models.

VI. MODELING AND QUANTIFICATION OF CCFS EXCEEDING PRESENT CCF COMPONENT GROUPS

To address the first problem, a generalization of the concept of a CCF component group was developed. According to this concept, CCF component groups are replaced by generalized CCF component groups. A generalized CCF component group comprises the components that are susceptible to specific CCF phenomena and may be treated as statistically equivalent with respect to these CCF phenomena. Generalized CCF component groups are not disjoint, i.e. a component may be an element of multiple generalized CCF component groups.

For example, for the emergency diesel generators discussed above three groups are formed: Group 1 contains the four D1 emergency diesel generators (which are identical), group 2 contains the four D2 emergency diesel generators (which are also identical, but partly diverse to the D1 diesels) and group 3 contains all eight emergency diesel generators. The group of the D1 diesels is used to include CCF phenomena that may fail the D1 diesels but not exceed this group. Similarly, the group of the D2 diesels is used to consider CCF phenomena that may fail the D2 diesels but not exceed this group. The group of all diesels is used to include CCF phenomena that simultaneously may fail both D1 and D2 diesels.

These three groups imply four categories of operating experience:

1. Operating experience regarding CCF phenomena that simultaneously may fail both D1 and D2 diesels (e.g. since the CCF phenomenon affects an identical feature of diesels of both groups).
2. Operating experience regarding CCF phenomena that may fail only D1 diesels (e.g. since the CCF phenomenon affects a feature only present at D1 diesels).
3. Operating experience regarding CCF phenomena that may fail only D2 diesels.
4. Operating experience regarding CCF phenomena that may fail both D1 and D2 diesels, but not simultaneously (e. g. since the CCF phenomenon affects a general feature present at D1 and D2 diesels, which is however diverse between the two sets of diesels, such that a simultaneous failure of diesels of both groups is very unlikely).

Obviously, to quantify CCFs exceeding present CCF component groups, operating experience of category 1 has to be used. CCFs of D1 diesels are quantified using operating experience of categories 2 and 4, while CCFs of D2 diesels are quantified using operating experience of categories 3 and 4.

The X-CCFs of diesels can be considered as basic events in the fault tree since the sizes of the generalized CCF component groups are 8 and 4, respectively. This means that 247 basic events are needed to model the X-CCFs (group 3) while 11 are needed to model CCFs of D1 diesels (group 1) and further 11 are needed to model CCFs of D2 diesels (group 2). As an example, a fault tree describing the failure of the D1 diesel of train 1 is shown in figure 1.

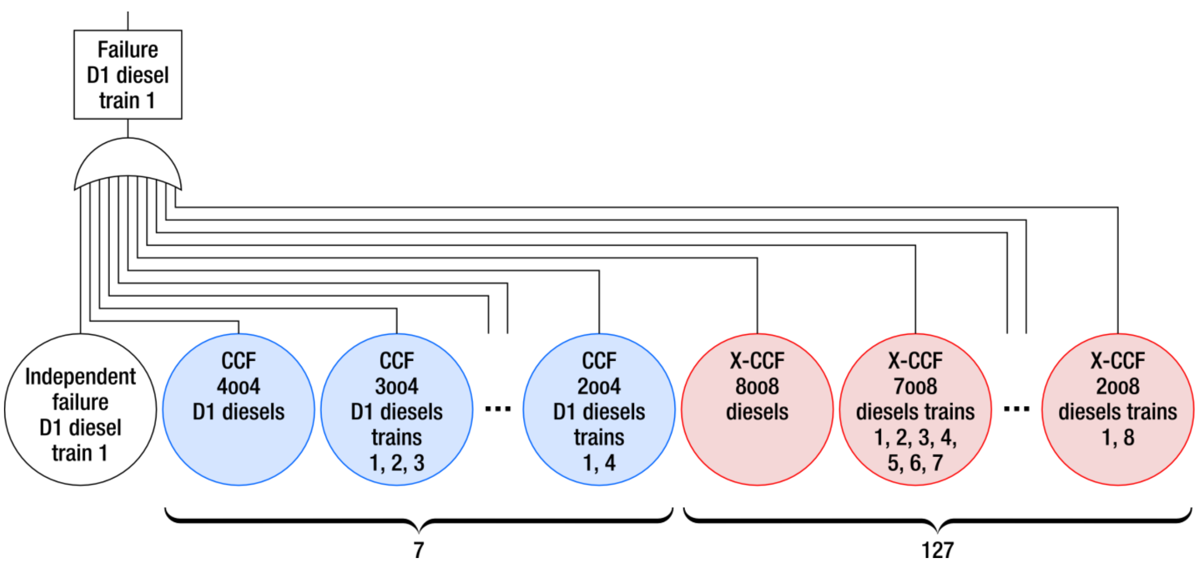

Fig. 1. Fault tree describing the failure of the D1 diesel train 1. D1 diesels are trains 1-4 while D2 diesels are trains 5-8.

To apply this approach, the basic events discussed above need to be quantified. To achieve this, the operating experience used to estimate CCF probabilities needs to be re-evaluated. For the present example, the operating experience of German NPPs up to the year 2010 was considered. Only plants and observation times were included where 2 groups of diesels were present. Three experts carried out the qualitative and quantitative assessments.

Initially, it has to be determined for each event which generalized CCF component group it should be assigned to, and the observation times of the respective groups have to be calculated. As a first step, it was investigated whether CCF events with phenomena specific to D1 or D2 diesels (categories 2 and 3) were observed. No such events were found. Therefore, it is only necessary to classify the CCF phenomena as (potentially) exceeding present CCF component groups (category 1) or not exceeding present CCF component groups (category 4). To achieve this, two different approaches were identified:

1. A phenomenon is assigned to class 1 if actual impairments were observed for both D1 and D2 diesels.
2. A phenomenon is assigned to class 1 if actual impairments were observed for both D1 and D2 diesels or if – as a consequence of the event – modifications were applied to both D1 and D2 diesels and no reasons are discernable why a simultaneous failure of both D1 and D2 diesels may be excluded.

In addition, an advanced approach was conceived which consists of identifying the respective probability that an observed phenomenon may lead to an X-CCF, utilizing expert judgements. This would mean that if p is the probability that a phenomenon present in a specific event would lead to an X-CCF, the event is assigned to category 1 with probability p and with $1 - p$ to category 4. When quantifying the basic events, all possible classifications of all events by all experts would be considered with their respective probabilistic weights. However, it was identified that in order to make quantitative expert assessments of these probabilities in a reliable and reproducible way, significant further research efforts are necessary. Therefore, this general approach has been deferred to future research projects.

Approach 1 has the advantage that no doubts can be raised that events assigned to class 1 are due to phenomena which may cause X-CCFs, since both D1 and D2 diesels have actually been affected. On the other hand, even for a phenomenon which may affect both D1 and D2 diesels (and hence should be assigned to category 1) by incidence, only diesels of one group may be affected and it is erroneously assigned to class 4. Hence, this approach would lead to a systematic underestimation of X-CCF probabilities. Therefore, for the present study we followed approach 2.

Then, for the events of class 1, the necessary quantitative assessments (impairments of the 8 diesels, applicability factor, time factor) were carried out by the three experts according to the established procedure for CCF assessments.[11]

It should be noted that for the comprehensive consideration of CCFs exceeding present CCF component groups in a PSA, two additional generalized CCF component groups regarding diesels should be considered: The first group would contain the D1 emergency diesel generators and all other components modeled in a PSA comprising similar 10 kV breakers as used as generator circuit breaker of these diesels. Similarly, the second group would include the D2 emergency backup diesel generators and all components of other types comprising similar 380V breakers. For the present study, however, these groups were not considered since only X-CCFs of diesels were included and no CCFs of diesels exceeding present CCF groups due to problems with breakers were observed.

VII. QUANTIFICATION WITH THE COUPLING MODEL

Based on this information, CCFs and X-CCFs were quantified using the CCF model of GRS, the coupling model, taking into account estimation uncertainties by using Bayesian statistical methods.[4,12] Both rates for the failure mode “failure to start” (Table I) and probabilities for the failure mode “failure to run” (Table II) were estimated.

TABLE I. X-CCF probabilities of EDG, failure mode “failure to start” (test interval 1 month, staggered testing)

Failure combination	2oo8	3oo8	4oo8	5oo8	6oo8	7oo8	8oo8
Mean	2.24E-05	2.17E-05	1.70E-05	1.14E-05	6.91E-06	3.69E-06	1.65E-06
Standard deviation	5.02E-05	3.70E-05	3.07E-05	2.29E-05	1.69E-05	1.19E-05	7.37E-06

TABLE II. X-CCF rates of EDG in 1/h, failure mode “failure to run” (test interval 1 month, staggered testing)

Failure combination	2oo8	3oo8	4oo8	5oo8	6oo8	7oo8	8oo8
Mean	7.45E-05	4.99E-05	3.00E-05	1.63E-05	7.71E-06	3.18E-06	9.20E-07
Standard deviation	1.01E-04	7.54E-05	5.38E-05	3.59E-05	2.06E-05	1.14E-05	4.08E-06

It should be noted than when considering X-CCFs, the CCF probabilities also have to be re-estimated to reflect that some CCF events are due to phenomena leading to X-CCFs and should not be included for CCF estimation. Therefore, when considering X-CCFs, the CCF rates and probabilities are generally lower (up to 33 %). The resulting CCF probabilities of EDG are shown in table III.

TABLE III. Comparison of expected CCF failure probabilities and rates of EDG (test interval 1 month, staggered testing) when considering X-CCFs and when not considering X-CCFs

	Failure combination of CCF	2oo4	3oo4	4oo4
"failure to start"	when X-CCFs considered	1.66E-04	1.12E-04	5.88E-05
	when X-CCFs not considered	1.85E-04	1.23E-04	6.25E-05
	Ratio	0.90	0.91	0.94
"failure to run" in 1/h	when X-CCFs considered	2.05E-04	1.38E-04	6.75E-05
	when X-CCFs not considered	2.84E-04	1.93E-04	1.01E-04
	Ratio	0.72	0.71	0.67

To get a first idea of the relevance of modeling X-CCFs, the probabilities that all diesels fail to remain available during a mission time of 10 h (either because they fail to start or because they fail to run) due to CCFs and/or X-CCFs were calculated. Such failure of all diesels would immediately lead to a plant hazard state[1] when the initiating event "loss of offsite power" has occurred.

When not considering X-CCFs, the most likely cause of all eight diesels to fail is the coincident occurrence of CCFs of four diesels each in both the groups of D1 and D2 diesels. The point estimate (expected value) of a 4oo4-CCF is $p_{4oo4}^{no\ ECCF*} = 1.07\mathrm{E}-03$, leading to an estimate of a probability of all diesels to be unavailable at the end of mission time of $p_{total}^{no\ ECCF*} \approx (p_{4oo4}^{no\ ECCF*})^2 = 1.14\mathrm{E}-06$. All other combinations of events are substantially less likely, since three or more events need to occur coincidently.

When considering X-CCFs, the most likely cause of all eight diesels to fail is the occurrence of a 8oo8-X-CCF with probability $p_{8oo8}^{ECCF*} = 9.31\mathrm{E}-06$, this being a factor of 8.15 larger than $p_{4oo4}^{no\ ECCF*}$. The coincident occurrence of CCF of two 4oo4-failures in the groups of D1 and D2 diesels has approximately a probability of $(p_{4oo4}^{ECCF*})^2 = 5.38\mathrm{E}-07$. Summing up those probabilities yields $p_{total}^{ECCF*} \approx p_{8oo8}^{ECCF*} + (p_{4oo4}^{ECCF*})^2 = 9{,}85\mathrm{E}-06$, which is larger than $p_{total}^{no\ ECCF*}$ by a factor of 8.62, i.e. approximately by one order of magnitude.

This suggests that the inclusion of X-CCFs would have a significant impact on PSA results. The effect is analyzed more accurately in the following chapter.

VIII. QUANTITATIVE ASSESSMENT OF THE IMPORTANCE OF CCFs EXCEEDING PRESENT CCF COMPONENT GROUPS

In order to quantitatively assess the possible influence of modeling X-CCFs on PSA results, a comparative study based on an existing PSA model of a modern German PWR with 4 D1 diesels and 4 D2 diesels was carried out. The required basic events to model X-CCFs were added to the model and quantified as outlined in chapters VI and VII. A house event allows switching on and off all basic events corresponding to X-CCFs.

The initiating event "loss of offsite power" was investigated. When X-CCFs are included the expected frequency of plant hazard states increases by a factor of 3.6.

This finding is in contrast to other studies pertaining to plants of different designs where no large contributions of X-CCFs to plant risk have been identified.[13,14] Possible future research efforts will be devoted to the question of what exact characteristics regarding operating experience and plant design determine the significance of contributions of X-CCFs.

IX. CONSIDERATION OF CCFs OF A VERY LARGE NUMBER OF COMPONENTS

[1]Hazard states are defined as plant states which lead to core damage if preventive accident management measures are unavailable or fail.

To address the second problem, the consideration of CCFs of a very large number of components, where no explicit modeling of all basic events is possible, a novel approach was developed. It is based on the idea that CCFs exceeding current CCF component groups can be thought of as a correlation of different CCF basic events (in the example discussed above, CCF basic events of D1 emergency diesel generators and CCF basic events of D2 emergency backup diesel generators). As discussed above, X-CCFs are generally less frequent than normal CCFs. Therefore, the correlations are not very strong. They principally could be accounted for in a post-processing of minimal cut set lists: Each minimal cut set containing at least two correlated CCFs is re-quantified, taking into account that the conditional probability of the additional CCF given the first CCF is larger than the unconditional probability of the additional CCF. These conditional probabilities need to be estimated from operating experience. In the diesel example, for cut sets containing CCFs of D1 diesel basic events, the unconditional probabilities of CCFs of D2 diesels would be replaced by the respective conditional probabilities of CCFs of D2 diesels, given a CCF of D1 diesels. For practical applications, the number of minimal cut sets is too large to be considered completely and cut-off criteria need to be applied by PSA software tools which generally depend on the unconditional probabilities.[15] Hence, the problem may arise that relevant cut sets are disregarded. Future research will be devoted to the assessment of the relevance of this problem and a possible development of strategies for solving it.

X. CONCLUSIONS

A detailed analysis of German operating experience showed that common cause failure events in many cases affected components that in PSA modeling do not belong to one CCF component group. Hence, they are presently not modeled adequately in PSAs. This applies to a large number of different component types, e.g. pilot valves and other valves, batteries, relays, breakers, transducers, diesel generators and ventilators. In total, approximately 15% of all observed CCF phenomena exceeded CCF component groups as defined in present PSA studies.

To address the importance of X-CCFs in more detail, emergency diesel generators were considered. A PSA model of a modern German PWR was modified such that X-CCFs of diesels are included as additional basic events. These basic events were quantified from German operating experience, using a newly developed procedure. A quantitative analysis of the initiating event “loss of offsite power” has shown that including X-CCFs of diesel generators increases the expected frequency of plant hazard states by a factor of 3.5. Therefore, additional research efforts are planned to further investigate CCFs exceeding present CCF component groups. This includes the consideration of X-CCFs that may affect very large numbers of components, e.g. breakers. A novel approach to achieve this was developed.

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