

## IDENTIFICATION OF FIRE MODELING ISSUES BASED ON AN ANALYSIS OF REAL EVENTS FROM THE OECD FIRE DATABASE

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*Precursor analysis is widely used in the nuclear industry to judge the significance of events to safety. However, in case of events that may damage equipment through effects which are not ordinary functional dependencies, the analysis may not always fully appreciate the potential for further evolution of the event. For fires, which are one class of such events, the paper discusses modelling challenges that need to be overcome when performing a probabilistic precursor analysis. The events to exercise the approach on are selected from the OECD FIRE Database.*

### I. INTRODUCTION

Precursor analysis based on PSA is widely used in nuclear power industry to judge the significance of events to safety. This typically involves evaluating the effect on plant risk caused by known unavailability of equipment, while all other equipment retains the usual failure probability. In case of fire, the failure probability of components can be elevated according to their spatial vicinity to the fire source and the possible failures of fire detection and suppression. Even though the damage caused by the fire may be considered given for an individual event (Ref. 1), applying the concept of retaining the failure probabilities of equipment not failed to fire in a literal fashion requires the analyst to consider both the likelihood and the impact of failures of the measures credited to prevent spread of the fire.

It may be attempted to model the fire by directly using the fire scenarios created in order to obtain the CDF; however due to the unavoidable need for screening it is not ensured that the degree of refinement is such that the course of the event can be modelled in sufficient realism by relying on these events, as was already found before (Ref. 2) Therefore, in this work for each event a set of dedicated scenarios for aggravation of the fire is developed. The probability of these scenarios is determined by means of a Detection Suppression Event Tree (DSET) whose top events reflect the conditions of the individual event as far as known.

In order to gain experience with the approach, a number of events from the OECD FIRE Database (Ref. 3) are selected and sensitivity studies are conducted in order to check the feasibility of the implementation of the presented approach and to obtain an idea of the impact of aggravated scenarios.

### II. GENERAL APPROACH TO RISK EVALUATION

This section will first give an overview on how the various steps in the risk evaluation developed here are sequenced (Section II.A.), then introduce the rationale of how the DSET is structured (Section II.B.). Finally, Section II.C. introduces two candidate models for the evaluation of the fire brigade performance and show how the probabilities for the various aggravated scenarios are derived from those.

#### II.A. Method

The method to obtain a risk estimate in the form of Conditional Core Damage Probabilities (CCDP) for a given fire event follows these steps:

1. Determination of the timing of fire detection and suppression from narrative and timeline of the event
2. Identification of the original damage footprint and unrelated unavailabilities
3. Identification of PSA-relevant targets and associated propagation times beyond the original damage footprint
4. Identification of conditions for flashover and multi-compartment propagation
5. Grouping of the various propagation possibilities to consequence groups for the DSET
6. Determination of the structure of the DSET

- 7. Quantification of the DSET
- 8. Quantification of the PSA model with the consequences of the DSET as initiating events

Iterations may be necessary, especially between steps 5 and 6.

**II.B. The Detection Suppression Event Tree for a Simple Fire**

In order to develop the various sequences to which the fire event could have evolved, a fire event tree is quantified in MS EXCEL®, accounting for all success probabilities. The layout (Fig. 1) generally follows the one suggested in NUREG/CR-6850 (Ref. 4). However, for this paper the compartment isolation is queried before the fire brigade action, as the former may influence performance of fixed halon or carbon dioxide based gaseous suppression systems, which are then considered along with the latter. Furthermore, prompt detection and suppression are neglected since they are mostly relevant for welding scenarios or specialized detection devices that, if installed in any of the cases examined here, were not actuated. Finally, the top event for the fire brigade response is merged with the one for fixed manual suppression and becomes a multi-state top event to account for the various stages of fire aggravation given by the consequence groups.

In line with the general principles of precursor analysis, it is considered impossible for any of the equipment reported to have failed in the event narrative to be credited during the 24 h mission time of the transient model, while all other equipment may fail with the usual failure probability for the mission time. Wherever a sequence of the DSET is expected to lead to a damage footprint equivalent to the one observed in reality, the consequence *REAL* is assigned. This consequence may appear for multiple branches since not every failure is consequential by itself. Depending on the various combinations of failures in the top events of the DSET, types of consequences considered are intermediate propagation within the compartment (*INTERMEDIATE*), a full compartment fire after flashover (*WHOLE\_ROOM*) and effects outside the compartment of origin (*PROPAGATION*). Consequence categories *INTERMEDIATE* and *PROPAGATION* may of course comprise multiple individual consequences differing in severity. With the exception of smoke interfering with operator actions, propagation outside the compartment of origin is only treated as credible after flashover.

Reliability data for the detection, isolation and suppression events is chosen within the ranges found in NUREG/CR-6850 (Ref. 4) and the German PSA Guide (Ref. 5).

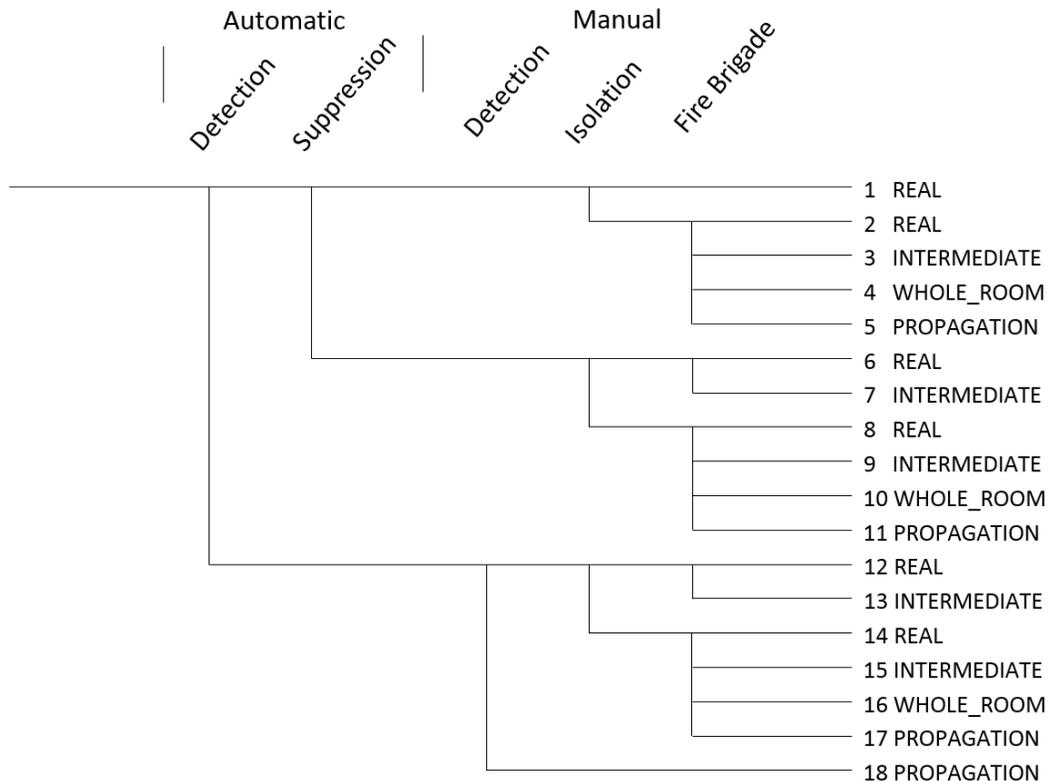


Fig. 1. A Detection Suppression Event Tree for a simple fire

## II.C. Fire Brigade Performance

As is done with component failures, it is desired to model the fire brigade in such a way that it certainly could not have performed better than during the actual event, but may have performed worse. Estimates of fire brigade performance based on averages of parameters such as suppression time over all fires in a broad category, e.g. electrical fires, may not be very meaningful for this purpose because they neglect the individual circumstances of the event, for example ease of access or the size of the fire. Therefore, it is sought here to derive the failure probabilities for the fire brigade as realistically as possible from the actual event, with two different models as candidates.

### II.C.1. Median-of-Half-Life Model

The idea of the Median-of-Half-Life Model is depicted in Fig. 2. After elapse of the response time  $t_r$  observed in the actual event between the detection of the fire and the attack by fire fighters, an exponential curve for the median probability of non-suppression  $P_{50}$  is started, with a half-life equal to the time from attack to reported extinction  $t_{obs}$ :

$$P_{50} = e^{-\frac{\ln 2}{t_{obs}}(t-t_r)} \quad (1)$$

In order to be consistent with mean-based point estimates, this median half-life is converted to a mean characteristic time  $\bar{t}$  with respect to the natural exponential function using the error factor  $EF$  derived from the quantiles of the suppression rates reported for the type of fire in NUREG-2169 (Ref. 6). With the characteristic time distributed lognormally over the degree of confidence, inserting equations (7.31) and (7.34) of Ref. 7 into equation (7.29) of the same reference leads to:

$$\bar{t} = e^{\left(\frac{\ln EF}{1.645}\right)^2 / 2} * \frac{t_{obs}}{\ln 2} \quad (2)$$

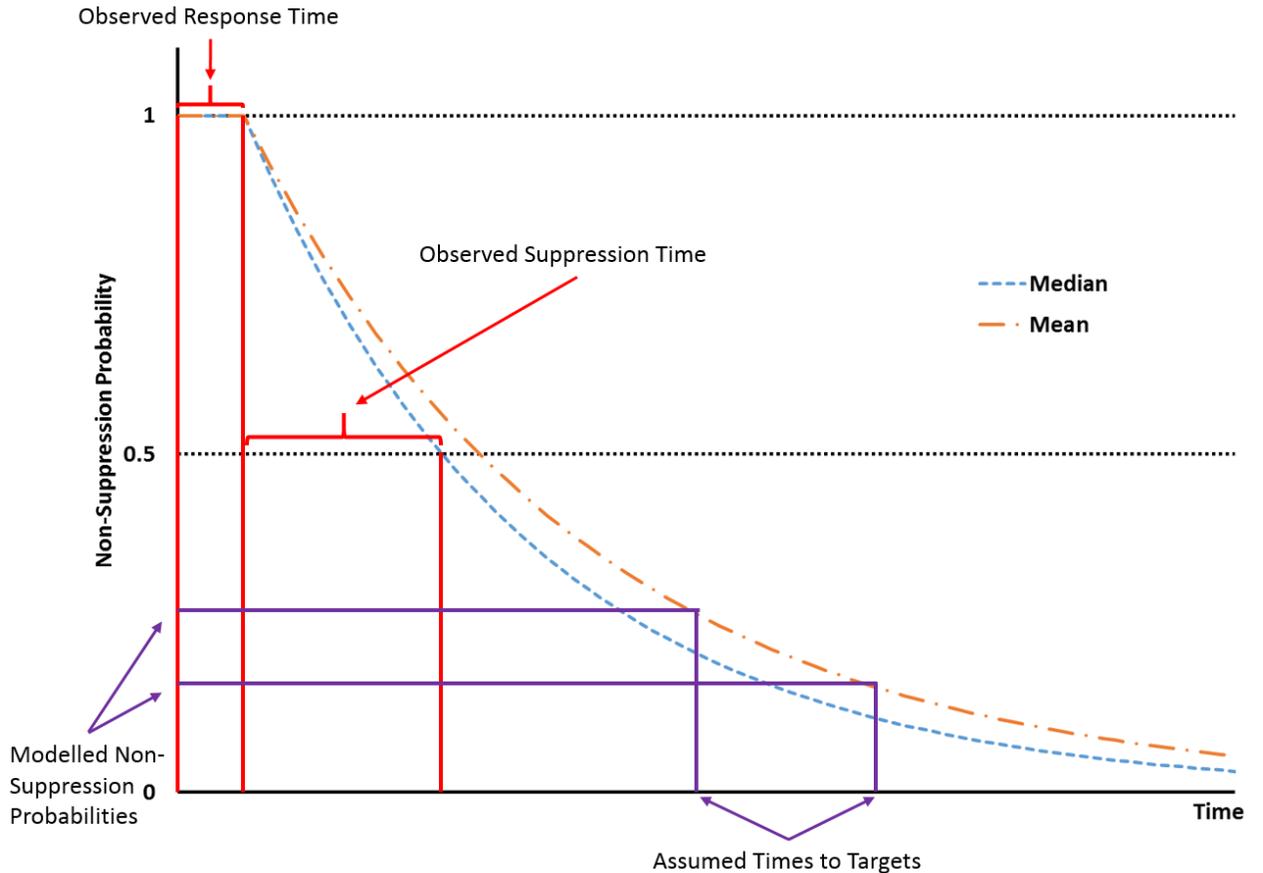


Fig. 2. The concept of the Median-of-Half-Life Model

It is acknowledged that this approach may introduce some conservatism as it implicitly assumes the uncertainty of the characteristic time, which NUREG-2169 reports including  $t_r$ , is dominated by the time from attack to extinction, which is the meaning of both  $t_{\text{obs}}$  and  $\bar{t}$  here. In addition, the error factor reported for all the fires in a broad category such as “electrical” not only captures the variability in performance of the fire brigade between shifts, which is what is needed here, but also any variability in ease of attack between the individual fires in that category, which of course would not vary for any given fire. In any case, the distribution for “electrical fires” being rather narrow and applicable to the bulk of the events considered here, both effects have minor influence.

### *II.C.2. Bayesian Model*

Alternatively, a Bayesian update of a generic suppression rate with the inverse of  $t_{\text{obs}}$  as evidence may be performed. Taking the median  $\lambda_M^*$  of a suppression rate as defined by NUREG-2169 (Ref. 6) and again lognormally distributed with respect to confidence, in a first step an arbitrary time of 2 min is subtracted from the associated characteristic time to account for  $t_r$  being included in the suppression time by the reference:

$$\lambda_M = \frac{1}{\frac{1}{\lambda_M^*} - 2\text{min}} \quad (3)$$

This leads to a prior distribution for the suppression rate  $\lambda$

$$P(\lambda) = \frac{1.645}{\lambda \ln EF \sqrt{2\pi}} e^{-\frac{1}{2} \left( \frac{1.645}{\ln EF} \ln \frac{\lambda}{\lambda_M} \right)^2} \quad (4)$$

and a likelihood function:

$$L(t_{\text{obs}}|\lambda) = \lambda e^{-\lambda t_{\text{obs}}} \quad (5)$$

The posterior distribution thus becomes:

$$P(\lambda|t_{\text{obs}}) = \frac{P(\lambda)L(t_{\text{obs}}|\lambda)}{\int_0^\infty P(\lambda)L(t_{\text{obs}}|\lambda)d\lambda} \quad (6)$$

The mean value  $\bar{\lambda}$  of this distribution may be used to again define the characteristic time:

$$\bar{t} = \frac{1}{\bar{\lambda}} \quad (7)$$

It turns out that due to the narrowness of the generic distribution for the “electrical fires” bin, the characteristic times rarely leave the interval from 8.0 min to 8.5 min, which causes this model to show very little adaptation to the actual event. Of course, the distribution might be artificially broadened, but such a measure would again introduce yet another degree of arbitrariness.

### *II.C.3. Fire Brigade Failure Probabilities*

As illustrated by Fig. 3, it is assumed that the fire will destroy any equipment within the damage footprint reported by the Database, and spread further outward from the source until suppressed, with the non-suppression probability reducing as time passes and additional targets are damaged one by one. Regardless of the model chosen for the characteristic time, the probability  $P_{\text{ab}}$  for the fire propagating up to target  $a$ , but not as far as target  $b$ , can be expressed by the respective propagation times  $t_a$  and  $t_b$ :

$$P_{\text{ab}} = e^{-\frac{t_a - t_r}{\bar{t}}} - e^{-\frac{t_b - t_r}{\bar{t}}} \quad (8)$$

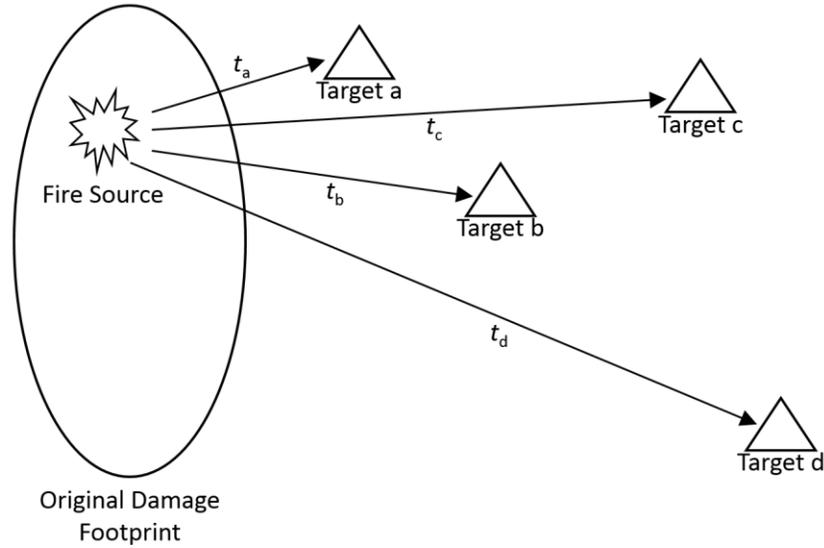


Fig. 3. The sequencing of fire impacts

If there is a fixed suppression system available that is either be designed to be manually actuated or was not actuated automatically due to failure of automatic detection, the failure probability is reduced by a factor of 10 in line with typical reliability data (Ref. 5) for any target  $c$  reached in a  $t_c$  of more than 15 min after the beginning of the attack, with target  $d$  to be reached later at time  $t_d$ :

$$P_{cd} = 0.1 \left( e^{-\frac{t_c - t_r}{\tau}} - e^{-\frac{t_d - t_r}{\tau}} \right) \quad (9)$$

Taking  $c$  as the first target, this arrangement would correspond to the event tree detail in Fig. 4 were the top events for fire brigade and fixed manual suppression separated. Trivially, when calculating the probability of the fire propagating up to the last target to be reached in the compartment, the second term in above probabilities disappears.

To account for the potential of a fire brigade response slower than in the actual event, a weighted average over the  $P_{ab}$  evaluated with different  $t_r$  is taken. For lack of applicable data, the default distribution is arbitrarily assumed with 70 % on the real response time, 20 % on a 2 min longer and 10 % on a 4 min longer response time. Only the real response time is accounted for if at the time of attack, personnel was already waiting next to the fire site, and had not yet commenced the extinguishing actions e.g. because a busbar in the fire area needed to be deenergized due to safety considerations.

Taking inspiration from the Thomas criterion (Ref. 8), if enough time passes for the heat release rate to grow large enough to credibly bring the temperature to 500 °C within minutes, a flashover is considered credible. Where credible given the sequence-specific state of compartment isolation, the flashover probability is assigned to the branch by expert judgement. This probability is removed from the corresponding *INTERMEDIATE* branch and assigned to the *MAXIMUM* or *PROPAGATION* branches as appropriate. Multi-compartment propagation is neglected where the neighbouring compartment contains no additional targets or has plentiful open space to dissipate any hot gas emanating from the source compartment.

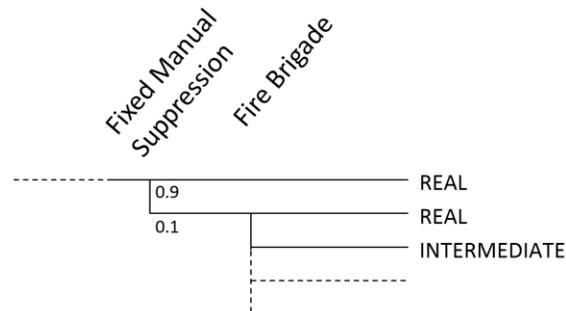


Fig. 4. Fixed manual suppression as a separate top event

### III. SCENARIO GENERATION

#### III.A. Selection of Events and Mapping to Plant Location

From the OECD FIRE Database, release 2014:2 (Ref. 3) of January 2016, a number of events among those that occurred in plants of broadly similar make as the reference plant (see Section III.B.) and involved a reactor trip or rapid administrative shutdown is selected for modelling. Criteria for selection are such properties of the record as

- loss of safety trains,
- impact on other components,
- impact on other rooms, or
- necessity for fire brigade intervention.

These criteria are meant to ensure that the work concentrates on substantial fires which would not likely have self-extinguished if left unattended. Of the nine events chosen from the Database, six took place in the electrical building, two in the turbine hall and one in a bunkered independent emergency building.

From the narrative of the event, the type of component where the fire started is identified. Mapping the fire from the plant that experienced the event to the reference plant trivially means that the CCDPs presented here cannot be attributed to any actual event in a nuclear power plant, but need to be regarded as applicable to a hypothetical event that might have happened at the reference plant, but did not.

#### III.B. Transient Quantification

The individual consequences of the DSET are assigned individual initiating events in a simplified PSA model (designated as reference plant) quantified using the fault tree/event tree software FinPSA (Ref. 9). No formalized screening of negligible consequences according to CCDP impact is performed, so all physically credible sequences of the DSET are quantified.

### IV. SPECIAL CASES

In the following part the cases among the nine events from the Database for which above method was found in need of modification are discussed. All of the information was derived from the narrative and timeline of the OECD FIRE Database.

#### IV.A. Ventilation Faster than Smoke Detector

While locally investigating an electrical fault on a switchboard, operators noticed visible smoke emanating from the cabinet. Smoke detectors were installed in the room, but did not actuate during the event, and when they were tested with fumigants, they operated as required. It was concluded that the room ventilation had diverted the smoke in such a way that the smoke detectors did not reach actuation during the event. Therefore, it is judged that the fire would have had to reach a size capable of damaging the entire cabinet of origin before being detected by automatic systems. This implies that the real consequence, which is the failure of just a single component supplied by the switchboard, is only possible upon success of manual detection. In contrast, success of automatic detection in combination with failure of manual detection would lead to a somewhat larger damage footprint.

#### IV.B. Hydrogen Release in the Turbine Hall

The event was a loss of hydrogen from a pipe plug on the generator hydrogen system, which quickly ignited and burned steadily for some ten minutes until isolation of the hydrogen supply. It is conventional wisdom that combustible mixtures in industrial settings will always find an ignition source (Ref. 10), however there is no guarantee that ignition will always occur before the amount of mixture created is large enough to create more serious damage than observed in the actual event. Thus, as the DSET introduced before would not accommodate the possibilities for event escalation, the event tree shown in Fig. 5 is used for this event. Top event “Ignition Source” serves to account for various delays in ignition, meaning a larger damage footprint of the following deflagration, with the top branch leading to the real consequence with no deflagration at all. “Secondary Combustible” refers to damage on the turbine lube oil system caused by the deflagration resulting in a regular fire that needs to be controlled by the fire brigade and, failing that, isolated from other plant areas. Since gaseous suppression systems would be a rather unusual choice for a turbine-generator area, the “Isolation” top event can be conveniently placed after the suppression.

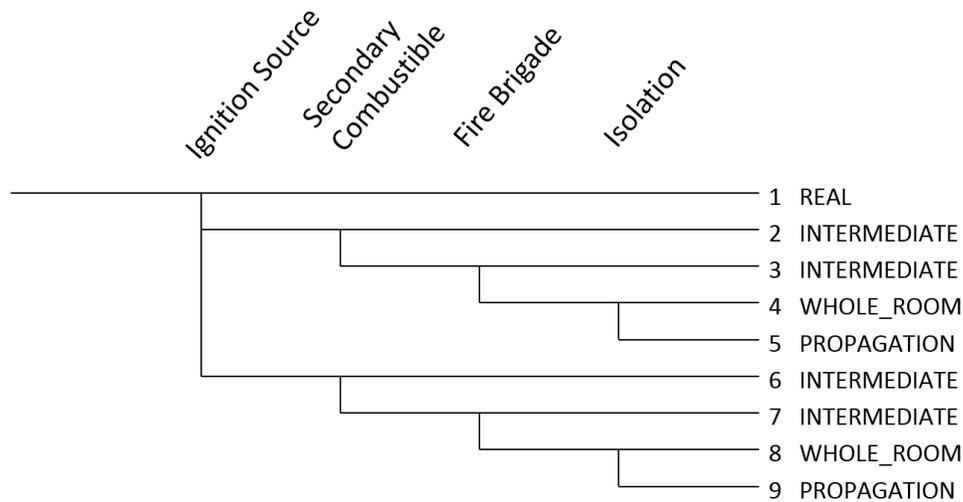


Fig. 5: DSET for a hydrogen release

#### IV.C. Fire inside an Electrical Penetration

This event was caused by a power cable overheating in a penetration between electrical building and turbine hall. The fire was attacked from both sides of the penetration, but progress was slow as the fire brigade first had to wait for the main control room to deenergize the cables inside the penetration, then break the structure around it to gain access to the fire source.

The deenergization of the cables was delayed due to the necessity to obtain information about cable routings from the company headquarters. This communication process may create a significant potential for deenergizing cables that are really routed somewhere else and would not pose a hazard to personnel during extinguishing. To capture this effect, a probability for human error to identify the right cables to deenergize is distributed evenly across the neighbouring sectors of the penetration as assigned for the walkdown, so all power and signal cables routed through a given sector would be failed dependently if that sector is erroneously deenergized. Of course, only open circuit failure modes need to be considered, but no hot shorts, as the cable insulation would stay intact. The relevant failure probabilities are included in the systems model by means of fault trees controlled by house events.

Using the observed suppression time of more than two hours to evaluate fire brigade performance would give an unrealistically high probability of propagation along the cable trays, as the non-suppression probability would decline only very slowly. However, during the real event, the fire did not propagate; the fire fighters needed time to break open the structure surrounding the fire source. Therefore, a more realistic value of the characteristic suppression time with regard to the partial success of preventing within-compartment-propagation is judged to be somewhat higher than the generic one reported in NUREG-2169 (Ref. 6) for electrical fires.

#### IV.D. Consecutive Fires

In one case, two causally related fires occurred in medium voltage switchgear within a few hours, so even though the Database lists two events, a single CCDP is assigned. The first event was a high energy arcing fault (HEAF) in a crosstie cable between two 4 kV buses. The ensuing fire was extinguished within 5 minutes with a response time of 4 minutes, which directly yields the parameters for the models described in Section II.C.

The second fire took place when operators tried to bring tripped equipment back to service. The busbar damaged by the previous arc was inadvertently reenergized, causing another arc on a circuit breaker. This time, suppression time for the fire was 18 minutes and response time 9 minutes. Only 5 minutes after the arc field personnel reported the fire, so it seems that it was not obvious to plant staff that another event had occurred. Therefore, it is judged that fire detection would be required for the response to take place in a timely manner. Because the automatic fire detectors had not been reset after the first fire, any further fire detection would have to be manual.

These considerations lead to the event tree shown in Fig. 6, with bypassed events for automatic functions removed for simplicity. It should be noted that another minor fire had occurred as a consequence of the first event, which caused an auxiliary pump on the balance-of-plant to loose seal water and catch fire.

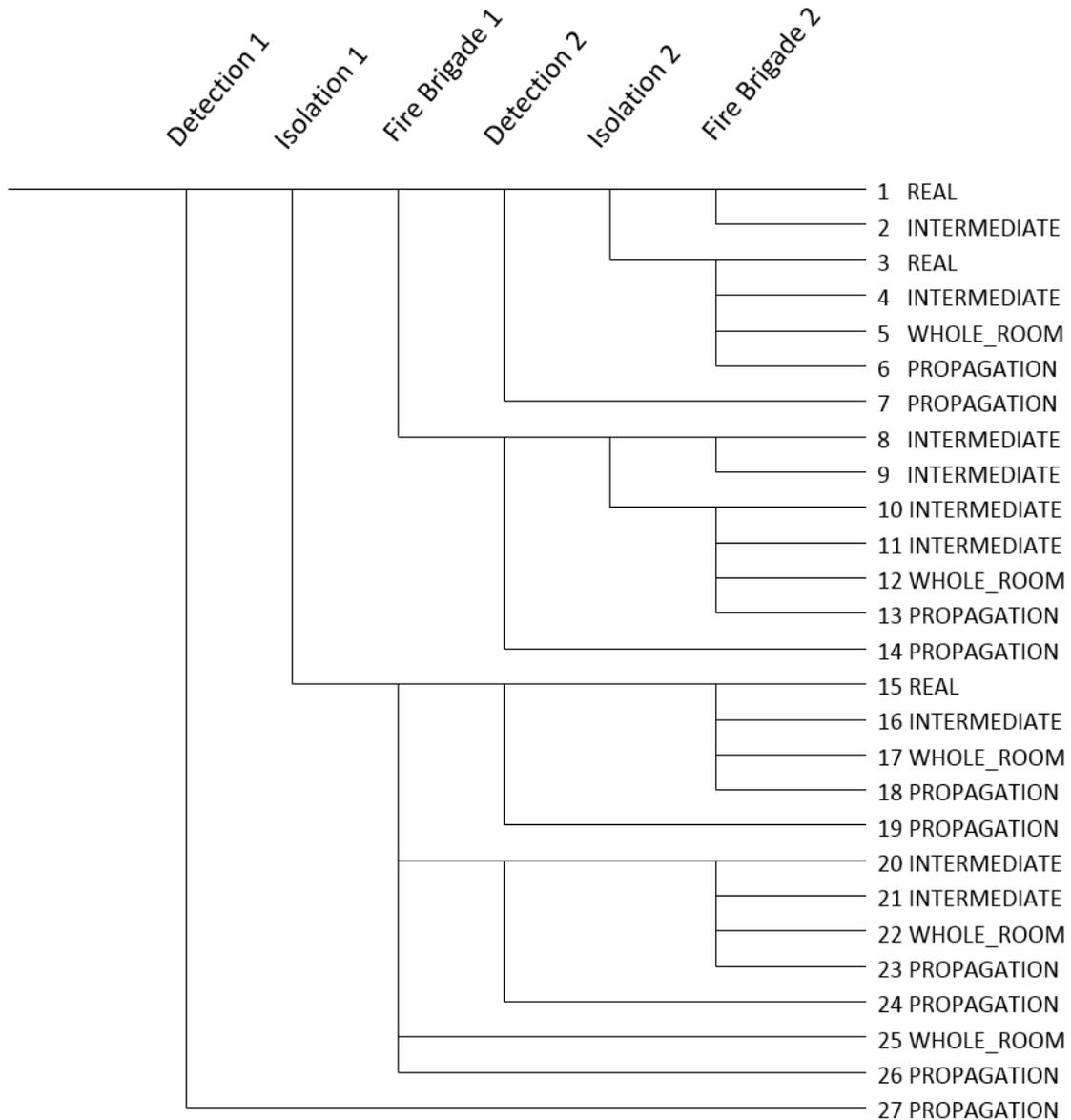


Fig. 6: DSET for two consecutive fires

## V. RESULTS

In order to estimate the effect of potential propagation on the risk, the relative risk increase  $RRI$  is defined as the ratio between the CCDP with propagation  $R_P$  and the CCDP of the real event without propagation  $R_R$ :

$$RRI = \frac{R_P}{R_R} \quad (10)$$

The cumulative distribution of the  $RRI$  is shown in Fig. 7. Two of the nine events had no conceivable propagation targets around the mapped location of the reference plant, so their  $RRI$  is 1. It should be noted that the total risk for a further four events is dominated by a whole-compartment fire after flashover. Changing assumptions on this phenomenon, which is legitimate given the uncertainties involved, may influence results heavily for these events.

The  $RRI$  tends to be lower with the Bayesian Model for the fire brigade, however, as already mentioned in Section II.C.2., it takes rather imperfect account of the observation due to a very narrow prior distribution.

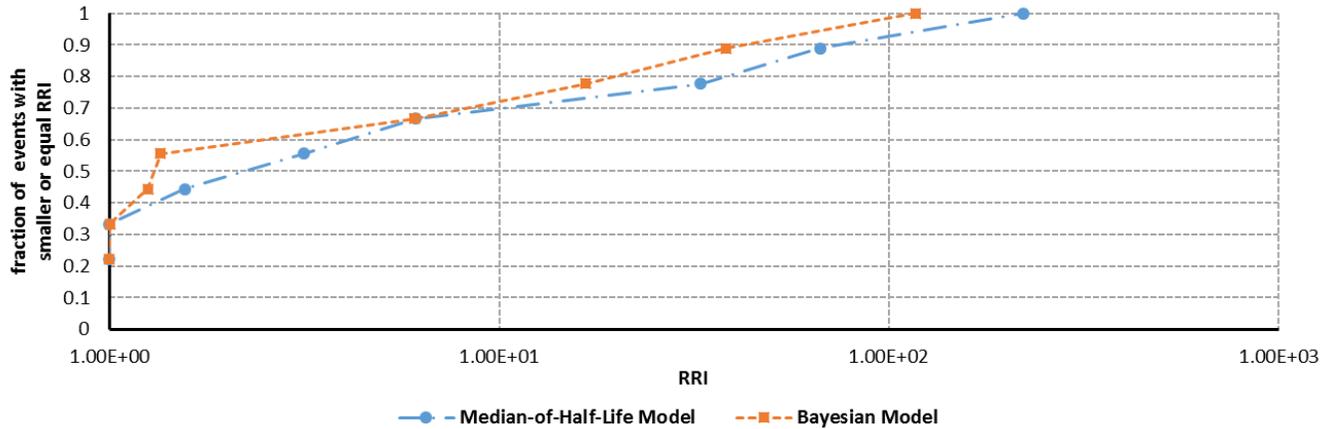


Fig. 7: Risk increases found in this study

## VI. CONCLUSION

The CCDP of a fire event can be affected by including the potential for fire propagation; however the size of the effect strongly depends on the location and nature of the event. Due to the multitude of factors influencing fire behaviour and the response of plant systems and operators to a fire, an exhaustive description of all the possible modifications to the logic models necessary to realistically model the possible sequence of an event may not be achievable for the foreseeable future. It was shown that such modifications may range in scope from a judgement call regarding a single split fraction on an event tree to the development of an entirely non-standard pre-tree.

The modelling of the suppression time needs to be carefully considered, especially if the risk increase due to the potential for propagation is significant. Although generic suppression times are easily applied, they may not be consistent with the actual event sequence.

## ACKNOWLEDGEMENTS

The author would like to thank Annette Ramezani, Bernhard Reer and Gerhard Schoen of ENSI, Marina Röwekamp of GRS and Matti Lehto of STUK for helping him to figure out what he was trying to say. He also wants to acknowledge the support provided by the members of the OECD FIRE Database Project, making the mission of this Project a successful one through their active contributions.

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