Consideration of Long-Lasting External Flooding Within PSA – Modelling Supplementary Emergency Measures

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Abstract: A methodological approach has been developed to adequately consider supplementary emergency measures in long-lasting hazard events within Level 1 probabilistic safety analysis (PSA*). Those measures are established in the short-term using the available time during long-lasing events and have not been planned in advance. The methodology has been applied to a riverine flooding event of an exemplary nuclear power plant (NPP) site in Germany. In this context, two assumptions have been made: the site will not be accessible by road or rail, and there will be a consequential complete loss of offsite power. Consequently, the operation of the emergency diesel generators over a period exceeding seven days at maximum and a permanent exchange of the shift personnel are needed.

Two supplementary emergency measures ensuring the supply of the plant with fuel and shift personnel have been analysed in detail. The supply is ensured via a ferry service using amphibious vehicles or with helicopter transport. These measures have been implemented and quantified in an existing Level 1 PSA model of the reference NPP, taking into account the event-specific boundary conditions. The quantification revealed that ensuring the shift exchange provides a significantly higher contribution to the success of the mitigation measures than ensuring the fuel supply.

This paper presents the results of the methodological enhancements and extensions as well as its application to an exemplary NPP site in Germany.

1. INTRODUCTION

Some events in the recent past, particularly the nuclear accidents at the Fukushima Daiichi nuclear power plant (NPP) resulting from the impact of a hazard combination, have revealed the relevance of long-lasting events within probabilistic safety analysis (PSA). Consequently, the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH has developed a methodological approach [1] for considering long-lasting event sequences within Level 1 PSA. This activity was part of a recently completed comprehensive research and development project sponsored by the Federal German Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).

In general, long-lasting event sequences can impair the safety of a NPP in different ways. First, the failure rates may increase because of the prolonged time of the demand of certain safety systems, such as the emergency diesel generators. Second, the possibility for recovery of system functions increases with more time being available for the recovery. Third, measures established in the short-term to prevent harm from the NPP, which have not been planned in advance, may be carried out because sufficient time is available. They have been observed in the long-lasting accident sequences at Fukushima Daiichi, where the power supply of some systems was established using automobile (bus) batteries [2]. Such measures are different to common recoveries (point 2), which are usually well-known (knowledge based) by the personnel. The first two aspects have already been considered within PSA,

* In this paper, consistent with usage across various countries, the abbreviations PSA (Probabilistic Safety Analysis) and PRA (Probabilistic Risk Assessment) are used interchangeably.

e.g. [3], while the third one has so far been rarely considered. This revealed the need for focusing on so-called ‘supplementary emergency measures’ (SEMs) during long-lasting event sequences.

In this line, first, possible single and combined hazards which may result in event sequences of longer durations have been identified for an exemplary NPP site in Germany using the GRS Hazards Screening Tool HST [4]. Second, GRS has developed a methodological approach for considering SEMs in such long-lasting event sequences. One possible scenario analyzed was a long-lasting external flooding scenario with loss of offsite power (LOOP), for which these SEMs were included in the already existing Level 1 PSA plant model of the reference NPP. The SEMs are based on two principles: first, a long-lasting event allows the planning of additional measures which have not been planned in advance, and second, the SEMs are not specific to the reference NPP but more or less generic and for this reason also applicable to other NPP sites in Germany and abroad with similar structures and background means.

For the analysis, pessimistic assumptions such as a flood duration of up to 18 days have been made. During the assumed external flooding scenario, the plant will not be accessible by road and there will be a complete LOOP. As a result, there is a need for operation of the emergency diesel generators over a long period requiring a supply with external diesel fuel as well as a regular exchange of the shift personnel to prevent increased human error probabilities (HEPs) in the event of prolonged shift durations. To continuously ensure such a regular exchange of shift personnel and the permanent operation of the emergency diesel generators over the entire flooding duration, two SEMs for ensuring the supply of the plant with personnel and fuel have been considered within the PSA, a ferry service with amphibious vehicles and an air transport by helicopters. The unavailability of these SEMs has also been determined, taking the postulated scenario-specific boundary conditions and plant operational states into account.

This paper is structured as follows: Section 2 describes the methodology starting with the scenario to establish the boundary conditions. Moreover, the SEMs and their implementation in the Level 1 PSA plant model are presented. Section 3 provides the results of the extended Level 1 PSA plant model with a discussion of the assumptions made. Finally, some conclusions and a brief outlook are presented in Section 4.

2. METHODOLOGY

The SEMs were developed for a long-lasting flooding scenario (Section 2.1). During this scenario, particular resources of fuel and shift personnel are required (Section 2.2). To provide these resources, the SEMs were defined, and their availability quantified (Section 2.3, Section 2.4). Finally, the available Level 1 PSA plant model of the reference NPP was adapted for considering long-lasting event sequences and SEMs (Section 2.5).

2.1. Scenario Description

The reference NPP site in Germany shown in Figure 1 is a riverine site with two reactor units, one in commercial operation, the other under decommissioning. During normal operation, the power supply is provided by a double connection to the external grid via a 400 kV switchyard. In the event of the unavailability of the switchyard, the power supply is ensured via a 110 kV standby electric supply with a standby transformer.

The scenario assumed is the long-lasting external riverine flooding with durations of up to 18 days. In detail, the flood durations are assumed to be cf. [1]: longer than 3 days with 45 %; longer than 6 days with 5% and longer than 9 days with 1 %. The flood results e.g., from a combination of extreme precipitation and melting snow. It is assumed to reach a water level slightly below the protection line of the buildings important to safety which has never been observed before at the given NPP site. Such an event combination of correlated hazards is infrequent. However, it was postulated for the PSA model extension without taking the occurrence frequency into account.

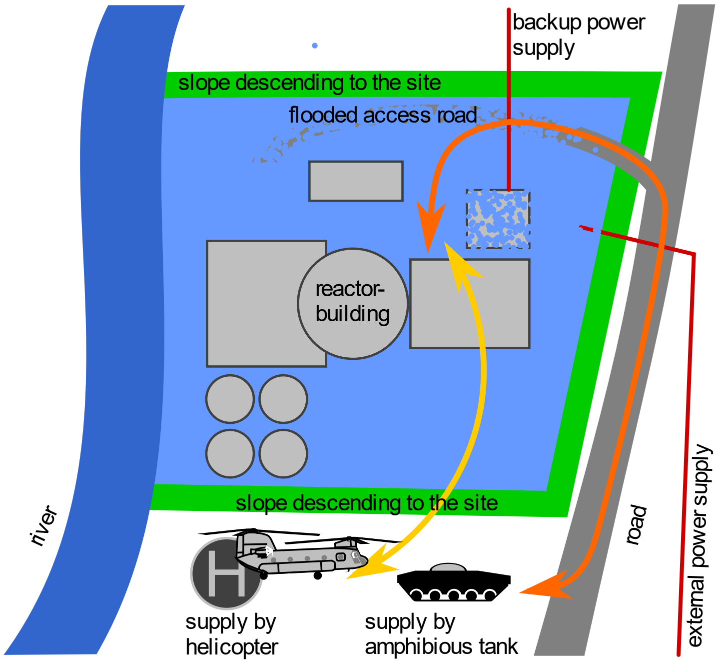

Figure 1: Schematic Representation of the NPP With Fuel Supply and Shift Personnel Exchange Via Supplementary Emergency Measures During the Long-lasting Flooding and LOOP

The plant is permanently protected against external flooding for water levels with expected frequencies of 1 E-03 /a. For higher flood water levels, temporary flood protection measures are foreseen for some buildings since the site becomes submerged. Large bulkheads are permanently installed at all four redundant trains of the emergency diesel building important to safety. At the building entrance portable flood barriers are installed well before submergence of the site. The turbine building is not protected by mobile flood protection equipment. Therefore, if the submergence level, namely the water level above the 'zero level' of the site, exceeds 0.32 m submergence of the reactor unit starts in this building. Turbine building submergence causes at least a loss of the main feedwater pumps, of the shutdown pumps and of the main condensate pumps resulting in the transients 'loss of main feedwater' and 'loss of main heat sink'.

The event sequence assumed here starts as soon as the water level reaches the submergence level of 0.16 m with all flood protection systems properly installed before submergence. At this level, first NPP systems are assumed to be deteriorated and a LOOP can occur consequential to the flood. Moreover, it is pessimistically postulated that the plant operational state is 'subcritical, hot'. These assumptions are in line with approaches in other flooding PSAs.

The development of the submergence water level is shown in Figure 2. As stated above, the flood duration may reach 18 days but is modelled probabilistically. To characterize the evet sequence independently from the random flood duration, times in this paper are presented in a relative manner. In detail, the relative time is the time passed after the submergence level reached 0.16 m divided by the random flood duration. Hence, the event sequence starts at the relative time 0 with a submergence level of 0.16 m and the flood decreases again to 0.16 m at the relative time 1. The sequence ends if either a safe plant state is reached or core damage occurs, independent of the end of the flooding itself.

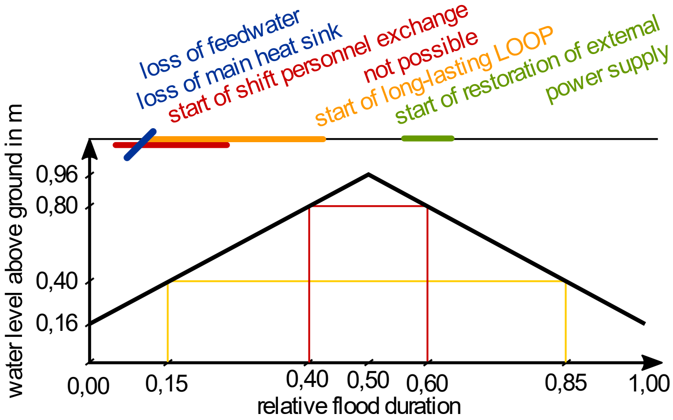

Figure 2: Submergence Water Level Development Over the Relative Flood Duration

The event sequence assumed in this study is subdivided into the following three phases:

- Phase 1: The water level rises between the relative times t = 0.0 with a submergence water level of 0.16 m and t = 0.4 with a level of 0.60 m above the zero level of the NPP. The use of vehicles is widely limited. Accessibility of buildings with items important to safety by foot is also difficult but in principle possible if necessary. However, an exchange of shift personnel can no longer be assured due to the limited accessibility starting at the random relative time point U(0.05;0.25). The assumed uniform distribution U reflects uncertainties during the flooding around the mean value 0.15 (submergence level of 0.40 m). A shift personnel exchange is necessary after a random shift duration U(12;48) h. Otherwise, an increase of the HEPs during operator actions is expected. The prolongated shift duration of up to 48 h considers that recreation phases of the shift personnel are temporarily possible even without exchange of personnel. The crisis team located outside the flooded area around the site initiates the SEMs early at a random relative time of U(0.0;0.2).
- Phase 2: The phase starts at the relative time t = 0.4 at a submergence water level of 0.80 m, reaches a maximum level of 0.96 m at t = 0.5 and ends at t = 0.6 with a level of again 0.80 m. In this phase, the water nearly reaches the protection line of buildings important to safety. Movements of persons and vehicles outside the flood protected buildings are significantly limited. External fuel supply by common vehicles is no longer possible.
- Phase 3: The water level decreases during this phase. It lasts until the submergence level reaches 0.16 m at t = 1.0. The limitations are the same as in phase 1. Namely, some vehicles able to cope with water levels of 0.80 m can access the site. Starting at a random relative time of U(0.75;0.95) (around the submergence level 0.40 m) a full accessibility of the site and its buildings is possible again. Restoration work on the external power supply can be started at a random relative time U(0,55;0,65). The availability of the offsite power supply has the highest priority, the restoration duration is assumed with a random non-relative time of U(0;3) days. This distribution covers also negligible repair durations in case of very small damages. After completion of the restoration, the operation of the emergency power supply including its supply with fuel is no longer needed.

2.2. Resources Required at the Site During the Long-lasting Scenario

During the flooding scenario, all tasks needed to be carried out in the operation of the NPP, in the event of incidents or accidents, and for conducting emergency measures must be possible. For this purpose, a minimum number of shift personnel of 13 persons plus 5 persons in the main control rooms (MCRs) of both reactor units are needed according to the plant operating manual. In addition, 50 persons for the onsite fire brigade need to be present. Plant personnel for security services and for administration must be considered as well due to the long duration of the event. For these duties in both units, 40 to 70 persons are needed. In principle, the shift personnel required during the whole flooding event can be completely ensured by the available NPP staff. Summing up, approximately 105 to 135 persons are needed on-site per shift and must be exchanged every 12 hours to prevent extended shift durations leading to increased HEPs in case of human actions.

The power supply is assured via the emergency power supply 1 in the event of an external flooding and a consequential LOOP. For this purpose, enough diesel fuel is stored on-site for common LOOP durations. In case of a longer lasting LOOP the following procedure has been postulated: Two of four generators will be taken out of operation early, resulting in a reduction of the fuel consumption which approximately leads to a duplication of the operating time. Additionally, fuel for the emergency power supply 2 may be used in case of long-lasting LOOPs. With these measures, the emergency power supply 1 can be operated over a total period of nearly 7 days. Based on this information, it is assumed that additional fuel for the emergency power supply is needed from a time point of U(3;7) d. The minimum value was chosen referring to German regulatory guidance. Afterwards, a fuel amount of approximately 4 t per hour is required for the continuous operation of the emergency power supply.

2.3. Supplementary Emergency Measures for Supply with Fuel and Shift Personnel Exchange

The assumed flooding event does not only affect the NPP site under consideration site but also a much larger area. In that area, no other NPPs are affected. However, other industrial installations and critical infrastructures maybe threatened and have to be protected from the flood. It is nevertheless assumed that priority will be given to the protection of the NPP site by the German authorities in charge. This assumption is supported by the experiences from the events at Fukushima Daiichi.

In Germany, regional professional fire brigades and the German Federal Agency for Technical Relief provide support for intervention and taking mitigative measures in case of larger flooding events. It is assumed that they will also cope with the above-mentioned threats during the assumed flooding event. Additionally, the German military may assist. But since the flooding of the reference NPP site is assumed to have one of the highest priorities, all military means will be available for use at the NPP. Hence, it is assumed that the crisis team will demand support by the German military to set up two alternative supply routes as SEMs for the required fuel supply and shift personnel exchange.

For both supply routes, the military uses a nearby safe place outside the facility as temporary base (see Figure 1). From this base, up to 135 persons are transported first to the turbine building for the shift handover. Then the shift personnel to be replaced is transported back to the temporary base. The shift personnel exchange takes place every 12 h and shall be completed within 2 h. The fuel supply is a continuously repeated task: 4 t of fuel are transported to the site every hour.

The SEM ‘supply by air transport’ is intended to bring persons and fuel to the site via helicopters. For this purpose, the heavy-lift transport helicopter ‘CH-53’ is suitable. It is able to transport around 30 passengers or 7 t of other loads. One flight including return to the base takes about 12 to 20 min for the transport of persons and 10 to 16 min for the transport of fuel, respectively. As a consequence, two CH-53 are required for the personnel exchange and one for the fuel supply. The three helicopters can be used for other tasks during the remaining time. It takes an estimated time from 12 to 36 h from the initiation of the SEM to its realization at the site.

The SEM ‘supply via ferry service’ shall realize the transportation with amphibious vehicles of the type ‘M3’. The M3 can carry up to 60 persons or 20 t of load. One tour for personnel exchange takes about 8 to 16 min and one tour for fuel supply needs 11 to 22 min. Hence, one amphibious vehicle is required for the personnel exchange, one is required for fuel supply, and one is additionally used as backup for the staff exchange. The three M3 can be also used for other tasks if available. The required preparation time of the ferry service after its alarm is estimated to be 19 to 48 h.

Particularly the issue related to long shift durations might be resolved in different ways, e.g., by means of smaller boats or ad hoc bridges. However, these might be more vulnerable with respect to unfavorable weather conditions. On-site quartering of the personnel needed to be present on-site over the entire flood duration might be also another opportunity to achieve a regular personnel exchange.

This was exercised in some German NPPs as a precautionary measure during the SARS-CoV2 pandemic. This additional measure has not been analyzed in the study presented here. Higher uncertainties are expected how the fresh water supply or hygienical issues can be ensured if such a measure is taken since these are of major concern in case of long flood durations.

2.4. Unavailability of the Supplementary Emergency Measures and Consequences from Their Failure

It is obvious that both SEMs, the ‘supply by air transport’ and the ‘supply via ferry service’ can fail to be established at the time when either shift personnel exchange or fuel supply is required. Different causes for failures are:

- ‘Base availability’: The means are not available at the military base (e.g., due to their use somewhere else), or they are not ready for use.
- ‘Time availability’: The means are not available at the site in time when either shift personnel exchange or fuel supply is required.
- ‘Means applicability’: The means cannot be applied at the site (e.g., due to environmental reasons or other randomly occurring technical failures).
- ‘Site accessibility’: The site cannot be reached by the means (e.g., because of obstructions on their route from their military base).

The latter two failure causes can be neglected because the helicopters and the amphibious vehicles are designed to cope with difficult environmental conditions and obstructions on their way. Also, they are accompanied by repair teams to cope with spontaneous technical failures. For the first two failure causes, different key facts are summarized in Table 1.

Table 1: Factors for the Availability of the SEMs 'Supply by Air Transport' and 'Supply via Ferry Service'

Factor	Air Transport with CH-53	Ferry Service with Amphibious Vehicle M3
Means required for fuel supply	1	1
Means required for shift personnel exchange	2	1+1 as backup
Means required in total	3	2+1 as backup
Distance between base and site	more than 100 km	more than 300 km
Number of helicopters at the base	5 to 20 out of in total 60	5 to 10 out of in total 30
Availability of one helicopter / vehicle	0.22	0.25
Required time to reach the site after alarm	12 h to 36 h	19 h to 48 h

The exchange of shift personnel is successfully established or not required if

- the required number of helicopters or amphibious vehicles for shift personnel exchange are available at their bases, and
- helicopters or amphibious vehicles are available on-site before the shift personnel exchange is required, or
- a combination of both SEMs was established, partly as for fuel supply before the exchange of shift personnel is required, or
- the shift personnel exchange can be realized via the normal access in time (flood decreases sufficiently early).

Similarly, the fuel supply is successfully established or not required if

- the required number of helicopters or amphibious vehicles for fuel supply are available at their bases, and
- helicopters or amphibious vehicles are available on-site before fuel supply is required, or

- the fuel supply can be realized via the normal access in time (flood decreased sufficiently early), or
- the external power supply can be restored before fuel supply is required but after 10 h of LOOP, or
- the external power supply can be restored early, corresponding to a common LOOP of less than 10 h.

Once, a SEM has been established, it is assumed that its operation lasts successfully until the flood has decreased to a submergence level of 0.40 m plus the required repair duration of the offsite power supply.

The long-lasting flooding scenario might result in different consequences (see Figure 3). First, neither shift personnel exchange nor fuel supply are necessary because of short flood durations. Second, if both SEMs have not been successfully established in time the external power supply can be restored before the on-site diesel fuel is completely consumed. In this case, also a supply gap of less than 10 h is considered where the essential power supply is maintained by batteries. Third, if the exchange of personnel is realized over the flooding period the HEPs of human actions do not change. If not, the HEPs increase by a factor 5 following the performance shaping factor ‘fitness for duty’ of SPAR-H [5]. And fourth, if the fuel supply with both SEMs fails and the external power supply cannot be restored the NPP experiences a station blackout (SBO).

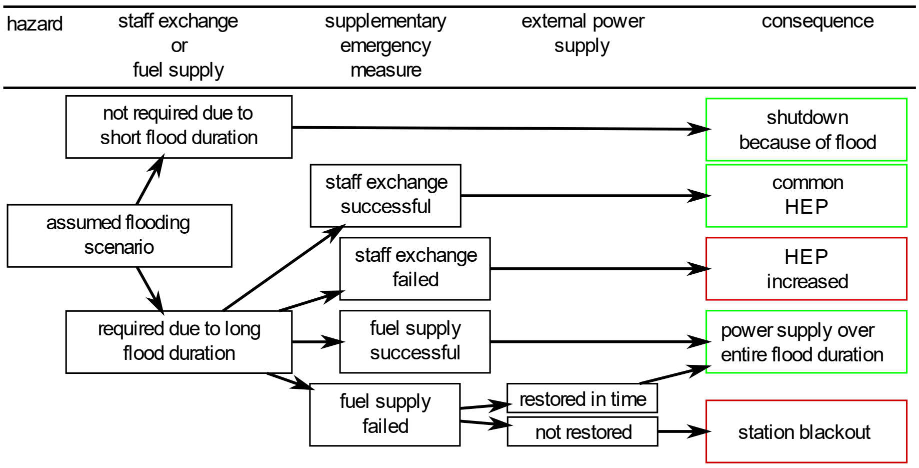

Figure 3: Potential Consequences During the Flooding Event Sequence Depending on Its Duration and the Availability of SEMs or the External Power Supply

Based on this description, the probability of failure on demand of the SEMs is quantified. With these results, the measures are implemented in the existing Level 1 PSA plant model of the NPP under consideration.

2.5. Implementation in the PSA Model

To analyze long-lasting flooding event sequences, the existing Level 1 PSA plant model of the reference NPP was extended by consideration of the SEMs and the consequences in case of their failure. The implementation of the shift personnel exchange was mainly subjected to the HEPs of the required tasks. In case of failure, the HEP is increased by a factor 5 with a maximum HEP of 1. The fuel supply and the restoration of the external power supply are also included in the system functions of the event tree. The implementation is in line with the scenario described in the earlier subsections. The event tree is shown in Figure 4.

The initiating event is assumed to be the LOOP resulting from the flooding. Hence, a shutdown in advance of the flood is not considered although this has been meanwhile realized in the reference NPP as a precautionary measure. The event sequences are further split up into scenarios in which the connection to the external grid can be restored within 10 h and into scenarios where the LOOP lasts longer. The first case corresponds to a common LOOP which is not analyzed in more detail. The second case is a long-lasting flooding scenario. The system function ‘long-duration power supply’ considers the supply of the emergency diesel generators with diesel fuel via the SEMs.

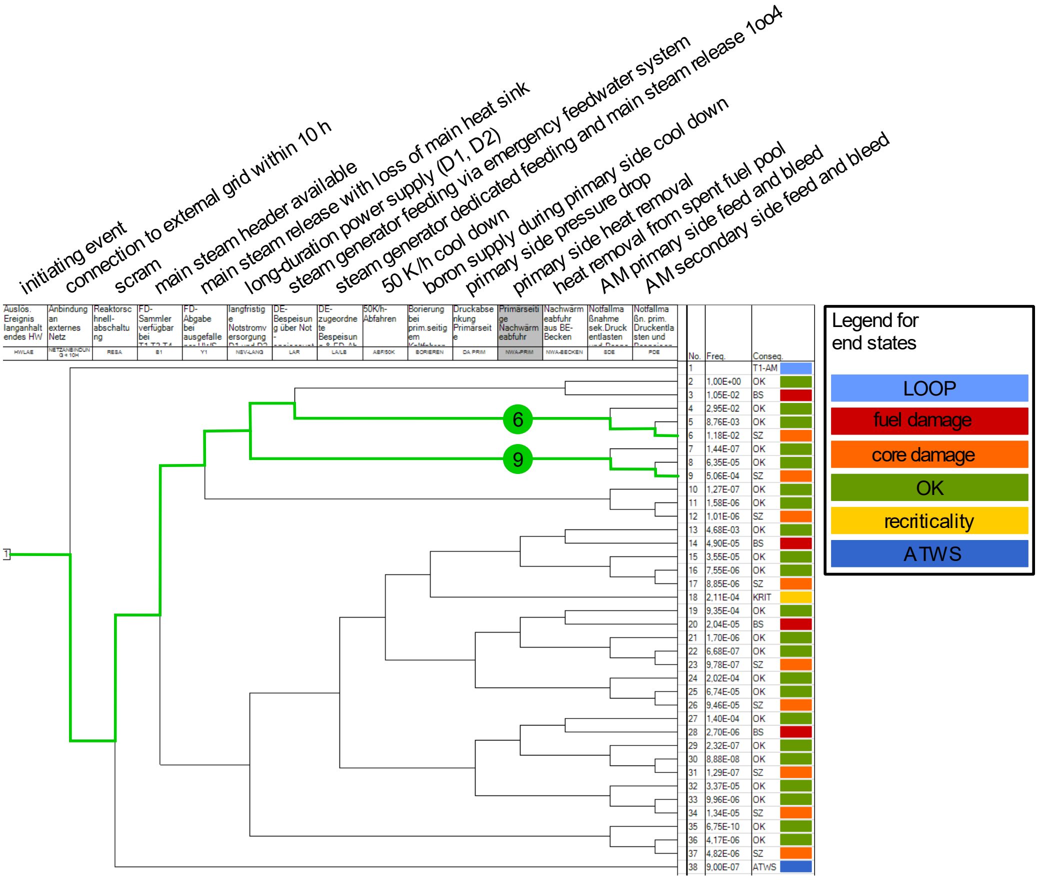

Figure 4: Event Tree for a Long-lasting Flooding Event

The failure probabilities of the ‘supply by air transport’ and ‘supply via ferry service’ depend on the duration of the flooding. For consideration of the event duration, the basic events for human failures and for the fuel supply during long-lasting event sequences are adapted by exchange events for five different event durations from 0 to 18 days.

3. RESULTS AND DISCUSSION

The long-lasting external flooding scenario described above was quantified without considering the initiating event frequency. This limitation was applied because of the very low frequency due to several pessimistic assumptions (e.g., long-lasting flood in combination with LOOP with the ‘subcritical, hot’ plant operational state at the beginning of the scenario). This limitation is also applicable according to the purpose of the PSA extensions presented, namely, the development of an extended methodological approach to consider SEMs for long-lasting event sequences. Consequently, the conditional core damage probability (CCDP) after the occurrence of the long-lasting external flooding is presented in the following instead of the core damage frequency (CDF).

3.1. Availability of Supplementary Emergency Measures and Scrutiny of Assumptions

Before implementation of the SEMs in the PSA model their availability has been separately estimated using Monte Carlo simulation. This approach was used to account for the many time-dependent interactions, e.g., the start of the long-lasting LOOP and the time of the initiation of the SEMs directly affecting their availability. Both factors are assumed to be random. These temporal dependencies cannot be considered properly within a classical (static) PSA code.

The calculation took 26 random variables into account. Some examples are

- the flood duration,
- the relative time to initiate the SEMs,
- their required preparation time,
- the total number of means (helicopters, amphibious vehicles) present at the base,
- and the restoration duration of the external power supply.

These variables are characterized in Section 2.1. The exchange of shift personnel and the fuel supply are successfully established as outlined in Section 2.4. The required numbers of means are given in Table 1. With these inputs, the Monte Carlo simulation provided the failure probabilities in Table 2. In this context, it has to be noted that the total failure probability in this table is derived from a combination of the SEMs for each scenario. It is not the sum of the single measures because of correlations.

Table 1: Failure Probabilities of Shift Personnel Exchange, Fuel Supply and (Early) Restoration of the External Power Supply

Item	Total	Ferry Service	Air Transport	Combination	Normal Access
Shift personnel exchange	4.6 E-01	8.7 E-01	6.5 E-01	7.7 E-01	8.3 E-01
Fuel supply	2.3 E-03	4.6 E-01	9.0 E-02	---	5.5 E-02
Restoration of external power supply	1.4 E-01	---	---	---	---
Early external power supply	nearly 1	---	---	---	---

It has been observed that the fuel supply is more reliable than the exchange of shift personnel. The reason is that the fuel supply is required much later than the personnel exchange. Accordingly, the restoration of the external power supply is less reliable because it can start only after the flood has decreased below a given threshold (when the available fuel may be likely consumed). In addition, the failure probability of the fuel supply via ferry service is remarkably higher than via air transport. This result is caused by the low 'base availability' of the amphibious vehicles. Moreover, the early external power supply is nearly not possible as a result of the assumed distributions for the flood duration and the required time for the restoration of the external power supply.

Several assumptions have been made during the development of the SEMs. To scrutinise these assumptions, their effects on the availability of the SEMs have been evaluated in a sensitivity analysis. For this purpose, the assumptions have been classified following the approach of [6]. The focus was on assumptions based on 'weak strength of knowledge', namely assumptions for the variables highlighted above. For these variables, the domains have been adapted to larger parameter ranges. For example, the minimum and maximum of the assumed preparation time of the SEMs have been divided / multiplied by a factor 2, respectively. The effect on the availability has been quantified with the Spearman's correlation coefficient.

The sensitivity analysis revealed the result that the time for the initiation of the SEMs as well as the flood duration have the strongest effect on the availability of the SEMs. The effect of the flood duration is highlighted in Table 3. The preparation time for the air transport had only slightly smaller effects, while the preparation time of the ferry service showed only a negligible effect on the availability. Similarly, the total numbers of helicopters and amphibious vehicles are not important for the result. With regard to the restoration of the external power supply, the flood duration has a stronger effect on the result than the time required for the restoration.

Table 2: Failure Probabilities for Shift Personnel Exchange and Fuel Supply as well as CCDP Depending on the Flood Duration

Flood Duration	Shift Personnel Exchange	Fuel Supply	CCDP	K95 (CCDP)
0 - 2 d	3.3 E-01	1.0 E-06	8.07 E-03	8.5
2 - 4 d	4.9 E-01	1.0 E-04	1.19 E-02	7.8
4 - 6 d	5.0 E-01	6.0 E-03	1.22 E-02	6.5
6 - 8 d	4.8 E-01	2.3 E-02		
8 - 10 d	4.7 E-01	3.2 E-02	1.30 E-02	7.0
10 - 12 d	4.6 E-01	3.9 E-02		
12 -14 d	4.7 E-01	3.9 E-02	2.67 E-02	4.2
14 - 16 d	4.5 E-01	4.2 E-02		
16 - 18 d	4.8 E-01	6.4 E-02		

3.2. Effect of the Supplementary Emergency Measures on the CCDP

The failure probabilities of the SEMs depending on the flood duration given in Table 3 have been included in the Level 1 PSA plant model as described in Section 2.5 and the CCDP has been determined. The results depending on the flood duration are shown in Table 3 as well as in Figure 5.

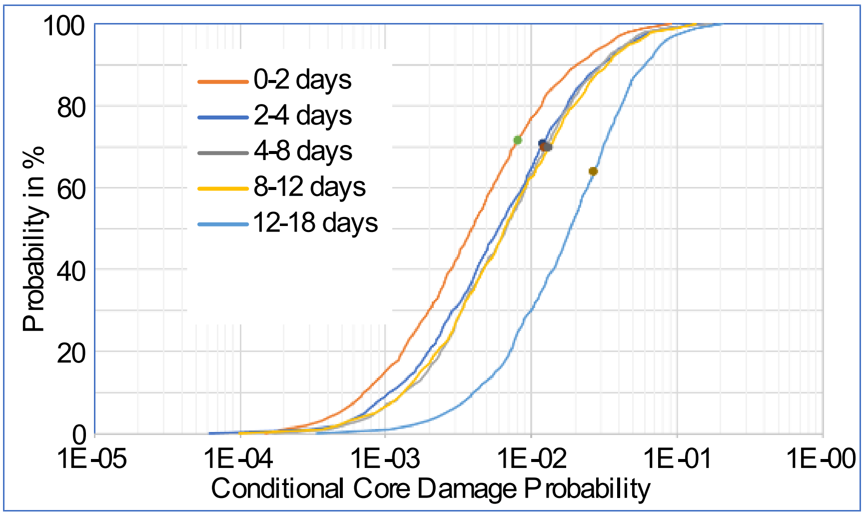

Figure 5: Cumulative CCDP Distribution for Different Flood Durations

The clear increase of the CCDP for flood durations longer than 2 days can be linked to the increase of the failure probability for the exchange of shift personnel. The failure of shift personnel exchange leads to higher HEPs. Between flood durations of 2 days and 12 days, the CCDP remains mainly constant. After that, an increase can be observed again, which is caused by the higher failure probability of the fuel supply.

The exchange of shift personnel could be also realized in different ways as discussed in Section 2.3, which may be easier to implement. But these were not considered in this study. However, in the event of a successful personnel exchange but failed fuel supply, only the measures secondary and primary feed and bleed remain to prevent core damage. As a consequence, the SEMs for fuel supply have a high safety significance.

The CCDP for short flood durations is dominated by sequence 6 in the event tree as highlighted in Figure 4. This sequence is subjected to the steam generator feeding via the emergency feedwater system in combination with the failed primary and secondary feed and bleed with increased HEPs due to the failed exchange of shift personnel. For flood durations between 12 and 18 days, sequence 9 highlighted in Figure 4 dominates the CCDP. This sequence represents the failure of the fuel supply, the failure of the restoration of the external power supply, and the failures of primary and secondary feed and bleed in combination with failed shift personnel exchange.

For all flood durations, the basic events for exchange of shift personnel as well as primary and secondary feed and bleed provide the highest contribution to core damage. The basic event for operator actions for steam generator feeding via the emergency feedwater system has a non-negligible effect on the core damage until flood durations of 12 days, and reduced effects for longer flood durations. In contrary, the effect of the basic events for the restoration of the external power supply and the fuel supply have an increased effect for flood durations longer than 12 days.

In summary, the quantification in the Level 1 PSA plant model demonstrates that in a long-lasting external flooding event ensuring the shift personnel exchange provides a significantly higher contribution to the success of the mitigation measures than ensuring the fuel supply. The reason for this result is the decrease in human reliability in case of long shift durations much earlier than the fuel supply is required. Hence, a regular exchange of shift personnel will significantly affect the success of the event mitigation measures.

3.3. Other Aspects During Long-lasting Event Sequences Not Considered in This Study

The reliability data for systems, structures, and components (SSC) applied within Level 1 PSA are usually based on much shorter mission times. For example, the operation time of diesel generators during their periodic in-service inspection every four weeks is 2 h according to the German regulations [7]. A test with 72 h of operation is carried out only every eight years. However, from these tests, no conclusions on the effect of the longer operation times during long-lasting events on the reliabilities can be drawn. In consequence, this study was based on the commonly available failure rates for mission times of 24 h.

Furthermore, long-lasting events may increase the possibilities to recover failed SSC. Since the major contribution to core damage in this study results from operator actions, no large effect of repair on the CCDP is expected. Therefore, repair possibilities were not considered in this study.

4. CONCLUSIONS AND OUTLOOK

A methodological approach has been developed by GRS to adequately consider supplementary emergency measures in long-lasting event sequences resulting from hazards within Level 1 PSA. It has been successfully applied to an exemplary long-lasting external flooding event sequence with consequential LOOP at a reference NPP site. Two supplementary emergency measures ‘supply by air transport’ and ‘supply via ferry service’ have been identified and included in detail in the Level 1 PSA plant model for the NPP under consideration. The quantification of the PSA plant model has demonstrated that ensuring the supply of personnel provides a significantly higher contribution to the success of the mitigation measures than ensuring the fuel supply. The reason for this is the decrease in human reliability in case of long shift durations occurring much earlier than the required external fuel supply. A regular exchange of shift personnel will therefore significantly affect the success of the event mitigation measures in case of long-lasting event sequences.

The SEMs are based on two principles: first, there is sufficient time available for their planning during the long-lasting event scenario, and second, the SEMs are rather generic and might be applicable to other NPP sites (in Germany and abroad). Moreover, it has to be emphasized that SEMs reduce the risk estimates from long-lasting event sequences within PSA. The SEMs to be considered should therefore be (i) realistic but still conservative, (ii) simple to be carried out, and (iii) related to existing emergency procedures. The SEMs presented in this study meet these aspects since their required means are available at the German military and their availability has been conservatively determined (i). Only one type of transportation vehicle is required (ii), and the existing structures of the crisis team, which is included in the emergency planning of the reference NPP site, are used for SEMs (iii). Since several assumptions have to be made during the modelling of SEMs, these assumptions should be scrutinized. If these prerequisites are met, SEMs offer an opportunity for modelling possibilities for human actions in a realistic manner enabling the analysts to draw conclusions with respect to plant internal precautions and procedures.

In this respect, alternatives (other ways for shift personnel exchange, on-site quartering) to the SEMs have been discussed in Section 2.3 but have not been considered yet. Temporal aspects play a non-negligible role for long-lasting events, particularly under consideration of SEMs. In the event of a long-lasting external flooding, the success of the SEMs strongly depends on the following three factors: rate of water increase, initiation of the SEMs, and required preparation time for the air transport or the ferry service. In this context, the application of dynamic PSA methods seems to be useful. Such methods enable the analysts to consider the duration of the long-lasting event in detail, e.g., for estimating the failure probability of components, repair periods, time periods for recovery of the external power supply and a time dependent failure of the SEMs.

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