Assessing Combinations of Hazards in a Probabilistic Safety Analysis

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Guidance on how to systematically address combination of hazards in the PSA context is scarce. As, a combination of hazards can be seen as a new single hazard, in principle it can be treated in the same way as a traditional single hazard. This paper proposes a framework for the systematic assessment of combinations of hazards. The proposed framework uses three steps; identification of hazards to be considered, determining dependency in a combination, and screening of the combinations, using the single hazards screening results. For identification, the results of the single hazard screening can be used after reconsideration of hazards screened out based on quantifiable grounds (e.g. within design base), and hazards screened out based on the frequency of the consequence. Next, it is assessed if a combination has some form of dependency. If there is a dependency, the same independent combination is enveloped and disregarded. If there is no dependency at all, the dependent combination is non-existent and disregarded. Lastly combinations are screened on their possible impact on the plant compared to the single hazards.

Keywords: PRA, Hazard Combinations, PSA

Introduction

Since the Fukushima accident, the robustness of the design of NPP against the threats caused by external hazards has been a focal point of studies and reports (IAEA, 2015; WENRA RHWG, 2015; WENRA RHWG, 2013; Kumar, et al., 2017). In these studies the importance of combinations of (external) hazards is emphasized. Although this recent emphasis on (combinations of) hazards seems to indicate that hazards are something new in Probabilistic Safety Analysis (PSA), this is not the case. Hazards have been an integral part of a PSA since the first PSA; Wash 1400 (NUREG, 1975) already considered external hazards.

That combinations of hazards need consideration is already recognized in 1995 through IAEA 50-P-7 (IAEA, 1995), a predecessor of SSG-3 (IAEA, 2010), the most recent IAEA guide for PSA. ASME-ANS also mentions combinations of hazards in its 2008 version (ASME-ANS, 2008), although rather limited. Guidance on how to systematically assess which combination of hazards need consideration in the PSA context is however scarce.

In general, guidance on combined hazards only involves natural (thus external) hazards. However, combinations of natural hazards and human-induced hazards are also possible and cannot be excluded a priori. This paper proposes a framework to assess all combinations of hazards using the identification and screening results of the single hazards analysis. A methodology which allows for a straight-forward and efficient evaluation of combinations of internal and external hazards in a PSA. The framework is used to identify combinations of hazards to include in the PSA of the High Flux Reactor (HFR) in Petten.

Background

Combined hazard impact

A combination of hazards does not need to occur at the exact same time. Rather, a combination of hazards should be seen as a hazard occurring while the plant has not yet recovered from the first hazard.

Following the occurrence of a hazardous event, the state of the plant may be compromised due to a potential unavailability of Structures, Systems and Components (SSC). These SSCs provide fundamental safety functions to the plant, and their potential unavailability must be taken into account in the assessment of hazard combinations. In case a combination of hazards occurs, the list of SSCs unavailable due to the combined hazards is at least the combination of the SSCs unavailable due to the different single hazards. A combination of hazards could also result in an increased load on SSCs, shifting the fragility curves and increasing the number of unavailable SSCs or the failure rates of SSCs.

At present, there is very little guidance on the assessment of combinations of hazards in PSA – the most detailed reference found to date is the SKI Report 02:27 (Knochenhauer, 2003). However, as this report deals solely with external hazards, no guidance is given on how to evaluate combinations including internal hazards.

Inclusion of internal hazards directly leads to the need to also consider independent combinations. Internal hazardous events generally have a relative high frequency of occurrence compared to external events. Therefore, exclusion of hazards occurring by coincidence based on their individual frequency of occurrence cannot be done upfront. This especially true when considering a combination of internal hazards.

For a consistent treatment of hazards in a PSA, the inclusion of combination of hazards should follow the same methodology that has been used for the assessment of individual hazards; i.e. identification, screening, bounding assessment, detailed analysis and PSA modelling. Of these five steps, the first two steps receive attention to make them suitable for combinations of hazards. Thus, in order to evaluate which combinations of hazards need consideration in a PSA, a framework for identification and the screening needs to be established.

Identifying combinations

The general approach, used for the identification of a realistic set of hazard combinations, is based on a systematic check of the dependencies between all hazards. In principle, the combinations of hazards generally considered are based on the following (IAEA, 2010):

1. Hazards have the potential to occur under the same conditions and at the same time (e.g. high winds and (snow) precipitation): *correlated hazards*;
2. External hazards can induce other external hazards (e.g. seismically induced tsunami): *consequential hazards*;
3. External hazards can induce internal hazards (e.g. seismically induced internal fires or floods): *consequential hazards*;
4. One internal hazard can induce other internal hazards (e.g. internal floods induced by internal missiles): *consequential hazards*;
5. Internal hazards can induce external hazards (e.g. external explosion induced by a steam turbine rupture): *consequential hazards*;
6. Hazards coincide by coincidence: *independent hazards*.

Correlated and consequential hazards are those hazards for which a simultaneous occurrence is more likely than could be expected based on the combined frequencies of the single hazards. There is some form of dependency between the hazards. Therefore, in this paper, correlated and consequential hazards are grouped as dependent hazards.

Dependent and independent combinations

While all combinations can always be the result of independent hazardous events, just a number of combined hazards will show dependency. Dependent and independent combinations of hazards are not mutually exclusive as in principle all dependent combinations of hazards can also coincide by chance. An example for this is the internal fire hazard. Fires in adjacent rooms can arise by chance within a certain time window (independent), but also by collapse of the wall between the two rooms (dependent). The impact on the plant of the independent combination is equal to the impact of the same dependent combination. Therefore, the frequency will be the discerning factor.

Dependent hazards are those for which a simultaneous occurrence, within a restricted time frame, is more likely than could be expected based on the combined frequencies of the single hazards. Therefore, by definition, the dependent frequency will be higher than the independent frequency of the same combination. As a result, the independent combination is enveloped by the same dependent combination; the impact is the same, but with a lower frequency. If the dependent combination is screened out, the independent combination can also be screened out. If the dependent combination is screened in, there is no need to assess the combination as independent, as it is enveloped by the dependent combination.

As a basis, all combinations of hazards should be evaluated both as a dependent and as an independent combination. However, by assessing the dependency of a combination one can reduce the amount of evaluations. If there is a dependency, the independent combination can be disregarded, because the same dependent combination is enveloping. If there is no dependency at all, the dependent combination is non-existent and can be disregarded as such. The combination should then only be assessed as an independent combination.

For some hazards determining dependency is complex as they consist of multiple initiating events. This is especially common for internal hazards. It is possible that for some scenarios in a combination of hazards a dependency exists, while others are considered independent. It is therefore possible that a combination of hazards is regarded as partially dependent, and partially independent. During the screening process it should be specified which scenario is being assessed.

The actual assessment of dependency of a combination is done on qualitative grounds. A guide like ASAMPSA_E D21.2 (Decker, 2016) or engineering judgement can be used to determine dependency. A question like ‘is it conceivable that hazard A causes, results in, or coincides with hazard B’ is often sufficient to identify a dependency. Whenever documentation or research is available on the dependency between two events it should be used.

Screening framework

The proposed framework for assessment of combinations of hazards is shown in Figure 1. It uses three steps; identification of hazards to be considered, determining dependency of the combinations, and screening of the combinations. The methodology is tailored to build on the results of the single hazard assessment.

Identification of hazard combinations

From an analytical point of view, a combination of two hazards does not differ significantly from a single hazard. In both cases, it is a threat with possible consequences on the plant safety. These consequences comprise the whole spectrum from “no impact” to “direct core damage”. Therefore, the screening criteria used for single hazards can also be used for combinations. However, this does not mean that the screening results of the single hazards assessment can be copied blindly.

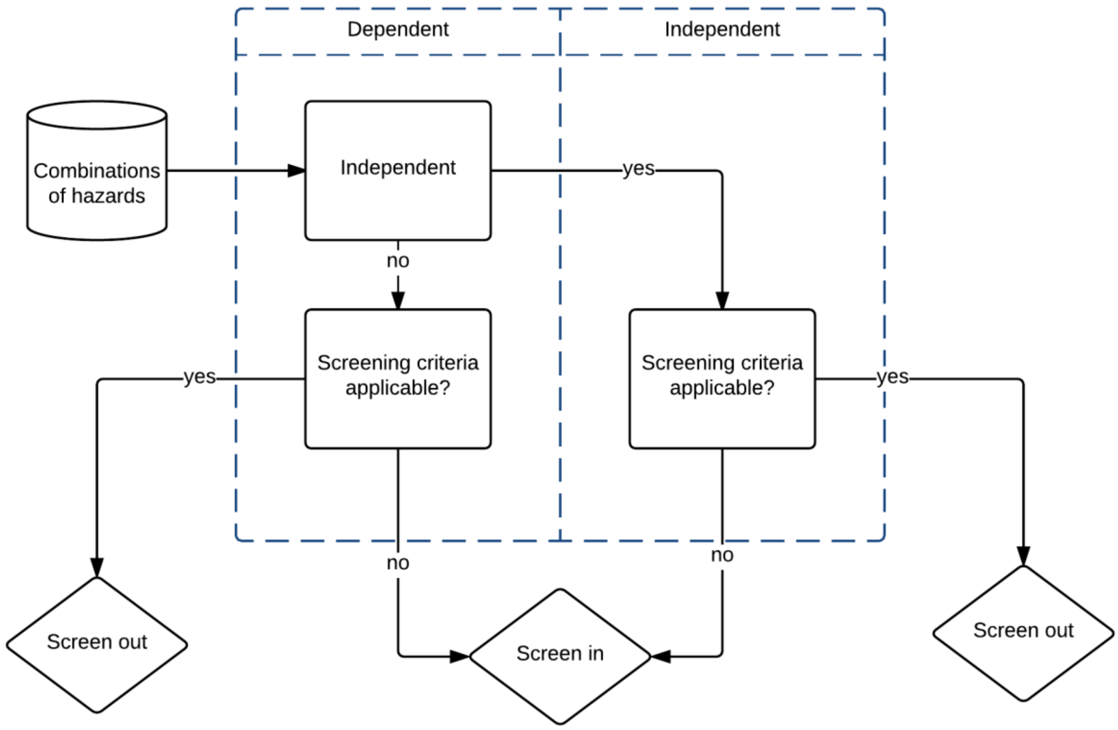

Figure 1. Schematic Framework for Assessing Combinations of Hazards

The list of hazards screened in by the single hazard assessment can be used as a starting point, and should be complemented with hazards screened out on quantitative grounds. As a single hazard these might have a negligible impact on reactor safety, and could be screened out. However, in combination with another hazard their impact might just tip the scale.

Qualitative screening process

In the qualitative screening process the only (semi)quantitative criterion is that hazards that are "within design base" may be screened out. These hazard can be screened out because the plant is designed to handle the maximum magnitude of the hazard applicable for the site. However, in a combination with another hazard these hazards should be reconsidered.

For example, the maximum impact load of a falling container on a structure is known. If the structure can handle such a falling load, a container drop is within design base and screened out as a single hazard. Yet, in combination with an extreme wind event the total load on the structure could increase to a level that a container drop cannot be handled. Consequently, the combination is not within design base.

Therefore, hazards screened out, in the single hazard qualitative screening process, using the criterion within design base should be reconsidered for inclusion when evaluating combinations of hazards, unless the load is equal to zero.

Quantitiative screening process

Reconsideration of single hazards screened out in the quantitative screening process depends entirely on the screening criterion used. In general, two criteria can be distinguished; the initiating event frequency, and the consequence frequency (in general core damage).

The frequency of a combination cannot be higher than the lowest frequency of the hazards in the combination. If the single hazard screening has been done on the initiating event frequency, the hazards that are screened out do not have to be reconsidered in the combination analysis. Screening on initiating event frequency is only done when the consequences are unimportant and could be direct core damage without significant impact on the Core Damage Frequency (CDF).

On the other hand, a single hazard screened out on the consequence frequency should be re-assessed in the combination analysis. The hazards in a combination may affect different SCCs, and the consequence frequency of this combination may be above the screening value.

Hazards to consider

Effectively, the starting point of hazard combination analysis is a list of all the single hazards that are retained for detailed analysis after the individual screening process. This list needs to be expanded with the hazards screened out on the qualitative criterion "within design base", and the hazards screened out on the quantitative criterion "consequence frequency".

Screening criteria

For the actual screening the criteria from the SKI report (Knochenhauer, 2003) are adopted in a slightly modified form as three Hazard Combination Criteria (HCC). A combination of hazards can be screened out, if;

HCC1: The combination is included in the definition or analysis of another event, which is already analysed for the plant, or;

HCC2: The impact on front line systems of the hazard combination is equal to the impact of one of the single hazards in the combination, or;

HCC3: The frequency (initiating event or consequence) is lower than the screening value.

The criteria are applicable for both dependent and independent combinations of hazards. As long as there is at least one screening criterion valid, a combination can be screened out.

Criterion HCC1

Criterion HCC1 screens on possible rework. If a combination of hazards is included in the definition or analysis of another event, that is already analysed for the plant, the combination can be screened out.

In conjunction with this criterion, it is recognized that generally correlated and consequential hazards are part of the single hazard scenario development. In case of High Energy Line Break (HELB) for instance; missiles, blast, jet impingement, steam flooding and pipe whip are hazards that are considered when assessing the possible consequences.

Criterion HCC2

Criterion HCC2 screens on the impact on the safety functions. Combinations of hazards by definition have a lower frequency than the least frequent of the individual hazards involved. A combination can therefore be screened out if the impact of the combination on the front line systems (safety functions) is equal to the impact from one of the single hazards in the combination.

In other word; if the available front line systems needed to mitigate the effects of the first hazard (the mitigation path) is not affected by the effects of the second hazard, than the combination can be screened out. Therefore, to be able to use criterion HCC2 efficiently the single hazards PSA should be available. This implies also the availability of the internal events PSA, as this is the basis of the hazards PSA. The impact assessments are based on the findings in the Accident Sequence Analysis report.

In case of direct consequence scenarios, where there is no mitigation whatsoever between the hazardous initiating event and the consequence, it will be clear that there is no need to assess combinations as screening criterion HCC2 is always applicable.

Criterion HCC3

Criterion HCC3 screens on frequency. It is suggested to use the same criterion and screening value as used for the single hazard screening. This can be the initiating event frequency, while assuming direct core damage, or the consequence frequency. A combination of hazards with a lower frequency than the screening value is screened out.

Screening order

The order in which to apply the screening criteria is not important and will not influence the outcome. However, as determining the degree of dependency between the hazards requires a lot of effort, in general it is most efficient to screen dependent hazards first on HCC1 and HCC2 before screening on HCC3. This way, there is no need to know the exact dependency between the combination of hazards. Only if screening on these two criteria is not possible the dependency degree is needed.

For independent combinations, it is advisable to first attempt screening using criterion HCC3. Most frequencies of the single hazards are already known. The frequency of a combined hazard is therefore straightforward.

Screening on frequency; HCC3

In order to use screening criterion HCC3 the probability of hazard B given the manifestation of hazard A (P(B|A)) needs to be established. For independent combinations this probability equals to the frequency of hazard B (F(B)) multiplied with the time (TA), given in hours, necessary to restore the safety level of the plant to its normal level, e.g. to mitigate the effects of hazard A, in other words the time needed to restore the plant to its original safety level. The formula for screening a combination of hazards on frequency can be written as;

$$F(A) \cdot \left(F(B) \cdot \frac{T_A}{8760}\right) < F_{scr} \qquad [1]$$

For screening on consequences direct core damage is assumed for each combination of hazards. In the case when direct core damage was already assumed for a single hazard of a combination, HCC2 is already applicable. Taking this into account, for independent combinations P(B|A) = P(B).

However, consideration of the combination is only relevant when hazard B occurs when the plant is still affected by the consequences of hazard A. Therefore for screening of independent combinations the probability of hazard B is bound by the duration that hazard A affects the plant; timeframe TA.

For dependent combinations the specific conditional probability (P(B|A)) needs to be established, for instance through data analysis. The formula for screening is;

$$F(A) \cdot P(B|A) < F_{scr} \qquad [2]$$

When determining this conditional probability, one needs to take into account that the frequency of occurrence of the combination cannot be higher than the lowest frequency of the two hazards in the combination. For instance, hazard A has a frequency of 10^{-3}/y and hazard B a frequency of 10^{-5}/y. The conditional probability of B, given A, has a maximum value of 0.01 (e.g. 10^{-3}/y * 0.01 = 10^{-5}/y). A higher conditional probability would after all lead to a yearly frequency of the combination that has a higher value than that of hazard B itself.

For some combinations, conservative screening with direct core damage as a consequence will not be sufficient. To get a more accurate assessment, the conditional core damage probability (CCDP), given the occurrence of the hazard combination, can be determined. Each combination could be analysed in depth in order to find a specific CCDP, or an indicative existing single event CCDP can be used. When incorporating the CCDP the screening formula for dependent combinations will become;

$$F(A) \cdot \left(F(B) \cdot \frac{T_A}{8760}\right) \cdot CCDP < F_{scr} \qquad [3]$$

or, for independent combinations;

$$F(A) \cdot P(B|A) \cdot CCDP < F_{scr} \qquad [4]$$

An indicative CCDP can be calculated using the internal events part of PSA model.

Application

Hazards to consider

The screening methodology is applied in the PSA for the Hoge Flux Reactor (HFR) in Petten, the Netherlands. In the single hazard screening process, six hazards are screened in. After revisiting the screening process two previously screened out hazards, that were screened out based on being within design base, are added to the list. These are extreme rain and extreme snow. Making a total of eight identified hazards to consider in the combination of hazards analysis.

Determining dependency

All possible combinations of hazards are evaluated pairwise. This means A followed by B, B followed by A, A followed by A, and B followed by B, as shown in Table 1. Each combination is assessed if, and in which way, the combination is dependent or not. Mind the direction of the dependency. For example, there is a correlation between internal flooding (A) and strong wind (B) but this is covered in the reversed combination (B-A). Dependency in this case (A-B) would mean that the occurrence of internal flooding would influence the probability of a strong wind event. This is not possible, and therefore this specific combination is considered independent.

Table 1. Overview of the dependency of the hazard combinations; dependent (o), independent (x), or partially dependent and partially independent (+)

Hazard name	**Hazard ID B A**	**I1**	**I2**	**I5**	**A1**	**A6**	**A7**	**W3**	**M20**
Internal flooding	**I1**	o	+	x	x	x	x	x	x
Internal fire	**I2**	+	+	+	x	x	x	x	x
Dropped or impacting loads	**I5**	x	x	x	x	x	x	x	x
Strong wind	**A1**	o	+	x	o	o	o	o	o
Extreme rain	**A6**	x	x	x	x	o	o	o	o
Extreme snow	**A7**	x	x	x	x	o	o	o	o
High water level	**W3**	o	o	x	x	x	x	o	x
Aircraft crash	**M20**	+	+	+	x	x	x	x	x

Screening dependent combinations

Due to rather conservative assumptions in the single hazard analysis all identified dependent combinations are screened out using screening criteria HCC1 and HCC2. For combinations that were found to be partially dependent and partially independent, HCC1 was found to be applicable for the dependent combination scenarios. All relevant hazard combination scenarios were already included in the single hazard analysis.

When either of the hazards in the combination would result in direct core damage, HCC2 is applicable. The consequences of the combination cannot be more severe, and the frequency of a combination is always less than that of the single hazard resulting in direct core damage. In theory the frequency of the combination can be equal to that of the single hazard. However this would not change the screening results as this would indicate that the combination has been taken into account in determining the frequency of the hazard.

Screening independent combinations

Independent combinations with hazards previously screened out as within design base cannot directly be screened on frequency (HCC3), because the frequency of occurrence has never been determined in the single hazard analysis. Combinations including these hazards were screened using HCC1 and HCC2 and could be screened out.

All other independent combinations have been screened on frequency (HCC3), assuming direct core damage, using equation [1]. The screening value used is a CDF of 10^{-9} per year. As the recovery time differs between hazards, an initial conservative recovery time of one week (168 hours) is assumed for all hazards. For hazards with multiple initiators, the highest initiator frequency was used for the whole hazard. This bounding assessment led to the screening of all, but nine, combinations. These nine remaining independent combinations were assessed in more detail.

Three of the nine combinations included a heavy load drop, or a combination of two heavy load drops. A heavy load drop is modelled in such a way that this would either lead to direct core damage, or no damage at all. In both cases the consequences of the combination were equal to one of the hazards in the combination, thus HCC2 is applicable.

The impact of the final six combinations is compared to that of a large loss of containment (LOCA). It is concluded that a large LOCA has more severe consequences than either combination. Therefore the CCDP of a large LOCA is used as a benchmark for the CCDP of the six combinations of hazards. Using this CCDP in equation [4] all combination can be screened out.

Overview

Using the proposed screening methodology all identified combinations of hazards in the PSA of the HFR are screened out. The results of the screening are shown in Table 2.

Table 2. Overview of applicable screening criteria for the HFR. The numbers shows the HCC that is applicable. The left columns show results for dependent combinations, right columns for independent combinations.

Hazard ID B A	**I1**		**I2**		**I5**		**A1**		**A6**		**A7**		**W3**		**M20**	
I1	2	n/a	2	1	n/a	1	n/a	1	n/a	2	n/a	2	n/a	1	n/a	1
I2	2	1	3	1	3	1	n/a	1	n/a	2	n/a	2	n/a	1	n/a	1
I5	n/a	2	n/a	2	n/a	2	n/a	1	n/a	2	n/a	2	n/a	1	n/a	1
A1	2	n/a	2	1	n/a	1	2	n/a	n/a	2	n/a	2	2	n/a	3	n/a
A6	n/a	2	n/a	2	n/a	2	n/a	2	3	n/a	3	n/a	n/a	2	3	n/a
A7	n/a	2	n/a	2	n/a	2	n/a	2	3	n/a	3	n/a	n/a	2	3	n/a
W3	3	n/a	2	n/a	n/a	1	n/a	1	n/a	2	n/a	2	2	n/a	n/a	1
M20	2	1	2	1	2	1	n/a	1	n/a	2	n/a	2	n/a	1	n/a	1

Conclusions

We have developed a practical methodology to identify and screen all combinations of hazards in a PSA. This includes all possible combinations of internal and external hazards. The methodology uses three steps; identification of hazards to be considered, determining dependency of the combinations, and screening of the combinations.

For identification, the results of the single hazard screening can be used. Hazards screened out based on quantifiable grounds (e.g. within design base), and hazards screened out based on the frequency of the consequence should be reconsidered as their consequences in a combination may be more severe.

To reduce rework, all combinations assessed if they have some form of dependency. If there is a dependency, the same independent combination is enveloped and disregarded. If there is no dependency at all, the dependent combination is non-existent and disregarded. Thus each combination only needs to be screened once. Whether a combination is dependent or independent determines the most practical way to screen the combination.

Three screening criteria can be applied for screening combinations of hazards; HCC1 - the combination is included in the definition or analysis of another event, which is already analysed for the plant; HCC2 - the impact on front line systems of the hazard combination is equal to the impact of one of the single hazards in the combination; HCC3 - the frequency is lower than the screening value.

To reduce the work for the analyst, it is suggested to screen dependent combinations using HCC1 and HCC2 first. HCC3 requires some effort to apply. For independent combinations it is suggested to use HCC3 first in the screening.

The methodology was successfully implemented in de PSA of the High Flux Reactor, in Petten, the Netherlands. A total of eight hazards were identified, out of which two previously screened out as single hazards. Using the screening methodology, and thanks to rather conservative assumptions in the single hazard analysis, all identified combinations of hazards have been screened out.

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