HOW TO INTRODUCE HAZARDS IN LEVEL 1 PSA AND ALL POSSIBILITIES OF EVENTS COMBINATIONS. EXAMPLES OF LEARNINGS FROM THE EUROPEAN ASAMPSA_E PROJECT

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This paper is associated to the European project ASAMPSA_E Advanced Safety Assessment: Extended Probabilistic Safety Assessment (PSA) which gathers more than 30 organizations (industry, researchers, universities, technical safety organizations and regulators) from Europe, USA and Japan. This is a 3-4 years project on extending PSA (e.g. in order to better represent external hazards), which aims at identifying some meaningful practices to extend the scope and the quality of the existing PSA developed for nuclear power plants.

This paper is focused on summarizing some good practices from this project for the implementation of external hazards in Level 1 PSA. The first learnings come from a review of existing guidelines: available documents provide usable recommendations to evaluate failure probabilities of Systems, Structure and Components depending on the influence of single hazard or events combination, especially for earthquake and fires hazards. Some limitations are also found: some external hazards are not covered so deeply maybe due to their specific site nature. The multi-units dependencies, the correlated hazards impacts and the potential for human response after an external event are in general not fully considered in guidelines and PSAs in general but should be in the future.

I. INTRODUCTION

The objective of this paper is to provide examples from European ASAMPSA_E project. The ASAMPSA_E end users [1] recommended providing guidance to cover questions of developing an extension of current PSA including the methods to model the combinations/correlations/dependencies of hazards, possible secondary effects, multi-unit response, mitigating and aggravating factors. To address End- users' recommendations, the ASAMPSA_E project discussed the implementation of the following external hazards in Level 1 PSA: earthquake, external flooding, meteorological hazards (i.e. extreme wind, extreme temperature and extreme snow pack), biological infestation, lightning, accidental aircraft crash and man- made hazards including natural external fire and external explosion. The scope of this paper would be very wide, if all of the ASAMPSA_E selected hazards will be included, therefore this paper is providing a generalized methodology to the extended PSA[1] and guidance on how to introduce hazards in Level 1 PSA and all possibilities of event combinations. For each hazard, the paper considers the following four topics:

1) Impact on the System, Structure and Components (SSCs) modelled in Level 1 PSA event trees;
2) Impact on Human Reliability Assessment (HRA) modelling in Level 1 PSA;
3) Site impact modelling (multi-unit impacts) in Level 1 PSA event trees;
4) Link between external initiating events of PSA and Nuclear Power Plant (NPP) design basis conditions.

By state of the art PSA methodologies, it is possible to identify practices to assess the frequencies for each type of hazards or combination of hazards (including correlated hazards) as initiating event for PSAs. The sources and quality of hazard data as well as elements of hazard assessment methodologies and relevant examples are discussed pointing out how

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[1] Definition of the ASAMPSA_E project: an extended PSA applies to a site of one or several NPPs and its environment. It intends to calculate the risk induced by the main sources of radioactivity (reactor core, spend fuel storages and other sources) on the site, taking into account all operating states for each main source and all possible relevant accident initiating events (both internal and external) affecting one NPP or the whole site.

these could be used for hazards assessment and extended PSA. Classification and criteria to properly assess hazard combinations as well as examples and methods for assessment of these combinations are included in hazard correlation charts developed by ASAMPSA_E [2]. The general procedure, modelling principles and major analysis steps in the development of a Level 1 PSA model for external hazards are in good agreement with that of Level 1 PSA in general. A major limitations and gaps of external hazards PSA are related to the data preparation and its implementation. Main uncertainties appear from the hazard evaluation and plant response analysis issues (buildings resistance, missile impact, long-term effects, mitigation of human errors, etc.). Description of these and other features of external hazards PSA modelling can be found in this paper. The PSA lesson learned from Fukushima accident [3] is also considered and addressed in this paper.

II. GENERALIZED METHODOLOGY FOR DEVELOPMENT OF EXTENDED PSA

The availability of the Level 1 PSA model for internal events and hazards is a prerequisite for developing an extended PSA. Taking into account the fact that this methodology should be adapted to the purposes of extended PSA developing of any NPP site located in different climatic zones, question of hazard screening is not raised in this paper directly. More accurate information about hazards screening/events selecting is presented in [4]. The identification of external hazard conditions shall include the following steps:

- the external hazards data of national and international networks and agencies shall be analyzed with quantitative and qualitative criteria (see [4]), and all meteorological and climatological conditions of the region around the site shall be identified and their effects shall be evaluated,
- phenomena and credible combinations of phenomena potentially resulting from extreme weather conditions shall be determined,
- also, those hazards shall be identified that may not directly impact the plant, but could lead to failure of important infrastructure in the vicinity of the site or threaten neighboring installations, which in turn threaten the safety of plant; especially attention in this way is needed for the impact on the high-voltage lines switchyard related damage which may cause significant disruption to the NPP operation; similar could be the case with the external communication lines related with relevant internal systems,
- special consideration shall be given to causal dependencies between various external hazards [2] e.g. forest fires induced by drought or biological hazards triggered by extreme weather conditions (e.g. high water temperatures might be favorable for the growth of algae).

The list of hazards generated shall serve several purposes, e.g. identification of potential links between hazards with respect to the underlying natural phenomena (e.g. causal links) or with respect to similar impacts on the plant (potential for the implementation of measures providing protection against both hazards) and revision of natural hazards as part of safety review processes, in response to changes in extreme weather conditions (e.g. climate change) or due to operating experience feedback. Natural hazards identified as potentially affecting the site can be screened out on the basis of being incapable of posing a physical impact threat or being extremely unlikely with a high degree of confidence. In the same time, the extremely unlikely but possible events have to be carefully considered. Care shall be taken not to exclude hazards that in combination with other hazards have the potential to pose a threat to the facility. The screening process shall be based on conservative assumptions. The arguments in support of the screening process shall be justified. Thus, in the frameworks of risk assessment from external hazards, one shall collect and assess the data specific for NPPs and site, and relevant general data required for the further quantitative analysis.

For all natural hazards that have not been screened out, hazard assessments shall be performed using deterministic and, as far as practicable, probabilistic methods taking into account the current state of science and technology. This shall take into account all available data in the NPP and in the specialized institutions, and produce a relationship between the hazards severity (e.g. magnitude and duration) and exceedance frequency, where practicable. An exclusion of hazards due to their lack of physical capability to cause adverse effects or exclusion based on the extreme unlikelihood have to be analyzed for possible prospects of weather conditions in the considered region in future. As well, special care should be taken not to screen out hazards, which are at present negligible, but may become relevant in the future due to non-stationarity, e.g. climate change / consequences of climate change. Besides, possible combinations of weather conditions that do not pose a threat on their own should be considered before screening out hazards. The output from this screening should be a list/matrix of hazards and their combinations which are relevant to the site and which need to be analyzed in detail as the involved phenomena potentially pose a safety threat to the site.

Based on screening results, it is necessary to analyze vulnerability of a power plant in order to define those SSCs that are fragile in relation to the considered external hazard. Preparation of input data for the model includes construction of hazard curves for external hazards and SSC vulnerability curves. An alternative method is to compare parameters of external hazards with design data for SSCs – boundary evaluation. Such a method is simplified and can be used only in case of unavailability of any statistics for hazard occurrence. The given analysis will allow correlation of external hazards (see Fig.2. ASAMPSA_E proposed approach to analyses impact of correlated hazards which is discussed more in detail in ASAMPSA_E reports) with internal initiating events from Level 1 PSA.

The next step is related to changes that should be made to the probabilistic model in order to account impact of external hazards (additional event trees, modification of fault trees, review of basic events and human errors, common cause failures modelled). Under this stage, one shall consider combination of hazards and secondary effects, dependent failures and common cause failures (CCF) in the probabilistic model. The final stage includes performance of probabilistic calculations. Summing up all the tasks and steps of extended PSA they generally can be expressed through the flow chart, Fig.1. shown below:

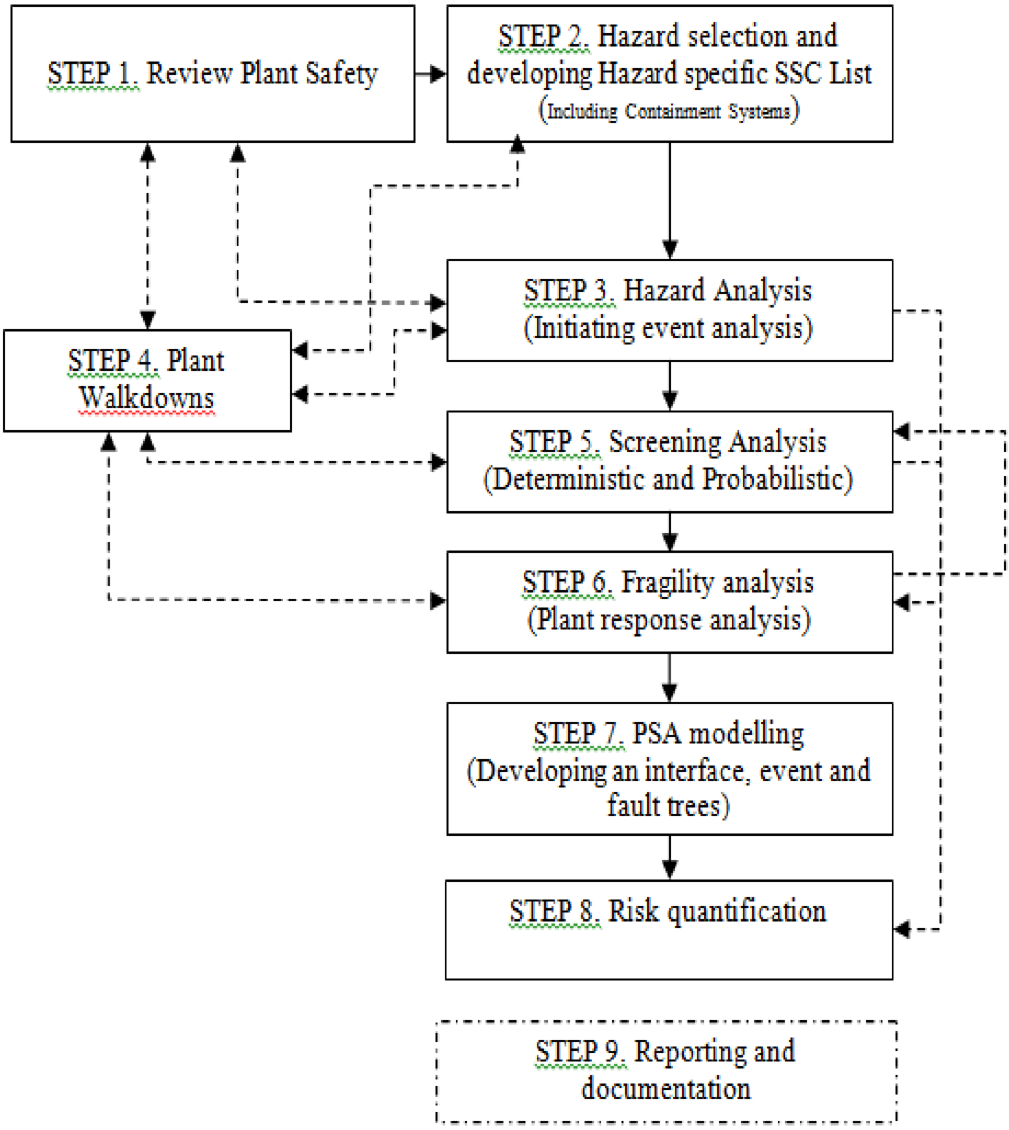

Fig.1. Flow chart for extended Level 1 PSA

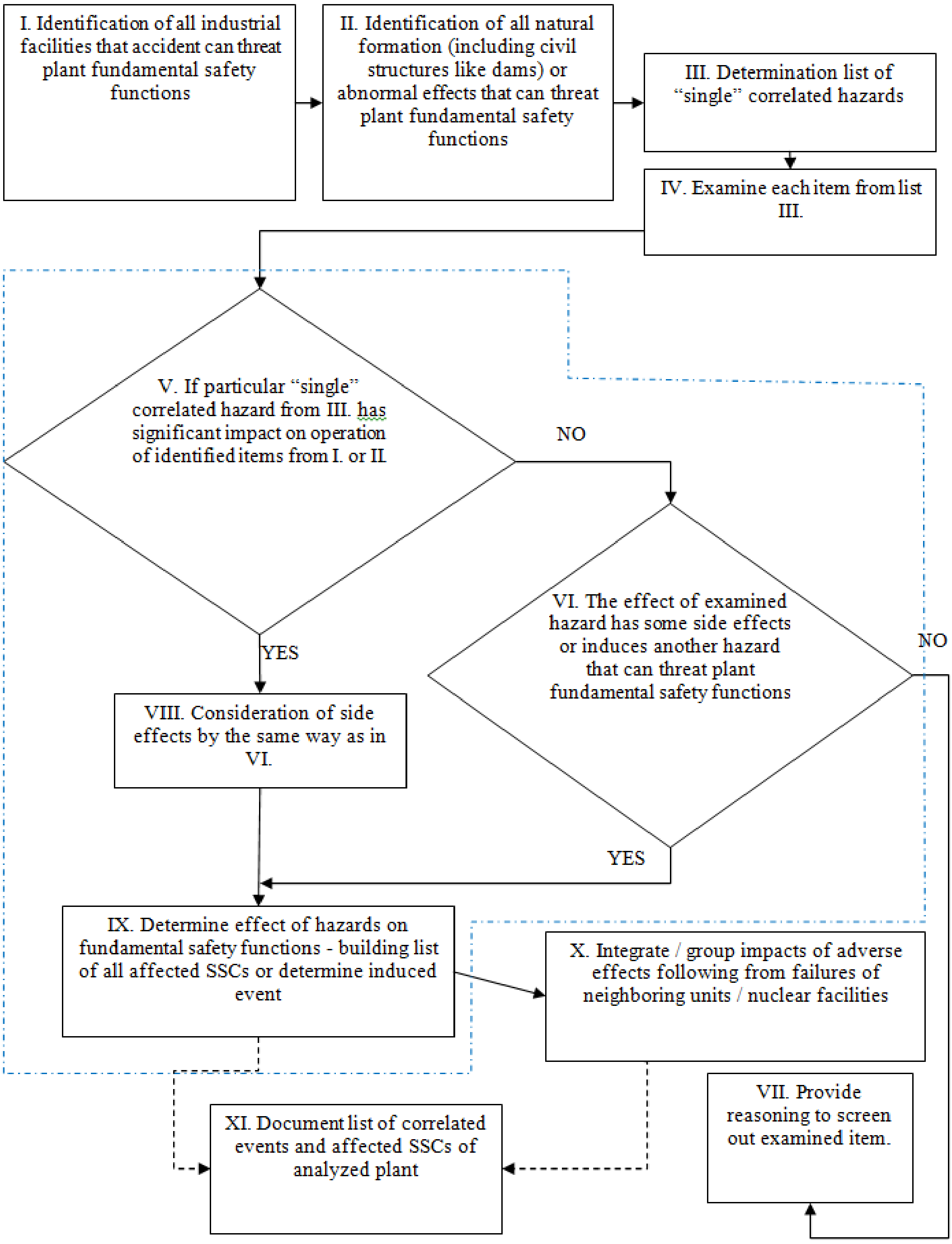

Fig.2. Flow chart of approach to analyse impact of external correlated hazards

II.A. External Hazards on SSC Modelling in Level 1 PSA

The evaluation of impact of external hazards and combination of events on the SSCs modeled in Level 1 PSA event trees is divided in three basic parts: 1) Practices to assess the (conditional) failure probabilities of SSC depending on the influences of hazard or combination of events induced by particular hazards; 2) Assurance of consistency between the assumptions used in existing Level 1 PSA and assumptions for extended PSA covering external hazards; 3) Modeling the impact of events combination in PSA.

Practices to assess the (conditional) failure probabilities of SSC are depending on the influences of combination of events induced by particular hazards. The available guidelines provide usable recommendations to evaluate failure probabilities of SSCs depending on the influence of single hazard or events combination. The most detailed guidelines are devoted to the seismic events and fires. Even if these guidelines deal only with single event impact, but can be also used for combined events purpose to evaluate particular effects induced by analyzed external hazards. Consequently if assessment of SSCs failure probabilities can be supported by data for example from design basis, relevant inputs for PSA can be obtained. For external hazards exceeding design conditions, difficulties can be encountered to determine such failure probabilities, which are discussed in the ASAMPSA_E project.

Consistency between assumptions used in existing PSA and extended PSA covering combination of events induced by external hazards is discussed. This part deals mainly with determination of scope of SSCs for extended PSA and failure modes. Many of quoted guidelines provide general systematic framework how to develop such extended list of components. Scope of considered failure modes obviously follows from nature of analyzed hazards like mechanical load, heat produced by fires etc. Modelling of impact of events combination in PSA is presented. This part provides a generic example of typical approach that uses standard PSA software to combine fault and event trees. It should be noted that particular approach is strongly depend on used software. In general available guidelines provide detailed framework for analysis of seismic event. The other external hazards are not always covered so deeply. This is probably caused by specific site nature of these hazards like external floods, fires etc. Within ASAMPSA_E, examples of applications are discussed for seismic events and solutions for the other hazards. In general modelling the SSC for external hazards PSA should take into account the following basic issues:

1. Modelling of building resistance and tolerance level of the buildings, missile impact, impact on ventilation system and Diesel Generator (DGs), long term effects:
    - estimation of the responses of building and components (SSCs), electrical cables, common pathways (propagation of extreme conditions inside the building, loss of ventilation, air-conditioner and electronics),
    - use of equipment qualification regarding extreme temperature i.e. high, long lasting effects, duration of the fire, vibration, explosion,
    - consequences from a failing SSC on other SSCs,
    - common cause failures.
2. Calculation of fragility or failure probability (if applicable), taking into account human’ safety (high temperature, toxic gases), personal protection devices and personnel behaviour;
3. Importance of walk downs and plant specific data;
4. Uncertainty analysis.

In order to obtain the necessary level of detail it is reasonable to organize this process (at least for the first three points above) in an iterative way. The following detailed modelling aspects are considered for development of extended Level 1 PSA: 1) defining the failure modes for SSCs; 2) categorization of failure modes as transient initiating events and failures in mitigation systems; 3) event tree modelling with multiple transient initiating failures and systems failures (see example, Fig.3.); 4) fault tree development including transfer of failure modes to include external hazards induced component failures (see example, Fig.4.) and related dependencies (see example, Fig.5.); 5) analysis of human errors and 6) analysis of input reliability data.

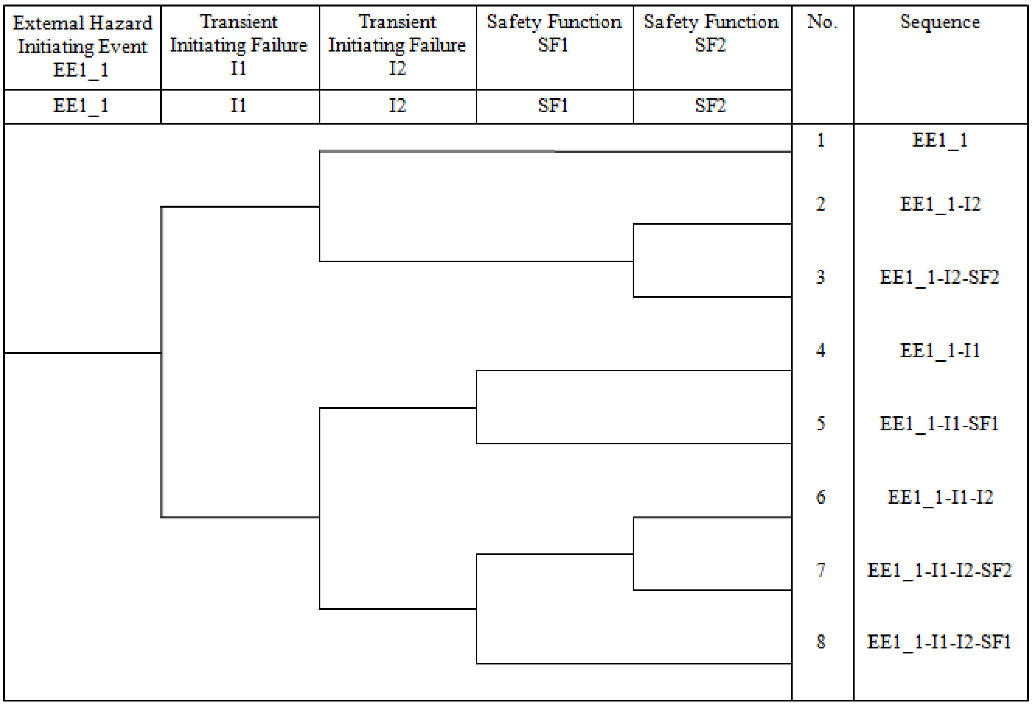

Fig.3. Example of a Generic Event Tree Structure

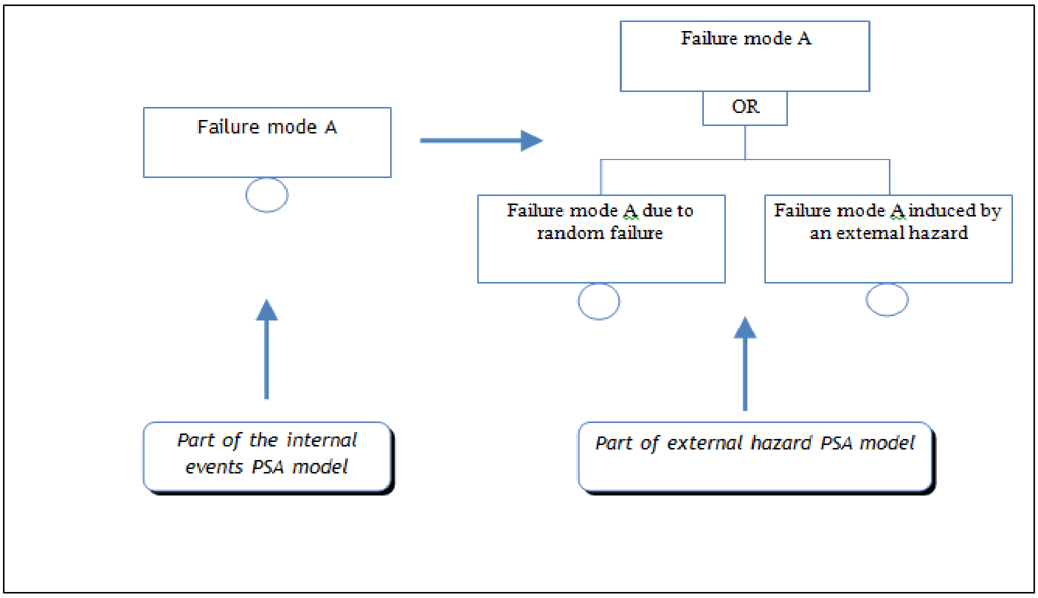

Fig.4. Transfer of Failure Modes to Include Hazard Induced Component Failures

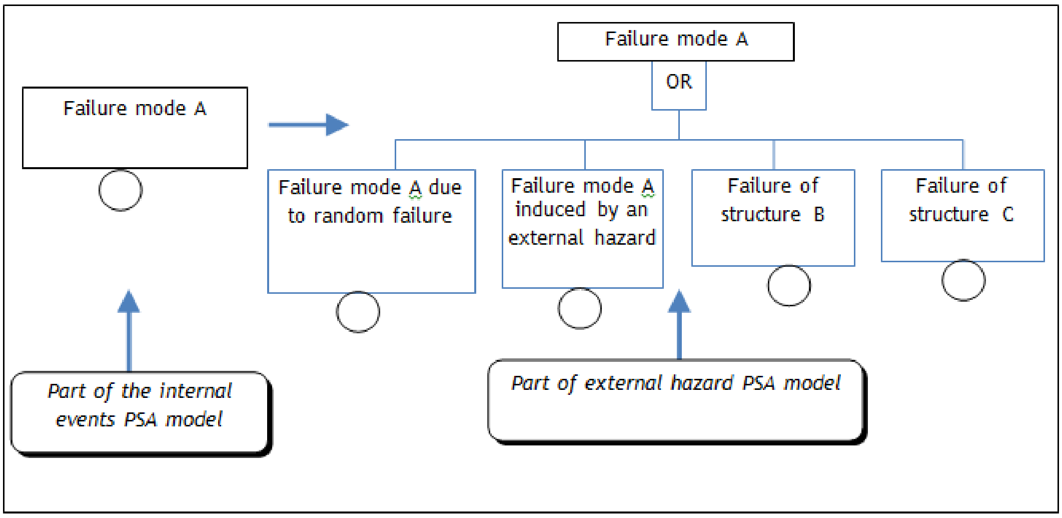

Fig.5. Scheme for Modelling Specific Hazard Related Dependencies

II.B. Human Risk Assessment

Most of the available guidelines provide general recommendations and a framework to assess the human factor depending on the external event. More detailed information and HRA models are available for seismic events or induced internal fire events. For the other external hazards, the literature with regard to HRA is not well developed. It may be concluded that the PSA for external hazards should take account the potential for human response to be affected by the external event. The grace time for operator intervention for mitigation of external event effects is an important factor that needs to be considered in analysis. The additional stresses that can increase the likelihood of human errors or inattention should be examined, compared to the likelihood assigned in the internal events HRA, when the same activities are undertaken in non-hazard accident sequences. However, the basis for determining these increases is not well developed in the PSA literature.

HRA is aimed at identification and quantification of human failure events that may occur either prior to a plant disturbance or during evolution of an incident/accident. These are failure events that represent human actions or failures to take human actions which can be considered inappropriate in the given context so that they can substantially contribute to the development of a severe accident. The potential human failure events are identified in the course of event tree and fault tree development. The methods used to quantify the probability of human errors typically vary depending on (1) the type of the action (e.g. maintenance operation or emergency response), (2) the anticipated error modes, the main influences on performance, and (3) the availability of data and other information sources for the estimation. Based on their direct consequences the inappropriate actions (referred to as human “errors”) are taken into account in one of the following ways in the PSA model for internal initiating events: a contributor to an initiating event, a basic event at fault tree level and a basic event at event tree level. The specificities of incorporating human actions and the associated failure events into the external hazard PSA model can be for the different categories (i.e. pre-initiator (type A), initiator (type B) and post-initiator (type C)) of human actions generally considered in the PSA.

To address HRA issues, it is important to identify personnel actions performed within the accident management strategy and caused by external extreme hazards, and to define human error probability for such actions. In those cases, when external hazard initiates the internal initiating event, human reliability analysis comes to recalculation of human error probabilities defined in Level 1 PSA for internal initiating events. Reassessment shall consider stress state of the operator in connection with occurrence of the external hazard, the lack of understanding of the accident sequence progression due to damage of Instrumentation and Control (I&C) devices, the physical impossibility of some local actions, and the effect of external hazard on the time required for individual recovery actions. Human reliability analysis should be based on the same methodology that was used for PSA of internal initiating events. The following factors shall be taken into account:

1. stress of personnel (including other performance shaping factors) proceeding during and following the occurrence of external hazard;
2. physical impossibility to perform certain actions outside Main Control Room (MCR);
3. lack of information on progression of the accident resulting from I&C failure (probable in cases of extremely high temperatures, loss of venting etc.);
4. effect of external hazard on the available time.

The HRA analysis shall be very detailed as personnel may react "in panic" in case of severe external events like earthquake and other. Even events like "magnetic storms" (sun eruptions / protuberances may affect the mental state of the people). The possibility to take into account "spare team" of operators on the affected site shall be estimated.

II.C. Multi-Units Impacts

The general practice of performing safety assessment for multiple reactor units on the site is to analyze one reactor at a time and not considering several important multi-unit dependencies and interactions in both deterministic and probabilistic safety assessments. In order to obtain the site's risk profile, the Core Damage Frequency (CDF) for the site rather than the unit is necessary to be considered. Many recent standards are applicable to plant level which is defined as a nuclear power facility, which may refer to a single-unit or multi-unit site. Many aspects highlighted by these standards are directly, or with a minimum of adaptation, applicable to the modeling of events affecting multi-unit sites. The existing PSA methods and tools are, in general, applicable for the PSA of multi-units events. The main issue of PSA for multi-unit sites is to ensure the analysis completeness mainly regarding the treatment of the aspects which are more specific for such sites and events. The ASAMPSA_E is focused on these aspects: ensure the completeness of the analysis and modeling (based on existing PSA modeling techniques) of specific aspects for PSA treating events affecting multi-units on one site and integration of obtained results on plant and site level. Regarding the risk metrics for a site PSA the existing standards give some high level requirements. Moreover, methodological documents which propose acceptable methods to deal with the risk metrics for a site PSA are not available and it would be interesting to develop them. Also the impact of the modelling of the site aspects on the definition of Level 1 PSA accident sequences End States as well as on the interface with the Level 2 PSA is an interesting subject which is further developed in the frame of ASAMPSA_E project [5].

For multi-units initiating events modeling, a classification system that utilizes existing single-unit PSAs and combines them into a multi-unit PSA is presented in [6]. Two methods which can be used for creating a multi-unit PSA have been identified. One method is to develop an entirely new multi-unit PSA, and the second one is to integrate existing single-unit PSAs. It is stated that the prohibitive cost of developing a PSA and the potential technical impediments of creating a state-of-practice multi-unit PSA make the latter method more feasible both practically and economically because of the ability to utilize existing data and models. The multi-unit methodology proposed [6] defines a unit as a reactor core and it's front-line and support SSCs i.e., everything inside of the primary containment building and power generation and supporting systems. There are many types of events that could create a dependency between multiple units from a risk perspective. In order to effectively account for these risks when looking to create a multi-unit PSA, six main commonality classifications have been established (see Fig.6.): initiating events, shared connections, identical components, proximity dependencies, human dependencies, and organizational dependencies. The first step in the proposed process is to sort the events in the single unit accident sequences into classifications. This allows the dataset to be reduced from typical 100 plant systems to just seven classifications (one independent and six dependent) that need to be analyzed.

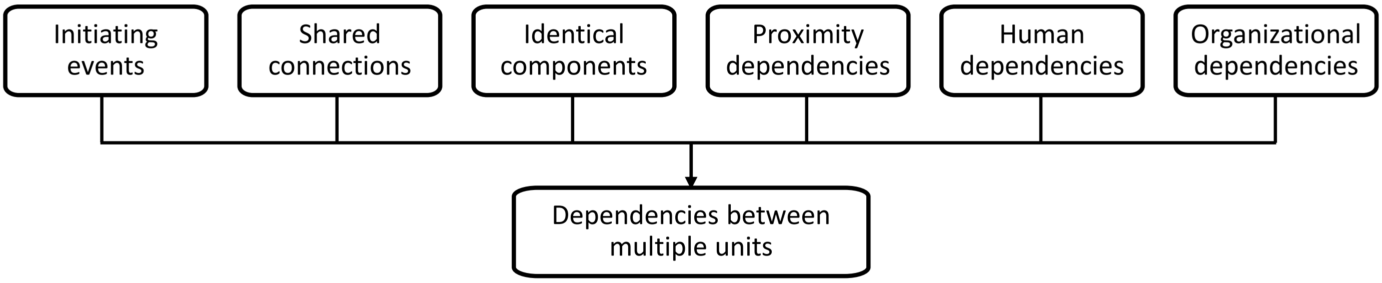

Fig.6. Commonality classification of dependent events

The initiating events can be divided into two subclasses: events that will always affect multiple units, referred to as "definite" events, and events that will only affect multiple units under certain circumstances, referred to as "conditional" events. Those events that will always affect multiple units include many external events including external flooding. In the study [6], the following five different type methodologies have been identified to account for multi-unit dependencies: combination, parametric, causal-based, extension, and external event type methodologies. The definite initiating events that will always affect multiple units would only need to use the combination methodology to be integrated into a multi-unit PSA. Since the single-unit PSAs should contain all of the potential initiating events, they would simply need to be combined. The items (SSCs, initiating events, etc.) that are already common to multiple plants will always be common; they simply need to be represented as one item in the multi-unit PSA so that they are not double counted in the quantification of the site CDF. For these items, there will be no effect on the site CDF (i.e., the site CDF is the CDF of one unit multiplied by the number of units on the site); however, the importance of the items may increase in the final risk importance measures.

It is important to note that in some accident scenarios developed in the Internal Events PSA, shared systems or systems with cross ties between units can be credited as mitigating systems. But when an external hazard occurs (e.g. flooding), all the equipment on site may be concerned. Thus, crediting shared equipment or safety systems of a twin unit can only be done on a case by case basis. The analysis of flooding scenarios must be done at the site level and the status of each unit of the site, in terms of components failed due to the flooding propagation at a given instant, must be taken into account.

In the case where the same initiating event is induced by the hazard scenario in these units, some systems required to mitigate this initiating event may be subject to inter-unit CCFs. This is the case for identical systems present in each unit which are required for the mitigation of the initiating event. As they are identical, this makes them potentially sensitive to "inter-unit" CCFs, in addition to "intra-unit" CCFs that are usually modelled for systems with redundancy. The main diesel generators of the units constitute an example of such a type of system. If each unit has two redundant diesel generators, an "intra-unit" CCF group of two is generally modelled in internal event PSA. In the event of a Loss Of Offsite Power (LOOP) affecting two units, the potentiality of a CCF affecting the four diesel generators should be studied. The same requirement applies for systems with cross ties between units. These systems are identical and present in each unit; interconnections exist and a system on one unit can be backed up by the same system on the other unit.

II.D. LINK WITH DESIGN BASIS

If one frequency is to be used, this should be the conservatively assessed hazard level that corresponds to a 10^{-4} p.a. Annual Exceedance Probability (AEP). The 'conservatively assessed' is generally understood to correspond to the 84th percentile[2] confidence level, i.e. one standard deviation. It must however be recognized that data is not always be available to carry out a suitable statistical analysis. Where this is the case engineering judgement must be used. Where cliff edge effects may occur (e.g. external flooding) a lower frequency should be considered. It is noted that frequencies of 10^{-5} and 10^{-6} p.a. have been used for this hazard. The frequency level for design extension conditions should also be defined. A value of below the design basis level to 10^{-7} p.a. or 10^{-8} p.a. (depending on the overall risk target) should be considered. Defining the hazard at a given frequency is not in itself enough. There should also be a statement as to whether the hazard is conservatively assessed, and where this is the case the conservatism should be quantified (if practicable). Finally the approach needs to take into account whether the frequency and hazard levels are to be used for design basis purposes (i.e. with a conservative approach) or for design extension and PSA purposes (i.e. best estimate). The data derived should be used appropriately.

II.D.1 Additional Emergency Measures and Mobile equipment

ASAMPSA_E experience gained from the study of the accident at Fukushima NPP is considered in details in [7] and [2]. If any design basis measures based on lessons learnt from the accident at Fukushima NPP have been implemented at NPP, they should obligatory be considered in the probabilistic model, since they can significantly affect accident sequences related to a complete loss of NPP power supply or loss of ultimate heat sink. The use of additional technical means and emergency teams to mitigate consequences of NPP accidents can have an impact on the possibility for occurrence of an initiating event and on accident progression scenarios. Specific attention should be paid to analysis of accident progression scenarios and equipment that potentially can be damaged and secondary effects of hazards. Since the secondary effects may progress in time and depend on severity of a hazard and its confinement, the following factors should be taken into account to consider additional technical means and external support:

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[2] The 84th percentile is generally understood in the UK and was used in Germany. Therefore this confidence level is stated.

- location of emergency teams (important in term of time needed to deliver equipment and take the required actions);
- type and quantity of available special equipment (important in terms of efficiency, and severity of hazards that shall be overcome);
- presence of blockages and other obstacles on the way (important in terms of time for delivery of equipment and for taking required actions);
- category of hazard consequences severity (important in terms of efficiency in their overcoming or possibility to overcome them in principle); and
- preparedness for the particular impact.

Thus, for correct accounting of the above factors, it is necessary to perform analysis of hazard progression scenarios and to explore the possibilities of additional technical means and emergency teams. The main success criterion to mitigate hazard consequences is the time of “deployment”, which plays one of basic roles in the analysis. For a positive outcome (for example, non-damage of additional equipment), the “deployment” time should be less than time for secondary effects to reach “key” points (should this include access ways of personnel to the required equipment or equipment important to safety). Therefore, the “deployment” time shall be defined taking into account training of emergency teams, time for delivery of special equipment taking into account blockages (for scenarios that envisage presence of blockages or obstacles), available NPP emergency response plan, procedures for obtaining permits from the physical protection, etc. In addition to the “deployment” time, success criterion includes specific nature of a hazard, category of hazard severity, hazard confinement, training of emergency teams, type and quantity of special equipment. The relevant analysis involves searching of correlation between the list of screened emergency events (scenarios of hazard progression) and the possibility of emergency teams to overcome or mitigate the consequences of a hazard.

In modelling response of external emergency teams, depending on the availability of statistical data on overcoming the consequences of hazards taking into account their specific nature, there are two ways to consider mitigation of accident sequences: 1) discrete/Boolean (based on results of deterministic analysis), which postulates a complete success or a complete failure in mitigation of consequences (confinement of equipment, ensuring access for personnel, complete overcoming of hazard consequences without its progression into the initiating event). 2) probabilistic, which considers representative statistics on successful/unsuccessful overcoming of relevant consequences of a hazards, taking into account their specific nature. With availability of sufficient and representative statistics, it is necessary to define probability of successful mitigation of consequences and to supplement the model with the relevant events (for example, top events in the interface event tree), which reflect probability of mitigation of hazard consequences. Application of any of the two described approaches requires collection of additional information and consultations with experts.

III. CONCLUSION

The state of the art methods are suitable for the modelling and assessment of frequencies for external hazards. However, dealing with combination of hazards (including correlated hazards) brings more open issues. On the other hand, the sources of hazards data and quality of hazard data as well as elements of hazard assessment methodologies and relevant examples could be used for hazards assessment within extended PSA, however complexity of work is increasing.

ASAMPSA_E project issues/outputs provide explanations and applicable solutions how to cope with different issues that appear in the process of assessment and evaluation of likelihood combinations of external hazards and their impacts. Examples of hazard assessment methodologies included in ASAMPSA_E documents just demonstrate usage of some practical methods and tools, which can be effectively used for calculations estimating frequencies of external events and which provide means for analysis of different data and its impact on the uncertain result. In majorities of cases, for external hazard assessment the extreme value theory is used in one or another way. The practical application of extreme value theory may differ depending on scope available data and parameters which are considered for the specific hazard. The issue of hazards combinations is solved by initial classification of dependencies between hazards and criteria, which allows to avoid irrelevant combinations of external events. It is important to note that some individual hazards (phenomena) already are combinations of hazards, so that analysis of such compound already covers analysis of individual hazards. Such analysis may depend on site and NPP design limits and is performed at the stage, when information necessary to assess the frequency and effect of combination is known. In the ASAMPSA_E project, as examples, the specific combinations were discussed and then methodologies suitable for the assessment of these hazard combinations were identified. It can be concluded that there are no difficulties in PSA model's logic and structure building for external hazards. A major limitations and gaps of PSA for external events are related to the data preparation and its implementation. Main uncertainties appear from the hazard evaluation and NPP response analysis issues.

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