

# Event Tree Methodology as Analytical Tool for Fire Events

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**Abstract:** A key element of performing Fire PSA is the determination of fire induced failure probabilities of components and cables for those fire sources identified as relevant. Such determination is usually made by means of fire event trees. The Fire PSA analyst derives specific fire event trees for all possible fire sequences taking into account plant characteristics (e.g. on-site plant internal or only external fire brigade), the compartment specific situation and boundary conditions (e.g. room volume and ventilation conditions), potential fire sources (e.g. location, material) and safety targets (e.g. components, cables). Generic fire event trees could be a helpful starting point for the analyst, but these generic event trees must be adapted within a plant specific Fire PSA, e.g. the branch points have to be checked if they are really reflecting the plant characteristics and the branch point probabilities have to be determined by applying plant specific data.

Generic event trees can be applied for another purpose as well. A set of standardized generic event trees can be used to describe the main fire specific characteristics of fire events observed from the operating experience. This approach is particularly convenient for the analysis of sets of fire events. Within an ongoing research and development project a set of generic fire event trees has been developed, consisting of:

- a time dependent event tree which sub-divides a fire event into different phases,
- an event tree specifically addressing fire detection, and
- an event tree specifically addressing fire suppression.

The set of generic fire event trees characterizes all the possibilities of the phases of fire initiation, fire development and spreading as a stochastic process. Each fire event having occurred represents a realization of this process and can be described by a corresponding sequence number.

Presently, the international fire events database OECD FIRE contains more than 420 fire events from 146 nuclear power plants (PWR and BWR) from 12 countries. The above mentioned set of generic fire event trees can be used to analyze the fire events reported to the OECD FIRE Database. In other words, for the entity of fire events observed from the operating experience collected from nuclear power plants in these countries the corresponding sequence numbers of the generic fire event trees can be determined. The triplet of sequence numbers represents an additional attribute of each reported fire event, which will be stored in the OECD FIRE Database as additional information. The paper presents examples how to use this new attribute of the OECD FIRE Database to retrieve additional information on trends of the fire events observed, which may be used to solve future fire analysis tasks.

**Keywords:** Fire PRA, event tree, OECD FIRE, database, operating experience

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## 1. INTRODUCTION

One of the key elements of performing Fire PSA is the determination of fire induced failure probabilities of components and cables for those fire sources identified as relevant. Such determination is usually made by means of fire event trees. The Fire PSA analyst derives specific fire event trees for possible fire sequences taking into account plant characteristics (e.g. on-site plant internal or only external fire brigade), the compartment specific situation and boundary conditions (e.g. room volume

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and ventilation conditions), potential fire sources (e.g. location, material) and safety targets (e.g. components, cables). Generic fire event trees may be a helpful starting point for the analyst, however, these generic event trees must be adapted within a plant specific Fire PSA, e.g. the branch points have to be checked if they are really reflecting the plant characteristics and the branch point probabilities have to be determined by applying plant specific data.

Generic event trees can be applied for another purpose as well. A set of standardized generic event trees can be used to describe the main fire specific characteristics of fire events observed. This approach particularly supports the analysis of samples of fire events.

## **2. FIRE EVENT TREES**

Fire events are complex continuous stochastic processes. Such processes depend on numerous random variables that characterize the fires from ignition to suppression. The event tree methodology can be used to discretize complex fire events.

Within Fire PSA, the conditional probability of fire induced initiating events as well as of failures of safety related components is calculated by means of the fire event trees. A fire event tree is used to assess the possibilities of fire growth and spreading. Such a fire event tree covers the characterization of the incipient fire at a fire source (e.g. by location, component where the fire started, fire load, etc.) taking into consideration the fire location characteristics in terms of fire detection, fire alarm and fire suppression. Normally, there are several potential fire sequences with different consequences depending on the effectiveness of the factors determining fire growth (branch points in the fire event tree). Consequences may range from no damage (fire self-extinguished at the fire source, no impact on components relevant for the risk) to damage of one or more components up to complete compartment failure (all components inside the compartment are assumed to be failed) or fire propagation to adjacent compartments.

There are given generic fire event trees in several Fire PSA guidelines. It is proposed that these generic trees are used for performing Fire PSA, hence they have to be adapted taking into account the plant specific characteristics. In the following, two examples of such generic trees are given:

- IAEA [1], Appendix IV provides an example of a fire event tree. This fire event tree is also given in the German Guide on PSA Methods [2].
- In [3], Appendix P, a generic fire event tree and its use to determine the likelihood of fire damages are extensively discussed. This event tree is also used as one of the generic trees within our method to assess the fire events from the OECD FIRE Database (cf. Section 4).

One observation from Fire PSA performed according to the NRC/EPRI Guideline for Fire PRA [3] is the inconsistency between the fire event descriptions in these Fire PSAs and the operational experience. In [4], it is mentioned that the Fire PSA results are too conservative suggesting that they are really not suitable for subsequent use in safety related assessment and decision making. A set of application areas is provided where further research and development are necessary to perform Fire PSA more realistically. Some of these application areas are closely linked to the generation of fire event trees, e.g. assumptions for identification of an incipient fire, fire suppression, and fire spreading as well as fault conditions of components. In this context, it is important that all fire events compiled in the OECD FIRE Database are also analyzed as fire sequences of a fire event tree from verification of the fire to fire alarm and extinguishing [5]. The development of a real fire event is a realization of a stochastic process described as a set of possible sequences within a fire event tree.

## **3. OECD FIRE DATABASE**

Presently, the international fire event database OECD FIRE contains more than 420 fire events from 146 nuclear power plants (PWR, BWR and PHWR) from 12 countries [6].

The current version of the OECD FIRE Database contains, in addition to the previously available search functions, a variety of new ways to automatically evaluate the existing pool of fire events. Each fire event is characterized by a number of properties, such as “operating condition prior to the fire” and “operating condition after the fire”. For each of these characteristics a nomenclature is given (see e.g. Table 1) in order to compare various fire events and to enable quantitative evaluation of fire events.

**Table 1: Exemplary nomenclature for two selected attributes of fire events and numbers of fire events in sample 1 (red) and sample 2 (black)**

Operating mode prior to fire				Operating mode due to fire			
CONST	construction phase	1	1	NCH	No operation mode change	22	35
DECOM	decommissioning	-	-	HSB	Hot stand by	5	4
HSTND	hot standby	1	2	SHD	Shutdown mode	6	16
POWER	power operation	22	35	UNK	unknown	1	-
SHUTD	shutdown mode	9	15				
START	start-up mode	1	2				
UNKNW	unknown	-	-				

In the examples presented in this paper two samples of the fire events as collected in the Database version 2013:1 [6] with data up to the end of 2012 [7] have been used: sample 1 consists of 34 fire events from German nuclear power plants, and sample 2 consists of 55 severe fire events in nuclear power plants from all member countries characterized by the loss of one train, several trains or all safety trains.

In a probabilistic study with respect to the effectiveness of fire safety measures in nuclear power plants, it is recommended to use existing operating experience, i.e. to evaluate experience with real fires and their safety measures. Depending on the problem, the analysis applies to a defined sample from the total amount of data of the OECD FIRE Database. If e.g. the analytical task regards the reliability of automatically actuated fire detectors, the sample should include only those fires where fire detectors were installed in the fire area or in its vicinity. In the current version of the OECD FIRE Database such samples can be easily collected and prepared for analysis.

Using samples 1 and 2 it is exemplarily shown in Table 1 and Table 2 which reports can be derived from the OECD FIRE Database [6]. Moreover, a new analytic option that corresponds to the complex nature of fire events is presented in Section 4 theoretically and in Section 5 practically based on samples 1 and 2.

**Table 2: Cross table for the attributes in Table 1 (sample 1, sample 2)**

	HSB		NCH		SHD		UNK	
CONST	-	-	1	1	-	-	-	
HSTND	-	-	1	1	-	1	-	
POWER	5	3	10	17	6	15	1	
SHUTD	-	1	9	14	-	-	-	
START	-	-	1	2	-	-		

#### 4. CHARACTERIZATION OF FIRE EVENTS BY MEANS OF GENERIC EVENT TREES

Generic fire event trees are mainly used for the following two tasks:

- Providing a guideline for generating specific fire event trees as a tool to determine conditional fire damage probabilities for a given fire source (as described in Section2), and
- Providing a guideline for mapping fires observed.

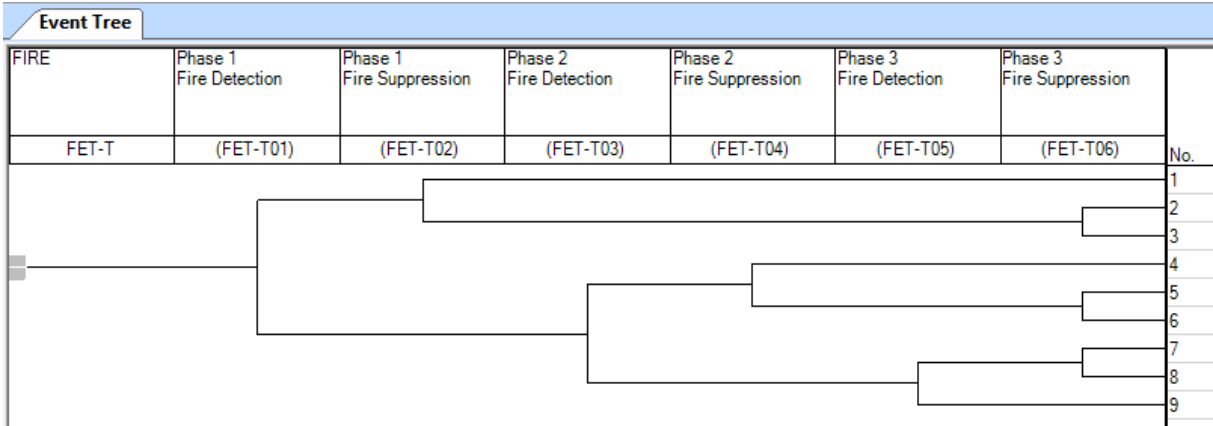
The second task starts with a reported fire event. If a generic fire event tree is given, this real fire event can, neglecting some details, be assigned to the generic event tree. The observed fire event represents one sequence of the generic tree. It is a realization of the stochastic fire process roughly characterized by the generic fire event tree. The fire event observed is assigned to a characteristic sequence number of the generic tree. Thus this fire event can be compared with other ones observed and be subjected to statistical reasoning.

When deriving a suitable description for fire events allowing the events to be mapped in a generic fire event tree the information collected in the OECD FIRE Database (properties and description of fires) can be used.

Within an ongoing research and development project a set of generic fire event trees has been developed, consisting of:

- a time dependent event tree FET-T which sub-divides a fire event into different phases (Figure 1),
- an event tree FET-D specifically addressing fire detection (Figure 2), and
- an event tree FET-S specifically addressing fire suppression (Figure 3).

**Figure 1: FET-T event tree**



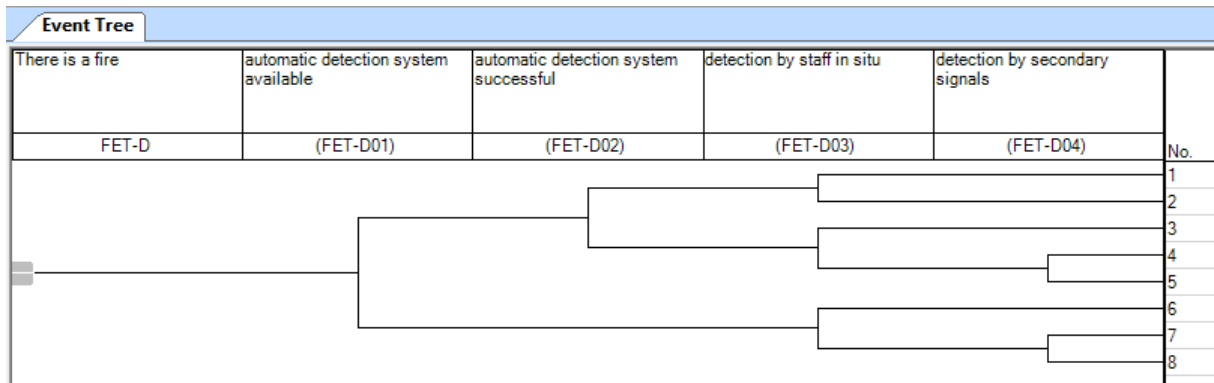
The time-related event tree FET-T is adopted from [3], Appendix P (details see Section 2). Three phases can be distinguished in the course of fire:

- prompt fire detection and suppression (phase 1),
- automatic fire detection and suppression (phase 2) and
- delayed (manual) fire detection and suppression (phase 3).

Each phase is characterized by boundary conditions, e.g. prompt (immediate) fire detection in phase 1 can be credited only, if staff is permanently present in the fire compartment. Prompt fire suppression is e.g. possible in case of hot work fire scenarios with humans being present in the plant area.

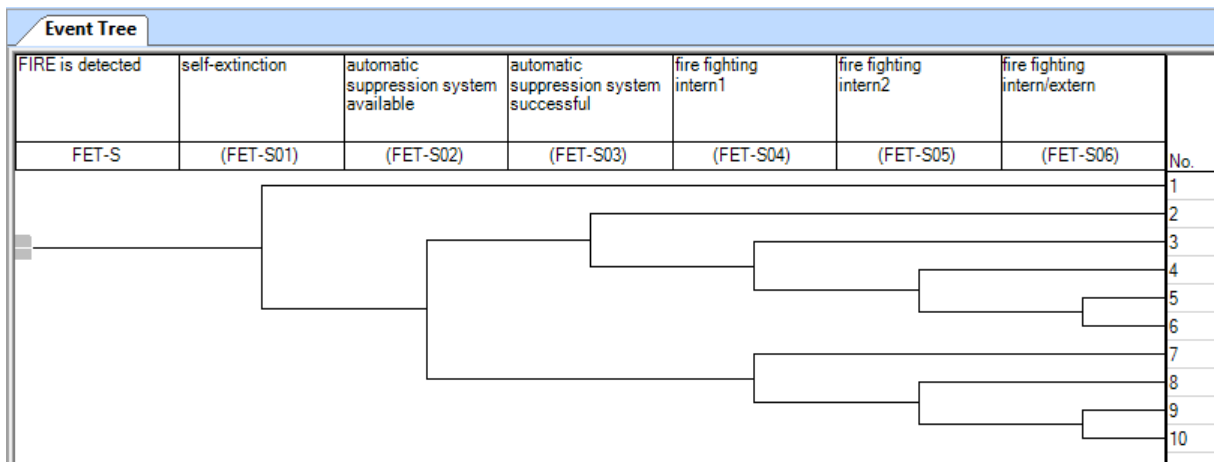
Automatic detection (phase 2) refers to cases where an automatically actuated fire detection system equipped with either smoke or heat detectors is installed. Similar availability considerations are applied to automatically actuated stationary fire extinguishing systems including water based sprinklers or water deluge systems, CO<sub>2</sub> gas extinguishing systems, etc. Phase 3 is characterized by delayed detection of the fire, either by fire detectors in other compartments in the vicinity of the fire compartment itself or indirectly by secondary signals. In this case response by the fire brigade may be necessary. The actions of the fire brigade cover manual actuation of stationary fire extinguishing systems, confinement of fire sources, de-energizing of systems, as well as manual firefighting by portable fire extinguishers or water hose.

**Figure 2: FET-D event tree**



The event tree FET-D is related to fire detection distinguished between fire events that were detected automatically, by secondary signals and/or manually by staff or other people.

**Figure 3: FET-S event tree**



The event tree FET-S addresses the suppression of fires distinguishing between fires self-extinguishing, those being extinguished by automatic suppressions systems and manual firefighting by internal/external personnel over a short/long time.

## 5. ANALYSIS OF FIRE EVENTS WITH GENERIC EVENT TREES

Any set of fire events can be analyzed by means of the generic fire event trees in Figures 1 to 3. However, the event trees (Figures 1-3) have been specifically developed for and on the basis of the OECD FIRE Database.

For each and every fire event the corresponding sequence number is determined through the generic fire event trees (Figures 1-3). Moreover, for the benefit of transparency regarding the determination of the sequence number a clarifying text can be assigned to each fire event and fire event tree. In Table 3 an extract of this data is presented.

In the following, the fire event sequences of samples 1 and 2 (cf. Section 3) are analyzed by means of the method presented. For each sample the sequence numbers are generated and with the help of a small EXCEL sheet the corresponding event trees with associated number of events and percentage are produced. In Figures 4 to 6 this is demonstrated for both samples. The two samples have several similarities worth mentioning. Both samples consist of a similar number of events (34 and 55 events respectively) of fire events having occurred in nuclear power plants of the OECD FIRE member

countries during the last 40 years. Furthermore, both samples consist of fire events that have involved safety equipment.

Moreover both samples contains fire event from Germany causing the samples to overlap each other regarding a few (nine) events. One of these German fire events, included in both samples, occurred in 1979 and is unfortunately of low detail level which disqualifies the event for the analyses presented in Section 5 of this paper. Therefore, the total number of event assessed in Section 5 is for sample 1 – 33 and sample 2 – 54.

**Table 3: Sequence mapping**

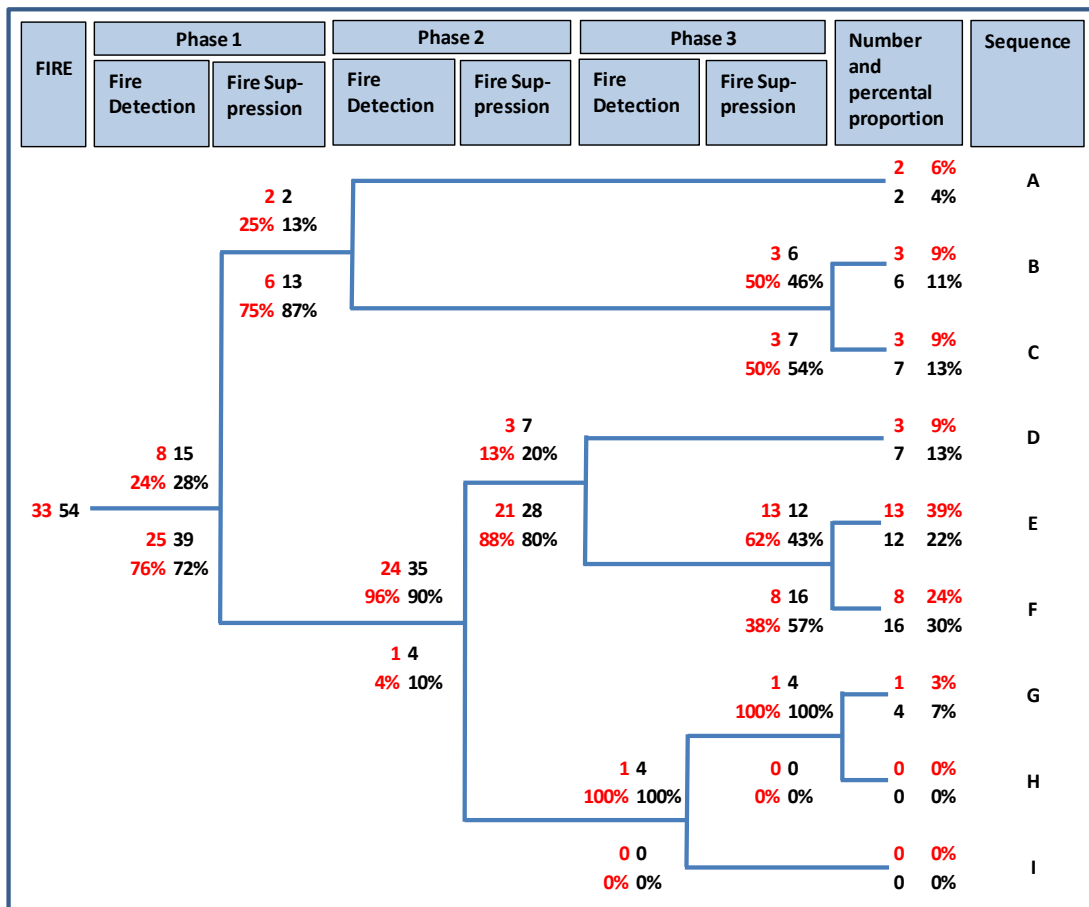
ID <sup>†</sup>	Sequence number			Clarifying text for the mapping of the sequence number		
	FET-T	FET-D	FET-S	FET-T	FET-D	FET-S
81	5	2	7	<u>Detection:</u> t < 5 min <u>Suppression:</u> ca. 30 min	Fire detector	Manually through internal fire brigade (several attacks needed), no fixed fire extinguishing equipment present
93	7	6	7	<u>Detection:</u> t < 15 min <u>Suppression:</u> t < 15 min	Detection through personnel, fire detectors were not involved	Manually through shift personnel (one attack needed), no fixed fire extinguishing equipment present
124	6	2	8	<u>Detection:</u> t < 1 min <u>Suppression:</u> t < 60 min	Fire detector and indirect signals	Manual actuation of the fixed fire extinguishing equipment through the internal fire brigade (several attacks needed)

However, there are a number of differences as well. As presented in Figure 4, sample 1 contains a higher percentage of sequences E than sample 2. This is most probably due to the difference of severity of the fires in the different samples. More specifically, about the same ratio of events (approx. 88 % - German ones, approx. 80 % - severe ones from sample 2) were not identified in the first 5 minutes, but identified by smoke detectors and then not suppressed by an automatic fire extinguishing system but by internal and/or external personnel. The difference of the samples is demonstrated through the required number of extinguishing attacks. This leads to the conclusion that fires that cause loss of one or more safety trains (sample 2) tend to be larger and are more difficult to extinguish than those of a more general sample such as sample 1.

Another significant difference between the two samples can be found in sequence G with a percentage of approx. 7 % for sample 2 and approx. 3 % for sample 1. Sequence G represents fire events that are not immediately detected either by humans being present or by automatically actuated fire detectors, but are detected in a later stage by personnel. The reason for the difference between the two samples is not distinct, since both samples contain the same type of fire events in sequence G. Both samples include fires without fire detectors present in the fire compartment. In addition, sample 2 contains one event with fire detectors present in the compartment where the fire started, however due to very little smoke released detectors did not actuate. Except for these two dissimilarities the samples, evaluated according to Figure 4, are essentially the same.

<sup>†</sup> event ID in OECD FIRE Database [6]

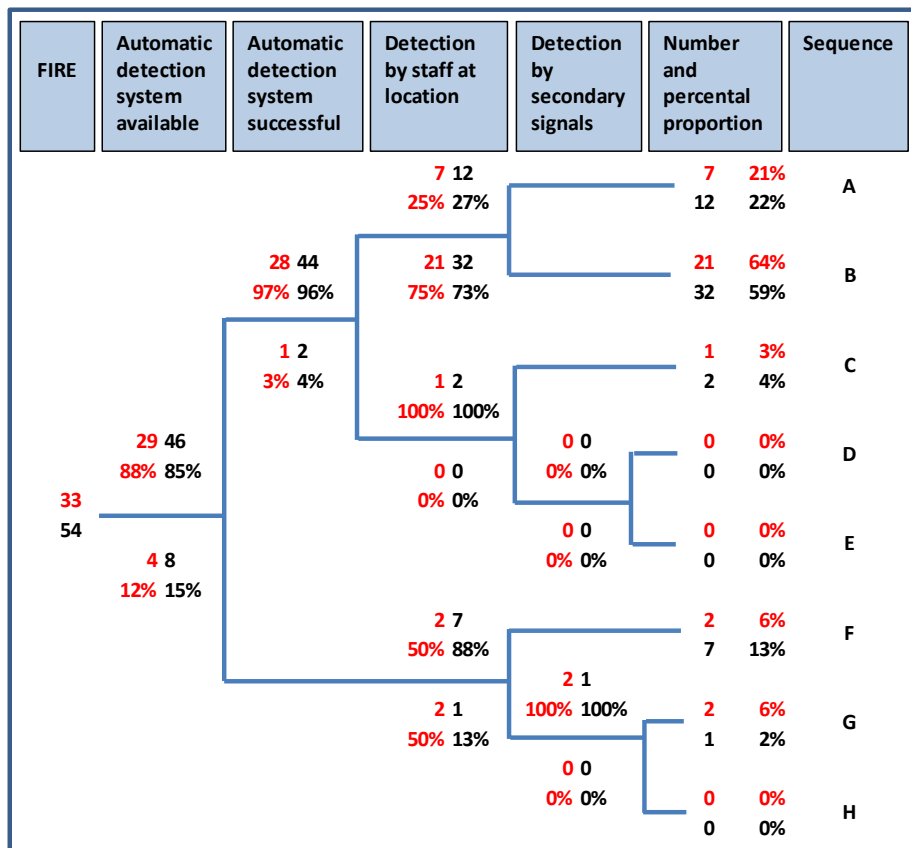
**Figure 4: Results of FET\_T (red – sample 1, black – sample 2)**



In Figure 5, the sequence F is the most striking one with about 6 % of the events in sample 1 and 13 % in sample 2 respectively. The major contributor for this result is the difference in the number of events that did not involve smoke detectors but were detected by plant personnel. In two of the fire events the reason for no smoke detectors being involved was that the fires took place outside of buildings, in the case of two other fire events the fires occurred inside closed volumes (e.g. electrical cabinets), the remaining fires were coded as “no fire detectors involved/installed in the area”. However, the reason that a higher percentage of the fires of sample 2 were detected by staff rather than secondary signals is due to the fact that most of these events (5 out of 7) were detected immediately by staff present close to the fire location.

Moreover, sequence G is the striking one in with 6 % of the events in sample 1 and 2 % in sample 2. These are fire events that were neither detected by fire detectors nor by personnel present in the affected plant area, but could be identified as fires according to indirect signals. In both samples, the fires occurred in compartments where no fire detectors were present (sample 1 - switchyard, inside drying facility, sample 2 – inside electrical cabinet). Therefore, this does not indicate a difference in fire safety concepts. Further differences in Figure 5 are only minor ones.

**Figure 5: Results of FET\_D (red – sample 1, black – sample 2)**



The suppression event tree as shown in Figure 6 exhibits major differences between the two samples. Sequence B accounts for those fires which did not self-extinguish, however, they were extinguished through automatically actuated fire extinguishing systems. The fact that German nuclear power plants only contain a small number of stationary fire extinguishing systems automatically actuated, explains that sample 1 does not contain such events. Nuclear power plants in other countries participating in the OECD FIRE data collection have more automatically actuated fire extinguishing systems in place, corresponding to the data in sample 2.

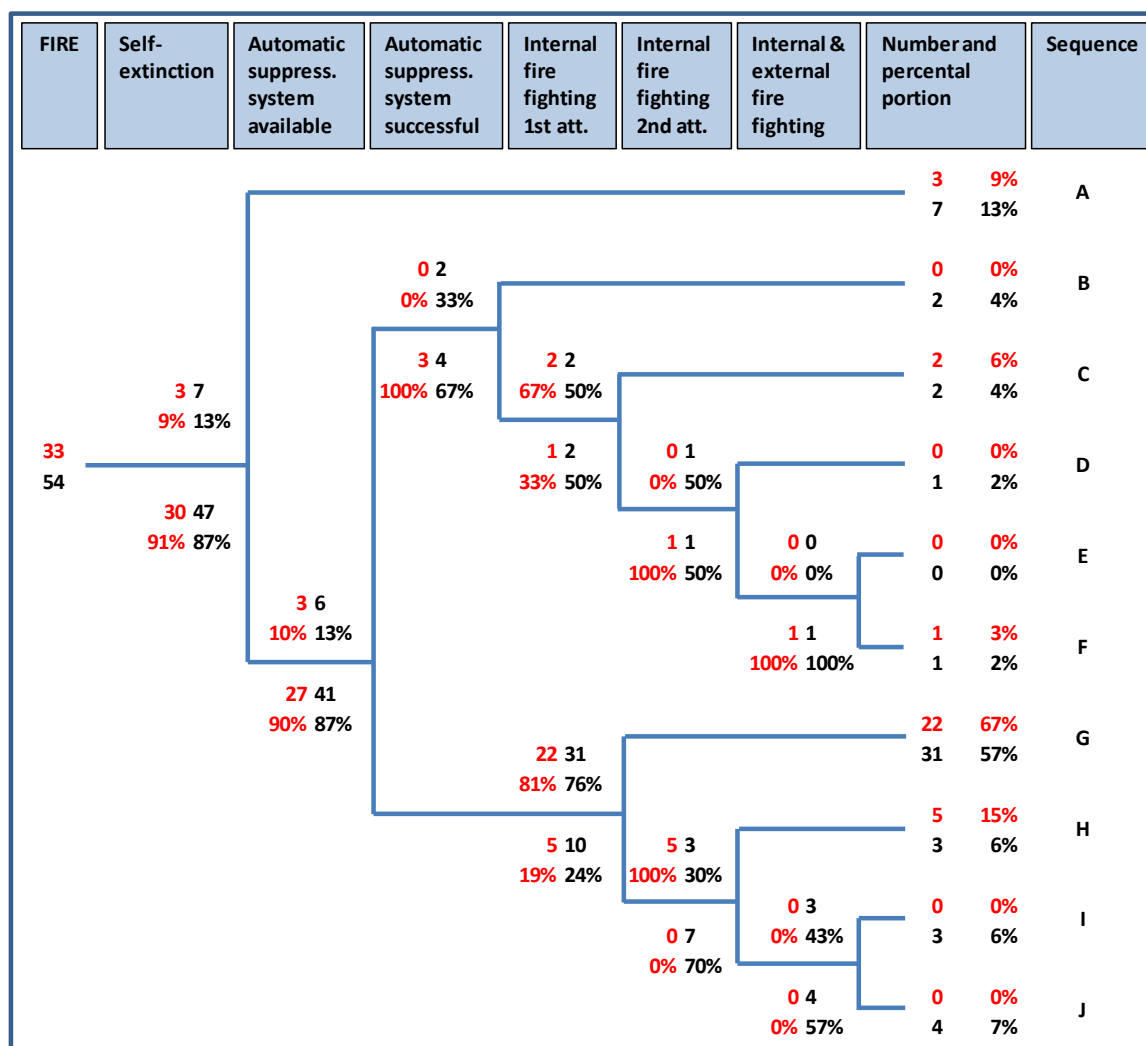
Moreover, on the bottom of Figure 6 further differences can be found between the samples. Sequence G represents fire events that did not self-extinguish, for which no automatic fire extinguishing system was available and finally, the fires were put out by the on-site plant fire brigade or plant personnel (1<sup>st</sup> attempt). Two thirds of the fires in sample 1 were extinguished this way, compared to 57 % in sample 2. One reason for this difference could be due to fast reaction/action times by the on-site fire brigades in the German plants.

Sequence H represents almost the same fires with the difference that these fires were extinguished after several attempts by the on-site plant fire brigade. Again, sample 1 obtains a higher percentage (15 %) than sample 2 (6 %). This result can be explained by the availability of professional on-site plant fire brigades in German plant, which is not necessarily the case in other countries.

Furthermore, in sample 2 a total of 13 % of the fires were extinguished by external fire fighters, in some cases together with the on-site fire brigade (see sequence I - 6 % und J - 7 %), compared to only one German fire event (2 %) involving external fire departments (see sequence F). Two factors are significant in this comparison: on the one hand, sample 2 only contains more severe fires that generally lasted longer (60 min on average) than in sample 1 (average of 50 min). On the other hand, there is less need for participation of an off-site fire brigade at German plants because an on-site professional fire brigade is mandatory.



Figure 6: Results of FET\_S (red – sample 1, black – sample 2)



## 6. CONCLUSIONS

The possibilities for flexible statistical evaluation of the information contained in the OECD FIRE Database have been significantly improved in the recent past. In the latest Database version [6] it is meanwhile possible to generate samples of fire events corresponding to the objective of the analysis to be carried out. Such samples may be automatically analyzed with respect to the entirety of the characteristics of fires available in the OECD FIRE Database by means of standardized queries. The evaluation indicates how often selected characteristics are present in the sample. There is also the possibility to analyze dependencies between two arbitrarily given characteristics of fires through cross tables.

A new evaluation option that corresponds to the complex nature of fire events has been presented. Thereby, real fire incidents are assigned to individual sequences of pre-determined generic fire event sequences. This analytical approach is currently being tested. For this purpose, fire events of two samples were classified, i.e. each fire event from the samples was assigned to the corresponding sequences in the generic event trees FET-T, FET-D and FET-S.

By means of the developed generic fire event trees a clear picture of both similarities and differences of fire events could be demonstrated. Through the mapped differences additional information could be

derived from the fire events. The outcome of the mapping of events also generated a corresponding sequence number for each generic event tree which can also be stored in the OECD FIRE Database.

More specifically, the fire event samples analyzed show a number of differences, mainly due to difference in severity and according to differences in the protection concepts against plant internal fires in nuclear power plants as required by national standards.

### Acknowledgements

The German participation in the OECD FIRE Database Project is funded by the Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (Bundesministerium fuer Umwelt, Naturschutz, Bau und Reaktorsicherheit, BMUB) within the frame of the project 3610R01375. Furthermore, the Authors are grateful for the support of the participating countries to the joint OECD FIRE Database Project.

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