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Probabilistic safety assessment of fire hazards

Keywords

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Abstract

An as far as possible exhaustive conceptual approach has been developed to systematically address all kinds of internal and external hazards and their potential combinations in Level 1 PSA in a comprehensive manner. The approach assumes a comprehensive generic compilation of hazards being available. By means of site-specific screening process it is decided which hazards need to be analysed in detail by means of probabilistic methods. The requested extension of the plant model is carried out by a systematic approach for those hazards to be analysed in detail. For this purpose, lists of hazard relevant structures, systems and components and their failure dependencies according to the hazards are derived. The comprehensive extension of Level 1 PSA by hazards is demonstrated at the example of plant internal fires.

1. Introduction

Endangering of people and environment as a potential consequence of the operation of a nuclear power plant (NPP) can be analysed and quantified by means of probabilistic safety analyses (PSA). Moreover, PSA is an effective tool to assist decision making for safety and risk management in NPPs. For that purpose, as a basic principle the entire so-called “initiating” events are analysed. Initiating events trigger sequences of events challenging the control of the plant and its safety systems the failure of which may lead to damage of the reactor core and/or the nuclear fuel.

There is an additional risk by internal and external hazards [5]. Hazards are events with damage mechanisms that can affect the whole site of nuclear facilities. Internal hazards originating from sources located onsite of a nuclear site, external hazards from sources offsite. Examples of internal hazards are internal fires, explosions or floods or missiles, e.g. from the turbine. Examples of external hazards are seismic hazards, external floods or severe weather conditions as well as external fires, pressure waves, etc. Subsequently, a methodological approach is outlined, how a given Level 1 PSA for a NPP can be extended to be used as quantification tool for the risk from the impact of the variety of hazards and their consequences to nuclear safety. The corresponding systematic extension of Level 1 PSA is described in more detail at the example of plant internal fires as an internal hazard.

In a first step, it is assumed that a standard Level 1 PSA for plant internal events is available to the analyst for assessing the entire initiating events of a NPP and that the corresponding quantifiable plant model is ready to be used for an extension by events from internal and external hazards. This plant model characterises the whole (technical) configuration of the NPP and the random failure behaviour of its structures, systems and components (SSC) by means of event and fault trees.

The given plant model can be extended by conditional SSC failures for all hazards relevant at a given plant site. Hazards are called relevant if it can be decided within a screening process by means of suitable weighting criteria that a detailed probabilistic analysis is needed. The extension of the standard Level 1 PSA plant model is systematically carried out using lists of SSC. One of these lists contains all SSC which are both important for the safety of NPP and vulnerable by the hazard considered. A second list contains the failure dependencies of those SSC which have to be examined if a hazard occurs (cf. Section 3).

In Section 4, the methodological approach developed is exemplified by the internal hazard fire. It is demonstrated how the standardized method of plant model extension needs to be adapted in case of a fire hazard.

2. Performing PSA

For more than 30 years PSA have been performed to enhance the safety of nuclear power plants. Insights from and findings of PSA resulted in safety significant improvements of SSC as well as procedures. PSA results significantly contributed to an increase of the safety level of NPP operation. After the severe reactor accidents at the Japanese NPP site of Fukushima Dai-ichi site in March 2011 intense activities focusing on methodological developments are ongoing worldwide to systematically address hazards in deterministic as well as probabilistic safety analyses in a comprehensive manner.

A hazard is defined as a plant internal or external incipient event that can result in initiating events or in failures of safety functions. The impact of a hazard does not only affect single components or structures but can cause damage to the whole plant site. Hazards are events with damage mechanisms which may concern the whole NPP site. In principle, two types of hazards have to be distinguished: internal hazards such as plant internal fire, explosion, or flooding and external hazards. The latter can be subdivided in two groups: natural hazards such as earthquakes, external flooding, or biological infestation, and man-made hazards (e.g. aircraft crash, explosion pressure wave.

Chapter 4 of this paper particularly addresses plant internally occurring fire events as internal hazards. In a first step, a general overview on how to perform Level PSA 1 aiming on the determination of core damage and fuel element damage frequencies is given. In a second step, a conceptual approach for extending Level 1 PSA for all plant operational phases by the impact from hazards is introduced.

PSA methodology applies the inductive procedure of event tree analysis, well-known from decision theory. The root of an event tree is given by an initiating event, e.g. a leakage of a pipe or a loss of power. The initiating event alone normally cannot result in core damage because there are redundant safety related systems for mitigation of its consequences. That means that for any core damage scenario several safety systems must fail. The branches of the event tree are defined by potential failures of safety systems or of accident mitigation measures. The branch point probabilities can be calculated by means of the fault tree method. The leaves of the event tree are attained if the initiating event is either successfully controlled or if core damage cannot be anticipated. The results of such a given scenario are frequencies of core damage states representing those leaves of the event tree ending with significant damage.

The sum of the core damage frequencies for the entire scenarios being relevant for the analysis is the overall annual core damage frequency of the NPP.

A Level 1 PSA model comprises all relevant initiating events and their corresponding occurrence frequencies. The set of the entire event and fault trees generates the so-called "*Level 1 PSA plant model*". The smallest units of the plant model are called *basic events*.

In the most cases, Level 1 internal events PSA basic events characterise failures of the required functions of technical components. In such cases the basic event model describes the scope of the component (Which elements are part of the component? What are the component's boundaries?), the component failure modes, and reliability parameters which are needed to calculate the failure probability (What is the operation mode of the component? How is the maintenance procedure organized?). There are some other failure modes which also can be characterised by basic events in the plant model, e.g. faulty performance of human actions, malfunction of support systems or reduction of redundancies due to maintenance and repair.

3. Probabilistic Analyses of Hazards

For extending probabilistic analyses systematically to the variety of hazards to be addressed the Level 1 PSA plant model for plant internal events has to be extended. In the following, it is therefore assumed that a Level 1 PSA for internal initiating events and the corresponding plant model are available. This plant model should be extended on the level of basic events such that hazard induced failures of SSCs can be comprehensively considered. For that purpose, for each hazard or combination of hazards a list of SSC is compiled such that a failure of any SSC of the list contributes to the frequency of core and/or fuel element damage states. This list of SSCs *H-EL* is called *hazard equipment list* due to the hazard regarded. In case of an earthquake a seismic equipment list S-EL is generated.

In the following, a short outline of the methodology performing a site-specific Hazards PSA is given. In this context, an important task is to realise a comprehensive Level 1 PSA. The plant model for internal initiating events is derived for the risk characteristics needed (e. g. core damage frequency for the reactor in operation and fuel damage frequency for the spent fuel pool) and ready to use. This probabilistic analysis should be extended to cover damages and their frequencies as consequence of hazards. For that purpose, all site-specific internal and external hazards including potentially relevant hazard combinations have to be assessed probabilistically. The procedure is depicted in *Figure 1*.

A generic list of internal and external hazards and their combinations represents the basis for performing a site-specific Hazards PSA. This annotated list contains in a first stage at least all known hazards which have been observed worldwide. The annotations are to the occurrence frequency of the hazards, the corresponding site characteristics and the generated damage.

The potential hazards on site must be categorised; therefore classification criteria have to be derived. The following three categories can be distinguished:

- *Category 0* (contains hazards without relevance for the site to be analysed),
- *Category A* (contains those hazards for which a rough risk estimation is sufficient for the given site), and
- *Category B* (contains those hazards for which a comprehensive in-depth probabilistic analysis is necessary).

For each hazard of category B, which may significantly impact the plant safety, the initiating events possibly induced by these hazards and their dependencies need to be determined and modelled within the Level 1 PSA plant model. The fault trees charactertising the failure behaviour of the safety systems are the main part of the plant model. These fault trees must be extended by hazard induced failures of SSCs. Therefore the concept of equipment and dependency lists (hazard equipment list *H*-EL, hazard dependency list *H*-DL) has been developed.

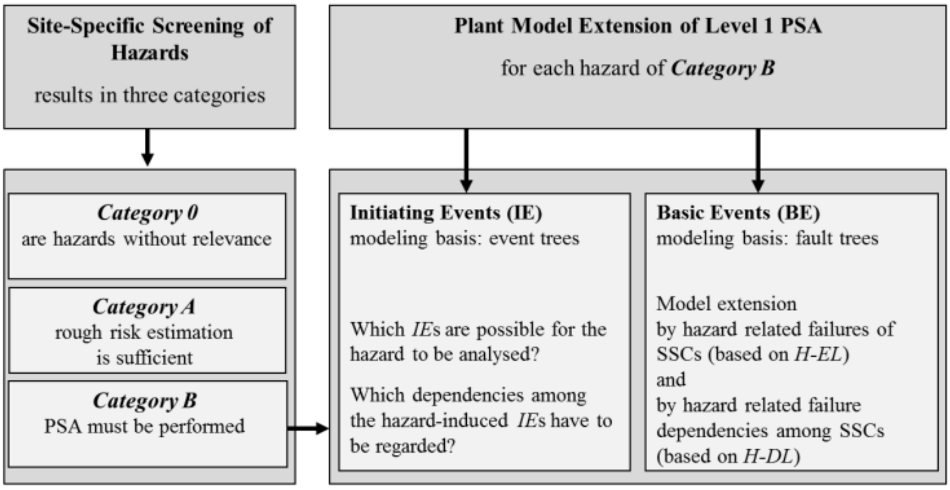

Figure 1. Plant model extension of Level 1 PSA for internal and external hazards [6]

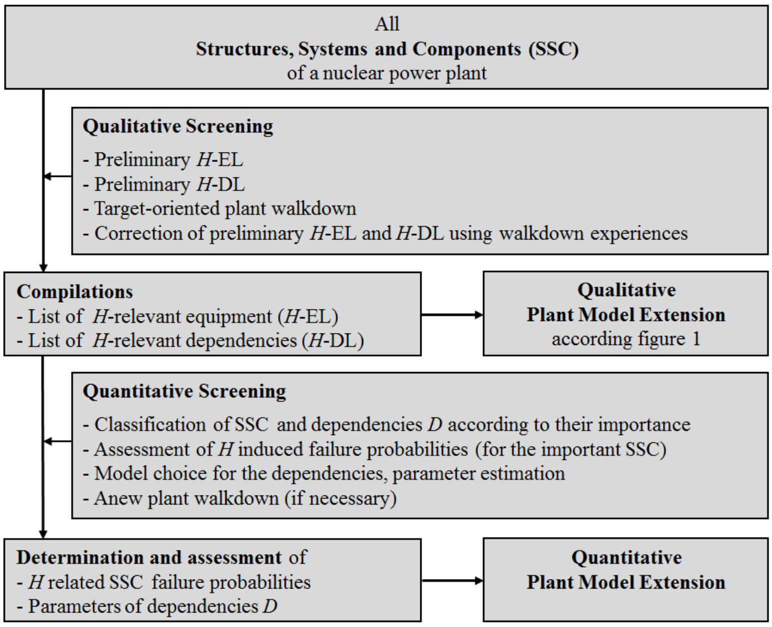

Figure 2. Determination of *H*-EL and *H*-DL (two-step screening approach)

In the following, a short overview of this approach (see also *Figure 2*) is presented. A more detailed description is given in Section 4 for the example of fires as internal hazards. The whole concept and its application are provided in detail in [2], [4] and [6].

It is assumed that a given Level 1 PSA plant model should be supplemented by describing the failure behaviour of SSCs with regard to a hazard *H*. For that purpose, it has to be checked for each basic event in the fault trees of the plant model if the corresponding SSCs can also fail as consequence of *H*-impact. In addition, it has to be analysed, if there are *H*-induced SSC failures not addressed in the given Level 1 PSA.

The so-called "*hazard equipment list" H*-EL is derived to be applied for the systematic extension of the plant model with all *H*-induced failures. This list contains the entire SSCs which can fail as a consequence of a hazard *H* and the failure provides a risk contribution.

A two-step screening approach has been developed to determine *H*-EL and to perform the plant model extension (cf. *Figure 2*). In the first step, the fault trees are extended by additional basic events characterising *H*-failures of SSCs (cf. *Figure 3*). In the second step, the corresponding failure probabilities depending on *H*-intensities have to be determined. This step is called the quantitative plant model extension. During the quantitative screening a decision is needed for which SSCs of the *H*-EL it is really necessary to estimate the conditional failure probability according to a given hazard *H* and in which detail this needs to be performed. This approach has been successfully demonstrated for seismic hazards supported by a database application [3].

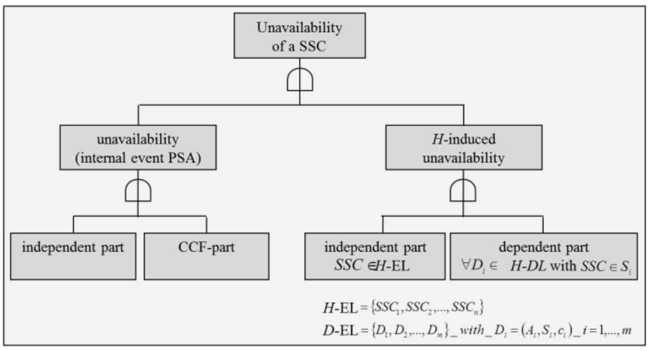

Figure 3. Fault tree extension by *H*-induced independent and dependent failures [6]

Another list to be generated is the so-called *hazard dependency list* (H-DL). This list contains all dependencies *D* among those SSCs, which have to be considered when modelling *H*-induced failures. This dependency list is also derived within the two-step screening approach presented in *Figure 2*.

Any hazard related dependency of failure behaviour between more than one SSC is characterized by a triple called *D*; *D = (A, S, c)*. *S* symbolizes the set of SSCs which are assumed to fail dependently in case of a hazard. The symbol *A* denotes the common attribute of all SSCs of *S* which may be responsible for the failure of more than one up to all SSCs of *S* in case of a hazard. The coupling function *c* describes to which extent the common attribute *A* causes failures of more than one SSC of *S* due to the hazard.

The list *H-DL* includes all dependencies *D* between those SSCs, which have to be considered in case of hazard induced failures. For the compilation of *H-DL*, a screening approach is recommended. Both lists *H-EL* and *H-DL* are verified and supplemented in the course of extensive plant walk-downs.

If a SSC is an element of *H-EL* and if this SSC is also part of a dependency *D* from *H-DL*, the fault tree characterizing the unavailability of this SCC can be complemented as shown in *Figure 2.*

4. Fire PSA

The risk originating from operating nuclear facilities can quantitatively assessed by means of Level 1 PSA. It is necessary to derive a mathematical model of the facility, the so-called "*PSA plant model*", which comprises all initiating events. In Section 3 it is shown that the plant model can be extended in a standardised manner for characterising the impact of any given hazard. In the following, the plant model extension is demonstrated for the internal hazard fire.

4.1. Concept of Rooms

In order to carry out a probabilistic analysis of the effects of fires in nuclear power plants to the overall risk, the layout of the plant is sub-divided into appropriate spatial units. This procedure is called plant partitioning. These spatial units are referred to as rooms hereafter. This is a notational convention only, because a so-called room does not necessarily indicate a room in colloquial sense, namely, that such a room has got walls, a ceiling and a floor. As a general rule, the plant partitioning performed for the purpose of the analysis is carried out by using the existing structure of plant compartments or areas for which a nomenclature does already exist. Depending on the necessary level of detail for the analysis, a finer or coarser spatial partitioning may be chosen. The fire induced risk of the NPP is the sum of the fire induced risks posed by the individual rooms resulting from the partitioning. In this context, it is assumed that the entire rooms (for Fire PSA purposes often also called "compartments") identified cover at least all NPP buildings relevant for the analysis and that there is no overlap of any pair of rooms. Buildings are referred to as relevant ones, if in the event of fire any equipment inside the building may be damaged and the failure of this equipment would contribute to the target value of the analysis. Modelling applying event and fault trees depends on the analysis target of the study. In the case of Level 1 PSA at full power operation, the target is the determination of the core damage frequency (CDF), for low power and shutdown states it is the fuel damage frequency (FDF).

A Fire PSA is performed step by step. The screening approach starts with a wide mesh room grid. More and more rooms can be screened out stepwise according to a negligible risk contribution, e.g. if there are no safety related components in the room and in the near vicinity. Other quantitative screening criteria require that the risk contribution is less than a given threshold value. For the remaining rooms in-depth investigations with detailed analyses have to be carried out (see *Figure 4*). That means that the room grid is chosen more closely.

In order to determine the risk from fire inside a room applying a quantifiable plant model in line with the analysis target, the following data and information are required:

- Room specific fire occurrence frequencies,
- Equipment lists for all rooms including cables,
- Equipment classification with respect to their potential risk significance,
  (1) Items important to safety (so-called "*PSA equipment"*),
  (2) Items, which in case of their fire induced failure may contribute to an initiating event (so-called "*IE equipment"*), and
  (3) Other equipment (irrelevant for fire risk analysis);
- Arrangement of rooms in the building (neighbouring influences) and probabilities of fire spreading from one room to an adjacent one;
- room-related fire damage probabilities for the entire class (1) and (2) equipment.

The room related fire damage probabilities as well as the probabilities of fire spreading are determined by means of fire event trees, considering available information and knowledge about fire detection and alarm and fire extinguishing as well as about possible operator actions. It is assumed that the conditional fire induced damage probability is the same for all the equipment installed in a given compartment. This probability is also referred to as the *compartment damage probability*.

The total fire induced risk of a NPP can be derived adding up the fire induced risk contributions from the entire rooms (see *Figure 5*).

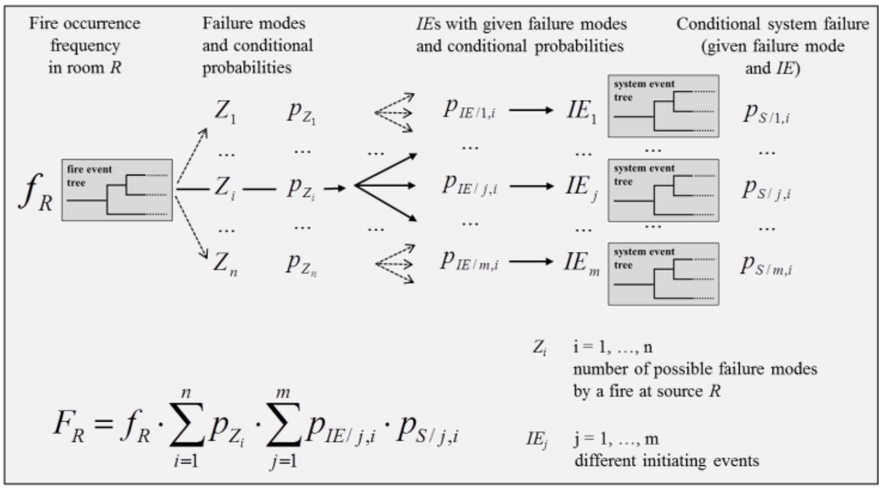

Figure 4. Determination of the fire risk of room *R*

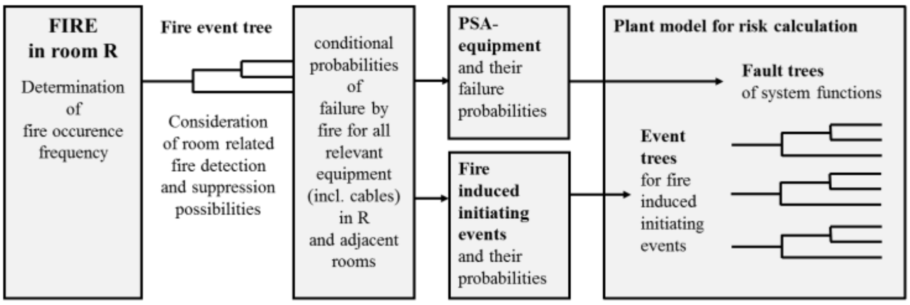

Figure 5. Rough modelling steps for fire risk determination of room R [1]

4.2. Systematic Extension of Level 1 PSA by Fire Events

A Level 1 PSA and the corresponding quantification model are given. A systematic fault tree extension should be performed as described in Section 0. The necessary partitioning of the NPP and its buildings into rooms (cf. par. 4.1) has been carried out and is known. The next step consists of compiling the corresponding fire equipment list F-EL and fire dependency list F-DL.

The fire equipment list contains all those SSCs which may fail due to the effects of fire. Their failure provides a contribution to the overall risk of the plant. These SSCs are called "*fire relevant SSCs*". Typically these are essential technical components including their power and control cables. For each SSC in *F-EL* its location represented by the corresponding room is provided (see the example in *Figure 6*). Starting point for the *F-EL* compilation is the list of all basic events in the given Level 1 PSA. The entire corresponding components are analysed in respect if fire induced failures are possible. The list of fire relevant components must be supplemented by all power and control cables which are necessary to fulfil the required safety functions of the components.

The procedure for determination of IE-equipment and their recording in the fire equipment list *F-EL* is the same as described above if there are fault trees included in the Level 1 PSA which are used to calculate the frequencies of initiating events based on component failures. If that is not the case, those components must be found which failures contribute to the onset of an initiating event. After that, it has to be determined for each room if in case of fire (and the assumption that the entire components including cables in the room fail) an initiating event will occur. The fire conditional probability of this initiating event has to be roughly assessed.

The fire dependency list *F-DL* contains the fire spreading probabilities (c_{AB}, c_{BA}) for each pair of adjacent rooms (R_A, R_B). The modelling of fire spreading on to adjacent rooms (spreading depth 1) is presented in *Figure 6*. The consideration of a fire spreading depth greater than 1 is possible. The fault trees must be extended recursively. The fire spreading probability from a fire source in room R_A to room R_C (R_A and R_C are not adjacent) is characterised by the product of the spreading probabilities of consecutive adjacent rooms. If there are different fire spreading possibilities, the total spreading probability is roughly estimated from the sum of spreading probabilities of all these possibilities. According to experience, for the majority of applications the consideration of spreading depth 1 is sufficient.

Now, such extended plant model can be used to quantify and assess the impact of fire events on the risk operating the nuclear facility.

It is illustrated that the general method presented in chapter 3 is easy applicable, but - of course - the concrete procedure must be adapted for any individual hazard. In case of hazard fire that means that the basic events describe failures of rooms and the dependencies are defined as the possibilities of fire spreading between adjacent rooms.

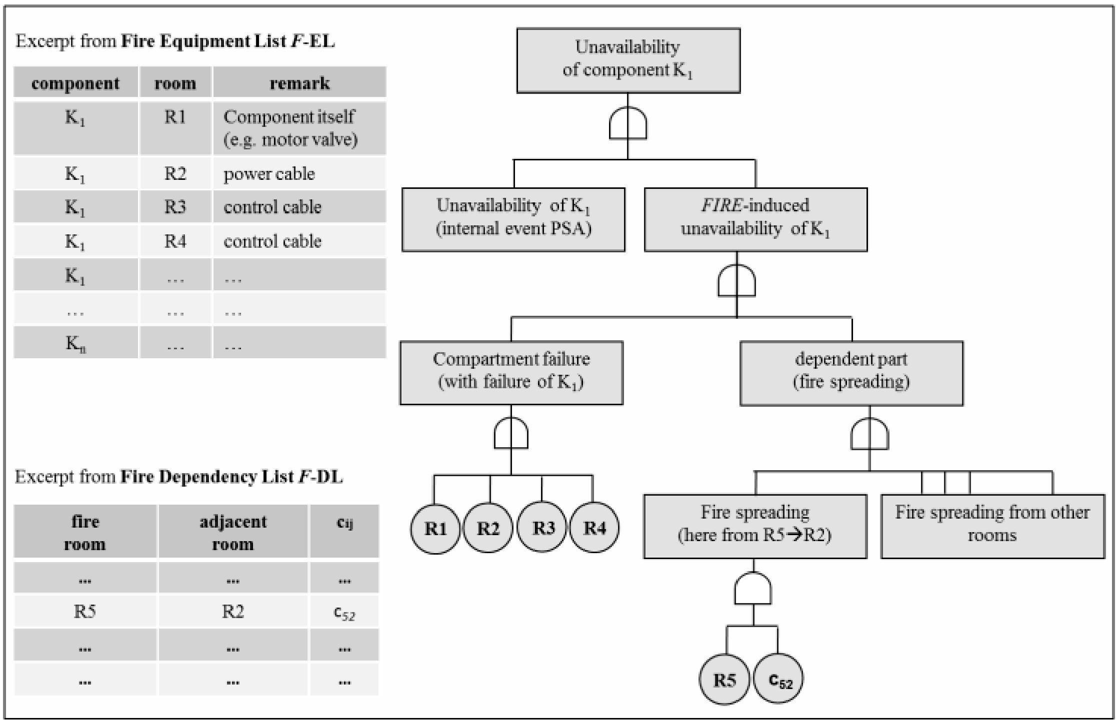

Figure 6. Application of equipment and dependency lists to extend the fault trees by fire induced failures [6]

5. Conclusion

As a result of the investigation of the reactor accidents at the Fukushima Dai-ichi nuclear site, a systematic and as far as possible exhaustive conceptual approach has been developed to address all kinds of internal and external hazards in Level 1 PSA in a comprehensive manner. In this approach, it is assumed that a comprehensive generic compilation (list) of hazards including potential hazard combinations is available. Within a site-specific screening process it has to be decided how each hazard is to be assessed: the risk contribution of a given hazard can either be neglected, or the risk needs only to be roughly assessed, or the risk has to be calculated in detail by means of probabilistic methods.

A consistent approach for the requested extension of the plant model is proposed for all those hazards which must be analyzed in detail. For this purpose, lists of hazard relevant SSC (*H*-EL) and their hazard related failure dependencies (*H*-DL) are derived in a systematic way.

In the paper, a successful application of the approach to the plant internal hazard fire is presented. It has been outlined how the systematic (and partly automated) extension of the fault trees is carried out applying the fire equipment list (*F*-EL). The *F*-EL contains a compartment assignment for all relevant components including cables. Furthermore, it is explained, how the possibility of fire spreading can be adequately addressed applying a fire dependency list (*F*-DL).

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