Dynamic Modelling of A Nuclear Power Plant Internal Flooding Scenario Under Severe Weather Conditions

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Abstract: Within external hazards probabilistic safety assessment (PSA) for nuclear power plants (NPPs) human actions outside buildings are often assumed as failed due to potentially aggravating environmental conditions. But even more frequent ‘severe weather’ events not inducing an initiating event themselves, can adversely affect human actions outside buildings. Consequential time delays may lead to a failure of human actions for mitigation.
In the frame of a recent research and development project on probabilistic safety assessment for combined hazards GRS has analyzed a combination of an assumed plant internal flooding and a coincidental external hazard of the hazard group ‘severe weather conditions’. The flooding is caused by a fire extinguishing water pipe break in the reactor building annulus of a pressurized water reactor. The water flow can only be stopped by manually closing valves of the fire water supply located outside buildings. Items important to safety will fail if the water reaches a critical volume. The scenario has been modelled applying dynamic PSA methods. This model reproduces and extends an existing classic PSA model (with event and fault trees). For example, it includes the effects of aggravating conditions from severe weather events on the human actions to close the valves, e.g., the walking speed can be reduced.
Under normal weather conditions, the analyses reveal a high sensitivity between the critical water volume and the conditional probability for the failure of items important to safety. Time delays by aggravating conditions to stop the water flow can thus lead to a notable contribution of sequences with a successful but too late closure of the valves for preventing equipment failure. These sequences notably contribute to the overall flooding probability in the dynamic model. It may therefore be beneficial to analyze the effects of more likely severe weather events in accident sequences with human actions outside buildings.

Keywords: Dynamic probabilistic safety assessment, hazard combination, human action, internal flooding with severe weather.

1. INTRODUCTION

The impact from internal and external hazards on nuclear installations often results in complex and dynamically developing event scenarios regarding the spatial and temporal development of hazard specific phenomena [1], e.g., the water level increase in case of flooding. These scenarios usually involve interactions between humans, the hazard phenomena and the states of systems and components important to safety. In this context, it is important that several human actions are often interrelated and that some of these need to be carried out outside buildings. Their success thus depends on environmental conditions, typically from severe weather conditions; therefore, such actions are often assumed failed in the event of external hazards such as seismic, high winds or external flooding occurring coincidental to the internal hazard. Even severe weather conditions not resulting in an initiating event themselves can lead to aggravating conditions adversely impairing human actions outside buildings, e.g., strong winds above Beaufort Scale 8 (17 to 20 m/s), heavy rain, extremely high or low temperatures, snow or black ice.

Several examples can be found for severe weather conditions where activities outside buildings were not possible or significantly impaired. For example, the German weather service lists six heavy wind situations between 2017 and 2020 as well as seven strong or long duration rainfall situations between 2017 and 2024 over Germany [2]. These lists are not comprehensive and focus on remarkable weather situations involving multiple severe weather conditions. Moreover, GRS has determined a wind event frequency of 0.2 /yr for Beaufort Scale 10 gusts at 2 m elevation above ground for a location at the Mediterranean coast. For another location close to the North Sea coast, events with winds (1 h average at 10 m) of more than 17 m/s occur twice a year in average. Finally, the event combination of a long-lasting external flooding and a coincidental internal fire which occurred at the Fort Calhoun NPP site located at the Missouri river in the United States (cf. [3]) in 2011, constitutes a well-known example from the nuclear operating experience.

GRS has developed the analytical tool MCDET (*M*onte *C*arlo *D*ynamic *E*vent *T*ree) [4] for several years, which allows detailed integral deterministic and probabilistic analyses of complex and dynamic scenarios with and without human interactions. In contrast, classical PSA codes are based on event and fault trees and can only indirectly include time dependent effects. MCDET has already been used by GRS in several studies, e.g., [5], [6].

Furthermore, GRS has recently compared a dynamic PSA model using MCDET for a plant internal flooding scenario in a pressurized water reactor building annulus to the corresponding classic PSA models using RiskSpectrum® and SAPHIRE [7]. The scenario is based on an existing PSA plant model generated with RiskSpectrum®. It meets the requirements for internal flooding analysis defined in the IAEA Specific Safety Guide on Level 1 PSA SSG-3 [8] (§ 7.72 ff) and thus includes dynamic elements as described above. The flooding scenario starts with a fire water pipe break in the reactor building annulus and can lead to failure of the residual heat removal (RHR) pumps needed for the safe shutdown of the plant. The water flow can only be stopped by manually closing valves to prevent failure of the pumps. Since the valves are located outside buildings the scenario was selected to illustrate the effects of aggravating conditions from external hazards on event sequences.

In Section 2 of this paper, the scenario and the corresponding dynamic PSA model are outlined. More detailed information is provided in an Appendix to this paper. The results of the model are shown and discussed in Section 3. Finally, conclusions are drawn from the results, e.g. that even rather small delays in stopping the water flow due to the aggravating conditions from the external hazard occurring coincidentally can significantly increase the conditional probability of equipment failure.

2. METHODOLOGY

The scenario outlined in the following was first published by Berchtold and Eraerds [7]. That publication focuses on the comparison between the dynamic MCDET model with two classic PSA models using the PSA codes RiskSpectrum® and SAPHIRE. The description of the scenario and its dynamic MCDET model in [7] is replicated in the Appendix to this paper with the focus on the dynamic model. This methodology section only highlights the differences between the dynamic and the classic model and describes the effects resulting from aggravating conditions due to a coincidentally occurring natural external hazard.

The scenario starts with an assumed break in one of two sections of the fire water main ring within the reactor building annulus of a pressurized water reactor (see Figure 1). These sections are located between the building penetrations of the pipes and the first isolation valves inside the building, and are always pressurized. The assumed break leads to an outflow of approximately 500 m³/h. The frequency of such breaks is expected to be very low since these pipe sections have a total length of less than 10 m only. Thus, the break of one of the pipes is a precondition for this study and the occurrence frequency of this scenario is not considered.

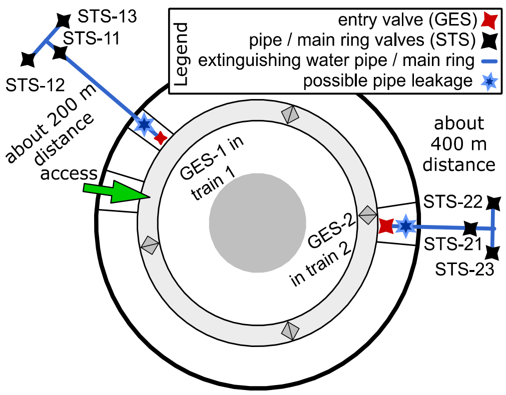

Figure 1. Scheme of the reactor building annulus of a pressurized water reactor with the relevant fire water supply facilities (figure not to scale), adopted from [7]

The scenario in the dynamic model continues with the steps shown in Figure 2. Namely, the steps are 'I' as initiating event, 'M1' and 'M2' as signals of the leakage detection, 'D1' and 'D2' for the diagnosis of the leakage, and 'A1' to 'A3' for the measures taken by plant operators or firefighters to close valves outside buildings with the aim to stop the water flow into the reactor building annulus. The scenario ends either without or with a successful stop of the water flow (steps E0 or E1). In this scenario, it is important to maintain the function of the RHR pumps for a potential manual shutdown. However, the RHR pumps are failed as soon as the water flow into the annulus has reached a volume of 1274 m³ as shown in Table 1. These flood induced failures occur approximately 2.5 h after the pipe break. In case of their failure, the end state ‘annulus flooded’ is reached, otherwise the end state is ‘safe’. In this context it should be noted that the end state ‘annulus flooded’ might be reached even in case of a stop of the water flow (‘E1’) as the stop may come too late.

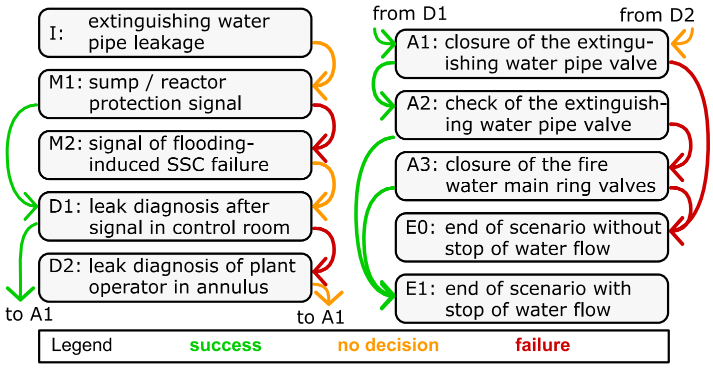

Figure 2. Steps of the scenario considered in the dynamic model

Table 1. Submergence water volume limit for systems important to safety in the reactor building annulus

System	Water Limit
Containment venting system in the reactor building annulus	645 m³
High pressure safety injection (HPSI) pumps	738 m³
Extra borating system pumps	1175 m³
Residual heat removal (RHR) pumps	**1274 m³**
Spent fuel pool (SFP) pumps	1367 m³
Component cooling pumps for safety related cooling	1367 m³

The steps M2 for the second option to detect the leakage and D2 for the second option of a local diagnosis of the event in the reactor building annulus have been added to the accident sequence of the classical model; the event tree is shown in Figure 3. Step M2 comes into effect after the failure of M1, i.e., as soon as the sump and the reactor protection signals from the leak detectors fail. Due to the failed signal, the water level in the reactor building annulus will further rise without being recognized by the main control room staff. The water will reach the containment venting system at a water volume of 645 m³ (see Table 1) and cause its failure together with triggering an alarm in the main control room. This alarm is expected to occur approximately 75 to 80 min after the pipe break and directly leads to the diagnosis step D1 by the control room staff. In case of no or wrong diagnosis, the control room staff will send two plant operator shift members to the reactor building annulus, who immediately recognize the leakage (step D2). In summary, these two steps cannot be considered by the classical modeling approach without considering the times needed since both of them will always lead to a specific signal or a specific leakage diagnosis by the plant operator staff in the reactor building annulus. Thus, the events for ‘leak detection’ and ‘leak diagnosis’ in the event tree of the classic model would be obsolete as the respective recovery steps M2 and D2 are assumed to be successful. Branches for discrete temporal effects on the failure of these steps could be introduced in the event trees of the classical model; however, such effects have to be analysed first, typically by a dynamic model.

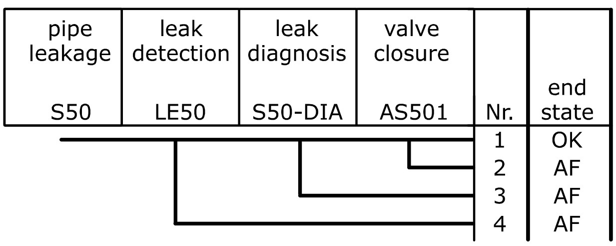

Figure 3. Event tree of the classic PSA model

The following two adverse effects on the human actions resulting from aggravating conditions due to severe weather conditions have been assumed in the dynamic model:

- First, human actions outside buildings will be impaired in step A1. As a result, the normal walking speed of 1.2 m/s will be reduced to 0.1 - 0.5 m/s. This leads to a required period of 3 min (100 m distance at 0.5 m/s walking speed) to 66 min (400 m at 0.1 m/s) for the firefighters to reach the valves, while at normal conditions it takes less than 6 min. The broad time range results from the unknown location of the fire brigade at the time of the alarm, and its distribution was chosen based on geometrical considerations. In addition, in step A1, increased stress of the firefighters is assumed, leading to an increased human failure probability for the closure of a valve of 2.4 E-05 in comparison to the normal failure probability of 4.8 E-06 according to [9] (Tab. 20-16a, item 6: stress factor 5).
- Second, it is assumed in step D1 that the control room staff is aware of the longer durations for human actions outside buildings under such aggravating conditions. Hence, they complete the diagnosis and the planning of the necessary tasks already after 30 min instead of 60 min under normal conditions. The reduction leads to an increased human error probability for the diagnosis of 5.3 E-03 according to [9] (Table 20-16a, item 4; Table 20-3, item 4), under normal conditions it is 1.7 E-03. In the classical model, the increased stress of the firefighter from the on-site professional fire brigade in step A1 and the reduced time for diagnosis in step D1 are also included, but not the reduced walking speed.

3. RESULTS

The frequency of the assumed pipe break is quite low, thus the pipe break is a precondition for the scenario. The conditional probability for the end state ‘annulus flooded’ after the pipe break is presented here without considering the occurrence frequency. This result is is the so-called ‘flooding probability’.

Table 2 shows the overall flooding probabilities of the dynamic model. Scenarios without successfully stopping the water flow (E0) dominate the results with about 97 %. Scenarios where the water flow was stopped successfully but too late (E1) are therefore rare. Under adverse conditions from a natural external hazard imparing human actions the overall flooding probability increases by a factor of 4.8 compared to normal conditions. Particularly, as soon as the water flow has been stopped (E1), the difference to the normal condition is high with a factor of 15.5. This result indicates a strong effect from delays during the steps to close the valves.

Table 2. Flooding probability determined applying the dynamic model

Condition	**Dynamic**		
	E0	**E1**	**Total**
normal	5.50 E-06	1.69 E-07	5.67 E-06
aggravating	2.47 E-05	2.62 E-06	2.73 E-05
aggravating / normal	4.50 E±00	1.55 E+01	4.80 E±00

For a more detailed analysis, different alternatives of the scenarios have been specified as shown in Table 3. The alternatives A, B, and C correspond to the event tree sequences 2 (failure of valve closure), 3 (failure of leak diagnosis), and 4 (failure of leak detection) of the classic PSA models. Since each sequence directly leads to the end state ‘annulus flooded’ in the classical model, there is no sequence corresponding to the alternative D with failures in both steps, M1 and D1.

Table 3. Variations of the scenario

Alternatives	Detection M1	Diagnosis D1	Event Tree Sequence
A	successful	correct	2
B	successful	false	3
C	failed	correct	4
D	failed	false	–

Table 4 shows the flooding probabilities under normal conditions. Looking at the alternative A, when the steps M1 and D1 are successful, the annulus can be flooded with a conditional probability of 4.71 E-09 despite the successful stop of the water flow (E1). However, the failure probability for stopping the water flow (E0) is a factor of more than 1,000 higher. Alternative A with E0 dominates the results of the dynamic model and is equal to the result of the classical model in sequence 2. Looking at alternative B, the diagnosis failure (D1) with its conditional probability of 1.7 E-03 causes a delay of about 30 min in step D2. This delay leads to a flooding probability in case of successful stop of water flow (E1) higher than the failure probability for stopping the water flow (E0). The results for the alternatives C and D are correspondingly. In conclusion, the time delay by the additional step D2 can lead to an increased contribution of sequences where the successful stop comes too late, thus resulting in ‘annulus flooded’. But this contribution is still lower than that of the compensation of the failure in step D1 (1.70 E-03) by step D2. For this reason, the dynamic model shows a lower flooding probability than the classical model.

Table 4. Flooding probabilities of the variations at normal conditions

	Classical Model	**Dynamic Model**		
Alternatives		**E0**	**E1**	**Total**
A	5.50 E-06	5.49 E-06	4.71 E-09	5.49 E-06
B	1.70 E-03	9.35E-09	1.58 E-07	1.59 E-07
C	1.00 E-08	4.78 E-14	6.96 E-09	6.96 E-09
D	–	< 1.00 E-14	1.70 E-11	1.70 E-11

The effects of aggravating conditions are shown in Table 5. In case of the alternative A, the successful stop of water flow (E1) is delayed by the aggravating conditions. This delay causes a flooding probability (E1) that is approximately 10 % of the probability to stop the water flow (E0). The total flooding probability of the dynamic model thus exceeds the results of the classical model in alternative A. But in case of the alternative B, the delayed diagnosis in step D2 still leads to a significantly lower flooding probability than the corresponding sequence 3 of the classical model. The alternatives C and D show corresponding results. Concluding, the alternative A in the dynamic model leads to a flooding probability higher than that in the classical model in sequence 2 but still lower than the flooding probability in the event of sequence 3 (failure of diagnosis) of the classical model.

Table 5. Flooding probabilities of alternatives with aggravating conditions from an external hazard

	Classical Model	**Dynamic Model**		
Alternatives		**E0**	**E1**	**Total**
A	2.47 E-05	2.46 E-05	2.48 E-06	2.71 E-05
B	5.30 E-03	1.31 E-07	1.35 E-07	2.66 E-07
C	1.00 E-08	2.38 E-13	1.47 E-09	1.47 E-09
D	–	< 1.00 E-14	4.57 E-11	4.57 E-11

Figure 4 shows the inverted cumulative probability distribution of the water volume in the reactor building annulus at the end of scenarios with a successful stop of the water flow. The figure also indicates the critical volume of 1274 m³ for the failure of the RHR pumps. Accordingly, several scenarios under aggravating conditions from an external hazard impairing human actions lead to smaller potential water volumes than for normal conditions despite the prolonged duration needed to reach the valves. This effect is caused by the assumed shorter duration of the diagnosis step D1. If this reduced duration would not be assumed, the water volume would be always larger than for normal conditions as it is shown by the curve for aggravating conditions with 60 min for step D1.

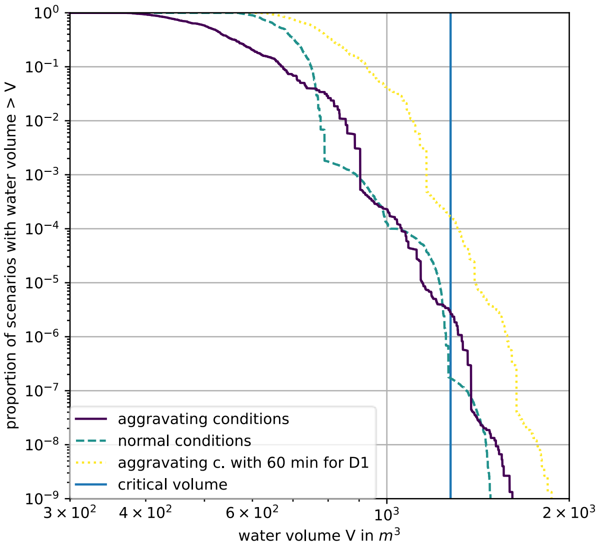

Figure 4. Complementary cumulative specific flooding probability in case of a successful water flow stop (E1) for normal and aggravating conditions and a flooding probability with the duration of D1 not being reduced in case of such conditions (still 60 min)

Figure 5 presents the complementary cumulative probability distribution function of the water volume specific to the different alternatives with a successful stop of the water flow. The probability for volumes higher than the critical volume of 1273 m³ (failure of RHR pumps) is called specific flooding probability. In case of alternative A and E1 for normal conditions, the specific flooding probability is 4.71 E-09 (see also Table 3). However, if the critical volume is about 25 m³ smaller, the specific flooding probability strongly increases by a factor of more than 200 up to a value of nearly 1.00 E-04 at 1000 m³ also shown in Table 6. Likewise, the aggravating conditions lead to a strong increase in the specific flooding probability due to the increased water flow into the reactor annulus, i.e., a time delay of 3 min leads to an additional water flow of 25 m³. This effect can be also observed in the difference between the flooding probabilities for the alternative A and E1 under aggravating and normal conditions with a factor of more than 500 (see Table 4 and Table 5). In case of a smaller critical volume or delays for stopping the water flow, the alternative 'A' could thus provide a non-negligable contribution to the overall flooding probability even with respect to the classical model results for the corresponding sequence 2 (success in the steps M1 and D1).

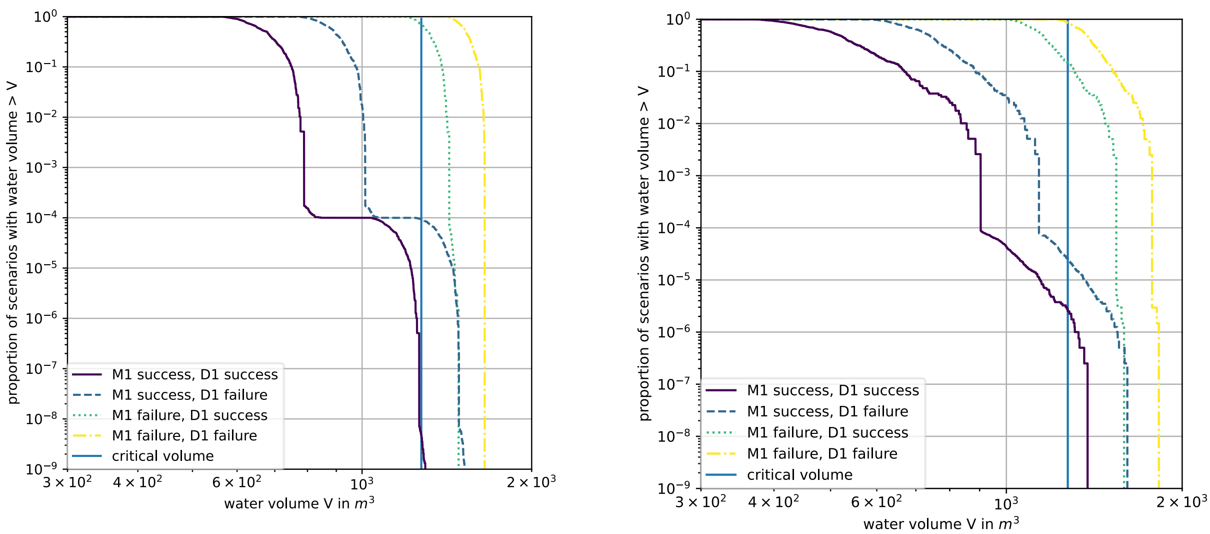

Figure 5. Cumulative specific flooding probability for the different alternatives under normal (left) and aggravating (right) conditions and a successful stop of the water flow (E1)

Table 6. Illustration of the high sensitivity between the specific flooding probability for alternatives A and E1 at normal conditions and the critical water volume for the failure of the RHR pumps

Critical Water Volume	Flooding Probability
1000 m³	9.98 E-05
1200 m³	1.85 E-05
1250 m³	1.01 E-06
1274 m³	**4.71 E-09**
1300 m³	2.95 E-10

As outlined above, the available time until a failure of the RHR pumps is approximately 2.5 h and the time required to stop the water flow must be less. The signal in step M1 occurs either after about 1 min (sump detector) or after about 60 min (reactor protection system). In case of M2, the signal is issued approximately 80 min after the pipe break. The diagnosis step D1 is scheduled with 50 to 70 min. In case of its failure, D2 takes about additional 30 min. Finally, the steps for closing the valves take less than 15 to 20 min under normal conditions. As a result, sequences with successful signal of the sump detectors (M1) and successful diagnosis (D1) take approximately 60 min, which leaves more than 90 min to successfully close the valves. This period is sufficient even under the most severe conditions. The same yields for a correct sump signal together with the diagnosis step D2 after a failed diagnosis step D1 adding up to approximately 90 min and approximately 60 min available to close the valves.

Next, the sump signal failure and the successful signal by the reactor protection system in step M1 together with a diagnosis time of 60 min leave about 30 min for the steps necessary to close the valves. This time should be sufficient under normal conditions. In conclusion, the accident sequence allows enough time for diagnosis and for actions to successfully close the valves. Single failures, e.g. sump signal or diagnosis failure in step D1, are therefore covered. However, failures in multiple steps or failures occuring under aggravating conditions can lead to a failure of the RHR pumps. The conditional probability for these sequences is in the range of the failure probability for closing the valves.

4. CONCLUSIONS

The detailed analysis of the internal flooding scenario by means of the dynamic model indicated a high sensitivity of the probability of the flooding induced failure of the RHR pumps (end state ‘annulus flooded’) to the critical water volume until its failure. In other words, if the critical water volume is 25 m³ lower (originally 1274 m³) or if there are time delays of 3 min to close the valves, the conditional probability for ‘annulus flooded’ after the assumed pipe break can increase by a factor of more than 200. However, for the critical volume and the other parameters as defined above, event sequences with a successful stop of the water flow only provide a negligible contribution to the probability of the end state ‘annulus flooded’ under normal conditions. However, aggravating conditions from severe weather events can cause those time delays. Such conditions can lead to sequences where all steps have been completed successfully but the end state ‘annulus flooded’ cannot be prevented because the closure of the valves is too late. These sequences contribute notably to the overall flooding probability in the dynamic model. In conclusion, it can be useful to analyze the effects of severe weather conditions in accident sequences with human actions outside buildings, particularly for nuclear sites where such severe weather conditions occur more frequently (e.g. coastal regions).

Moreover, the dynamic model does not always show sequences which are more conservative than those of the classical model. However, such less conservative sequences do not dominate the results of the classical model since the additional steps M2 and D2 are not considered. Thus, the failure of the diagnosis D1 provides higher flooding probabilities in the classical model than that in the dynamic model.

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Appendix: Description of the Scenario and of the Corresponding Dynamic Model [7]

This appendix replicates the description of the scenario, its dynamic model and of MCDET published in [7].

Description of the Scenario

"The scenario is initiated by an assumed extinguishing water pipe break, either in the first or in the second of four redundant trains, i.e., the quadrants, of the reactor building annulus (see Figure 1). In both cases, the location of the leakage is between the pipe entering the annulus and the entry valve, where the pipe is pressurized. After the leakage, the pumps for maintaining the water pressure start and provide a permanent water flow of about 500 m³/h into the annulus. This water flow cannot be stopped due to the difference in height between the locations of the leakage and the pumps. The leakage can be detected by several water level sensors in the reactor sumps. Once detected, the leakage must be properly diagnosed. Then the water flow must be stopped manually by closing an extinguishing water pipe valve (STS-11 or STS-21). If the closing of the valve fails, the water flow inside the containment can be stopped by closing both corresponding main ring valves." The scenario in the dynamic model ends with the successful or failed closure of the valves. In the classic models, the scenario continues in the latter case with a manual reactor scram. In the dynamic model "failures of systems and components important to safety in the reactor building annulus, are only assumed if these are submerged. The systems and the corresponding water volumes up to their submergence are shown in Table 1. Only the residual heat removal (RHR) pumps are needed after the scram. Hence, if the water volume remains below the critical volume for the RHR pumps of 1274 m³ the water flow is stopped successfully; otherwise, the annulus is assumed to be flooded."

"The scenario chosen as basis for this study had already been implemented in a RiskSpectrum® plant model for other purposes and validated and verified for different applications. The accident sequence comprises the initiating event 'pipe leakage' (S50), the 'leak detection' (LE50), the 'leak diagnosis' (S50-DIA), and the 'valve closure' (AS501)." The scenario ends as soon as the extinguishing water pipe valves are either closed successfully (all function events successful in sequence 1) or not (one function event failed). The corresponding end states are 'OK' in sequence 1 or 'annulus flooded' (AF) in the sequences 2, 3, or 4.

The dynamic model using MCDET comprises the following steps of the scenario.

"'I, pipe leakage' / 'S50': This step begins with the leakage of the extinguishing water pipe and comprises the activation of the pumps for maintaining the water pressure as well as their alarm in the control room. The water flow is between dV = 490 … 520 m³/h. The entire control room staff and three further plant operators are present in the main control room and available for carrying out different tasks. At the time of the leakage two firefighters are present in approximately 100 m to 500 m to the location of the relevant extinguishing water pipe valve. This step takes only a few seconds and directly leads to step 'M1'.

'M1, sump or reactor protection signal' / 'LE50': The water fills the sumps and spreads over the entire reactor building annulus. The sensors in the sumps trigger a signal within less than a minute, the reactor protection system leads to a signal within 55 to 60 min. The failure probability of the signal is 1 E-04. There are two options: either at least one signal is triggered and recognized in the main control room leading to step 'D1' within the time period mentioned above, or all signals fail leading to step 'M2'.

'M2, signal of flooding induced SSC failure' / not included in the classic PSA plant models: The leakage resulting from the pipe break has not yet been correctly diagnosed. Thus, the water flow will cause a failure of the containment venting systems as soon as a water volume of 645 m³ is reached in the annulus, which triggers an alarm in the control room after about 75 to 80 min. The alarm leads to step 'D1'.

'D1, diagnosis after signal in main control room' / 'S50-DIA': After the signal, the diagnosis is assumed to take 50 to 70 min. There are two options: either the diagnosis is successful, which leads to step 'A1', or the diagnosis is not successful without suitable subsequent measures (failure probability of 1.7 E-03) leading to step 'D2'.

'D2, diagnosis by plant operator in the reactor building annulus' / not included in the classic PSA plant models: Since there is no correct diagnosis two plant operators are sent to the annulus. They certainly recognize the leakage and inform the control room. This step takes more than 30 min and leads to step 'A1'.

'A1, closure of the extinguishing water pipe valve' / 'AS501': One plant operator and two firefighters are sent to close the correct extinguishing water pipe valve (STS-11 or STS-21). The time period for reaching the valve and closing it is less than 6 min. There are two options: either the action is carried out successfully at the time t_{close} leading to A2, or the action is not carried out correctly (probability of 4.8 E-06) leading to step 'E0'.

'A2, check of the extinguishing water pipe valve' / 'AS501': The flow through the pipe is checked by the control room personnel. There are two options: either the extinguishing water pipe valve closed successfully leading to step 'E1', or the valve did not close (probability of 5.9 E-04) leading to step 'A3'.

'A3, closure of the fire water main ring valves' / 'AS501': The plant operator and two firefighters go to the corresponding valves (STS-12/STS-13 or STS-22/STS-23) of the fire water main ring and close them in less than 7 min. There are two options: either both valves are closed successfully at the time t_{close} leading to step 'E1', or at least one of the two valves did not close (see 'A2' for the failure probability) leading to step 'E0'.

'E0, end of scenario without stop of water flow' / 'AF': The leakage with water flowing into the reactor building annulus could not be stopped. Further measures are not considered. Therefore, all systems shown in Table 1 are assumed to be failed.

'E1, end of scenario with stop of water flow' / 'OK': The water flow into the reactor building annulus could be successfully stopped at the time t_{close}. The water volume in the annulus is $V = dV \cdot t_{close}$ (see steps 'I' and 'A1' / 'A3'). The water level in the annulus results in the failures of systems important to safety as shown in Table 1. While the end state of both classic PSA plant models is 'OK', the dynamic model provides two options: either the RHR pumps are not damaged representing a safe end state, or the pumps are damaged.
In case of steps 'E0' and 'E1' with the damage of the RHR pumps, the scenario will continue with a manual reactor scram, which is not further considered hereafter."

Background Regarding MCDET and the Dynamic Model

"The GRS tool MCDET allows modelling complex time dependent sequences of human actions. The analyst can specify potential branching points in these sequences as well as uncertain input parameters, e.g., the duration and probability of different actions or the parameters which influence the next human action taken at a branching point. MCDET can simulate an action sequence based on a set of input parameters and the provided model. The analyst can also specify the uncertainty distribution for each input parameter. Simulation parameter sets get sampled from the distributions provided in a MCDET run. Each potential action sequence is simulated, the duration and probability of the action sequences are calculated and stored. Based on the information stored, the dependency between aleatoric and epistemic uncertainties and the final duration and probability of the action sequences can be analysed."

"The probabilities of all uncertain parameters are assumed to be uniformly distributed. Special cases are the duration of 'M1', the period until the sump signal or the reactor protection signal is triggered, and the period needed until either the plant operators or the firefighters reach the correct extinguishing water pipe valve ('A1'). The duration of 'M1' is modelled as dependent on the water flow per period and the redundant train of the reactor building annulus. The period until the first person (plant operator or firefighter) reaches the valve depends on the respective distance to the valve and on the walking speed. Since the starting point of the two firefighters in 'A1' is not fully known, a uniform distribution between 100 and 500 m has been assumed. In addition, a walking speed of 1.2 m/s has been assumed. All these inputs (human actions and component failures) can be modelled using the software tool FreeMind."