Method for Analysing Extreme Events

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Abstract:
PSA models for Nuclear Power Plants (NPPs) of today include comprehensive and detailed information related to plant safety, both quantitative and qualitative; the latter include e.g. safety functions and system dependencies at nuclear power plants.

The detailed information in the PSA model can also be used to analyse extreme events and their impact on safety functions and the ability for the nuclear power plant to withstand extreme events with regard to core integrity.

Lloyd´s Register Consulting, in cooperation with the IAEA, has further developed the method described in [1] utilizing an internal initiating events PSA model for assessing the impact of extreme events. A number of extreme events(including credible combinations) can be postulated, for example seismic, water levels, ice storm, etc, then associated initiating events, as well as structures, components, buildings and their susceptibility to the extreme eventsdefined. The extreme events analysis is linked to the PSA model directly to assure that the whole model is included in the evaluation of the impact of the event – or combinations of events. The outcome of the analysis is to:
- Identify sensitive scenarios for extreme events
- Analyse simultaneous extreme events
- Prove robustness of plant design, for individual components and for buildings

Keywords: PRA,PSA, extreme events, seismic events

1. INTRODUCTION

The detailed information represented by PSA models for nuclear power plants can be used, not only for reporting to the regulator for the application for license for operation of the nuclear power plant they represent, but it can also for example be used to analyse extreme events and combinations of extreme events and their impact on safety functions and the ability for the nuclear power plant to withstand extreme events with regard to core integrity. In fact, a PSA model representing all dependencies in the plant is an excellent base for deterministic evaluations.

2. PSA MODEL REQUIREMENTS

The method requires the use of a PSA model that includes comprehensive and detailed information related to requirements on safety functions and the interdependencies between safety functions and their support systems.Quantitative information can be used in an enhanced version of the method, but is not required as a basis. The model should be designed to enable risk assessments for the plant in different plant operating states and alignments.

3. THE METHOD

The method for carrying out the Extreme Event Analysis (EEA) is described in detail in [1]. Since that paper was written, the method has been further developed and a new software, called the Extreme Events Analyser has been developed.

The reasons for the development of a new tool are mainly:

- To make use of the complete logical model in the PSA.

- Include also initiating events in the PSA model and their susceptibility to occur, when generating the Minimal Cut Sets (MCSs) in the EEA.
- To facilitate addition of new hazards
- To provide a framework for further enhancements

The development of the method and the software has been realized through the cooperation of the IAEA and Lloyd´s Register Consulting, the developer of RiskSpectrum professional software.

The objective of the method is to assess plant protection against extreme events, including combinations of extreme events, beyond design basis. Especially, the thresholds at which the plant cannot meet its safety requirements are of special interest – and the combinations that would fail the plant.

Generally, the assessment approach is aimed at estimating the robustness of relevant safety systems and the continued presence of the defence-in-depth principle for load cases that exceed the design basis.

The Objectives of the analysis are:
- Identify sensitive scenarios for extreme events
- Analyse simultaneous extreme events
- Prove robustness of plant design, for individual components and for buildings in relation to the initiators.

The method can be described as an iterative process and is depicted in Figure 1 copied from in Ref. [1].

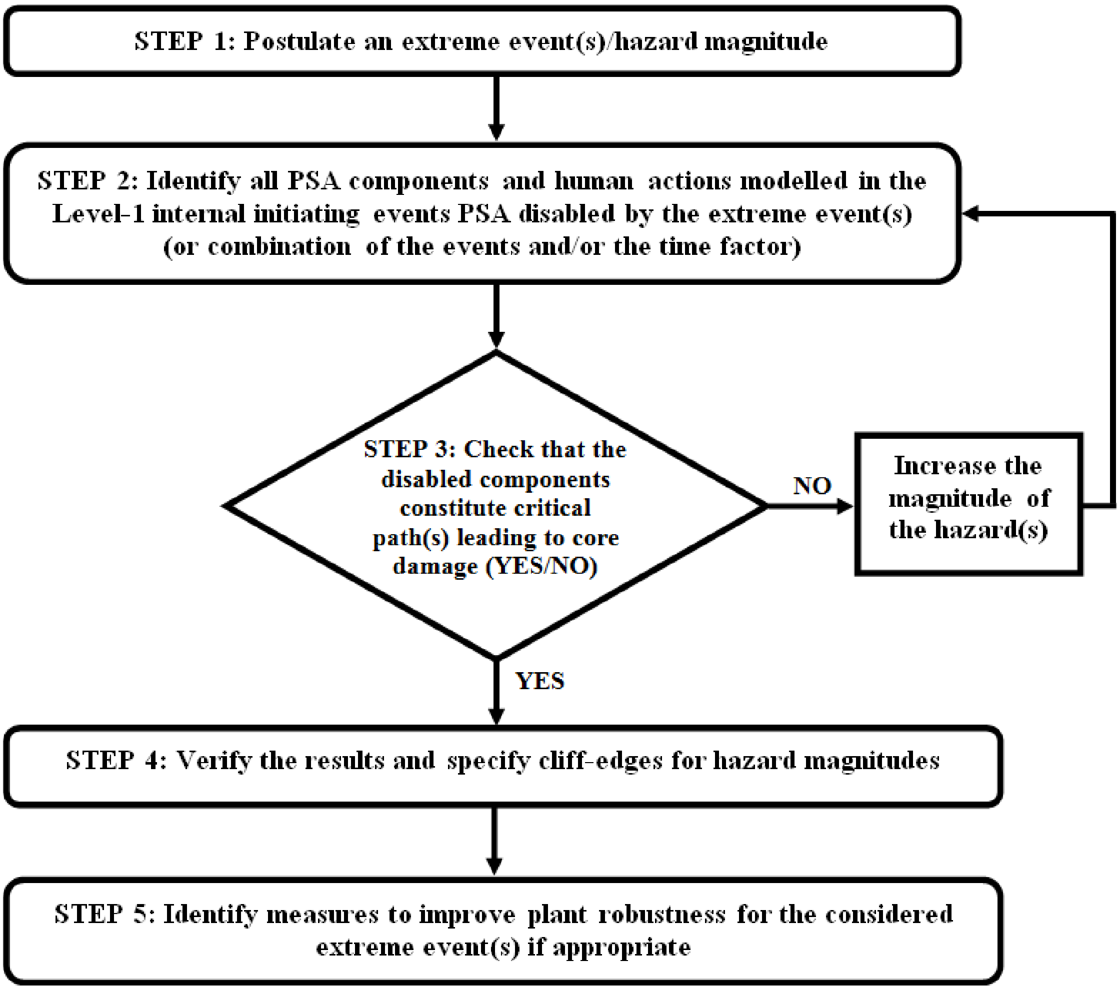


Figure 1. The method can be described as an iterative process.

It is easy to see that the process illustrated in Figure 1, is very well suited for propagating events set to true or probability 1.0 in a fault tree and event tree logic built for evaluating the consequence Core Damage for a nuclear power plant or other consequence of interest. This process includes Steps 1 to 3. At Step 4, the minimal combinations of events and hazards and their lowest magnitudes, that fail critical combinations ofcomponents, can be determined by slightly decreasing the hazard(s) magnitude(s)to and repeating Step 3. The final hazard(s) magnitude represents a cliff edge.

The critical combinations of events leading to core damage (identified in Step 4) provide the input to Step 5 for consideration of measures to take for e.g. increased seismic capacity, elevatingcomponents, etc.

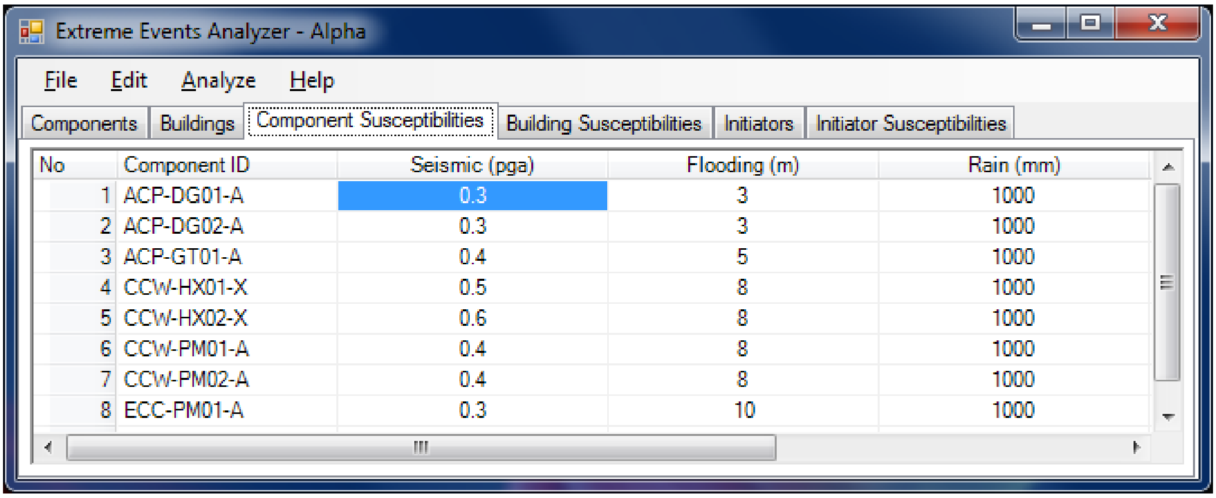
3.1. Applying the Method to PSA

A PSA model can be used to apply the method described above and in Ref[1].
Below is a list of sequential steps to do using the EEA to determine identify scenarios sensitive for extreme events:

1. Determine what hazards to include
2. Determine the components, buildings that can be susceptible to the hazards
3. Determine initiating events which can be triggered by the hazard
4. Determine the magnitudes of hazards that will fail the components, the buildings and trigger the initiators
5. Generate the minimal combinations of events given the occurrence of a hazard or combinations of hazards

The MCSs that are produce from the EEA can be generated considering one or many hazards and they represent the combinations of events that would lead to core damage. It is a qualitative result based on the logic in the fault trees and event trees in the PSA model. The method is, by definition, especially suitable for identifying cliff-edge effects for a facility. Sensitivities can also easily be evaluated by, for example, increasing and decreasing the susceptibilities for components, buildings and initiating events.

A substantial work is needed to produce information about component location and elevation in buildings and rooms/compartments as well as design operational limits for components and buildings to calculate and estimate their susceptibility to fail at different levels of PGA's, flood, rain, etc. This can, for example, be that a Peak Ground Acceleration (PGA) of 0.3 will fail thediesel generators and a flood of 5 meters fail the gas turbine. In Figure 2, a table of components susceptibilities, given a set of hazards, are shown. Regarding operator actions, the evaluation needs to consider at which threshold an action is no longer creditable. For example, if a flooding will affect the path that operator will have to take to make a local action – these operator actionsare no longer possible to account for when any room in the path is flooded.



No	Component ID	Seismic (pga)	Flooding (m)	Rain (mm)
1	ACP-DG01-A	0.3	3	1000
2	ACP-DG02-A	0.3	3	1000
3	ACP-GT01-A	0.4	5	1000
4	CCW-HX01-X	0.5	8	1000
5	CCW-HX02-X	0.6	8	1000
6	CCW-PM01-A	0.4	8	1000
7	CCW-PM02-A	0.4	8	1000
8	ECC-PM01-A	0.3	10	1000

Figure 2.Components susceptibilities given a set of hazards.

Buildings, containing equipment of importance for the safe operation of a nuclear power plant can also be included with the buildings susceptibility to fail due to hazards. Components locatedin a building are assumed to fail if the building fails. In the example shown in Figure 3, the diesel generators are located in a building, called "Electrical" and in Figure 4 a table showing building susceptibilities is shown. A component can be assigned to one or several "buildings", which means that e.g. an individual room, or floor, can be defined as a building. This may facilitate the evaluation of, for example, parts of a building is affected – or if the flooding will affect a certain floor.

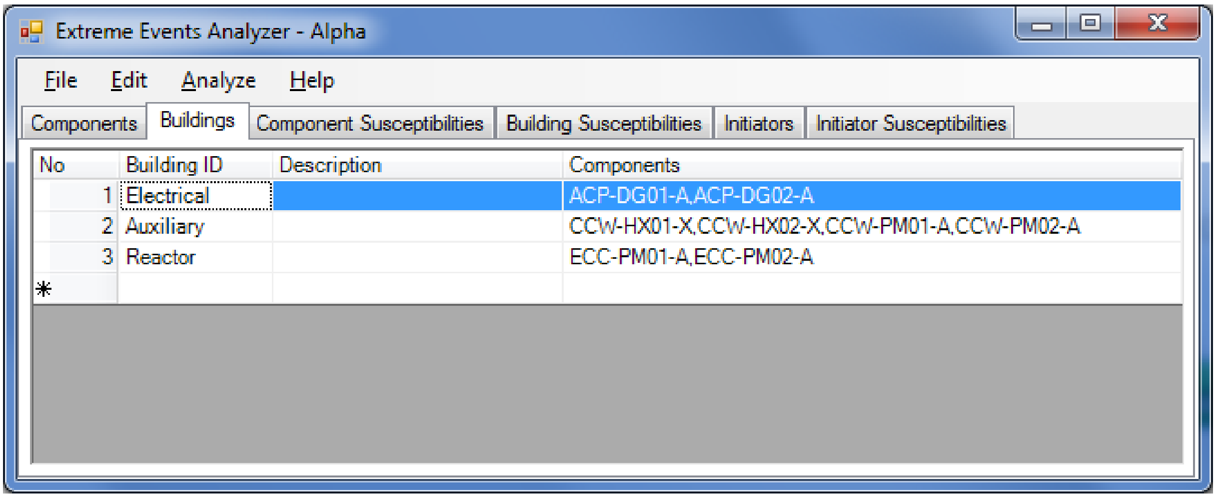


Figure 3. Components associated with the buildings in which they are located.

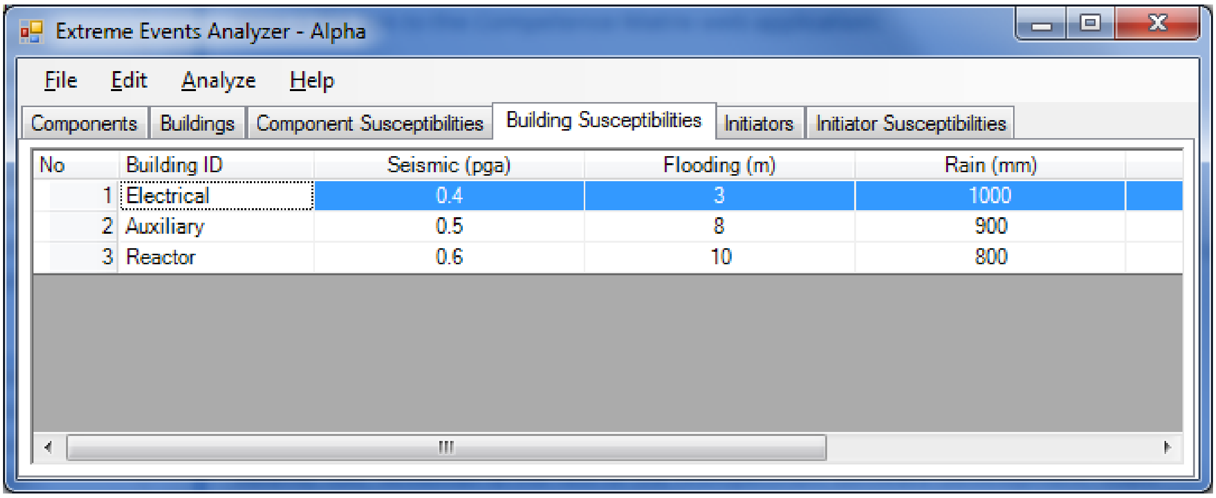


Figure 4.Building susceptibilities.

Susceptibilities for initiators (LOCA, LOSP, etc) can be assigned in a similar way. This approach will simplify the analysis, since the analysis will be performed versus several initiators at the same time – and this means that also combinations of initiators will be covered by the methodology.

With susceptibilities defined for components, buildings and initiators it is possible to find the minimal combination of events that would lead to an unwanted consequence, e.g. core damage using the fault trees and event trees in the PSA model.This is done by generating MCS using the PSA model. It shall be pointed out that the method can analyse and present the results for several consequences simultaneously.

3.2 Quantification of the PSA model

The quantification in the PSA model is is done in the following way:

1. Basic events representing components that fail due to the hazard(s) are set to probability 1.0.
2. All other basic events in the PSA model are set to FALSE.
3. MCSs are generated.

The MCSs that are produced represents the scenarios that would lead to core damage. If no MCS are generated, it means that there is no accident scenario leading to core damage, based on the PSA model and the defined susceptibilities for components, buildings and initiators, which would lead to core damage, due to the hazard(s).

Below is an example.
Initiating event: ‘Loss of Off Site Power’ (LOOP), external power is lost, reactor scrammed.

Hazards: Seismic and flood
Seismic:
0.3 g -> A & B fail
Flood:
3 m ->E & K fail
4 m -> D & E & K fail

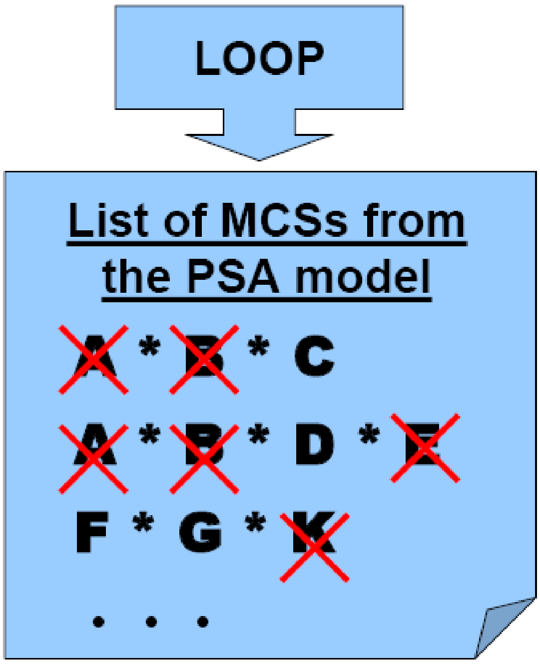


Figure 5.Scenario 1:Seismic 0.3 and flood of 3 m.

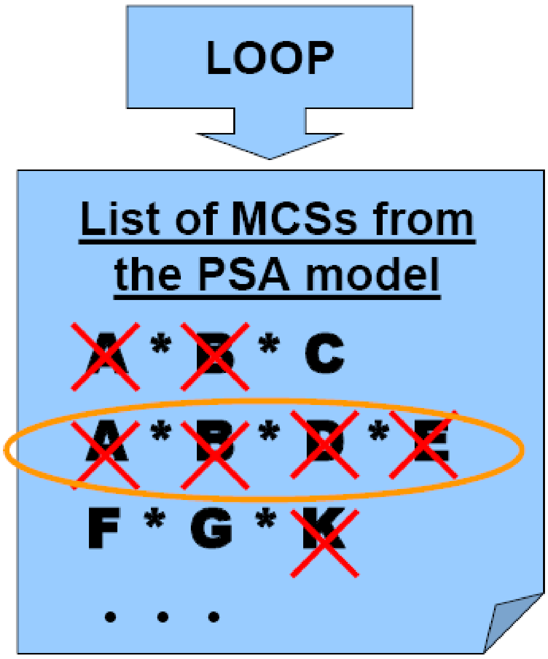


Figure 6. Scenario 2: Seismic 0.3 and flood of 4 m.

Figure 5 shows that the plant is protected against the combination of seismic event 0.3 g and flood level 3 m (or lower magnitudes) while Figure 6 show a scenario where the plant is not protected (one MCS where all components will be disabled by the hazards' combination is identified).

Once the scenarios that e.g. lead to core damage are found, the very important process of verifying that these are indeed critical begins. This has to be done by looking at each scenario in detail and clearly understanding that it really causes core damage. There may also be that some combinations are the effect of conservative assumptions.

It is also important to consider the probability of the events in the PSA model that are not part of the failed combination of events (due to the hazard). In the example above, the event C is not affected by either the seismic or the flood events, but it represents a *single event* that would, if it failed would lead to that the plant no longer is protected. Let´s assume, for example, that the event C has a high random probability of failing. In this case, Scenario 1, in which it was concluded that the plant is protected, may actually not be a very well protected plant. This means that there could be combinations of events that would not be identified as events leading to core damage, but actually present a very weak defence against the hazard(s).

For this reason, the analysis should include identifying events in the PSA model that potentially could cause hiding some scenarios. This has to be done prior to generating the MCS. Generally speaking the PSA model should be pruned of events if it is doubtful that they present a strong enough barrier on their own to defend the plant from e.g. core damage.

With the scenarios identified it is clear which safety functions, buildings, etc to improve with regard to seismic capacity, component locations, etc, if necessary. When the measures have been identified it is easy to evaluate again to verify that it has had its desired effect. If there are no measure that can be taken, a weakness in the plant design has been identified.

The method distinguishes itself by making it possible to evaluate different magnitudes of hazards in combination with other hazards and their different magnitudes. This means that different thresholds may be applicable at different hazard magnitudes.

3.3. Extensions to the Method

The method described in this paper is intended to use the PSA model for analysing robustness and identification of vulnerabilities at nuclear power plants. The method will however not, identify sequences where the likelihood of a severe situation is significant. Assume that, as in the example discussed in Section 3.2 above, the component C is an unreliable component (or maybe an operator action with high failure probability).In this case, instead of pruning the model as suggested aboveit could be considered to include probabilities of the *single events*. Then the conditional core damage probability could be assessed just below the thresholds where the plant is not longer protected, see the picture in Figure 7, below. This method could also be compared with the Seismic Margin Assessment Method [4]. It is important to stress that the use of the method described in this paper would not be comparable with a fully probabilistic approach, since definite failure of the system with regard to thresholds is postulated when the hazard magnitude exceeds the design basis. The probabilistic thresholds are applied in addition and increase the requirements (or rather understanding) of the plant behaviour at hazards.

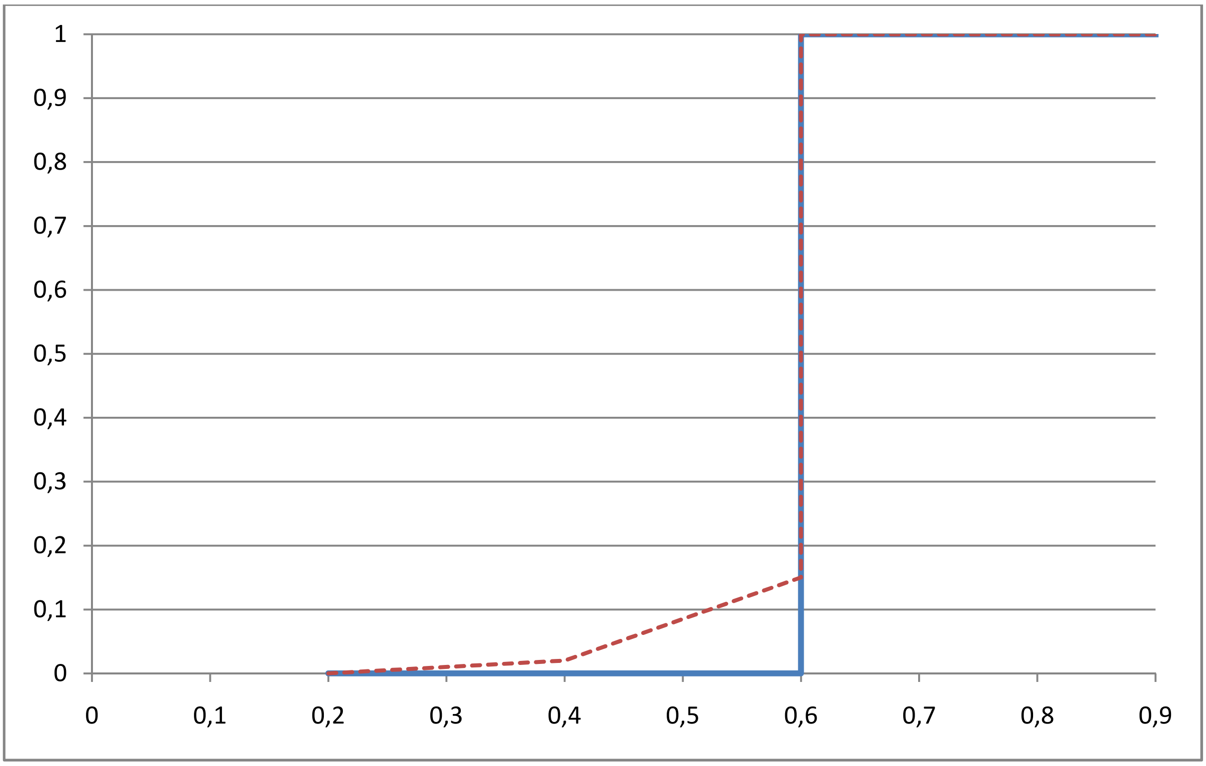


Figure 7.The Y-axis represents the probability that the plant is not protected against PGA (X-axis).

The robustness approach using the PSA model to quantify and generate MCSs as described in this paper, can be represented by the blue curve in Figure 7. With the conditional failure probability includedfor single failure events in the analysis, the dotted red curve would be produced illustrating the conditional core damage probability, given a certain seismic activity (PGA, X-axis). This would add information to the evaluation, and it would allow for definition of criteria representing sufficient margins (a type of "single failure" criterion).

Since the method allows for automatic generation of results of many different combinations of hazards, and of different thresholds – it is obvious that the results would be multi-dimensional, providing both definitive thresholds and combinations for which the barriers are insufficient.

4. CONCLUSION

The objective of the method described in this paper is to assess plant protection against extreme events, including combinations of extreme events, which are beyond the design basis. Especially, the thresholds at which the plant cannot meet its safety requirements are of special interest – and the combinations that would fail the plant.

The method requires access to a detailed PSA model.

A number of extreme events, for example seismic, water levels, ice storm, etc, are defined as well as structures, components, buildings and initiators and their susceptibility to the extreme events. The extreme events analysis is linked to the PSA model directly to assure that the whole model is included in the evaluation of the impact of the event – or combinations of events.

Using a software analysis tool it is easy to propagate events set to true or probability 1.0 in fault tree and event tree logic in the PSA and find the minimal combination of events that would lead to an unwanted consequence, e.g. core damage at a nuclear power plant. This is done by generating MCS using the PSA model. The method can analyse and present the results for several consequences simultaneously.

Once the scenarios that e.g. lead to core damage are found, the very important process of verifying that these are indeed critical begins. This has to be done by looking at each scenario in detail and clearly understand that it really causes core damage. There may also be that some combinations are the effect of conservative assumptions.

The method as described in this paper will however not identify sequences where the likelihood of a severe situation is significant. But since the method allows for automatic generation of results of many different combinations of hazards, and of different thresholds – it is obvious that the results could provide multi-dimensional data, providing both definitive thresholds and combinations for which the barriers are insufficient.

The method distinguishes itself by making it possible to evaluate different magnitudes of hazards in combination with other hazards and their different magnitudes. This means that different thresholds may be applicable at different hazard magnitudes. It is also very interesting to explore further the possibility to calculate the conditional core damage probability for combinations of hazards, just below the threshold in which they would definitely fail the plant.

Footnote: an extreme event is meant to be an event providing a widespread damage to the nuclear power plant; it could be caused by an individual hazard or combined hazards not explicitly included in the design basis, examples are natural or man-induced hazards of the magnitudes higher than the design basis

Footnote: A cliff edge effect, in a nuclear power plant, is an instance of severely abnormal plant behaviour caused by an abrupt transition from one plant status to another following a small deviation in a plant parameter, and thus a sudden large variation in plant conditions in response to a small variation in an input[1].

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