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Original Article

Identification of Fire Modeling Issues Based on an Analysis of Real Events from the OECD FIRE Database

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ABSTRACT

Precursor analysis is widely used in the nuclear industry to judge the significance of events relevant to safety. However, in case of events that may damage equipment through effects that 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, this paper discusses modelling challenges that need to be overcome when performing a probabilistic precursor analysis. The events used to analyze are selected from the Organisation for Economic Cooperation and Development (OECD) Fire Incidents Records Exchange (FIRE) Database.

1. Introduction

Precursor analysis based on Probabilistic Safety Analysis (PSA) is widely used in the nuclear power industry to judge the significance of events in terms of 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 the case of fire, the failure probability of components can be elevated according to component spatial vicinity to the fire source and possible failures of fire detection and suppression. Even though the damage caused by the fire may be considered given for an individual event [1], applying the concept of retaining the failure probabilities of equipment that did not fail due to the fire in a literal fashion requires the analyst to consider both the likelihood and the impact of failures of the measures credited to prevent the spread of the fire.

An attempt may be made to model the fire by directly using the fire scenarios created in order to obtain the core damage frequency (CDF); however, due to the unavoidable need for screening it is not ensured that the degree of refinement will be such that the course of the event can be modelled with sufficient realism by relying on these events, as has already been recognized [2]. Therefore, in this work, for each event, a set of dedicated scenarios of 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.

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In order to gain experience with the approach, a number of events from the Fire Incidents Records Exchange (FIRE) Database [3] of the Organisation for Economic Cooperation and Development (OECD) are selected and sensitivity studies are conducted in order to check the feasibility of the implementation of the approach presented and to obtain an idea of the impacts of the aggravated scenarios.

2. Methods

The method of obtaining 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; and (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.

2.1. *Detection suppression event tree for a simple fire*

In order to develop the various sequences into which the fire event could have evolved, a fire event tree is quantified in Microsoft EXCEL (Microsoft Corporation, Redmond, WA, USA), accounting for all success probabilities. The layout (Fig. 1) generally follows the one suggested in NUREG/CR-6850 [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 because 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 top event for fixed manual suppression and becomes a multi-state top event that accounts 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-hour mission time of the transient model, whereas 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 because 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 that differ 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 are chosen within the ranges found in NUREG/CR-6850 [4] and the German PSA Guide [5].

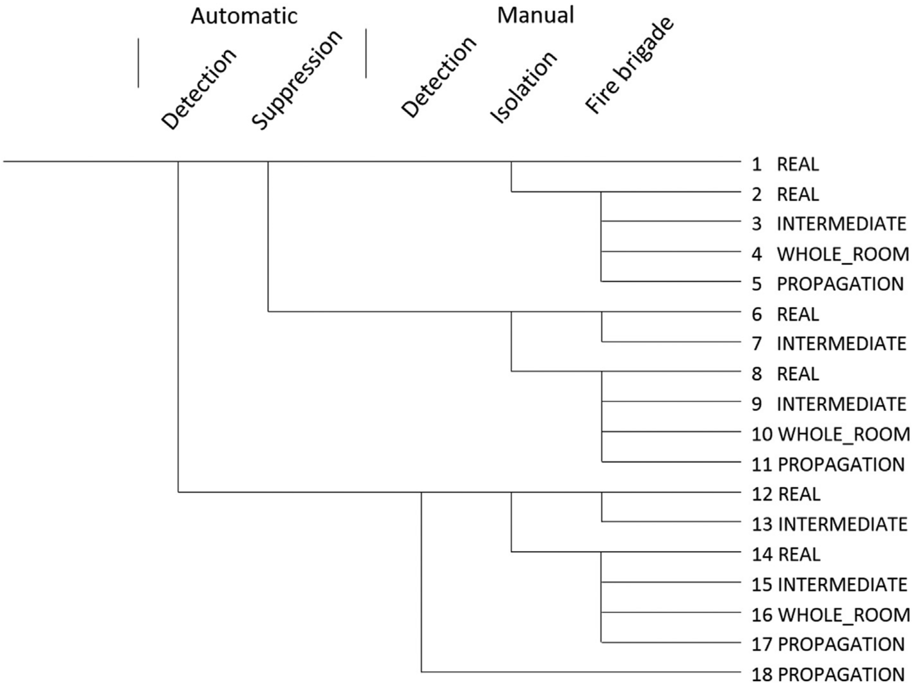

Fig. 1 – Detection suppression event tree for a simple fire.

2.2. *Fire brigade performance*

As is done with component failures, it is desirable 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 the 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, e.g. ease of access or the size of the fire. Therefore, it is attempted here to derive the failure probabilities for the fire brigade as realistically as possible from the actual event, with two different models as candidates.

2.2.1. *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 nonsuppression P_{50} as a function of time under attack t is started, with a half-life equal to the time from attack to the reported extinction t_{obs}:

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

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

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

It is acknowledged that this approach may introduce some conservatism as it implicitly assumes that 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_{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, because the distribution for "electrical fires" is rather narrow and applicable to the bulk of the events considered here, both effects have minor influence.

2.2.2. *Bayesian Model*

Alternatively, a Bayesian update of a generic suppression rate with the inverse of t_{obs} as evidence may be performed. Taking the median λ^*_M of the suppression rate as defined by NUREG-2169 [6] and again log normally distributed with respect to confidence, in a first step an arbitrary time of 2 minutes is subtracted from the associated characteristic time to account for t_r, which is included in the suppression time by the reference:

$$\lambda_M = \frac{1}{\frac{1}{\lambda^*_M} - 2\ \text{min}} \tag{3}$$

This leads to a prior distribution with median λ_M for the suppression rate λ

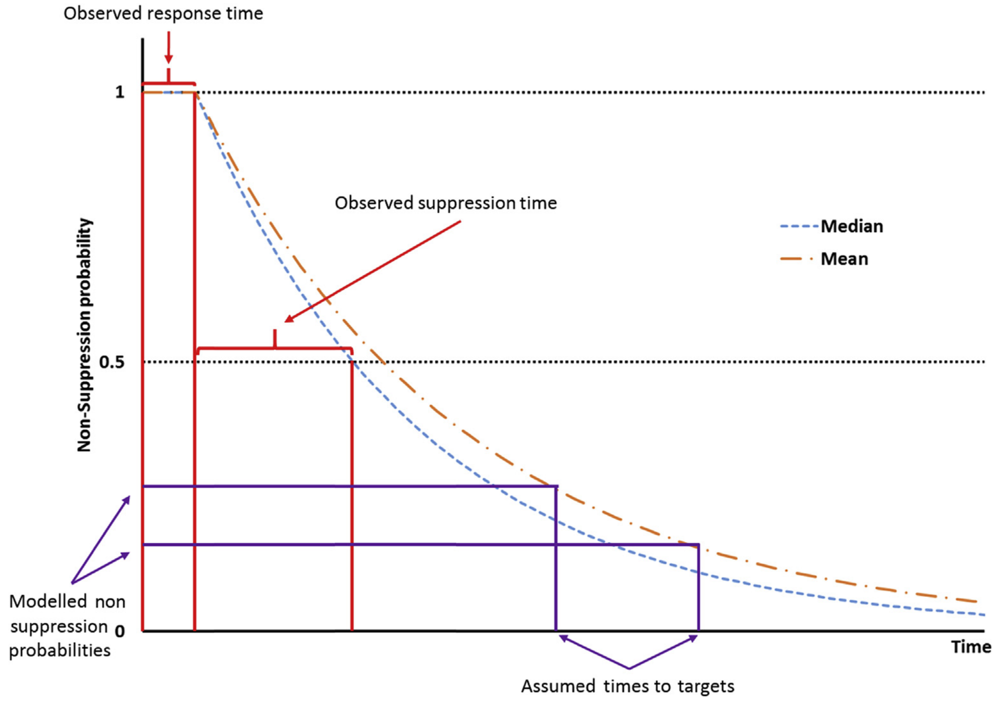

Fig. 2 – Concept of the Median-of-Half-Life Model.

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

and a likelihood function:

$$L(t_{obs} \mid \lambda) = \lambda e_{obs}^{-\lambda t} \tag{5}$$

The posterior distribution thus becomes:

$$P(\lambda \mid t_{obs}) = \frac{P(\lambda)L(t_{obs} \mid \lambda)}{\int_0^\infty P(\lambda)L(t_{obs} \mid \lambda)d\lambda} \tag{6}$$

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

$$\bar{t} = \frac{1}{\bar{\lambda}} \tag{7}$$

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 minutes to 8.5 minutes, 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.

2.2.3. *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 nonsuppression probability dropping as time passes and additional targets are damaged one by one. Regardless of the model chosen for the characteristic time, the probability P_{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:

$$P_{ab} = e^{-\frac{t_a - t_r}{\bar{t}}} - e^{-\frac{t_b - t_r}{\bar{t}}} \tag{8}$$

If there is a fixed suppression system available that is either 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 [5] for any target c reached in a t_c of more than 15 minutes after the beginning of the attack, with target d to be reached later at time t_d:

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

Taking c as the first target, this arrangement would correspond to the event tree detail in Fig. 4, if the top events for fire brigade and fixed manual suppression were 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 the 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. Due to lack of applicable data, the default distribution is arbitrarily assumed with a weight of 70% on the observed response time, 20% on a 2-minutes longer and 10% on a 4-minutes longer response time. Only the real response time is accounted for if, at the time of attack, personnel were 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.

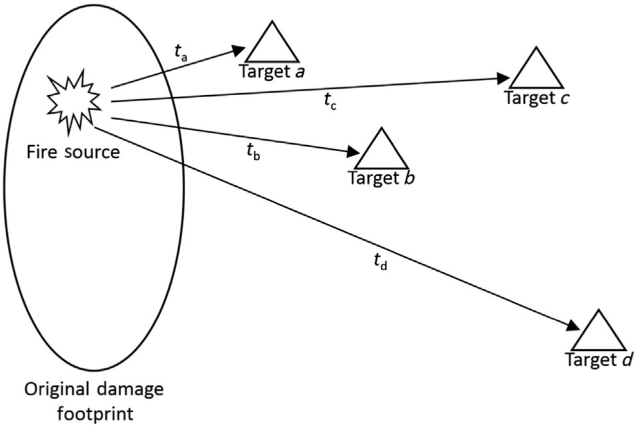

Fig. 3 – Sequencing of fire impacts.

Taking inspiration from the Thomas criterion [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 judgment. 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 neighboring compartment contains no additional targets or has plentiful open space to dissipate any hot gas emanating from the source compartment.

2.3. *Scenario generation*

2.3.1. *Selection of events and mapping to plant location*

From the OECD FIRE Database, release 2014:2 [3] of January 2016, a number of events among those that occurred in plants of broadly similar make as the reference plant and involved a reactor trip or rapid administrative shutdown is selected for modelling. Criteria for selection are such properties of the record as: (1) loss of safety trains; (2) impact on other

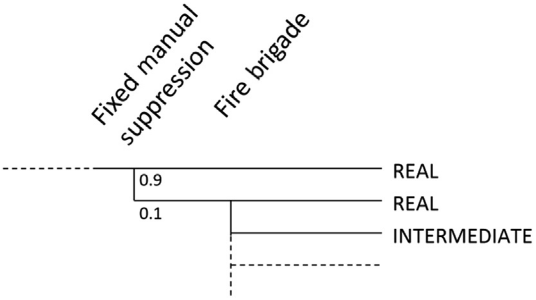

Fig. 4 – Fixed manual suppression as a separate top event.

components; (3) impact on other rooms; or (4) necessity for fire brigade intervention.

These criteria are meant to ensure that the work concentrates on substantial fires that 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 on which the fire started is identified. Mapping the fire from the plant that experienced the event to the reference plant 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.

2.3.2. *Transient quantification*

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

2.4. *Special cases*

In the following part, the cases among the nine events from the Database for which the 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.

2.4.1. *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 yet 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. By contrast, success of automatic detection in combination with failure of manual detection would lead to a somewhat larger damage footprint.

2.4.2. *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 10 minutes until isolation of the hydrogen supply. It is conventional wisdom that combustible mixtures in industrial settings will always find an ignition source [9]; 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 possibilities of event escalation, the event tree shown in Fig. 5 is used for this event. The 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 to 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. As 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.

2.4.3. *Fire inside an electrical penetration*

This event was caused by a power cable overheating in a penetration between the electrical building and the 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, and 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 regarding cable routings from the company headquarters. This communication process may

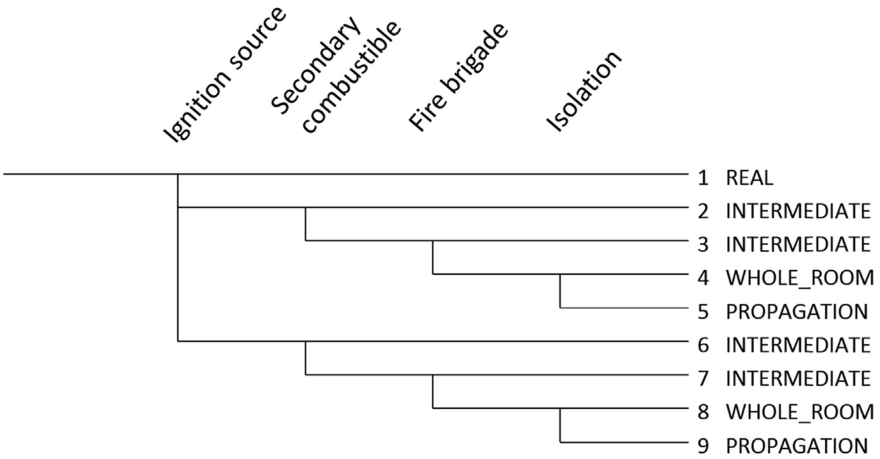

Fig. 5 – Detection suppression event tree (DSET) for a hydrogen release.

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 neighboring sectors of the penetration, as assigned for the walkdown, so all power and signal cables routed through a given sector would fail dependently if that sector were 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.

The use of the observed suppression time of more than 2 hours to evaluate the fire brigade performance would give an unrealistically high probability of propagation along the cable trays, as the nonsuppression 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 value reported in NUREG-2169 [6] for electrical fires.

2.4.4. *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 earlier.

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 was 9 minutes. Only 5 minutes after the arc field had occurred, personnel reported the fire, therefore, it seems that it was not obvious to plant staff that another event had occurred. It is thus judged that fire detection would be required for the response to take place in a timely manner. As 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 occurred as a consequence of the first event, which caused an auxiliary pump on the balance-of-plant to lose seal water and catch fire.

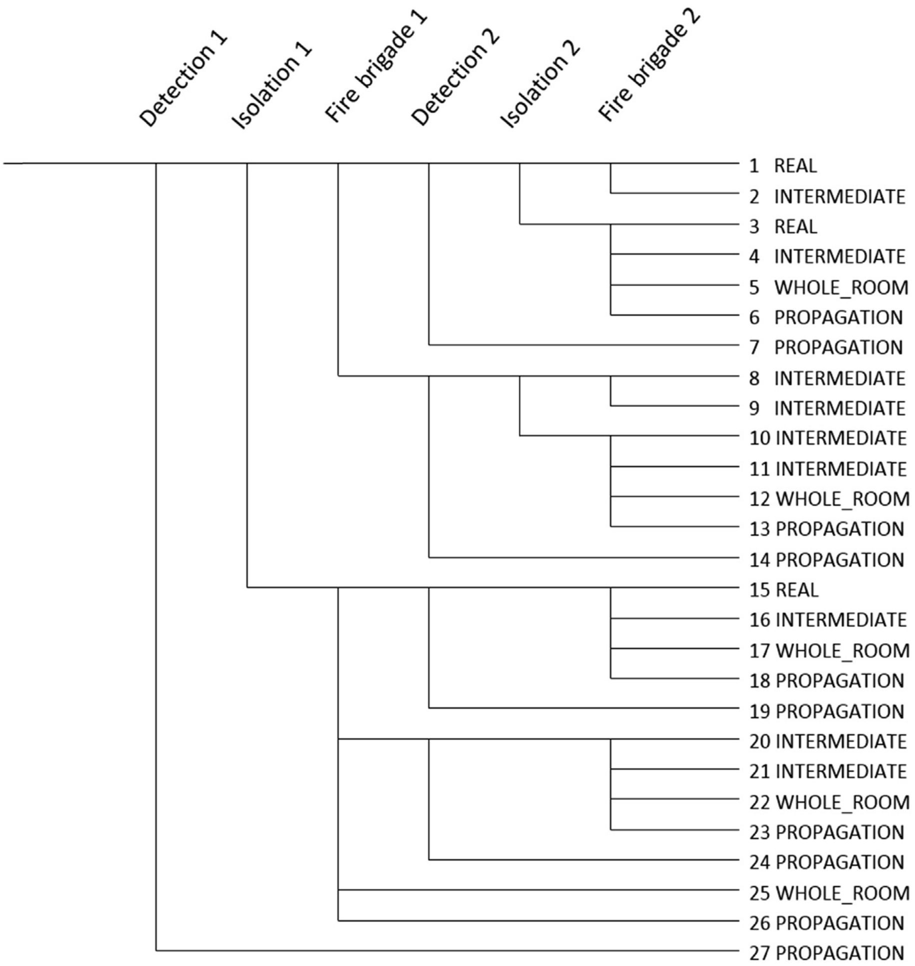

Fig. 6 – Detection suppression event tree (DSET) for two consecutive fires.

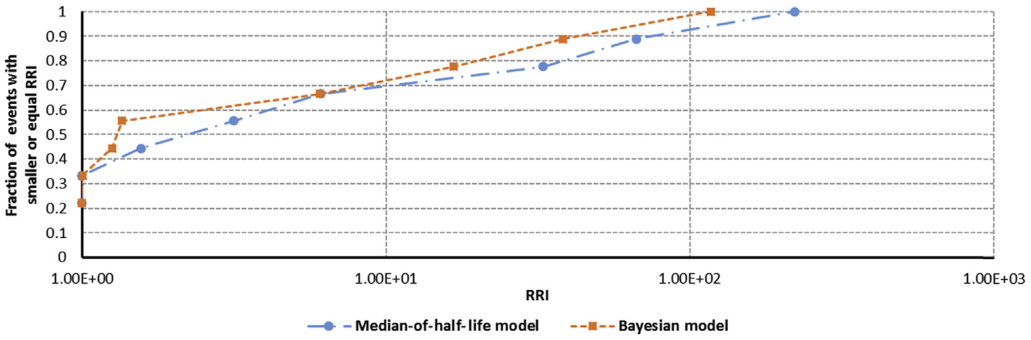

Fig. 7 – Risk increases found in this study.

3. 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, therefore, their *RRI* values are 1. It should be noted that the total risk for a total of four further events is dominated by the risk of a whole-compartment fire after flashover. Changing the assumptions for this phenomenon, which is legitimate given the uncertainties involved, may influence the results heavily for these events.

The *RRI* tends to be lower when using the Bayesian Model for the fire brigade; however, as already mentioned, this model takes rather imperfect account of observation due to the very narrow prior distribution.

4. 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 behavior 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 in the foreseeable future. It was shown that such modifications may range in scope from a judgement call regarding a single split fraction in an event tree to the development of an entirely nonstandard pretree.

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.

Conflicts of interest

The author has no conflicts of interest to declare.

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